Dissertation

Comparison of Off-Grid Electrification versus Grid Extension:

Influencing Parameters and The Role of Renewable Energy From a Geographic Point of View

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A daunting task lies ahead for scientists and engineers to guide society towards environmentally sustainable management during the era of the Anthropocene. [...] At this stage, however, we are still largely treading on terra incognita.

(Crutzen, 2002)

Danksagung

Nach nun mehr als vier Jahren intensiver Beschäftigung mit der Erarbeitung und Bewertung verschiedener Elektrifizierungsstrategien am Beispiel Nigeria, habe ich meine Dissertation fertig gestellt. Dies wäre mir nicht ohne die unentwegte Unterstützung von unterschiedlichsten Seiten gelungen. Dafür bin ich sehr dankbar.
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Berlin, 13. April 2018

Zusammenfassung

Eine zuverlässige und nachhaltige Stromversorgung ist in vielen ländlichen Gebieten Nigerias momentan nicht gegeben. Um diesem Defizit zu begegnen, haben die Vereinten Nationen und Nigeria selbst, das Ziel einer sauberen und sicheren Vollversorgung bis 2030 festgesetzt.
Im Rahmen dieser Arbeit werden zwei grundsätzlich verschiedene Ansätze dieses Ziel zu erreichen untersucht: Zum einen kann das bereits bestehende, zentral organisierte Stromversorgungssystem modernisiert und erweitert werden, zum anderen kann dezentrale Stromerzeugung ausgebaut werden. Um diese Optionen unter Berücksichtigung erneuerbaren Energien zu untersuchen und Empfehlungen abzuleiten, wird eine auf Geoinformationssystemen aufbauende Elektrifizierungsplanung für ländliche, nicht ausreichend mit Strom versorgte Regionen am Beispiel der fünf nigerianischen Bundesstaaten Cross River, Niger, Ogun, Plateau und Sokoto, durchgeführt. Hierbei liegt ein Schwerpunkt auf der räumlich aufgelösten Modellierung des Stromnetzausbaus unter Berücksichtigung verschiedener Faktoren, wie Topographie, existierende Infrastruktur und unterschiedliche Landnutzung (z. B. Wald, Wasserflächen und Naturschutzgebiete), mit dem Ziel eines möglichst konkreten, raumbezogenen Vergleichs, um eine integrierte, kostenoptimierte Planung zu erreichen, die anschließend in konkreten Handlungsempfehlungen resultiert.
Die Ergebnisse zeigen, dass die installierten Stromerzeugungskapazitäten des bestehenden Systems deutlich vergrößert werden müssen. Erst im Anschluss daran ist es sinnvoll, das bestehende Stromnetz zu erweitern. Parallel dazu empfiehlt sich die Installation von dezentralen Stromversorgungssystemen: Auf der einen Seite hybride Mini-Grids (Technologiekomponenten: Photovoltaik, Batteriespeicher und Dieselgenerator) in Wachstumszentren und größeren Orten, auf der anderen Seite kleinskalige Solar-Home-Systems auf Haushaltsebene in strukturschwachen und dünn besiedelten Regionen. Die Mini-Grids können zukünftig in ein ausgebautes Stromnetz integriert werden und dort zusätzliche Stromerzeugungskapazität einbringen. Netzausbau und dezentrale Lösungen schließen sich nicht aus, im Gegenteil, die Vorteile beider Ansätze können intelligent kombiniert werden und somit einer dichotomen Lösung entgegenwirken. Ermöglicht wird dies durch die Kostenreduktionen für erneuerbare Energie- und Speichertechnologien in den letzten Jahren und Nigerias großem Potenzial an erneuerbaren Energien, insbesondere an Solarenergie. Die Nutzung dieser Potenziale kann zu einer stärkeren Diversifizierung im Wirtschaftssektor, weg von dem Fokus auf die Öl- und Gasindustrie hin zu klimafreundlichen Alternativen führen, die gleichzeitig Entwicklung in ländlichen Räumen ermöglicht.
Herausforderungen liegen im Bereich einer transparenten, klar regulierten Planung, die benötigt wird, um den Privatsektor stärker an der Stromversorgung zu beteiligen. Mit der Verabschiedung der Mini-Grid-Regulierung Ende 2017 wurde ein erster wichtiger Meilenstein erreicht, welcher mit einer vermehrten Bereitstellung von Daten und Planungsvorgängen von Regierungsseite unterstützt wird.

Abstract

Reliable and sustainable electricity supply is currently not available in many rural areas of Nigeria. To address this deficit, the United Nations and Nigeria itself have set the goal of clean and secure full supply by 2030.

In the context of this work, two fundamentally different approaches to achieve this goal are examined: on the one hand, the existing, centrally organized power supply system could be modernized and expanded, and on the other hand, decentralized power generation could be expanded. In order to examine these options in the light of renewable energy and to derive recommendations, an electrification planning based on geographic information systems is conducted for rural regions not sufficiently supplied with electricity, using the example of five Nigerian states: Cross River, Niger, Ogun, Plateau, and Sokoto. The focus here lies on spatially resolved modeling of grid expansion, taking into account various factors such as topography, existing infrastructure, and different land uses (e.g. forests, water areas, and nature reserves). The aim is to make spatial comparisons as concrete as possible in order to achieve integrated, cost-optimized planning that can then be translated into concrete recommendations for action.

The results show that the installed power generation capacities of the existing system must be increased significantly. Only then does it make sense to expand the existing power grid. Parallel to this, the installation of decentralized power supply systems is recommended, on the one hand hybrid mini-grids (technology components: photo-voltaics, battery storage, and diesel generator) in growth centers and larger towns, as well as small-scale solar home systems at household level in structurally weak and sparsely populated regions. In the future, the mini-grids can be integrated into an extended power grid and provide additional power generation capacity there. Network expansion and decentralized solutions are not mutually exclusive; on the contrary, the advantages of both approaches can be used in an intelligent combination and thus counteract a dichotomous solution. This is possible due to recent cost reductions for renewable energy and battery storage technologies and Nigeria's great potential for renewable energy, especially solar energy. Exploiting this potential can lead to greater diversification in the economic sector, away from the focus on the oil and gas industry and towards climate-friendly alternatives that also enable development in rural areas.

Challenges lie in the area of transparent, clearly regulated planning, which is needed in order to increase the involvement of the private sector in the supply of electricity. With the adoption of the Mini-Grid Regulation at the end of 2017, a first important milestone was reached, which is supported by the increased provision of data and planning processes on the government side.

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Nomenclature

ARE	Alliance for Rural Electrification
BMZ	Bundesministerium für wirtschaftliche Zusammenarbeit und Entwicklung (German Federal Ministry for Economic Cooperation and Development)
CAPEX	Capital Expenditure
CFL	Compact Fluorescent Lamp
CO_2	Carbon dioxide
COP	Conference of the Parties
CRGIA	Cross River Geographic Information Agency
CRS	Coordinate Reference System
DAC	Development Assistance Committee
DisCo	Distribution Company
DMSP	Defense Meteorological Satellite Program
ECN	Energy Commission of Nigeria
EPSR	Electric Power Sector Reform
EU	European Union
EUR	Euro
FiT	Feed-in Tariff
FMPWH	Federal Ministry of Power, Works and Housing
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GHI	Global Horizontal Irradiation
GIS	Geographic Information System
GPS	Global Positioning System

GSM	Global System for Mobile Communication
GW	Gigawatt
GWh	Gigawatt hour
HDI	Human Development Index
Hz	Hertz
ICT	Information and Communication Technology
IEA	International Energy Agency
INDC	Intended Nationally Determined Contribution
IPCC	Intergovernmental Panel on Climate Change
IPP	Independent Power Producer
IRR	Internal Rate of Return
kV	Kilovolt
kVA	Kilovolt-ampere
kW	Kilowatt
kW_p	Kilowatt peak
kWh	Kilowatt hour
LCOE	Levelized Cost of Energy
LDC	Least Developing Countries
LED	Light Emitting Diode
LGA	Local Governmental Area
MDG	Millenium Development Goal
MEPI	Multidimensional Energy Poverty Index
MLP	Multi-level Perspective
MPI	Multidimensional Poverty Index
MTF	Multi Tier Framework
MW	Megawatt
MYTO	Multi Year Tariff Order
NASA	National Aeronautics and Space Administration

NDA	Niger Dam Authority
NEPA	National Electric Power Authority
NERC	Nigerian Electricity Regulatory Commission
NESP	Nigerian Energy Support Programme
NGN	Nigerian Naira
NIMET	Nigerian Meterological Agency
NOAA	National Oceanic and Atmospheric Administration
NREAP	National Renewable Energy Action Plan
NREEEP	National Renewable Energy and Energy Efficiency Policy
ODA	Official Development Assistance
OECD	Organisation for Economic Co-operation and Development
OPEX	Operational Expenditure
PAYG	Pay As You Go
PHCN	Power Holding Company of Nigeria
PPA	Power Purchase Agreement
PPP	Public-private partnership
PPPRA	Petroleum Products Pricing Regulatory Agency
PTFP	Presidential Task Force on Power
PV	Photo-voltaic
REA	Rural Electrification Agency
RES	Renewable energy systems
RESIP	Rural Electrification Strategy & Implementation Plan
RLI	Reiner Lemoine Institut
RLS	Reiner Lemoine Stiftung
SDG	Sustainable Development Goal
SE4All	Sustainable Energy for All
SHS	Solar Home System
SME	Small and Medium Enterprises

SRTM	Shuttle Radar Topography Mission
TCN	Transmission Company of Nigeria
UN	United Nations
UNDP	United Nations Develpment Programme
UNFCCC	United Nations Framework Convention on Climate Change
UNHCR	Office of the United Nations High Commissioner for Refugees
USD	United States Dollar
UTM	Universal Transverse Mercator
WACC	Weighted Average Cost of Capital

1. Introduction

Sustainable access to electricity remains a crucial challenge in today's world. Its dimension and importance are accelerated by the impacts of climate change, growing constraints in global resource availability, and the era of digitization. Although various technology options to facilitate access to electricity exist, more than one billion people remain subject to energy poverty.

This thesis elaborates on this challenge along the example of five Nigerian federal states and presents methods to facilitate advanced planning and decision-making for diverse electrification options considering the status quo of energy supply, energy access rates, and renewable energy potentials while highlighting the role of spatial planning.

This chapter introduces the motivation for the research topic, presents the state of science and research, and defines the research questions. In addition, the organizational structure of the thesis is presented.

1.1. Motivation for examining rural electrification planning in Nigeria

Electricity is a fundamental requirement for everyday life in the modern world. Household appliances, information and communications technologies (ICT), and industrial machinery are all powered by electricity. In many parts of the developing world electricity is reliably available at an affordable price. However, reliable and affordable access to electricity cannot be taken for granted: many parts of the world are still without or only with limited access (IEA, 2017c). This is a limiting factor for sustainable development of these regions, since there is a strong correlation between overall development and the use of electricity; globally (Kaygusuz, 2012) and in Nigeria (Oyedepo, 2012b).

Rural areas of developing countries are particularly affected by the prevailing lack of access to electricity. This is not a new insight or challenge, but has been a subject of discussion for more than 30 years (Pearce & Webb, 1987). Today, the largest share of people without access to electricity live in rural settings in Sub-Saharan Africa. Nigeria is the country with the largest population in Sub-Saharan African, achieving a gross domestic product (GDP) of around USD 400 billion in 2016, which is in the range between Austria's and Thailand's GDP (World Bank, 2017d). While this figure implies that Nigeria is home to the largest economy on the African continent, it hides the fact that Nigeria is also the country with the highest total number of unelectrified people in sub-Saharan Africa. Almost every second

person in Nigeria lives in energy poverty. This sums up to almost 100 million people, which is more than the entire population of Germany.
Although access to electricity as a modern form of energy is limited, the country is still rich in other energy sources: Nigeria owns large oil and gas reserves and has an abundant potential of renewable energy sources such as hydro power resources and solar irradiance.
The resulting opportunities of renewable energy for electricity supply are significant (Johansson, Kelly, Reddy, & Williams, 1993; Boyle, 2012), especially as costs decline as a result of steep technology learning curves and global economies of scale (Winkler, Hughes, & Haw, 2009). Progress is not just restricted to electricity generation technologies: on the one hand, solar photo-voltaic (PV) technology is becoming competitive to conventional fossil fuel-based electricity generation (Breyer & Gerlach, 2013), on the other hand, standard appliances powered by electricity are growing more efficient (McKane, Daya, & Richards, 2017).
Najam & Cleveland (2003) identify three aspects in which sustainable development is related to energy: (1) environmental impacts of energy usage, (2) economic growth through energy use, and (3) the meeting of basic human needs through energy services. Considering the societal challenges of climate change, environmental pollution and the finite nature of fossil fuel supply, renewable energy needs to be in the focus when discussing efforts to improve electricity supply. This is even more important in such a large and populous country like Nigeria to account for the country's overall carbon footprint and to allow for a sustainable development of the largest economy on the African continent.
Historically, the production and export of oil and gas was the main contributor to the country's revenue. In addition, parts of the hydro power potential have been harnessed by the installation of large dams and hydro power plants (Oseni, 2011). However, the country was not able to keep up the required development pace due to civil conflicts which were often followed by tremendous population growth spurts. Thereby, the development of energy systems and infrastructure as a whole fell behind, leading not only to a weak energy system but also to insufficient transport networks and water supply systems. The infrastructure currently installed is characterized by deficiency and decay in many areas and is further challenged by urbanization and the rapid growth of cities (Adenikinju 2005:11-12).
The challenge of electrification is nowadays acknowledged by the government of Nigeria, but also by the international community. In the year 2000, the United Nations (UN) developed and adopted the Millennium Development Goals (MDGs) to achieve universal sustainable development by 2015 (United Nations, 2015a). These goals included eight different themes, covering aspects such as poverty reduction, hunger eradication, education, and health. In general, these goals supported public awareness and political accountability for progress towards the achievement of those goals and their simplicity made them long-lasting in the debate (Sachs, 2012). However, after publishing the MDGs, heavy criticism arose that energy access was not included explicitly in the goals, even though its indispensable role for development is evident (Brew-Hammond, 2012).
With the time frame of the MDGs gradually passing, the subsequent compilation of the Sustainable Development Goals (SDG) superseded the MDGs, setting new targets for the period

2015-2030. With this change, a stronger focus was placed on ecological imperatives, to not only focus on the eradication of poverty but also on achieving environmental sustainability (Griggs, Stafford-Smith, Gaffney, Rockström, Öhman, Shyamsundar, Steffen, Glaser, Kanie, & Noble, 2013). For the first time in history, "access to affordable, reliable, sustainable, and modern energy for all" until 2030 was included as sustainable development goal number seven (SDG #7) (United Nations, 2015b). Alloisio, Zucca, & Carrara (2017) describe SDG#7 as an enabling factor for the implementation of the other SDGs, as energy plays a key role in development challenges such as overall poverty and health. The closest relation is found with the sustainable development goal number thirteen (SDG#13) to "take urgent action to combat climate change and its impacts"(United Nations, 2015b), since energy supply (excluding the use of traditional biomass) is the largest single sector contributing to today's green house gas (GHG) emissions (>25 %) (IPCC, 2007: 29). This is followed by GHG emissions of the industrial sector, the forestry sector (including deforestation), the agricultural sector, and the transport sector with approximately 13 % in fourth place. It is therefore of high importance to consider the need of an energy transition towards low-carbon sources while working on SDG#7.

In view of this background, Bridge, Bouzarovski, Bradshaw, & Eyre (2013) argue that such a transition to low-carbon sources "is fundamentally a geographical process", owing to the spatial variation of renewable energy availability, leading to two broader approaches which can be mapped geographically: (1) transformation of the existing system towards renewable energy as well as extending the system to not yet connected locations; and (2) including local renewable energy potential into electrification planning schemes, such as co-locating supply and demand such that distributed electricity consumers generate their own electricity, in contrast to a central electricity generation and distribution system. In this context, spatial contiguity and connectivity are concepts to classify potential electricity consumers and derive respective, location-specific electrification strategies.

In line with the importance of spatiality for the energy sector development, in paragraph 76 of the 2030 Agenda for Sustainable Development of the United Nations (2015b: 32), the role of geospatial data for support of the SDGs as well as their tracking process is highlighted:

> "We will support developing countries, particularly African countries, least developed countries, small island developing States and landlocked developing countries, in strengthening the capacity of national statistical offices and data systems to ensure access to high-quality, timely, reliable and disaggregated data. We will promote transparent and accountable scaling-up of appropriate public-private cooperation to exploit the contribution to be made by a wide range of data, including earth observation and geospatial information, while ensuring national ownership in supporting and tracking progress."

This support is clearly required, since public sectors, also energy sectors in most countries and regions, are strictly regulated and subject to considerable political influence. This highlights the importance of spatial data for planning purposes, which was recognized as early as the 1987 conference of the Urban and Regional Information Systems Association in Florida :

> "It has been estimated that 80 % of the informational needs of local government

> policymakers are related to geographical information" (Williams & Denmark, 1987)

In the context of Nigeria, the widespread lack of access to electricity despite the abundance of renewable energy resources and electricity generation technologies points to the need to review existing electrification strategies and identify areas for improvement. The role of geography and the importance of spatial analysis needs to be considered for gaining a full understanding of rural electrification planning challenges and past failures, in order to develop and implement modern, sustainable electricity supply systems.
The government of Nigeria has developed Vision 30:30:30 (Federal Republic of Nigeria, 2016), which aims at 30 GW generation capacity with a share of 30 % renewable energy until the year 2030. This ambitious goal demonstrates an awareness of the dire situation and the need for immediate action. However, the detailed planning of that objective remains mainly unspecified, especially in regard to rural electrification.
The aim of this thesis is to develop a model to compare different electrification options, to understand their implications with regard to their economic viability, the implications for energy poverty, and climate change impacts. Geospatial simulation provides a simplified representation of reality to model different development scenarios. Spatial data and spatial modeling by geographic information software (GIS) visualizes information on local situations, resources, and different options for electrification considering each specific location and its surroundings.
By creating transparency on the status quo and by analyzing and comparing different electrification options, fact-based decision-making will be enhanced. This creates awareness and knowledge, which will ameliorate existing electrification efforts and provide evidence towards achieving sustainable access to electricity across Nigeria.

1.2. Current state of research

The multi-dimensional and persistent challenge of providing access to electricity to a rapidly growing population, provides fertile ground for research across different areas encompassing the complex interdisciplinary field of energy access. Sovacool (2012) delineates this challenge into four broad barriers: technical barriers, economic and financial barriers, political and institutional barriers, as well as social and cultural barriers. Within these categories, specific challenges may be different in varying contexts, on local and regional levels, and also dependent on the technological options to generate and supply electric power.
With regard to the technical challenges, the requirements and available options for providing access to electricity are already well-understood in regard to their advantages and disadvantages (IPCC, 2012:121; Bazilian, Nussbaumer, Rogner, Brew-Hammond, Foster, Pachauri, Williams, Howells, Niyongabo, Musaba, Gallachóir, Radka, & Kammen, 2012), but awareness of the potentials and benefits of renewable energy technologies is not yet universally spread (Devine-Wright, 2007). Electrification strategies can be broadly divided into centralized and decentralized approaches: improving access to electricity either by extending national transmission grids or by installing stand-alone energy systems. Both

of these two different approaches can either be supplied by fossil fuels or renewable energy sources. A review of literature by Kaundinya, Balachandra, & Ravindranath (2009) describes the resulting challenge for decision makers to select suitable electrification options from the various possibilities, which are appropriate in the respective local context. An overview of the differentiation between centralized and decentralized classification of electrification paths is also provided by (Levin & Thomas, 2012), who, taking population density into account, propose centralized or decentralized solutions for different regions and countries. Historically, the technical development of the electricity infrastructure in the Global South was heavily influenced by colonialism. This is still visible in today's energy sectors in the affected countries, which are characterized by strongly centralized systems (Straeten & Hasenöhrl, 2017). However, opportunities for distributed energy generation and consumption, such as using small PV systems for providing access to electricity, have been discussed as early as in the 1990s (Acker & Kammen, 1996). At that time, these systems were not competitive because of their high technology costs, but today, this is not the case anymore because of ongoing technical progress (Akinyele, Rayudu, & Nair, 2015; Hosenuzzaman, Rahim, Selvaraj, Hasanuzzaman, Malek, & Nahar, 2015).

In recent times, the focus of research shifted towards the potential of renewable energy for electricity generation. Anthropogenic climate change is scientifically accepted (Oreskes, 2004) and cost-competitive technologies based on renewable energy have emerged (Deichmann, Meisner, Murray, & Wheeler, 2011). With increasing shares of renewable energy sources, the role of energy storage becomes more important due to the volatile character of most renewable energy sources, such as the diurnal provision of solar irradiation, the intermittent availability of wind, and the seasonal character of discharge availability for hydro power generation, which requires detailed modeling to understand the specific requirements for electricity generation from renewable energy sources (Alstone, Gershenson, & Kammen, 2015). The integration of this specific technical characteristic of renewable energy sources is of great importance, especially for sustainable and reliable electrification planning. With regard to economic barriers, Blechinger, Richter, & Renn (2015) identify the following challenges that make it particularly difficult to install renewable energy: high investment costs, lack of access to capital, high subsidies for fossil fuels, and the lock-in dilemma, that suggests that existing conventional energy structures block investments into novel approaches. The lack of an open market is an economic barrier, since no competition is available that would lower prices. In conjunction with state-owned assets, subsidies often lead to low prices for electricity and make it challenging for private market participants to compete with the subsidized goods (Alleyne & Hussain, 2013; Mills, 2017).

Furthermore, the countries with the largest deficit in rural access to electricity often have limited access to financial capital. Up-front costs for project developers as well as for connection costs on household level can be prohibitively high. A long pay-back period for most power generation assets leads to a long project lifetime before the assets fully pay off (Ibrahim, Anisuzzaman, Kumar, & Bhattacharya, 2002). Due to the dispersed settlement structure in rural areas, energy supply is costly and needs subsidies if prices are to be competitive with those in urban areas in the same country (Chaurey, Ranganathan, & Mohanty,

2004).
Political and institutional barriers can also hinder the development of rural electrification infrastructure. If governments are malfunctioning, transparent planning and implementation of measures such as enhanced energy generation are often difficult. Historically, governments have maintained a strong grasp on the national electricity sector. Most energy sectors are still heavily regulated, leading to complex and time-consuming processes of licensing for constructing and operating power plants as well as for selling electricity. The transmission and distribution of electricity is also state-owned in many cases, biasing respective governments (Pollitt, 2008).
Despite the clear need for additional investment, it is very difficult for new stakeholders to enter such a regulated, often monopolized sector. In addition, due to a lack of transparent planning and implementation schemes, opportunities for private sector participants remain shrouded in uncertainty, compounding the existing investment risk. Also, the governments build their decision-making often on historical evidence or processes, which may have happened under different circumstances. This prohibits a clear comparison of all alternatives from an economic perspective, but also from an ecological viewpoint. Apart from location-specific spatial planning, planning of infrastructure investments also requires a temporal planning – without time-bound objectives, progress in tackling energy poverty is hard to measure.
Social and cultural barriers can also be identified in regions with low rural electrification rates. Before electricity is introduced to a region, energy needs such as lighting are covered by the use of candles or kerosene. Once electricity is introduced, it can substitute parts of the needs served by traditional energy supply. For the case of fire, lighting needs can be substituted by electric lighting, however, the fire also provides heat for cooking and warmth on cold evenings that electric lighting does not cover. This can lead to challenges in user acceptance of new energy supply options (Ahlborg & Hammar, 2014).
Electrification can be seen as one aspect of sustainable development and needs to be understood in connection with other crucial aspects such as the provision of potable water and sufficient food, and more broader goals such as improving health, education, and the economy (McCollum, Gomez Echeverri, Busch, Pachauri, Parkinson, Rogelj, Krey, Riahi, Nilsson, & Stevance, 2017). These are all interrelated in complex processes and hence, a singular analysis of only one of those developments could potentially overlook certain inter-dependencies. This consideration of different interlinked development challenges is often referred to as “Nexus” approach (Ringler, Bhaduri, & Lawford, 2013; Machell, Prior, Allan, & Andresen, 2015), which also plays a key role in achieving the SDGs. SDG#17 underlines this through the objective to “strengthen the means of implementation and revitalize the global partnership for sustainable development”.
However, due to the complex nature of those relations, this thesis focuses primarily on access to electricity as specified in SDG#7 to first understand how rural electrification itself works without other variables, such as water supply or sustainable agriculture.
Available new technologies can initiate a socio-technical transformation (Rohracher, 2007: 134-138), which can potentially occur during electrification processes in rural areas. The mentioned barriers can be confronted and overcome by new developments impacting on the

current system: with new technology development, specifically in regard to novel small-scale systems and storage technologies, as well as progress in digitization such as mobile payment schemes, the whole traditional stakeholder and institutional structure is confronted with a potential system-wide transformation of the energy sector. Traditional roles and responsibilities can change and thereby, new solutions can be created to overcome the lack to access to electricity globally.

1.3. Research questions

Electrification planning and decision-making must be supported by spatial analyses: modeling of different electrification options allows a comparison of related costs and the performance of different options. It allows an estimation of the consequences of planning a certain type of electrification for a specific region. In order to understand the impacts of the different options, such as extension of the national power grid or decentralized solutions, detailed modeling tools are required to assess the various electrification options for not yet electrified regions. This allows deriving location specific recommendations for decision makers at various levels and to track the progress of implementation of suggested and approved development pathways.

The following research questions are developed and answered within the scope of this thesis by using the example of the five Nigerian federal states: Cross River, Niger, Ogun, Plateau and Sokoto.

- How can non-electrified off-grid regions be electrified by small, decentralized, hybrid systems based on renewable energy and by an expansion of the existing grid infrastructure?
  - Which geospatial characteristics are important in this context?
  - What is the role of renewable energy? Does the usage of renewable energy sources increase the economic sustainability of decentralized electrification?
- Is a decentralized electricity supply structure advantageous compared to an extension and connection to the national power grid?
  - What is the reliability of both systems and what are the limitations?
  - What are the differences in context of economic performance and financing requirements?
  - Which solution is faster or cheaper to implement and what does that imply in the Nigerian context?
- Which parameters have a significant influence on the decision between decentralized solutions versus centralized generation with grid extension and connection?
  - How is electrification planned currently?
  - How can those parameters be weighted and used to support decision-making in electrification planning?

  - How can those two different approaches be integrated in terms of planning and technical implementation?

- Where and when can decentralized systems be recommended although grid extension measures may be planned in the long term perspective?
  - Will local power supply for off-grid regions based on renewable energy present a viable option to supply local energy needs in the long term?
  - In which location is the use of decentralized power supply especially suitable? How can those locations be identified and classified to become integrated into electrification planning schemes?

By developing a methodology to contrast grid extension with decentralized hybrid mini-grids, a decision support tool for conceptualizing development plans for improving national access to electricity while increasing the use of renewable energy sources will be provided.

1.4. Research design and methodology

The research design is based on a combination of literature analysis, primary data collection, data analysis and compilation, and spatial modeling with a special focus on rural electrification.

To assess the status of electrification planning and data availability as well as to evaluate currently existing knowledge, structures, and processes related to rural electrification, discussions with experts and qualitative interviews are conducted. In parallel, a data collection process is initiated. Challenged by the absence of overviews for existing data and clear structures about the responsible agencies in charge of data management, methods are developed to derive certain information from other existing data sources.

Spatially-structuring models are developed in the interplay between geography, economy, and development by employing the collected and developed base data for the development of a GIS-based method to analyze decentralized options as well as grid extension. A detailed model development of the power grid expansion is emphasized, taking into account spatially relevant factors. Results of that modeling allow a comparison of those different options and unveil consequences of certain developments in terms of economic performance, required generation capacity to satisfy demand, and climate impacts of different development options. Optimized electrification strategies are derived for five Nigerian federal states. The findings are discussed in an iterative process with stakeholders involved in rural electrification planning in order to refine electrification strategies for specific locations embedded into an overall structural planning scheme in Nigeria. Based on the gained insights, recommendations regarding spatial development and usage of renewable energy sources in rural regions for holistic development opportunities and a sustainable future are derived.

1.5. Organizational integration of the thesis

The thesis is embedded into a joint project of the Reiner Lemoine Institute[1] (RLI) and the Nigerian Energy Support Programme [2] (NESP). This program is an initiative of Gesellschaft für Internationale Zusammenarbeit (GIZ) Nigeria, the government of Nigeria with the Federal Ministry of Power, Works, and Housing (FMPWH) on behalf of the German Federal Ministry for Economic Cooperation and Development (BMZ), with co-financing by the European Union (EU). The project duration is between 2013-2018 and the Nigerian partner states are the five federal states Cross River, Niger, Ogun, Plateau, and Sokoto. The project's objective is to achieve an increase of investments in renewable energy, energy efficiency, and rural electrification. To meet these three goals, the main activities of the project are to achieve a policy reform and the implementation of on-grid renewable energy, implementation of energy efficiency measures, planning, and acceleration of rural electrification by the creation of rural electrification plans and data management structures and capacity development for energy related issues (Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), 2015).

RLI is a non-profit research institute based in Berlin, Germany. The institute was founded by the Reiner Lemoine Foundation in 2010; its mission is to support research towards a sustainable energy supply based on 100 % renewable energy. The research is conducted within three different fields: the first research group focuses on the transformation of energy systems on national, regional and EU scale by integrated energy system analysis with storage technologies and new options such as Power to Gas and Power to Heat. The second team researches mobility concepts with renewable energy by analyzing battery electric mobility, hydrogen electric mobility, and synthetic methane gas based mobility via electrolysis. The third team supports the development of sustainable energy supply for rural electrification. Here, autarkic energy systems are simulated and combined with GIS-based analyses to identify potentials for decentralized energy supply and for the development of concepts for comprehensive rural electrification planning.

The embedding of the thesis into NESP supported the establishment of contacts to local stakeholders and decision makers and granted access to data.

The thesis is supervised at the Justus-Liebig-University in Gießen, Germany at the faculty of Human Geography and Development Research by Prof. Dr. Dittmann and by Prof. Dr. Winker, Statistics and Econometrics.

1.6. Structure of the thesis

This thesis starts with an introduction of the topic of access to electricity to present the focus and to describe the motivation, to show the state of research, and the resulting research questions in Chapter 1. Furthermore, the integration of the thesis into a multi-donor implementation project and the hosting research institution are introduced.

[1] http://reiner-lemoine-institut.de/

[2] https://www.giz.de/en/worldwide/26374.html

Chapter 2 presents the theoretical framework of rural electrification and its relation to development, economics, and spatial planning.
Chapter 3 provides background information on the status of access to electricity and describes options to supply electricity. Thereby, the status quo is described; challenges with regard to under-supplied people as well as people without access and options to measure access become apparent. The chapter answers the question, where efforts to improve electricity access are needed most. This is followed by an overview of technical electrification options to evaluate how people can be supplied with electricity and which options are available to generate electricity. The chapter concludes with an integration of the previous aspects in a discussion on the impacts of electrification on climate change.
Chapter 4 introduces Nigeria as the country of the study area. After a general introduction into the national situation, Nigeria's power sector is described as well as the involved stakeholders and their specific relation to rural electrification. Current research on electrification options and pathways in Nigeria are discussed in the last sub-chapter.
The following Chapter 5 discusses the developed and applied methodology, starting with data requirements and an introduction on the collected data, which is required for the developed methods to investigate different electrification options. This modeling is further described in detail, subdivided in demand estimation, grid extension, decentralized power supply, and least-cost modeling, followed by an assessment of climate change impacts of the different options.
The result Chapter 6 presents the least-cost electrification option within a three-phased electrification plan, and scenarios to understand the impact of the model results. Building on these results, Chapter 7 discusses their implications, limitations, and the integration of the findings in policy and regulation. The research questions are addressed accordingly. In addition, an outlook illustrates prospects and evaluates which further studies may enhance the electrification progress in Nigeria.
Chapter 8 concludes with recommendation in the framework of providing affordable access to modern electricity in a timely manner, while taking climate impacts into account.
In Appendix A the questionnaire for the data collection is listed, the programming routine for the developed grid extension algorithm is attached in Appendix B, and detailed electrification results are compiled in Appendix C.

2. Theoretical background

This thesis is related to the thematic field of development geography. Development geography focuses on the spatial dimension of progress and evolution with regard to economic, social, and cultural development. In this context, development is "concerned with what people can or cannot do, e.g. whether they can live long, escape avoidable morbidity, be well nourished, be able to read and write and communicate, take part in literary and scientific pursuits, and so forth" (Sen, 1983), thereby improving people's capabilities of living the lives they desire. Development is a requirement for overcoming poverty, defined as a lack of ability, opportunities, and freedom to fulfill one's needs (Durth, Koerner, & Michaelowa, 2002: 34).

To capture and measure poverty, indices such as the Human Development Index (HDI) (Stanton, 2007) and the Multidimensional Poverty Index (MPI) (Alkire & Santos, 2010), were established by the United Nations. These indicators capture different dimensions of development; of which poverty is one aspect, track the progress of development over time in a certain region, and allow a comparison of different countries, even though critics argue that a weighting of different criteria is difficult between countries of various development stages (Sagar & Najam, 1998). Nonetheless, they do provide information on the overall development and poverty level of countries – energy poverty as one subordinated form of poverty then becomes evident (Kaygusuz, 2012; González-Eguino, 2015). Energy poverty describes the lack of access to modern and clean energy sources, with the lack of access to electricity and a heavy reliance on traditional biomass sources representing an example of acute energy poverty (Pachauri & Spreng, 2011). The executive director of the International Energy Agency (IEA), Fatih Birol (2007), lists energy poverty together with environmental concerns and disruptive energy supply as a result of geopolitical conflicts and resource scarcity as one of the three key challenges for global energy systems today.

By analyzing the status quo of access to energy in Nigeria, huge development gaps are revealed in form of energy poverty and the accompanying environmental, social, and economic challenges. About 40 % of the population have no access to electricity (IEA, 2017c), while more than 70 % of Nigeria's population remain dependent on biomass fuels for cooking (IEA, 2017b).

Modern energy access is strongly cross-cutting with other aspects of development (McCollum, Gomez Echeverri, Busch, Pachauri, Parkinson, Rogelj, Krey, Riahi, Nilsson, & Stevance, 2017) and, as a consequence, the challenge of energy poverty in Nigeria compounds with the lack of basic institutional infrastructure for education and health care, leading to an increased vulnerability against natural catastrophes in less developed regions, which can quickly lead to widespread famine and diseases (IPCC (1998):403). At the same time, economic development through productive use of energy for income generating activities is often restrained due to a lack of electricity (Cabraal, Barnes, & Agarwal, 2005), while the predominant use of fossil fuels contributes to additional greenhouse gas emissions, further exacerbating the challenges described above.

The complex, multidimensional challenge of energy poverty in Nigeria and, more specifically, the topic of rural electrification as discussed in this thesis has strong links to energy geography, referring to the spatial component of energy generation, distribution, and consumption centers.

Several decades ago, Chapman (1961) stressed the role of geography related to energy research by suggesting the systematic consideration of local energy resources and spatial resource availability, the energy industry depending on different energy sources, electricity generation, transmission and distribution, the regulatory perspective, as well as the impact of ownership structures. Further, he underlined that in addition to economic considerations, social consequences also need to be considered before exploiting certain energy resources in specific geographic regions. In this regard, Hoare (1979: 512) argued that specifically the adoption and "development of alternative energies [such as wind, biomass and solar energy] is of immediate spatial interest", since new locations gain interest due to their newly valued energy resources. However, in most cases (except for biomass), those alternative energy resources need to be used locally, because they cannot be transported easily, which in turn calls for a demand and supply which is spatially coincident.

In recent times, the concept of energy geography was rediscovered and discussed by Brücher (2009: 38), who introduced a concept for energy geography as a model of inter-dependencies between socio-economic framework conditions, spatial relations, and energy systems with their complete value chain (Fig. 2.1). These linkages lead to the fact that in the emergent low carbon energy economy, spatial relations with regard to energy generation, distribution, and consumption are stimulating the need for the inclusion of geographic considerations in policy development for sustainable energy sector planning (Ritchie, Hardy, Lloyd, & McGreal, 2013). Policy design therefore forms the binding element between the three components of energy geography, namely spatial relations, socio-economic aspects, and energy systems.

This concept of the inter-dependency of energy and geography can be applied to better understand and tackle the challenge of rural electrification in Nigeria. Nigeria produces most of its revenue by exporting energy-intensive resources, while being unsuccessful at improving national access to electricity – a paradox that reveals geographic energy challenges and gaps, which need to be approached with appropriate policy design. Between 2000 and 2009, the share of the oil and gas sector contributed more than one third to the national GDP, while it accounts for more than 95 % to the country's total export earnings (Akinlo, 2012).

During the oil boom in the 1970s, Nigeria recorded a large per capita increase in GDP, which, however, dropped again in the 1980s and has remained relatively unchanged ever since. Per capita revenues from oil exports could not be increased (Sala-i-Martin & Subramanian, 2008: 63).

The spatial relations of energy poverty in Nigeria are uncovered by questions such as: where

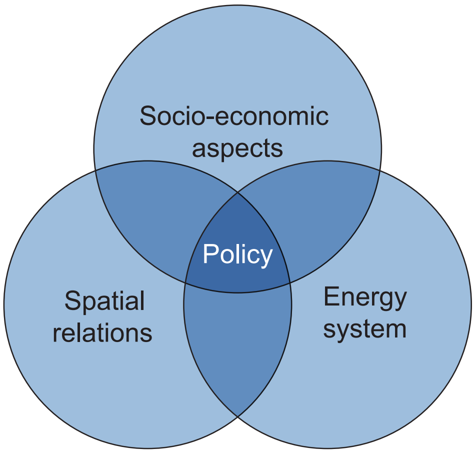


Figure 2.1.: A concept of the inter-dependencies of energy geography, highlighting the binding role of policies. Author's own diagram, adapted from Brücher (2009: 38).

is electricity required, where is electricity already provided, what are the spatial characteristics of settlements in rural areas, what are the resources in each location, and which regions are challenged by difficult accessibility or remoteness? Alongside these spatial relations, socio-economic aspects include the willingness and ability to pay for electricity, the need for electricity for productive use, migration movements due to the absence of electricity, and the currently used energy forms and sources. As shown in Figure 2.1, these two differentiated classifications are interrelated, as spatial structures can often influence socio-economic performance, but also the other way around. For example, when a region is doing well in economic activities due to a specific policy or geographic aspect, this region might attract more people. Further, these classifications are mutually influenced by the quality and availability of energy systems, for example, these are linked to socio-economic aspects, through the generation of electricity, but also through the creation of jobs. Furthermore, energy resources are often only available at certain locations and need to be transported to the respective power plants, highlighting the spatial relation between the location of resources and the plants and their dependence on economic factors.

An optimization of these inter-linkages must consider the spatial dimension, that is, the local resource availability and the capability to use these locally. The final distribution of generated electricity to the customer is also a clearly defined spatial problem. The mutual reactions are influenced by energy policies, such as pricing of fuel, tariff design for electricity supply, tax incentives, or political goals for the installation of certain technologies. These mutual effects can be summarized as socio-spatial relations (Calvert, 2015).

This thesis is an interdisciplinary research work combining different themes of development geography and energy geography, infrastructure planning, renewable energy research, and GIS techniques with the objective to support decision-making for improved access to electricity in rural Nigeria. The focus is placed on electricity, excluding other forms of energy such as energy requirements for cooking and heating as well as energy for transport. In most countries, biomass is the predominantly used energy source with a possible reduction by the introduction of electricity. As the traditional use of biomass is related to negative impacts such as deforestation, pollution, and resource conflicts, rural electrification may include beneficial effects of those externalities.

2.1. Human-environment relations and rural electrification

Human-environment relations have changed with the beginning of the Anthropocene era in 1800 (Crutzen, 2002). The historical dominance of nature over humans reversed to a new dominance of humans over the natural environment. Inter-dependencies in human-environment-related global challenges, such as climate change, can only be encountered by an interdisciplinary network of science, technology, politics, and societal actions (Ehlers, 2008). Reversing the impact of humankind on our planet during the Anthropocene requires urgent sustainability measures (Crutzen, 2002), as highlighted by the consequences of anthropogenic climate change, such as heat waves, droughts, sea-level rise, or flooding. The necessity to change human behavior is compounded by the fact that many people already suffer from avoidable climate change related effects, which are even expected to increase (IPCC, 2014). Environmental degradation, insufficient waste management, air and water pollution reduce the quality of life and deteriorate ecosystem services. The value of those ecosystems and their services is captured in the concept of ecosystem services, which are directly related to human-environment interactions (Costanza, d'Arge, Groot, Farber, Grasso, Hannon, Limburg, Naeem, O'Neill, Paruelo, Raskin, Sutton, & Belt, 1997). Especially sub-Saharan African countries are globally the most vulnerable group with limited options to augment local situations without external support - for example Nigeria is listed in a group of countries classified as moderately to highly vulnerable to climate variability and climate change (Brooks, Adger, & Kelly, 2005).

One consequence of human superiority over natural resources is that natural resources are often subject to competing claims without clearly defined ownership structures, which in many cases either lead to the over-exploitation of resources, resulting in environmental degradation or exclusive exploitation by powerful parties, often leading to the so-called *resource curse*, which describes negative impacts of wealth of natural resources (Durth, Koerner, & Michaelowa, 2002; Bazilian, Onyeji, Aqrawi, Sovacool, Ofori, Kammen, & Graaf, 2013; Sachs & Warner, 2001). One reason for this can be the neglect of other sectors, apart from the petroleum industry, which leads to a lack of competitiveness in other sectors. The production function of *mineral economies*, the ratio of capital to labor force, has the effect that only few people are employed and foreign capital is needed (Auty, 1993: 2-5). Impacts can occur on a local scale or globally, requiring complex action to understand relations and required countermeasures.

Due to a growing global population and economic interests, natural ecosystems and resources continue to be depleted unsustainably. Calvert (2015) describes this effect as the *energy-society-environment relationship*, which is currently characterized by intensive transformation processes, due to an ever-increasing global energy demand and technology innovations in the field of renewable energy, but also in conventional fuel technologies, such as shale gas and tar sand exploration, while being confronted with climate change.

By relating the topic of rural electrification to the context of human-environment relations, different overlapping and interrelated themes are identified: energy systems are based on the exploitation of resources and fossil fuel-powered systems emit GHG emissions into the environment. A comparative study of several cities by (Dodman, 2009) shows that cities do not in general account for the highest GHG emissions, the per capita emission of cities compared to the national emission per capita are substantially lower, pointing to the impact of rural areas.

Exploitation of resources can furthermore lead to a competitive use, contributing to land use conflicts or environmental degradation. Natural resources, that are common goods, are exploited in a resource-consuming competition, regardless of opportunity costs: the *tragedy of the commons* ultimately calls for "fundamental extension in morality" (Hardin, 1968), to allow for a global development in line with ecological imperatives.

Scholz (2004: 82) argues that the resulting societal challenge for research is to provide an input or a contribution to a development-related problem with the goal to eradicate poverty and to allow for a fulfillment of basic human needs. He further describes two explanations of the lack of development in some regions in comparison to others:

(1) The theory of modernization (or growth theory), departs from the assumption that underdevelopment is a consequence of backwardness based on internal structures. This theory argues that the exploitation and use of own resources for national development requires structural changes, which may be accelerated by external assistance. This theory is contrasted with (2) the dependence theory, which reasons that a dependency (such as a reliance on the world market or hierarchical relations between industrialized and developing countries) is the cause of underdevelopment and could be overcome by internal support for growth of domestic markets. This is argued based on the assumption by Senghaas (1983: 18) that the role of developing countries in a global economy, steered by multi-nation companies, leaves toady's developing countries with the role of commodity exporters, putting these countries into the periphery of the world economy.

2.2. Rural electrification in a globalized world

The age of globalization plays a role in development and alters established understandings of development: Scholz (2004: 221) argues that the negative consequences of inadequate development will be exacerbated in a *highly fragmented world*. This means, a countrywide perspective does not unveil national spatial fragmentation, as some regions in a given country might develop quickly, due to the involvement of international companies (effectively global regions such as Lagos in southern Nigeria), while other regions are left behind (rural Nigeria). This is characterized by an increased income gap, often between rural and urban areas, which is often averaged in national statistics and is easily overlooked due to the comparatively large rural population. In consequence, this might even exacerbate with increasing urbanization and migration into the cities. This theoretical framework argues that globalization is one key reason for the lack of development and indirectly the reason for locations being faced with insufficient electricity supply (ibid). The inequality gap within certain regions increases, leading a new understanding of developed and underdeveloped regions since the traditional development-related understanding of the Global North and the Global South is changing

towards global cities and the new periphery, which is observable in such global cities in defined developing countries, e.g. many countries in sub-Sahara Africa.
A positive consequence of globalization is an increased awareness of global problems, such as the UN's adoption of the MDGs in the year 2000, with the time frame set for achievement until 2015. Eight concrete goals were formulated after a discussion between 189 countries with the objective to improve global development. This was the first global attempt to improve well-being and livelihood around the world. What was achieved? The UN states that poverty and hunger were decreased heavily, schooling rates and gender parity were increased, and several health issues such as maternal health, malaria, tuberculosis, and HIV were improved. Furthermore, a significant amount of people received access to improved sanitation and potable water (United Nations, 2015a). Those improvements have shown success to some extent, but nevertheless also show that immense problems in the developing world prevail. As mentioned earlier, energy access was not defined as a separate goal (Brew-Hammond, 2012), but considered in the framework of the SDGs to address the global development challenges which remained unsolved within the period from 2016 to 2030. Within the new set of seventeen goals, energy access was defined as a specific goal, the SDG #7 (United Nations, 2015b: 21):

> Ensure access to affordable, reliable, sustainable and modern energy for all

- 7.1 By 2030, ensure universal access to affordable, reliable and modern energy services
- 7.2 By 2030, increase substantially the share of renewable energy in the global energy mix
- 7.3 By 2030, double the global rate of improvement in energy efficiency
- 7.a By 2030, enhance international cooperation to facilitate access to clean energy research and technology, including renewable energy, energy efficiency and advanced and cleaner fossil-fuel technology, and promote investment in energy infrastructure and clean energy technology
- 7.b By 2030, expand infrastructure and upgrade technology for supplying modern and sustainable energy services for all in developing countries, in particular least developed countries, small island developing States, and land-locked developing countries, in accordance with their respective programs of support

The energy sector is especially challenged, as its has a strong impact on climate change. Therefore, this energy-related goal needs to be understood in connection with SDG#13, aiming at a climate-friendly future. Despite stipulating goals, which represent clearly-defined problem areas, such as hunger, water, or energy, no concrete measures and practices are suggested to achieve these. In this context, one measure is SDG#17 calling for a global partnership for sustainable development, which is crucial to impact on the inter-weaved global economies, trade, and migration structures and foster the sustainable future of the global environment (United Nations, 2015b: 28).

Several organizations and institutions aim at implementing solutions towards progress of the SDGs. Specifically for SDG#7 Sustainable Energy for All (SE4All), Power for All and the Alliance for Rural Electrification (ARE) are institutions operating globally towards overcoming energy poverty.
From an historical perspective, at the time when inequality of development in different countries was commonly acknowledged and awareness about it rose, the idea of foreign support for those countries emerged (Hynes & Scott, 2013). Until today, the official development assistance (ODA) of richer countries for less developed countries plays a significant role for the global development. During the 1960s, the term was created by the Development Assistance Committee (DAC) of the Organization for Economic Co-operation and Development (OECD) to measure aid-related payments. These payments always include a grant of at least 25 % need to be spent in order to support economic development, and also need to be managed by public sector institutions such as governments.
Over the last decade international energy access provision changed steadily from pure technical assistance and donor-driven finance to a growing international market for energy access products and services. The accelerating cost decline in decentralized energy technologies, such as solar products and batteries, might affect and increase the options for local energy access technologies. Durth, Koerner, & Michaelowa (2002: 162) describe how technology advancement may be the crucial factor to allow a sustainable development under population growth and increasing consumption levels, while others (Meadows, Meadows, Randers, & Behrens, 1972) argue that the *limits of growth* prohibit further sustainable growth through global population increase, which is pressuring the natural resources due to unsustainable consumption. The expansion of access to electricity to a large underserved population will require sustainable options to prevent an unsustainable increase in CO_2 emissions as a response to a continuously increasing global demand for modern electricity services.
Providing access to electricity is especially challenging in rural regions, as people in these regions mostly live in spatially dispersed patterns which are characterized by generally low population densities (Zvoleff, Kocaman, Huh, & Modi, 2009). To account for this and to meet the national and international ambitions towards energy access for all, in many countries the formation of so-called “Rural energy agencies” or “Rural Electrification Agencies” by the government shows an increasing awareness and activeness from the public sector. Those agencies also act as change agents between the private commercial suppliers and providers and local communities.
In summary, it can be stated that from a global perspective, the social importance of access to electricity, specifically for rural regions in the Global South, is recognized. Nevertheless, locally adapted solutions must be developed, which will be discussed further in the following chapter.

2.3. Spatiality in the context of rural electrification planning

In the interplay of economic geography, regional sciences, and spatial economics, location theories are a decisive starting point for discourse. In the beginning of the 19th century, von Thünen (1826) published his work “Der isolierte Staat”, which became one of the first standard references of location theory. With his work, he aimed at answering the question of where and why economic activities take place at a given site. Assuming Adam Smith's homo oeconomicus, i.e. the concept of profit maximization of economic activity, he identified transport costs as a relevant parameter that determines how certain areas ought to be used depending on their location and quality. In the context of rural electrification, this can be applied to the question to what extent rural areas can be utilized for electricity generation or what transport costs arise when electricity has to be transported to the respective regions via electricity grids.

Another location theory, the theory of central places (Christaller, 1933), describes a hierarchical order of populated regions. The theory tries to explain settlement structures on the rationale that central locations are needed to provide specific services, while the hinterland regions only cover basic needs. These regions are also supplied with goods from the central locations. In his investigations, however, he assumes that there is an equal distribution of resources and people and concludes that longer distances are being traveled for higher-order goods. These notions are crucial in the question of productive use of electricity, because access to electricity is of similar importance in an industrial and service-based economy as transport costs, labor costs, and capital costs. When looking at rural and urban regions, one has to take into account the costs of overcoming space, which is what Weber does with the introduction of agglomerating factors. Clusters of different industries are formed in order to reduce overall costs.

To conceptualize the different location theories and to look at them from different spatial perspectives, the four-tiered theoretical strategy for development intervention policy, established by Rauch (2003: 151), is introduced. He describes a model in which the different levels global, national, regional, and local require different interventions through a common framework concept. It is stressed, that not only structural policy on a global and national level, but also a sufficient scope of action at a regional level and local approaches are required. The inclusion of the local and the regional level is specifically important to respond with actions according to the local situation. Therefore, all interventions need a joint planning and decision process to be effective. This concept can be applied to describe a multi-level strategy for electrification planning (Fig. 2.2).

Different electrification options are associated to different levels: decentralized options such as mini-grids or small solar powered devices relate mainly to the local and regional level, whereas the extension of the national grid is much more interconnected to national state level planning. Therefore, the different electrification options are analyzed in consideration of the importance of an integrated framework which reflects all those different levels and discusses requirements and roles of each level. For the case of Nigeria, the global level is addressed by the country's commitment to the SGDs, the national level by designing country specific objectives and policy frameworks. These are then adopted independently by each federal state, which relates to the regional level and is eventually brought to the local level when planning implementation of measures, such as the expansion of grid infrastructure or the installation of decentralized solutions.

Especially the use of renewable energy sources requires the consideration of different levels

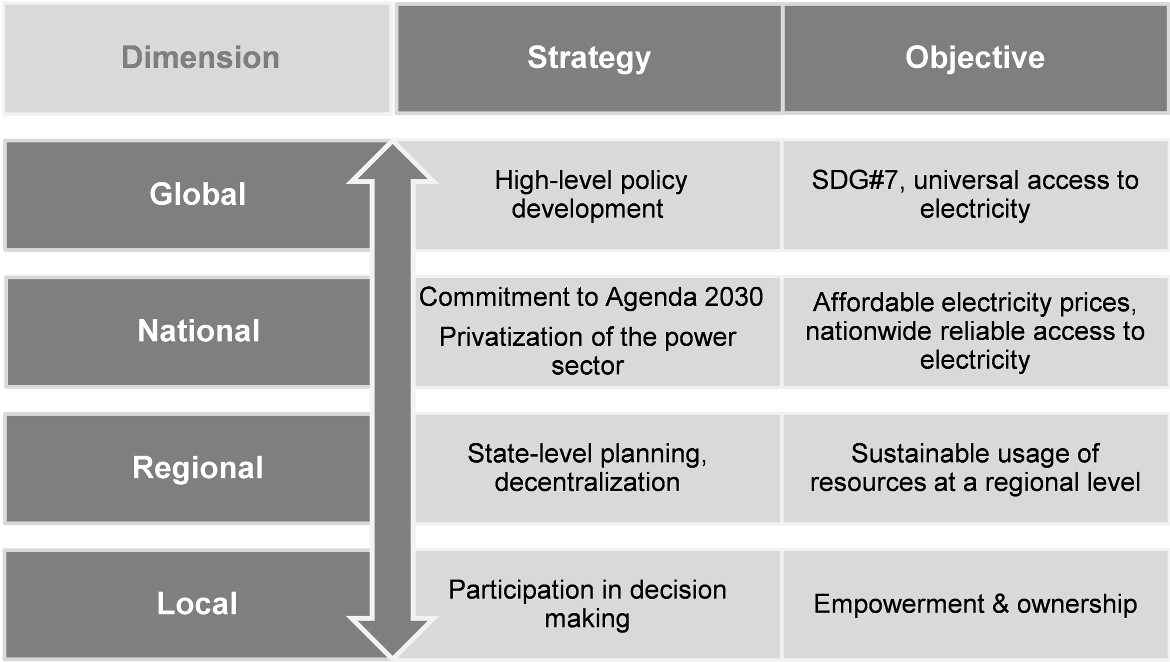


Figure 2.2.: Multi-level strategy for electrification planning. Author's own diagram, adapted theoretical framework from Rauch (2009: 254).

as renewable energy sources can be exploited across different spatial dimensions. The consideration of the local level is important when designing national structure policies, which are supposed to be implemented locally and where structures of those local levels need to be understood to create effective measures. A common understanding needs to be created to integrate different strategies and objective for each spatial dimension.

Sovacool, Ryan, Stern, Janda, Rochlin, Spreng, Pasqualetti, Wilhite, & Lutzenhiser (2015) point out that cross-disciplinary research is a requirement for sustainable energy access and development, while highlighting the role of geographers for introducing spatial analysis.

From a methodology point of view, GIS-based tools provide an appropriate option to store, manage, analyze, and visualize data across the different levels. Global datasets, such as solar irradiation data, national data, such as the network of the centralized power transmission grid, and data obtained from local and regional levels, such as the geo-coordinates of villages and the related number of inhabitants or the number of schools, can be tracked and combined. Many electric utilities are now starting to use GIS as a tool to for electricity planning EUEI PDF (2015). Examples on how results from such a usage of GIS systems could look like are published by Kaijuka (2007) alongside the example of Uganda and by Parshall, Pillai, Mohan, Sanoh, & Modi (2009) for the example of Kenya. Rural and urban planning in general benefits from the potential of modern cartography and map making in general. Some years ago, a shift towards digital map making with the availability of geo-information software was initiated. By today, local authorities in several regions have started to use digital systems for their planning processes and often provide open access to it, such as Tanzania[3].

[3]http://www.opendata.go.tz/en/

This holds many advantages, such as high accuracy of data, easily applicable processes, and ameliorated map making potentials. In addition, the often time and resource consuming process of printing high quality maps may become redundant.
GIS-related research was conducted previously for energy planning and renewable energy potential assessments on different spatial levels e.g. for rural Africa (Szabó, Bódis, Huld, & Moner-Girona, 2011) and with various focuses, such as single types of power generations or assessments of certain resources in defined areas of interest in the broader field of rural electrification (Mentis, Welsch, Nerini, Broad, Howells, Bazilian, & Rogner, 2015). However, examples of the integration of geospatial data for electrification planning are still very rare and as Mentis, Andersson, Howells, Rogner, Siyal, Broad, Korkovelos, & Bazilian (2016) formulate it very well: "Even though local approaches to electrification are inherently motivated by geospatial questions and challenges, the integration of GIS and energy system analysis and planning tools is still in its infancy".
Mapping data to visualize different electrification options on different spatial scales can prove to be very helpful for decision-making. Spatially explicit planning substantiates objectives and thereby creates transparency for planning processes and the following implementation of power-sector-related installations.
The consideration of spatial aspects can therefore present one appropriate tool to ameliorate planning frameworks. This is discussed by Herington, Fliert, Smart, Greig, & Lant (2017) as a requirement for grasping the complexity of the interdisciplinary work conducted by the responsible personnel for energy and electrification planning: stakeholder participation and local empowerment can be achieved by using the potentials of visualizing the spatial impacts of energy planning, which can create participatory processes that pay heed to local situations appropriately.

2.4. Socio-technical transformation for energy access

The introduction of electric energy had a significant impact on livelihoods and development phases. With an increasing demand for electricity and to account for the people without access to it, global electricity generation needs to be increased. The use of electricity was mostly well-established after the introduction of the modern dynamo and industrial generator in the 19 century. Technologies which were developed during that time are steam and gas turbines, water turbines, and internal combustion engines. Those technologies needed to be fueled either by fossil resources, such as coal and gas, or the energy of moving water and wind.
Today, new technologies for electricity generation emerged. One of them is the solar photovoltaic technology, where solar irradiation is converted to electric energy. In the context of rural electrification, developing countries are severely lacking sufficient electricity generation and distribution assets needed to meet the energy demand. The *multi-level perspective* (MLP) on socio-technical transition is a theory, which can be applied to this specific challenge (Geels, 2011) in order to understand if and how new technologies can provide options for electricity supply in those locations. The theory highlights the inextricable interdependencies between technological, economic, political, and cultural change processes and tries

to explain how socio-technical transformation processes emerge in niches, impact on regimes and potentially change landscapes.

Geels & Schot (2007) discuss how certain developments can affect existing technology landscapes: if there is a *disruptive change* putting pressure on existing technology landscapes, a transformation path can be entered. This is characterized by a new orientation of regime actors and viable alternatives can be presented by different stakeholders. This process often goes hand in hand with discussions and conflicts providing opportunities for niche innovations, as regulative frameworks and rules are often missing. If those niche innovations become successful, they can form the beginning of a new regime which replaces the old structure, described as technological substitution. This can have an immense influence on the economy and be the reason for large societal upheavals. Other advancements in technology development can also support electrification efforts, such as the role of mobile phone-based services, such as mobile payment systems. Those systems can simplify payment processes and lower the transaction costs for related services, such as fee or payment collection.

In the context of sustainable development, it is crucial that those innovations which could trigger the transition to new technologies are improved in terms of environmental soundness to mitigate the negative consequences. For the case of electrical generators, life cycle assessments are a method to calculate how much electricity and material was used for construction and decommissioning of power plants (Voss, 2006). An increase in efficiency is important here, which can be highlighted alongside the example of solar photo-voltaic technology. In this case, an unprecedented continuous improvement of the technology led to a heavy cost decline by a large increase in the overall efficiency. The most interesting question here is, how this development can provide new niches and possibly regimes, which can be transformed into landscapes for access to electricity in rural areas with prevailing limited opportunities today.

“Guiding visions” are discussed as important elements in the discourse of sustainable transition and socio-technical transformation processes (Späth & Rohracher, 2010). They can form a basis for engaging local stakeholders on low and high governance levels and have potential to engage new actors in a dialogue, which can potentially lead to the institutionalization of goals and tools such as certain energy policies.

To reach scale for increased energy access through socio-technical transformation processes, capacity building is required to introduce people in rural areas to local potentials of energy usage, new technologies, and opportunities for economic activities.

3. Concept of electrification and overview of power supply

When analyzing and comparing options for providing access to electricity in rural areas with the goal of understanding optimal energy supply systems and developing recommendations to policymakers and local stakeholders, a common understanding of underlying structures is required. Therefore, the following chapter presents the current status quo of rural electrification globally and describes options how to measure electrification. Subsequently, different technology options to provide electricity access are introduced and central and decentralized electricity supply schemes are presented. The economic and organizational characteristics of energy systems are presented and climate change impacts of the power sector are discussed.

3.1. Rural electrification – status quo and measurement options

Worldwide more than 1.1 billion people lack access to electricity (IEA, 2017c). Historically, the relative number of people with access grew between 2000 and 2012 from 79 % to 85 %, however, the absolute number of people without access to electricity decreased only slightly during this period due to constant population growth in the developing world (United Nations & Department of Economic and Social Affairs, Population Division, 2017). This situation leaves those without access in a position of limited opportunities regarding education, health care, and economic opportunities. It is undeniable that access to electricity improves the local living conditions. Alternatives to electricity are the use of open fire, kerosene, and candles for lighting. Those options are associated with emissions jeopardizing health and environment, fire hazards, poor lighting quality, and high costs (Sovacool, 2012).

The vast majority of people without access to electricity lives in rural areas (IEA, 2017c). In the context of electrification, the typology of regions is mostly reduced to urban and rural electrification, while both regions show differences in respects to available electrification measures. Within this framework, the term "rural" refers to sparsely populated regions without high-density population clusters. The classification of rural areas describes the specific situation of people living in remote regions in an agrarian setting. Typical characteristics are low population densities, mainly agricultural activities, and limited access to infrastructure. Chaurey, Ranganathan, & Mohanty (2004) define the term "geographically disadvantaged areas" as remote rural regions with few to no economically auspicious business cases for rural electrification, due to their isolated character. Unlike rural areas, urban regions are defined by high population densities, as seen in cities. Rural regions are characterized by considerable distances between facilities; and due to the dispersal of settlements only few people can be reached as a whole by infrastructure installations, such as grid extension. Therefore, electricity access rates tend to be much lower in rural settings than in urban areas (IEA, 2014b). However, the definition of urban and rural areas is not an unequivocal discrete classification – and on a global scale, there are many different manifestations between predominantly urban or rural regional typologies (OECD, 2016: 140). With increasing population growth and burgeoning rates of urbanization in many countries, the boundaries between urban and rural settings are changing.

The absolute number of people and percentage of the total population without access to electricity varies not only across urban and rural areas, but also across countries: while some countries succeeded in providing full energy access over the last decades, some countries are still facing a tremendous number of people without access to electricity – which can even be true for countries with comparably high electrification rates but large populations. Figure 3.1 shows that for example Nigeria has a higher national electrification rate than Uganda but the total number of non-electrified people is much higher in Nigeria due to its huge population. In general, the most affected countries with the largest number of unelectrified people are located in South and Southeast Asia, while the countries with the lowest overall electrification rates are located in sub-Saharan Africa. In this region, the countries with the largest unelectrified population are Nigeria with 74 million people, Dem. Rep. Congo with 68 million people and Ethiopia with 61 million people, respectively (IEA, 2017c).

However, how is access to electricity defined and measured?

Defining access to electricity is a research subject in itself, due to the complexity of the issue: one option to understand the whole spectrum of access to electricity in terms of consumption on a national level is to calculate the ratio between electricity production (accounting for import and export) and the supplied population. This value of available kilowatt hours (kWh) of generated electricity per capita shows that even for countries with comparably high electrification rates, the average consumption levels of electricity vary greatly (Bazilian & Pielke, 2013). However, this measure takes neither the disparity of the distribution of access to electricity within a country, where huge differences might exist due to inequalities into account, nor the role of industry, which can distort the domestic electricity consumption values. In consequence, different metrics for assessing the access to electricity were developed to quantify, compare, and track electrification in a more detailed way. Those indicators can be differentiated by measuring single or multidimensional characteristics of energy access, Nussbaumer, Bazilian, & Modi (2012) and Tenenbaum, Greacen, Siyambalapitiya, & Knuckles (2014: 52-57) suggest three different approaches to define electrification:

1. Defining electrification as connections: in the past, energy access was mostly a binary definition, resulting from either being connected or unconnected to a central supply system. Though with a myriad of options to provide access to electricity, the definition can be extremely multi-layered in terms of quality and quantity of power supply. The quality of grid electricity supply can vary significantly from being officially connected to a

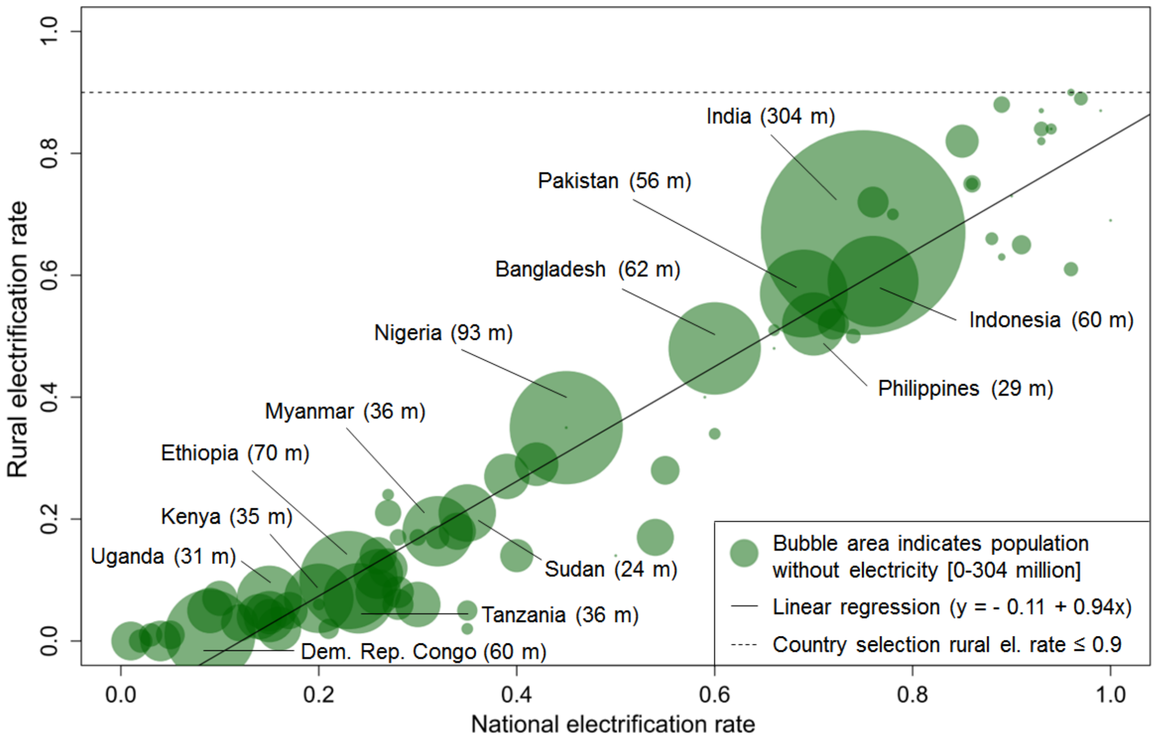


Figure 3.1.: Electrification rates and people without access to electricity. Author's own diagram, adapted from Cader, Blechinger, & Bertheau (2016), source data based on IEA (2014b).

non-functioning or underserved power grid, being exposed to frequent unplanned power blackouts, to planned load shedding in an announced schedule to restrict consumption due to a limited allocation of electricity, to a functioning, practically unlimited power supply by the grid. Further, a functioning, well-supplied grid might be within reach, but the up-front connection fee is exorbitantly high, preventing people from connecting (Cader, 2015; Golumbeanu & Barnes, 2013; Lee et al., 2016). In turn, people might connect to that grid illegally (Vleuten, Stam, & Plas, 2007).

2. Defining electrification as needs served: this approach considers the Multidimensional Energy Poverty Index (MEPI). MEPI measures different dimensions of energy access related to the purpose of use. The respective dimensions are cooking, lighting, services provided by household applications, entertainment and education, as well as communication (Nussbaumer, Nerini, Onyeji, & Howells, 2013). Those dimensions are often ranked into a so-called traditional ladder of electrification, which implies a step-wise increase in electrification from no electrification to pre-electrification to electrification; the energy sources and supply structures change over the course of the different steps with the highest step being grid-based power supply from a national power grid. This approach does not consider a skipping of steps or full electrification without a connection to the national grid.

3. Measuring electrification by its attributes: a more detailed framework to systemat-

ically understand the level of electrification has been introduced within the SE4All initiative's Multi-Tier Framework (MTF) for measuring energy access (Bhatia & Angelou, 2015). Correspondingly, several attributes have been assessed, such as the quantity and duration of supply, the evening supply, and the affordability and legality, as well as the quality and reliability of supply. The MTF groups different quantities and qualities of power supply in so-called *tiers* to systematically define access to electricity in different steps, not only in the binary measure of access or no access. This is reasonable as access can be very different, ranging from a more or less unlimited grid connection with cheap tariffs to a power grid connection with a three-hour limitation daily to a small solar home system which can only power two lights and a mobile phone for a few hours in the evening. This holds the advantage of achieving a very detailed and comprehensive assessment, with the potential to investigate local barriers or challenges more easily. On the other hand, this approach requires very detailed, time and cost intensive surveying, which hinders the use of this method for large regions.

Pachauri (2011) underlines the importance of agreeing on standard measures to defining modern energy access to facilitate a common understanding and Groh, Pachauri, & Narasimha (2016) suggest improvements to the MTF to account for local circumstances.
Challenges are also related to the metering options and related payment schemes, as the trend is progressively shifting away from a product based per-kWh-understanding to a service-based understanding of energy consumption, for example to power LED lights and a fridge. This way, a commodity (e.g. 1 kWh of electricity) becomes a service (e.g. powering all electric appliances of a household for a week). As a result, the question emerges of how households or villages can be considered electrified, as defined by SDG#7 – how many kWh does this refer to or how many devices does it sum up to?
To assess the demand for electricity of a household, a village, a state, or a country, it is necessary to estimate how much electricity is required for the use of needed devices. For that again, it is required to know when and how many electric devices are in use and how much electricity they require. Data regarding these issues is available from previously electrified communities and can be evaluated through interview surveys. This knowledge is essential for installing the right capacity of electricity generation to ensure that the system is not under- or over-sized. In most cases, it is assumed the electrification is a very dynamic process with a growing demand over time. Electricity may leverage the business opportunities and hence increases the ability to pay for more power in return. However, many cases exist where the lack of ability to pay is hindering the increase of electricity purchases.
Instead of defining access to electricity, it is also possible to distinguish between grid-connected people or households, referred to as *on-grid* and not-connected entities, referred to as *off-grid*. This does not account for current quality or quantity of supply, but in terms of energy access planning, previously grid-connected households might be evaluated differently: those locations that are already grid-connected should be able to consume electricity in theory, but the problem of lacking or limited access is related to an insufficiently functioning grid infrastructure. Also, if a central transmission grid is in geographical reach, an extension of that grid to the respective location is more likely in the near future.

This overview already opens up the complexity of electricity access – in terms of the global challenge and the measurement options of access to electricity. A requirement for improving access to electricity are energy systems, which are introduced in the next chapter.

3.2. Basic principles of energy systems

Rural electrification requires the provision of electricity, this, in turn, must be generated within energy systems, transmitted, and distributed to the consumer. Hence, an understanding of the concept is necessary to comprehend the complex relations between energy sources, electricity generation, distribution, and provision of electricity and their inter-dependencies and challenges in terms of technology and resources, economic framework, policy and regulation, as well as resulting climate impacts (Fig. 3.2).
Due to the different characteristics of urban and rural areas, appropriate technologies need to be chosen to provide access to electricity in a sustainable way (EUEI PDF, 2015). That implies a higher reliability of grid infrastructure in urban areas, since economic losses related to black-outs are high. Urban residents enjoy greater purchasing power and are thus able to pay for reliable supply as opposed to rural areas, where the load density is generally much lower, as well as the ability to pay, making a sustainable supply more difficult.
In the following section, different energy sources and energy system technologies are introduced and defined with regard to technical operation and economic structure, as well as respective policy frameworks and climate impacts to derive appropriate technologies for modeling different energy supply options for increasing sustainable rural electrification.

3.2.1. Technical characteristics of electricity supply structures

Electricity supply structures are technical systems which utilize energy sources to generate electricity and transport it to the consumer. Inputs into the electricity system stem from different energy sources; the output is electrical energy and, in some cases, diverse emissions. Emissions can either be GHG emissions, such as CO_2, particulate matter, and heat.
Different forms of energy exist and energy can be converted between the various states: the chemical energy stored in fossil fuels, nuclear energy in fissile material, kinetic energy of water and wind, as well as potential energy of stored water, thermal and radiation energy are converted by distinct power plant technologies into electricity. Electricity is then transmitted

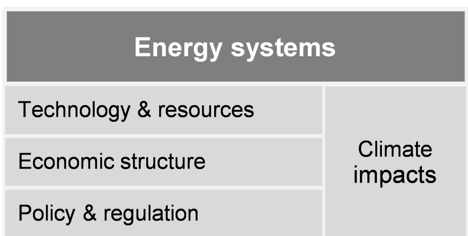


Figure 3.2.: Different aspects of energy systems. They can be classified in regard to their technology components and powering energy type, their economic structure, their regulatory framework, and their resulting climate effects. Author's own diagram.

and distributed to the consumer or stored for later use. These processes are often regulated by national laws and policies. In addition, electricity generation creates emissions as a by-product, which are emitted into the environment, proven to contributing to climate change (OECD/IEA, 2014).
For providing access to electricity, it can be differentiated between central and decentralized electricity supply structures, based on the geographical extent of energy systems, which can use various resources as input to produce electricity.
In a complete life cycle assessment, the overall system requirements for construction, production, and decommission of a plant are considered.
In order to use energy resources at peak efficiency, different types of power plants have been developed to exploit the respective resources for electricity generation. The following introduces the most common electricity generation technologies, Transmission and Distribution (T&D) infrastructure, and energy storage options.

Energy sources for electricity generation

Brücher (2009: 41) developed a fundamental concept for the historic development of the power sector which he called *energy from space* versus *energy for space.* This concept is based on the idea that the energy needs in pre-industrial times were covered by solar energy stored in biomass as well as kinetic wind and water energy, which relates to *energy from space*, in a decentralized approach. This shifted to energy for space at the time, when the beginning of the industrial age was characterized by the introduction of fossil fuel usage, such as for fueling centralized coal and oil power plants, and the evolution of electric utility companies with large-scale power plants and of related T&D networks. At that moment, the process of obtaining fuels to generate and distribute electricity changed the spatial relations: resource flows developed over large distances and large spatial coverage and generated electricity is distributed to the consumers over space. The aim of utilities was to preliminary connect regions with significant demand for electricity in order to maximize their profits. As a result of this development, regions with large reserves of fossil fuels came to the forefront of attention. With the introduction of modern renewable energy technologies, the post-industrial phase is started by questioning this current practice. The transition towards renewable energy leads back to the use of *energy from space* by using local energy sources provided by solar irradiance, wind, water, and biomass distributed over the landscapes. Electricity from those sources is mainly harnessed at its place of occurrence – which can lead to a more distributed use of energy sources. This is especially interesting for underserved regions with small demand, such as rural, sparsely populated areas.
In particular, the focus on the effect of renewable energy utilization requires the understanding of spatial relationships between resources and electricity demand clusters, as the advantage lies in the geographical proximity, possibly forming a unity of energy producer and consumer. The importance of location-specific analysis grows with the rising share of renewable energy – as resources vary in their spatial abundance. Such a prosumer model can form markets working in different set-ups – such as peer-to-peer mode or organized groups contributing to a micro-grid (Parag & Sovacool, 2016).

As a consequence, with decentralized solutions the transmission of centrally generated electricity is no longer a prerequisite for electricity provision in rural remote areas.

As previously mentioned, electricity generation is a conversion of specific forms of energy into electricity. Therefore, different sources can be used which differ in their price and local availability – as well as climate, social, and environmental impacts. Some of those criteria can be assessed very accurately, whereas for other factors, a classification of the social or environmental impacts is much more diffuse.

In general, fossil fuels and nuclear generation options can be contrasted against electricity generation based on renewable energy sources. The first one uses carbon derivatives such as coal, lignite, gas, diesel, or gasoline as its major source for internal combustion. Consequences are steep GHG emissions (Chap. 3.3) and other particulate matter emissions, negatively impacting climate, environment, and humankind. Different fossil fuel resources are bound to their deposits; global occurrence varies highly from resource to resource and from country to country. This results in international trade networks of such resources, adding transport costs to the total price. In particular, transport to remote regions can present a challenge in itself due to limited infrastructure and low demand.

From a historical point of view, the fossil fuel resources have been created though geological processes during the last 500 million years and preserved energy from biomass in specific chemical structures. Accordingly, there is only a limited reserve of those resources, which cannot be refilled at the current rate of depletion (IEA, 2017a). The effect for oil resources, for which the term "peak oil" originated, describes the point in time, when the highest production rates are achieved and the production rate and consumption will begin to decline. A polarizing discussion emerged, debating whether this point has already been reached and what consequences this would imply, seen in relation to technology shifts and climate change (Bridge, 2010).

Nuclear power generation is based on the use of fissile elements. The use of nuclear power for electricity generation is very controversial, due to its associated risk and subsequent production of radioactive waste material (Armaroli & Balzani, 2007). These two consequences are difficult to monetize and hence, some researchers find this energy source to be one of the cheapest sources with the advantage of no GHG emissions (Graves, Ebbesen, Mogensen, & Lackner, 2011), while others stress the dangers and risks including the possibility of harmful material emanating from nuclear resources (Armaroli & Balzani, 2007).

Renewable energy on the other hand is based on solar irradiation, wind, hydro power, biomass, and geothermal energy. The energy of those resources can be harnessed by respective technologies (Quaschning, 2011): solar irradiation can be used in form of concentrated solar power or by using photo-voltaic systems. Wind is used as the source for wind power plants and hydro power can be harnessed by diverse technologies, such as hydroelectric plants with related water storage dams, run-off-river plants, tidal, and wave power plants. Biomass is utilized through solid, liquid, and gaseous fuels, such as wood and respective secondary products like wood pellets or charcoal, bio-diesel, and methane.

By using these energy sources to generate electricity, solely the emissions for the production of the plant technologies plus transport and construction need to be taken into considera-

tion when assessing their impacts. A specific challenge of renewable energy sources is the volatility of resource availability. For example, solar power itself is only available during daylight and interrupted by the diurnal rhythm as well as by fluctuating daylight hours over the course of the year, increasing with spatial proximity to the poles. Also, cloud cover affects the efficiency of PV, as much as fluctuating wind speeds influence the respective efficiency of wind power plants. Due to that unsteady availability of energy generation, planning of the availability of those resources is difficult and requires detailed and exact weather forecasts. Energy system operators therefore classify the renewable energy sources as non-dispatchable energy resources, whereas fossil-powered electricity generation can be highly regulated and is therefore in most cases easily dispatchable. Due to the non-dispatchable characteristic of volatile renewable energy sources and their natural fluctuations and restrictions of availability, the role of energy storage to circumvent those effects is increasing (Teleke, Baran, Bhattacharya, & Huang, 2010).
Some renewable energy technologies also require resources, such as space and land, which need to be accounted for. PV, for example, requires a specific surface area (for exposure to direct sunlight) to install the modules.
Energy sources also vary in their quantity of availability and their quality over space and time. In consequence, different countries are endowed with different reserves of fossil resources and renewable energy potentials. In particular, biomass can easily become exploited in an unsustainable way. As these limited resources are used for conflicting purposes, such as food production, the natural resource falls into the quagmire of being endangered. Particularly, cooking energy requires firewood and has negative implications regarding environment and resource management. However, the scope of this thesis does neither cover the role of bioenergy for cooking purposes, nor concurrent water use (e.g. for hydro power generation versus irrigation).

Typical dimensions of power plants

Demand for electricity can vary from a few watts to power some light bulbs or other small devices in a household to the capacity required to power an entire city or region with all its industrial energy needs. As demand for electricity can vary immensely, so does the size of energy systems, depending on the type of technology as shown in Figure 3.3. The different resources outlined above can generally be used in small-scale and large-scale power plants. Due to the ever-increasing demand for electricity, the systems tend to ramp-up their capacity. The generation capacity of power plants is a measure for how much power can be produced and the capacity factor implies how much of the installed capacity is used. One example are gas power plants, which are continuously supplied with gas and have a generally high capacity factor, whereas hydroelectric power plants might have a much smaller capacity factor due to seasonality of the water flows and a strong reduction in available water resources during dry season, reducing the capacity factor, as the plant is not using its full capacity. The same holds true for PV technology, where no sunlight is available at night. However, PV power plants, unlike hydroelectric and wind power plants, are applicable in most locations, due to the universal availability of solar irradiance. Therefore, this technology can be installed almost

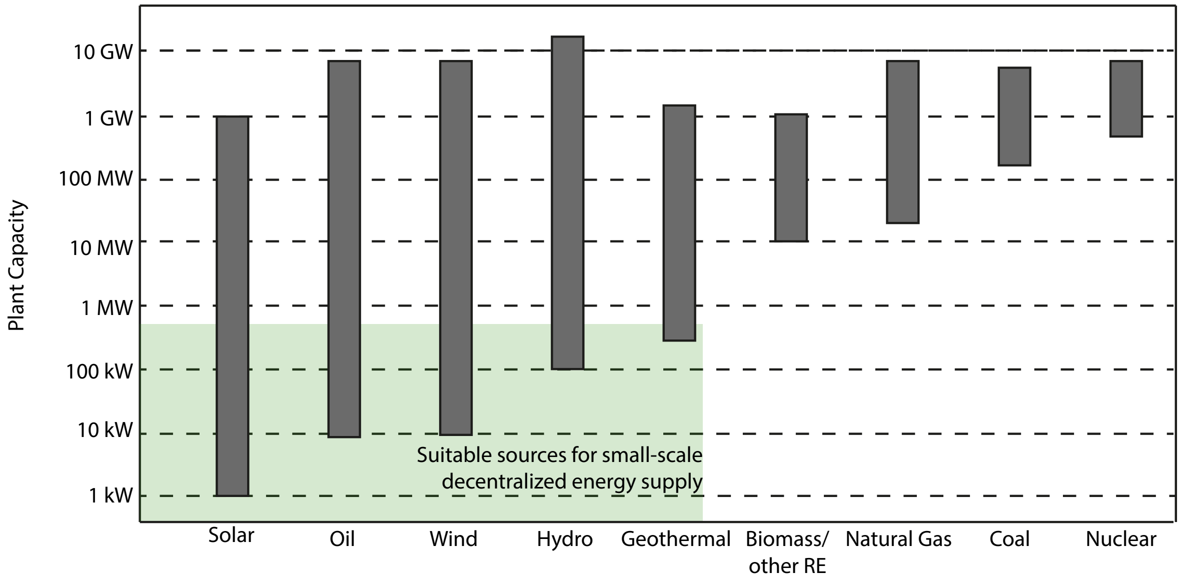


Figure 3.3.: Capacity range of different power plant types. Author's own diagram, data from U.S. Energy Information Administration (EIA, 2015).

anywhere. Furthermore, due to technical advancements, a modular form of PV systems is available, enabling use for all levels, from very small systems, powering single appliances such as lights, over households and village systems, to large-scale solar parks, which can combine thousands of PV modules, covering extensive areas and achieving generation capacity in the GW range.

One energy source generally used in larger plants is nuclear energy. This energy source takes on a special position: because of the high risk associated, the construction and operation of these plants is highly regulated and due to high security measures, required to be taken into account, large plants are constructed. Due to their size, nuclear power plants are integrated into centralized systems. Coal- and gas-fired plants are generally characterized by large capacities in the MW to GW capacity range. The different typical capacity ranges of the different technologies consequently lead to certain technology choices, which are applicable for small-scale decentralized electricity supply, such as solar, oil, wind, and hydroelectric technologies in the capacity sizes below 1 MW, while other technologies are unsuitable for decentralized electrification approaches.

Transmission and distribution grid infrastructure

Electricity generated in power plants needs to be transported to the consumer. Historically, T&D networks were established to interconnect customer groups with the supplier. As described by Kiessling, Nefzger, Nolasco, & Kaintzyk (2014), transmission systems are technologies composed of high- and medium-voltage power grids to transport electricity over large distances. The high voltage is required to minimize line losses during the transport. For the distribution to the customer, the voltage level is stepped-down by transformers to lower voltage levels. From the distribution network, a household connection is required to finally connect the consumer (Fig. 3.4). In that last step, a meter to track the consumption

Figure 3.4.: Village distribution grid infrastructure in Myanmar's central dry region. Author's own photograph (May, 2016).

can be installed and by internal wiring the single household appliances are connected. For household connections, heavy charges of up to several hundred USD are often applied, which hinder people to connect, because they cannot afford the single upfront payment (Cader, 2015). Some countries established programs for financing these connection fees (EUEI PDF, 2015).

Grid infrastructure can be constructed as overhead lines, underground cables, or as submarine cables. Overhead lines present an interference into the environment and can change the appearance of the landscape through large corridor routes or forest clearings (Brücher, 2009). Therefore, new grid infrastructure often requires complex planning phases to find consensus and official approval. Underground cables, on the other hand, disturb landscapes less, but the costs are significantly higher. Depending on the voltage level, investments for medium-voltage underground cables can be, in average, seven times as expensive as overhead lines, while for high voltage lines of around 700 kV, the costs can be approximate twenty times higher in average (Kiessling, Nefzger, Nolasco, & Kaintzyk, 2014).

Central power transmission infrastructure is faced with different external challenges: Akdeniz & Bagriyanik (2016) summarize three risks: terrorist attacks, internal failures, and adverse weather, which all can evoke blackouts. Specifically the latter recently occurred in Puerto Rico, when the tropical storm Hurricane Maria destroyed most parts of the island's power infrastructure in September 2017; CNNs headline read: "Puerto Rico Governor: Power could be out for months" (Yan, Almasy, & Santiago, 2017). As a result, many sectors, such as health institutions, could only rely on back-up diesel-powered generators, which are prone to shortages of fuel supply. This humanitarian crisis fueled the discussion on the role of centralized grid infrastructure versus decentralized options, as a break-down of those does not necessarily impact the island's power supply system as a whole and can be restored with less effort (Wood, 2017). The authors further discuss that a risk estimation of these indicators is challenging, because limited historical data exists and those events are unpredictable in their nature of occurrence. Another extreme weather event was Typhoon Haiyan, heavily affecting the Philippines and their power system infrastructure in 2013 with similar consequences in regard to the power supply (Abi-Samra, McConnach, Mukhopadhyay, & Wojszczyk, 2014).

Further, a more detailed classification scheme of threats to the security of power systems was developed by Bompard, Huang, Wu, & Cremenescu (2013). They categorize different types of threats into four super-ordinate groups: natural threats, accidental threats, malicious threats, and emerging threats. Natural threats can be disasters of various types, such as geological, hydrological, or meteorological disasters as well as fires, health, and space disasters and contamination. Accidental threats summarize operational faults and equipment failure. Furthermore, malicious threats are defined as physical threats which can be terrorist attacks, war, or sabotage. Human threats occur when people with physical access and inside knowledge about the infrastructure compromise its security or, by conspiring against energy systems through gaining unauthorized access into the control structures to control the system, disrupt operation or gather information. Emerging threats are systemic malicious threats, which developed through the evolution process of power system infrastructure and relate to failures in other infrastructures. Grid power is historically seen as desired option to provide area-wide access to electricity – while this perception has started to change recently (Straeten & Hasenöhrl, 2017).

Storage options for electricity

The volatile nature of renewable energy availability fosters the need for storage options to be able to supply electricity during periods, when no generation can take place due to the absence of renewable energy availability. Likewise, diesel-powered generation is also dependent upon planned transport and local storage of the fossil resource.

However, innovative storage options are available to overcome said limitation: it can be differentiated between various energy storage types which differ in the type of storage technology with their respective characteristics. Typical storage types are chemical storage, such as lithium ion and lead acid batteries, or mechanical storage, such as pumped hydroelectric energy storage (Schmidt, Hawkes, Gambhir, & Staffell, 2017). Characteristics are the respective capacity (total amount of energy which can be stored) and their rated power (amount of energy which can be allocated in one time step), as well as their environmental and social impacts. Environmental impacts, such as waste creation resulting from insufficient recycling structures, lead to effects such as lead pollution (Gottesfeld & Cherry, 2011). Social effects are created by relocation of villages, which often occur during large-scale hydroelectric dam constructions. Furthermore, the use of battery storage technologies requires the consumption of resources and energy for the storage manufacturing process. Those processes are often related to serious environmental and health effects (McManus, 2012): the high-

Figure 3.5.: Truck transporting charged batteries and lamps to a local night market in Myanmar's central dry region. Author's own photograph (May, 2016).

est impacts identified from lead acid and lithium ion battery storage production are human toxicity and metal depletion.

Storage options are available in all sizes, from small disposable batteries for household appliances such as torches, to rechargeable car batteries often used to power household appliances in rural communities (Fig. 3.5), to large scale battery storage containers or giant water storage dams, allowing the use of the stored energy at a different time and/or place. The choice of storage type depends on several aspects, for example, if long-term storage is required to overcome seasonal effects or short term storage for curbed usage, e.g. to provide for a night without solar irradiance.

The increasing importance of energy storage as a consequence of higher shares of renewable energy sources requires the development of sustainable battery storage technologies (Larcher & Tarascon, 2015) as one important aspect regarding the achievement of a clean energy future. This novel demand for battery storage triggers a dynamic development of battery storage evolution (Fig. 3.6), with new battery storage types being developed at a general cost decline (Kittner, Lill, & Kammen, 2017).

Central and decentralized options for rural electrification

Central electricity supply structures are characterized by one or more substantial energy generation units at one location and a corresponding T&D system which transfers the electricity to the customers. This results in large utility structures which supply a given demand for electricity. On the contrary, decentralized electricity supply structures describe systems where the power generation can take place at various locations, principally closer to the consumer. It is also possible that consumers themselves produce electricity and feed any surplus

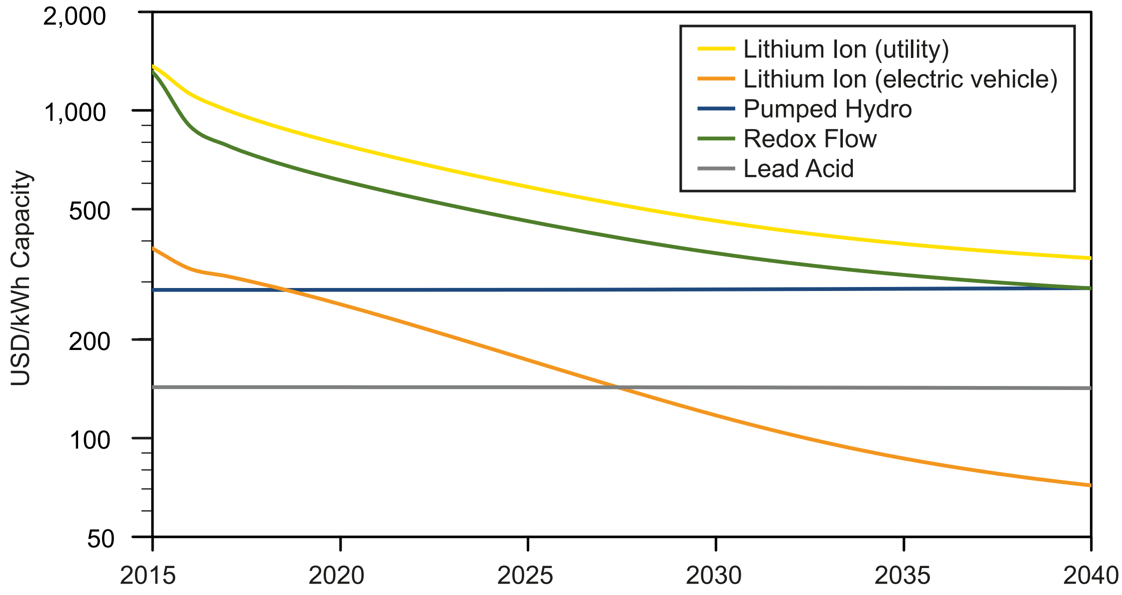


Figure 3.6.: Battery storage cost development. Author's own diagram, data based on Schmidt, Hawkes, Gambhir, & Staffell (2017).

electricity into a distribution network. For this model the term *prosumer* evolved recently (Kästel & Gilroy-Scott, 2015).

Generally, decentralized energy systems are smaller in size and for these systems, it is also possible that production and consumption take place isolated from any other electricity system and unconnected from any other production and consumption, combining one generation source with one device or one household. The most common example here are solutions powering individual households, such as solar home systems or small diesel generators.

Both options, decentralized and centralized structures are characterized by advantages and disadvantages: centralized systems create a dependency on the supplier – which can leave a customer with unplanned blackouts or planned load-shedding – while decentralized systems are often limited in size and power and hence, fewer devices can be powered.

Recent trends in the technical and institutional transitions of energy systems can be observed: technology development for using renewable energy achieves high learning curves which result in falling costs for technologies such as wind and solar power and storage technologies. With this development, the traditional power generation companies using technologies such as coal, oil, and gas are confronted with new competitors. The novel technologies are partly characterized by a strong modularity, which means that the size of systems is very flexible and that they can be very small in their capacities, allowing much more people to own such systems for the generation of electricity. This leads to an empowerment of non-utility related institutions or individuals on a household level, creating a new independence and new groups of players in the energy sector (Rohracher, 2007). An example for an uptake of a new technology is the success of solar home systems in Bangladesh, which was started by focusing on the needs of the rural population, considering usability, cost, and procurement, and repair and maintenance within the product design (Wimmer, 2012).

These developments come hand in hand with a liberation of the existing governance structures

for energy infrastructure. The image of renewable energy in society is improving and the potentials of renewable energy are becoming more and more self-evident.
With the central and decentralized types of energy systems, two different options exist to increase the global access to electricity: the first option is the extension of existing transmission coverage and upgrade of the respective central power generation capacity to allow for additional demand, while at the same time extending the distribution infrastructure to connect more customers. The second option is to create new electricity supply through decentralized energy systems, which are independent of any larger energy transmission network and centralized large scale power generation. These systems can be described as follows:

> Distributed generation is an electric power source connected directly to the distribution network or on the customer site of the meter. (Ackermann, Andersson, & Söder, 2001)

The latter option can be divided into large decentralized systems, such as mini-grids, which are defined as a small network of power generation units and optional storage able to connect and supply several households or villages by a distribution grid (Fig. 3.7), and stand-alone solutions on a household level, such as solar home systems or solar lanterns. Regarding the fuel source, renewable energy and fossil fuels can be used in both types of systems, whereas Onyeji, Bazilian, & Nussbaumer (2012) stress "the importance of renewable energy technologies cannot be overemphasized" for the purpose of extending access to electricity. The role of renewable energy is also stressed for its "social, technical, and spatial (disposition of supply and demand) advantages" especially in rural communities (Hoare, 1979). Another major mini-grid option based on fossil fuels are diesel generators. Diesel generators can be independent small-scale supply units for certain devices, or they power a small mini-grid (Oladokun & Asemota, 2015). They can power applications beyond lighting devices, such as cooling or powering of machinery for productive use. Mini-grids can either be fully independent of a larger supply infrastructure as an island system, or they can be operated in a grid-connected manner, allowing a connection to another system.
The other option of decentralized energy generation and supply is by stand-alone solution. A very common option here is a solar home system (SHS). SHS are typically small installations, where the production and consumption of electricity takes place at household level (Fig. 3.8). In addition to the provision of light, those systems can power mobile phones or small devices such as radios. In addition, even smaller solutions are available: pico-solutions are mainly single applications, such as rechargeable lamps or battery-powered torches. Although these are very small energy generation systems, all of these options may contribute to the achievement of SDG#7.
Supply structures for electricity in rural areas, locations which are not connected to the grid or which are under-supplied due to limited capacity or blackouts are often dominated by decentralized approaches. Without a connection to a major power transmission grid, the population is forced to look for alternatives. In the past, these have been mainly substitutes for electricity for lighting, such as kerosene lamps, which emit black carbon and are found to be a major cause for respiratory diseases as well as being a fire hazard. The other option for lighting purposes are candles, which are often expensive and not available everywhere.

Figure 3.7.: PV-battery mini-grid with battery house and solar module installation in Myanmar's central dry region. Author's own photograph (May, 2016).

Figure 3.8.: Solar home system in a village in Myanmar's central dry region. Author's own photograph (May, 2016).

One option in between mini-grids and stand-alone systems are solar kiosks (Shields, Louie, Blainedavis, Goldsmith, & Nausner, 2016). Those kiosks contain independent electricity generation units with photo-voltaic panels plus battery storage and offer services such as phone charging or solar lantern rental.
In this thesis it is distinguished between three different types of supply systems: grid extension, mini-grids, and stand-alone solutions.

3.2.2. Economic structure of energy systems

Due to the steadily increasing global demand for electricity (IEA, 2017a), electricity is an economic commodity with an associated value. Therefore, energy markets evolved for selling and purchasing energy resources to produce electricity and electricity markets emerged for trading the produced electricity. The former is embedded into highly complex worldwide commodity chains, such as the global crude oil market. The latter is specifically important in large electricity networks with different electricity generation companies and distribution companies as well as the end customer being a direct counterpart of a supply contract.
Production costs and prices for electricity vary over countries and regions and depend on different parameters which impact the cost: local resource availability and technology choices affect the electricity generation costs, while governments can influence prices by creating subsidies and taxes on either resources or technologies and private companies can develop own business models for generating and selling electricity within a given policy framework. In terms of financing, massive investments are required to achieve the electrification targets, independently of the chosen technology. The feasibility assessment of the energy system and the financing structures based on it reveal the need for financing options (Brew-Hammond, 2010; Bhattacharyya, 2013).

Determining the value and price of electricity

The production cost of electricity generation is a function of different parameters, depending on the technology in place and the respective energy source. Technologies can mature over time, leading to higher efficiencies and hence, lower payments, while the costs of energy sources can vary over time, increasing with higher demand and differing from country to country or on a local level, for example, due to higher transport costs. This makes power supply for remote areas generally more expensive, since either the foundation of both infrastructure and energy resources need to be transported to the remote site.
Technically, electricity costs for the end customer are a function of the costs for electricity production, electricity transport and distribution plus optional surcharges, such as taxes. Due to the long lifetime of transmission infrastructure and the complex cost structure considering land acquisition, forest clearance, and current prices for copper and aluminium, as well as local cost for labor plus varying maintenance, it is difficult to calculate an accurate price tag. For example, Brücher (2009) states that T&D related costs account for at least half of the production costs of electricity. In addition, distribution companies are responsible for the tariff collection, which, depending on the local tariff structure, can be either a fixed flat rate tariff or metered consumption. In countries with low coverage of banking facilities,

automated and digitized tariff collection remains a challenge, while today the concept of virtual financial services, such as mobile money, opens up new perspectives to simplify remote money transactions via the use of mobile phone technology (Alstone, Gershenson, & Kammen, 2015).

A good measure to compare costs of different energy systems is levelized costs of electricity (LCOE). LCOE is a measure to describe costs of electricity generation per unit of generated output during the lifetime of the system's technical components. This includes capital expenditure (CAPEX) for technology and financing as well as operational expenditure (OPEX) for operation and maintenance and return on investment/discount rate, divided by the generated electricity over the lifetime of the single components (Short, Packey, & Holt, 1995). CAPEX and OPEX can therefore be divided in fixed and variable costs. For fossil fuel-powered generation plants, the operational cost are generally higher than for the renewable energy plants, since fossil fuels need to be purchased on an on-going basis to operate the plant, impacting on the finite nature of fossil fuels due to limited reserves. Renewable energy generation on the other hand, is characterized by substantial initial capital investments, due to higher technology costs but lower operational costs, due to the advantage of energy resources available locally at no cost (e.g wind or solar irradiance).

Politically motivated pricing schemes for electricity and tariff settings can lead to various prices for different customer groups, such as domestic consumers or industrial consumers or according to different amounts of consumed electricity. Electricity prices can also vary depending on the availability of electricity which can be influenced by resource availability. A common example here is the varying availability of hydro power during rainy and dry seasons in regions with strong dry and wet seasons.

The chosen pricing scheme and also the role of taxes and subsidies for energy resources and electricity lead in some cases to economically unsustainable systems. This happens when for example, the prices of electricity for the consumers are artificially kept low so as to sell the electricity at an affordable rate. The price difference is paid by the government and can lead to a heavy burden for national economies. Such a scheme requires governments to cross-subsidize the costs for electricity generation to allow, on the one hand, more people to afford energy access. However, on the other hand, power utilities need to be in an economic position to maintain and upgrade systems as required.

To organize a market for electricity transactions, different schemes have been developed: Feed-in tariffs allow the option to sell electricity for a fixed price while energy auctions are reversed auctions, where an auctioneer aims at the lowest price for electricity: certain criteria such as the amount of required electricity or the plant capacity need to be met while the bid needs to be below a defined ceiling price (IRENA & CEM, 2015). With this model, a significant increase in renewable energy was achieved in South Africa (Eberhard & Kåberger, 2016), with a specific focus on large-scale systems. On the other hand, small scale systems nowadays are seen as an option for independent household solutions, introduced as the prosumer structure. Here, bottom-up energy transactions can start easily, where for example electricity can be traded with a neighbor at an agreed price.

By comparing electricity prices to different commodities which provide comparable services,

the economic benefits of electricity supply can be highlighted: Opportunity costs by using alternatives to electricity supply develop through the purchase of candles and kerosene, the rental of solar lamps, or the use of non-rechargeable batteries for torches or other appliances and are often high compared to the use of electricity (Mills, 2017). In addition, as stated by Yaqoot, Diwan, & Kandpal (2015), further effects can occur, such that for example the replacement of kerosene with electricity leads to improved air quality and better light quality among other effects.
The complex field of electricity pricing is interlinked with the different organizational structures of energy systems, which are introduced in the following sub-chapter.

3.2.3. Organizational structure and management of energy systems

Energy systems are related to resource flows and embedded into global and regional markets, as shown before, with customers from all different societal groups. Due to the external effects of resource use, such as emissions, exploitation of resources, and concurrent use of different resources, as well as the political will to provide universal access to electricity, various ownership structures emerged in different countries and regulation and policy development for the energy sector evolved, complementing the technical and economic dimension of energy systems.

Ownership structures of energy systems

As previously introduced, electricity supply systems can be framed in the T&D infrastructure and the electricity generation plants, most often these components underlay different ownership structures.
Assets can be either owned by a government, by a company, by a community, or by a private person. It is also possible that the owner of the assets provides concessions for certain parts of the infrastructure. Historically, the centralized energy system of a country was often, or still is owned by the government; at present, power sector reforms are on-going in many developing countries, with a trend to privatization, deregulation, and competition becoming the norm (Zhang, Parker, & Kirkpatrick, 2008). Due to the requirement of generally large capital investments to install large-scale systems, this resulted in the establishment of mostly centralized systems, as financing options for small-scale decentralized projects are still limited (Gujba, Thorne, Mulugetta, Rai, & Sokona, 2012). With the dispersal of increasingly more energy systems for generating electricity, governments took the role of the energy supplier in many cases. They are also holding the responsibility of supplying the basic needs of the population, which in many cases, is not successfully achieved due to malfunctioning systems and inadequate existing energy infrastructures.
Recently, a privatization of large scale systems is taking place in certain countries and decentralized usage of renewable energy opens up new opportunities to supply private needs and become independent and self-sufficient of external energy supply at the same time (Chaurey, Krithika, Palit, Rakesh, & Sovacool, 2012).
Small decentralized systems are often characterized by more privately owned generation assets because small systems are often much simpler in their operation and less capital is required for

the initial investment. Decentralized energy systems may become an investment opportunity for private sector involvement, however, certain barriers, such as high risks and long payback periods still exist and must be overcome (Williams, Jaramillo, Taneja, & Ustun, 2015). This transition of ownership structures from state-owned entities to private ownership structures means, that the system needs a clear regulative framework to guarantee its optimal level of functioning.

Regulation and policy design for energy systems

The regulation of a market or a sector has the intention to prevent the establishment of monopolies and to supply basic needs for electricity of the society and thereby aims at control structures. Certain strategic objectives can be pursued by the development of respective policies: restructuring of a national power sector, for example to enable additional generation for supplying increased demand or achieving rural electrification objectives, often goes hand in hand with power sector reforms. Power sector reforms can be initiated by several different, partly contradicting measures: market liberalizations to create competition in the market, vertical and horizontal unbundling to separate T&D and power generation, and – by a division of multi-sector utilities into pure electricity utilities – commercialization to improve market dynamics, privatization, and establishment of independent regulatory bodies (Haanyika, 2006).

Through financial incentives, such as tax reductions or power purchase agreements (PPA), clear business models can be created by establishing a clear framework of rules and responsibilities of the different stakeholders. Tax reductions or exemption can stimulate and support the import and installation of specific technologies, e.g. photo-voltaic modules or battery storage. Power purchase agreements are contracts which guarantee that the generated electricity is bought by the contractor, often regulated by a feed-in tariffs (FiT), which provide a fixed rate for generated electricity. A comprehensive regulation of the energy sector and the electricity market shall answer the following questions:

- Who is allowed to generate and sell electricity;
- How is electricity generation from various sources handled;
- For which price can electricity be sold to which customer group;
- Which energy sources or electricity generation types are supported by tax reductions and guarantees, such that respective technology choices will be reflected in profitable business models;
- Are standardized power purchase agreements with feed-in tariffs available in a region or country of interest;
- Is purchasing electricity from a national provider capped to a certain limit;
- What happens if regions supplied by decentralized energy infrastructure become connected to the national energy network?

In addition to a regulation for the electricity generation, the redistribution of electricity to an end customer can be regulated as well: electricity tariffs may be fixed for different consumer groups, securing the pay-back for the generation, transmission, and distribution, while supporting fair prices for the end customer. In central supply structures run by a state utility, electricity tariffs for the end customer are often set to a comparably low level to account for the predominant lack of ability to pay, leading to a possible finance gap between production costs and the collected tariff revenue. This requires subsidies from the government, which benefit the high-income groups most. For many cases, especially in sub-Saharan Africa, this subsidy scheme leads to artificially low electricity prices and exacerbates the entry of private utilities or generation companies to sell their electricity under a cost-covering tariff scheme (Alleyne & Hussain, 2013). Furthermore, price distortion can also be a consequence of subsidized resource prices for e.g. gas or oil, which limits the ability of alternative sources to compete. Also, the overall clearness and applicability of the regulation is of high importance: if a regulation is very complex in its processes and those processes are either capital or time intensive, it can hinder the interest of new stakeholders to enter the market, as the regulation may prove to be a prohibitive risk factor. Also, volatile regulation can create a strong uncertainty factor for electric utilities (Benth, Kholodnyi, & Laurence, 2013). Finally, regulation and policy development has the potential to frame incentives for certain sector developments, such as towards an increased use of renewable energy technologies. This is an opportunity to mitigate and reduce climate change impacts of electrification, which are discussed in the following sub-chapter.

3.3. Climate change impacts of electrification

The Intergovernmental Panel on Climate Change (IPCC) defines climate change as

> "a change in the state of the climate that can be identified by changes in the mean and/or variability of its properties that persists for an extended period, typically decades or longer." (IPCC, 2008)

Anthropogenic climate change presents one of the largest global challenges of this century, as human activities have been identified to make an aggravated contribution to climate change today, since emissions of anthropogenic GHG emissions have increased, as economies shifted towards industrialization in many countries (Oreskes, 2004; Hoffmann, 2011). The most important GHGs are carbon dioxide, methane, nitrogen oxides, and F-gases, such as hydrofluorocarbons. The concentration of these gases in the atmosphere has increased significantly since the beginning of industrialization, which was accompanied by the intensive use of fossil fuels. In addition, the CO_2 absorption capacity of the environment, in so-called carbon sinks, has been reduced by deforestation and soil sealing as a result of urbanization and intensification of agriculture. Intensive agriculture, such as rice cultivation and livestock farming also leads to increased methane emissions. Nitrogen oxides are mainly emitted through the use of fertilizers and pesticides as well as the combustion of fossil fuels (Maharjan & Joshi, 2013: 5).

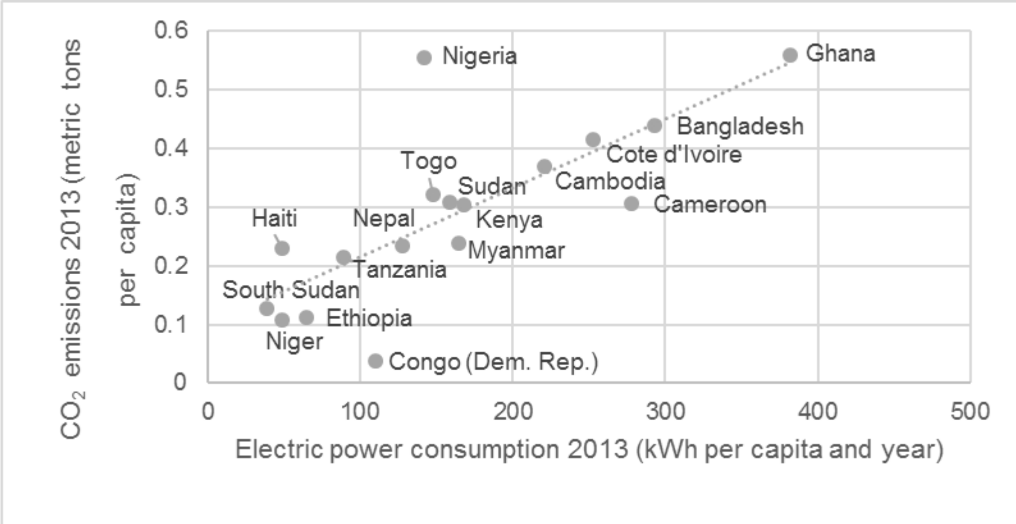


Figure 3.9.: Electricity and CO_2 emissions of selected developing countries per person and year in 2013. Author's own diagram, source data from OECD/IEA (2014).

When looking at the proportions of anthropogenic GHG emissions in the various sectors, electricity generation takes a pivotal role: approximately one quarter of the total anthropogenic emissions globally can be traced back to generating electricity, followed by emissions stemming from agricultural activities, forest and land use, industry, and transportation (IPCC, 2014). Emissions in the electricity sector, however, are distributed differently across the world – depending on the use of electricity, resulting from demand and the type of electricity generation technology.

Statistics show a wide range of per capita values for average national electricity consumption and CO_2 emissions: Countries with very low electrification rates use very little electricity on average, but are characterized by varying levels of CO_2 emissions. As shown in Figure 3.9, Nigeria for example reached a per person consumption of 144 kWh in 2013, with CO_2 emissions of approximately 0.5 metric tons, while Cameroon achieved a higher electricity consumption per person of 280 kWh on average with a lower CO_2 emission (approximately 0.3 metric tons). The reason for these variations is the different power generation mix, with a high proportion of renewable energy sources, especially hydro power, resulting in low CO_2 emissions. Comparatively lower CO_2 emissions are also the case for example for Nepal, Congo (Dem. Rep.), and Ethiopia, countries with the highest share of hydroelectric power in their energy mixture globally (IEA, 2014a). Furthermore, CO_2 and CO_2-equivalent emissions can also be linked to a country's economic performance: Here, it becomes clear that there are differences in the CO_2 intensity of national economies, depending on the dominant sectors and resources of each country. With the transition to the post-industrial phase, the role of electricity will increase, as more GDP will come from the services sector and digital products and services.

However, due to the present low overall consumption of electricity in countries, such as in sub-Saharan Africa, in the domestic and the industrial sector, the total national CO_2 emissions from electricity generation are still low. With respect to the projected increase in demand,

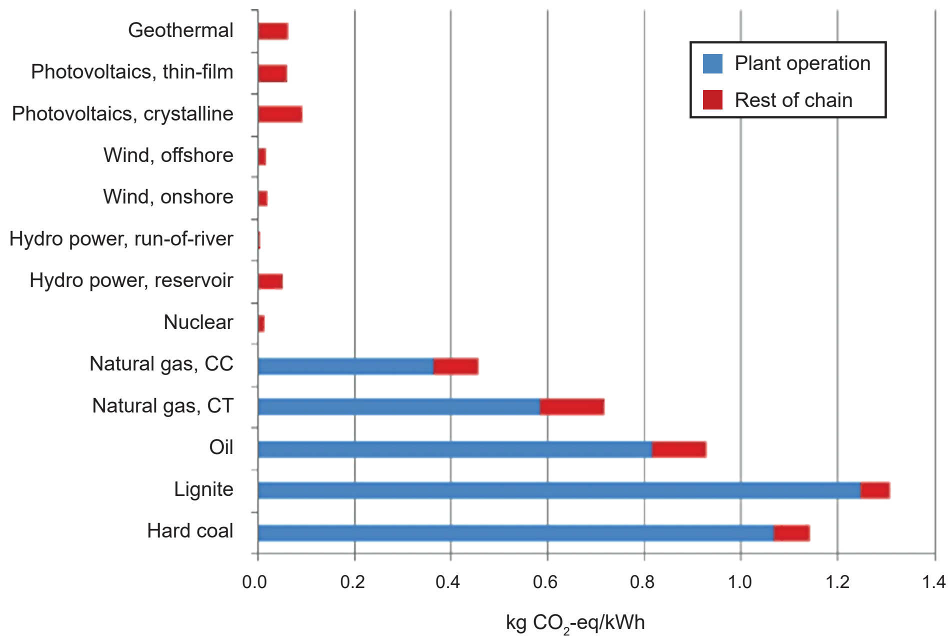


Figure 3.10.: CO_2 equivalent for different types of electricity generation. Fossil fuels emit the major share of GHG emissions during plant operation, whereas the renewable resources emit minor levels of CO_2, unrelated to plant operation. Author's own diagram, adapted from Bauer, Treyer, Heck, & Hirschberg (2015).

the importance of sustainable, low-carbon solutions for the generation of electricity becomes evident. While some highly industrialized countries aim at reducing their total carbon-footprints by the introduction of efficiency measures, for countries with weak economies this is more challenging, especially if carbon-based solutions are available easily.

By bringing electricity to regions where it was not available before, a shift in energy usage of different forms of energy takes place: traditionally, energy is mostly used for cooking and lighting and local resources, such as firewood or manure, are used. Today, the use of charcoal has increased as well. In addition, kerosene lamps became one common source of light, which may shift in future to decarbonized solution or technologies with lower CO_2 emissions per generated kWh electricity. Therefore, it needs to be considered that different energy sources lead to different CO_2 emissions for each generated kWh of electricity. For centralized energy supply systems, a grid emission factor can calculated by a detailed methodology, taking into consideration the currently installed electricity generation plant portfolio and the related emissions (Brander, Sood, Wylie, Haughton, & Lovell, 2011). The latter is based on CO_2 emissions and equivalents from the use of fossil fuels, which differ according to the energy content of the different fuels. The highest CO_2 emissions are produced by lignite, followed by coal and oil. Natural gas is the fossil fuel source with the lowest CO_2 emission per kWh of produced electricity.

As shown in Figure 3.10, renewable energy technologies are characterized by low or zero CO_2 emissions for plant operation. Minor CO_2 emissions stem from construction and decommissioning of plants, with the lowest impacts from hydro-electric run-off-river plants and wind power. In terms of CO_2 emissions, nuclear power is characterized by low emissions as well,

whereas those plants have a high risk profile and unsolved challenges in waste management of radioactive material.
Anthropogenic climate change is therefore of such great importance, since extreme weather events occur more frequently as a result of global warming and change local living conditions and ecosystems. Extreme weather events can be short-term events, such as storms, droughts, extreme rainfall with flooding, or long-term changes in historical climate patterns, such as late onset or absence of rainy and dry seasons, an increase in global temperature, and sea level rise. The effects of these changes have a direct impact on people's lives, today's settlement areas can become uninhabitable, diminished or crop failures lead to food shortages as well as loss of profits from agriculture. This in turn can lead to famine, which can be one reason forcing people to flee.
Different regions around the world are differently susceptible to these effects. The IPCC defines vulnerability in the context of climate change as follows:

> The degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity. (IPCC, 2001: 995)

The most vulnerable countries to climate change impacts are in most cases countries which are faced with severe poverty, such as many countries in sub-Saharan countries (Hallegatte, Bangalore, Bonzanigo, Fay, Kane, Narloch, Rozenberg, Treguer, & Vogt-Schilb, 2015).
While improving access to electricity will inevitable increase emissions, it is important to mitigate those on the one hand by appropriate technology choices based on renewable energy, while on the other hand limit the consumption of electricity by energy efficiency measures. A good example are new technologies, such as LED lights, which have a much higher energy efficiency compared to compact fluorescent lamps (CFL) or incandescent lamps, which are known as the traditional light bulbs, which are being phased out in many countries today. By comparing the performance of the lamps measured in lumen with their energy consumption, their efficiency can be measured.
Furthermore, demand side management holds the potential to direct the demand to a pattern that matches best with the power generation at a given time. The prime example here is that solar-powered electricity is most efficiently used during the day – thus, no large storage is required compared to the use of electricity generated by solar power during nighttime.
Brown, Hammill, & McLeman (2007) and Scott (2015) investigate to what extent climate change has an impact on international security and come to the conclusion that risks exist and that corresponding countermeasures and mitigation measures are of utmost importance. This shows all the more the role of a sustainable energy supply and supportive policy development, as this is the only way to counteract climate change.
As a reaction to anthropogenic GHG emissions and their impacts, the Kyoto protocol was formulated as a global attempt to alleviate the current trend of increasing GHG emissions, aiming at mitigating negative climate change impacts through climate policy design. This international treaty was signed in 1997 and came into force in 2005 (United Nations, 1998).

However, the national implementation of agreed measures is often threatened by different national interests opposing a reduction and therefore, requires pioneering to show how such measures can be implemented successfully (Sterner, 2011).

4. Study area: Electrification in Nigeria

A general introduction of Nigeria provides background information on its geography and the historical development of the country, as well as a history of the political system and its changes over time to facilitate an understanding of the country's overall situation today. In addition, the diverse societal groups are introduced and economic activities and key figures are presented. This is followed by a presentation of Nigeria's power sector and a stakeholder overview, introducing the different actors related to the power sector and rural electrification in particular. The next sub-chapter gives a detailed overview of the five Nigerian federal states Cross River, Niger, Ogun, Plateau, and Sokoto, which are in the focus of the detailed modeling of different electrification options. The chapter concludes with a summary of the current state of research, specifically on energy access topics and power sector development in Nigeria.

4.1. General introduction of Nigeria

Nigeria is one of the largest West African countries, in terms of size, population, and economy. It has a population of around 189 million people and its size is more than twice as large as Germany with 920,000 km^2 (Central Intelligence Agency, 2018).
Nigeria was never part of the Least Developed Countries (LDC) and is listed today in the group of countries of lower-middle income economies of the World Bank classification, together with 51 other countries, e.g. Cambodia, Kenya and Myanmar (World Bank, 2017c). The HDI, developed by the United Nations Development Programme (UNDP) ranks Nigeria 152th of 188 countries in the 2016 version of the Human Development Report, defining Nigeria as a country with a low human development (Jahan, Jespersen, Mukherjee, Kovacevic, Bonini, Calderon, Cazabat, Hsu, Lengfelder, Lucic, et al., 2016).

Geography of Nigeria

Nigeria is located between 4° and 14° north of the equator and between 2° and 14° east of prime meridian. The country is bordered by Cameroon in the East, Benin in the West, Niger in the North, and the Gulf of Guinea in the Atlantic Ocean in the South. Across Lake Chad in the Northeast, there is also a small border with Chad. The Niger River runs from the Northwest to its delta in the South of the country. Its major tributary is the Benue River, flowing from northern Cameroon into Nigeria and meeting the Niger south of Abuja (Fig. 4.1).

Figure 4.1.: Map of Nigeria. Source: United Nations (2014).

The highest mountain Chappal Waddi has an altitude of 2,419 m, located in a mountainous area in the Southeast of the country at the border to Cameroon Central Intelligence Agency (2018).

Due to its large size, the country can be divided into different climatic zones: the North of the country borders the Sahel, a transition zone between the Sahara desert and the more tropical South.

The country is divided into 36 federal states plus the Federal Capital Territory and is further structured into more than 700 local governmental areas (LGAs). In 1991, the capital of Nigeria was moved from the largest city Lagos in the South to Abuja, located in the center of the country. The country is divided into six geopolitical zones, South-East, South-South, South-West, North-East, North-Central and North-West (Odiegwu, Ubabukoh, Baiyewu, & Okpi, 2012).

Natural resources

Nigeria owns diverse natural resources such as tin, iron ore, limestone, niobium, lead, and zinc. As a result of its climate and its arable land, the following agricultural commodities are produced in Nigeria: cocoa, peanuts, cotton, palm oil, corn, rice, sorghum, millet, cassava, yams, rubber, cattle, sheep, goats, pigs, timber, and fish (Central Intelligence Agency,

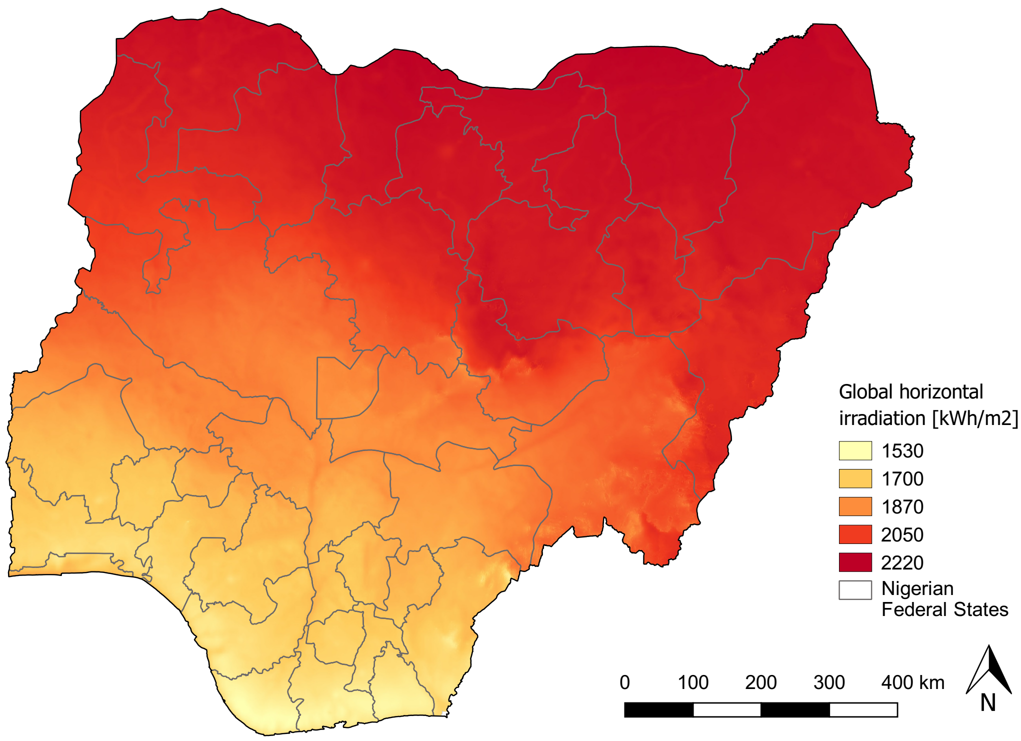


Figure 4.2.: Map of Nigeria's solar potential. Author's own map, solar resource data obtained from the Global Solar Atlas (2017), owned by the World Bank Group and provided by Solargis.

2018).

The country has a large deposit of energy resources, both fossil and renewable. Shaaban & Petinrin (2014) list natural gas, crude oil, tar sand, lignite, and hard coal as energy resources. Proven natural gas resources are the largest on the continent at 5.3 trillion cubic metes in 2016. Crude oil reserves are the second largest in Africa (after Libya) with almost 37 billion barrels (BP, 2017).

In terms of renewable energy resources, Nigeria also has an abundant potential: solar radiation is high in the South of the country and even higher in the North due to the dry climate in that region (Fig. 4.2). Global horizontal irradiation (GHI) in Nigeria is between 1,500 kWh/m² and 2,200 kWh/m², while Germany's GHI values yield between 1,000 kWh/m² and 1,200 kWh/m² (Global Solar Atlas, 2017).

Hydroelectric power sources are also available on the basis of river networks (e.g. Niger River), precipitation regimes and runoff, as well as topographical conditions for hydroelectric power generation (Sharma & Sharma, 1981; Ohunakin et al., 2011). The wind power potential in Nigeria is limited due to its climate and weather conditions, resulting in low wind speeds in most parts of the country. Only a few regions in the mountainous region may have sufficient wind speeds for large-scale electricity generation (Shaaban & Petinrin, 2014).

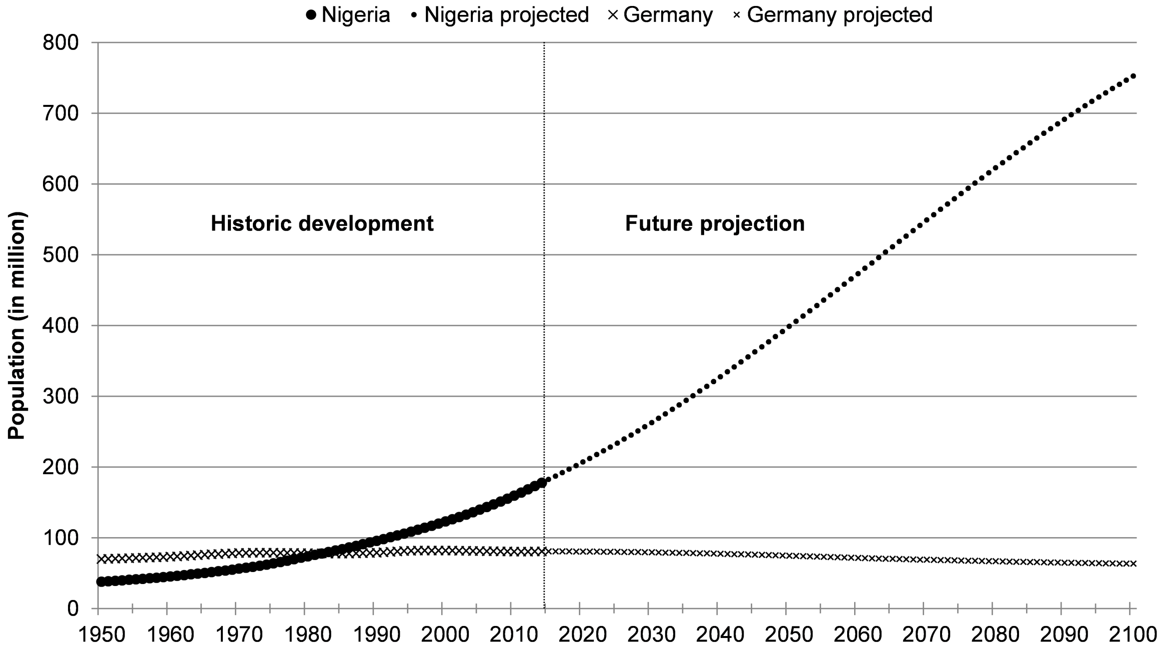


Figure 4.3.: Historical population development and future growth projection in Nigeria compared to Germany from 1950 to 2100, showing a high population growth in Nigeria while the population in Germany remains close to stable over the decades; only with a slight decrease in future. Author's own diagram, data based on United Nations & Department of Economic and Social Affairs, Population Division (2017).

4.1.1. Nigeria's people, history and political system

In terms of total population, Nigeria is home to the largest nation on the African continent. The country has the 7th largest population in the world today, characterized by a significant population growth doubling its number of inhabitants between 1988 and today. Comparing the population growth of Nigeria with the demographic development in Germany over the last decades and into the future, the rapid increase of population in Nigeria becomes even more apparent (Fig. 4.3). Population projections show that in 2050 Nigeria is likely to become the third most populous country globally (> 400 million people), following India and China in terms of population size (United Nations & Department of Economic and Social Affairs, Population Division, 2017). As a result of the large population, the rapid growth will augment already existing challenges for the overall development as defined by the SDGs.

A large country like Nigeria is characterized by an immense diversity of different social backgrounds and ethnically diverse cultures across the different regions. The northern part on the one hand is dominated by a Muslim majority, which was established as early as the 11th century through influences finding their way through the Saharan desert. In the North, different caliphates flourished, while in the South various kingdoms evolved. The state Sokoto in the North used to be a caliphate in the past and is governed by a Sultan until today. Sokoto is also one out of twelve northern Nigerian states where sharia law is still in use as legal system

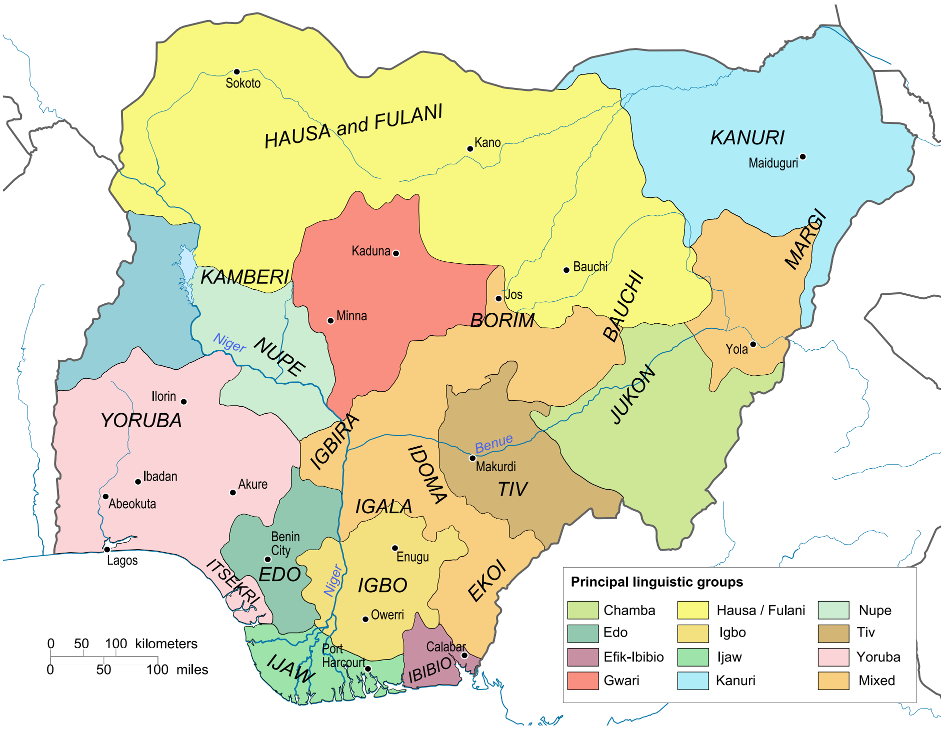


Figure 4.4.: Map of linguistic groups in Nigeria. Source: Hel (2015).

(Suberu, 2009).

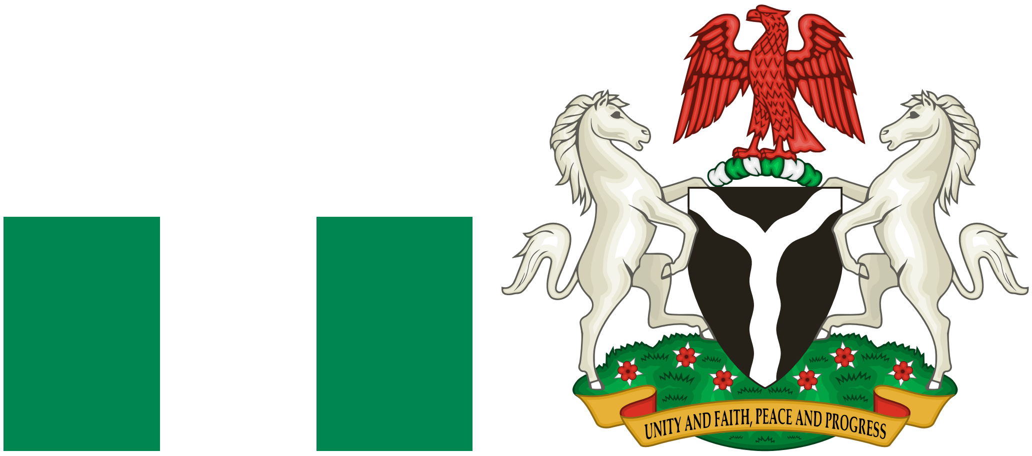
On the other hand, south Nigeria is dominated by a Christian majority, introduced in the region by the Portuguese in the 15th century. This has been leading to conflicts in the transition areas in the center of the country since ancient times. As a result of Nigeria's historical development, various ethnic groups evolved. This is also reflected in the large variance of spoken languages: in total, circa 400 traditional languages are spoken in the country (Akinnaso, 1991). However, the main linguistic and ethnic groups are Hausa and Fulani, Igbo, and Yoruba (Fig. 4.4). Besides these major traditional languages, English is also an official language today.

The location of those ethnic groups correlates with religious preferences, where Hausa and Fulani is dominated by the Islam, while Yoruba and Igbo are mostly dominated by Christianity.

So – when and how did the region become the Nigeria of today? Historically, British colonialism created the first artificial borders of Nigeria in 1914. At the end of World War I, the Treaty of Versailles was formed and Nigeria, as a British protectorate, obtained some of the western parts of Cameroon. Nigeria became independent in 1960 (Iloeje, 1965).

The first years of independence have been followed by a civil war between 1967-1970, the Biafran war, during which three Nigerian federal states proclaimed the Republic of Biafra in the South of the country (Omenka, 2010). After the reintegration of those states into the country a period characterized by alternating military regimes and democratic governments followed. Since 1999, civilian governments are in power, making it the longest period under civilian rule after the independence of Nigeria.

Today, Nigeria is a federal republic and the form of government is a presidential system,



(a) (b)

Figure 4.5.: Nigerian national symbols. Flag of Nigeria (a) and Coat of arms of Nigeria (b) (Lumia, 2014).

with a green and white-striped national flag (Fig. 4.5a). The national motto is "Unity and Faith, Peace and Progress" (Williams & Shenley, 2012), also reflected in the coat of arms (Fig. 4.5b). Since 2015, Muhammadu Buhari has been president of Nigeria, assuming the government of Goodluck Jonathan (Central Intelligence Agency, 2018).

One of the country's most pressing problems today is the prevalence of Boko Haram terrorist group, which is a cause of fear and terror attacks in different places across Nigeria, especially in the Northeast (Aghedo & Osumah, 2012). As a result, in 2015 more than one million Nigerians emigrated or searched for refuge outside the country and the number of internally displaced persons in Nigeria is even higher: more than 1.7 million people have fled from the Northeastern areas, where Boko Haram is threatening daily life, to other parts of Nigeria (UNHCR, 2018).

4.1.2. Economic activities and performance of Nigeria

In 2016, Nigeria's economy is the largest on the African continent in terms of its GDP at purchasing power parity (> 1 trillion USD), ranking 21st globally. However, in terms of GDP per capita, Nigeria ranks only 162th, being within the bottom third of all countries (Central Intelligence Agency, 2018). The currency of Nigeria is the Nigerian Naira (NGN).

Nigeria is classified as one of the newly-defined growing economies with large populations as MINT countries; Mexico, Indonesia, Nigeria, and Turkey (Akpan, Isihak, & Asongu, 2014). Furthermore, it is among the members of the "Next Eleven" grouping, an economic classification of countries that extends the BRIC countries (Brasil, Russia, India, and China), defined in 2001 (Chen & Huang, 2013). These countries are subject to high economic growth potentials, as a consequence of their macro-economic, technical, and political factors, as well as their available human capital and labor force.

At the beginning of the 21st century, Nigeria recorded strong economic growth with growth

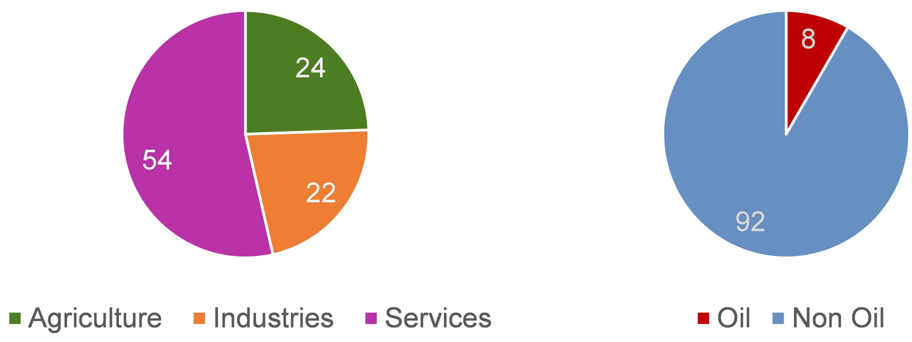


Figure 4.6.: Contribution of the different sectors to Nigeria's GDP in 2016 (in %) for each sector (left), as well as in regard to the role of the oil sector (right). Author's own diagram, based on data from NATIONAL BUREAU OF STATISTICS (2017a).

rates[4] of in average almost 8 % per year between 2000 and 2014, which decreased to approximately 3 % in 2015 and became negative in 2016 (WORLD BANK, 2017b). The largest share of Nigeria's population (>70 %) is employed in the agricultural sector, which accounts for circa 22 % of GDP in 2017. Unemployment rates are comparatively high (> 10 % in 2017) (NATIONAL BUREAU OF STATISTICS, 2017a), as is the share of the informal sector in Nigeria's economy (ARIMAH, 2002). The largest sector share of the GDP in 2016 was contributed by the industrial sector. The oil sector is also an important part of Nigeria's economy with close to 10 % share in the annual GDP (Fig. 4.6).

With limited capacity of refineries Nigeria, as the 6th largest producer of crude oil globally, imports 85 % of its oil demand for petrol and diesel fuel. In consequence, the resource wealth in Nigeria is not fully exploited – although crude oil exports account for almost 80% of the export volume (NATIONAL BUREAU OF STATISTICS, 2017a).

As Nigeria is rich in natural resources, the country's development is threatened by the theory of the curse of natural resources (SACHS & WARNER, 2001). Despite a comparably high resource wealth, as a result of ineffective political institutions, as well as poor regulation and governance, poverty remains a key challenge. The economy is focused on a few industries only and creates respective dependencies. Only few people are profiting from exporting available resources, whereas the majority suffers from direct and indirect external effects. RAUCH (1982) elaborates that spatial concentration of investments leads to deterioration of living conditions in all involved areas and, in consequence, through oil and gas extraction in Nigeria, corruption, environmental pollution, and civil war had evolved.

During the presidential term of Goodluck Jonathan, the oil sector as a whole was characterized by fraud, corruption and mismanagement (OWEN & USMAN, 2015), which led to severe attacks on oil extracting infrastructures in the Niger Delta by newly created militant groups. This region is especially heavily affected by negative effects of the oil drilling and gas explo-

[4]Annual percentage growth rate of GDP at market prices based on constant local currency. Aggregates are based on constant 2010 U.S. dollars. GDP is the sum of gross value added by all resident producers in the economy plus any product taxes and minus any subsidies not included in the value of the products. It is calculated without making deductions for depreciation of fabricated assets or for depletion and degradation of natural resources.

rations led by multinational oil companies – oil spills occur frequently. Population growth and migration from rural areas to the urban areas in the Niger Delta lead to an increase of urbanized areas, and a decrease in forest and mangrove areas. In consequence, in addition to societal losses, such as quality of life, a much lower ecological service value is preserved (Ayanlade, 2012).

The focus on capital-intensive sectors, such as export of crude oil results in comparative low employment rates, leading to low purchasing power for large parts of the population, excluding the periphery from economic growth and development (Rauch, 1979).

In Nigeria, some positive location factors for economic activity can be identified: large industrial ports can be developed in the South of the country at the Gulf of Guinea, a large young workforce and various natural resources are available. However, soft location factors, such as ease of doing business, are hindered by corrupt systems. With high corruption indices Nigeria can be described as a weak state (Durth, Koerner, & Michaelowa, 2002), characterized by weak institutions and a large informal sector.

The system of authority in the governmental sector is characterized by steep hierarchies and the valuation of traditional socio-cultural hierarchies. This is a specific problem for technology innovation, as very often, a sufficient understanding of the benefits of new technologies such as digital data is lacking with older generations, who tend to occupy authorities (Son-Allah & Baba, 2016).

The availability and distribution of mobile phones worldwide and in Nigeria (Fig. 4.7) is contributing to the progress of digitization and globalization. On the one hand, these technologies require electricity in order to be used, but on the other hand, they offer a multitude of new possibilities to use in the areas of communication, knowledge transfer and business opportunities. At the same time available options from the finance sector like mobile payments emerge and allow for new business models, such as so-called pay as you go (PAYG) systems.

Due to its resource wealth, Nigeria's economy is built on the export of those and hence, is very vulnerable to fluctuating world market prices of the respective resources.

Fuel subsidies and the role of currency exchange rates

Historically, the government of Nigeria introduced fuel subsidies to allow for stable prices for the imported oil products in case of world market price fluctuations. With the falling crude oil price in the beginning of 2015, Nigeria was confronted with dwindling profits of the crude oil exports (Fig. 4.8).

For the local economy, this protection against price volatility is very valuable because it lowers the risk of businesses and guarantees a stable fuel supply. Nigeria's Petroleum Products Pricing Regulatory Agency (PPPRA) is the responsible organization for the regulation of fuel prices, inaugurated in 2003. The government licenses Oil Marketing Companies (OMCs) that require import permits within their allocated import quotas. The Department of Petroleum Resources controls imports accordingly. A confirming import certificate is forwarded to the PPPRA, which then calculates the corresponding amount of subsidy from the Petroleum Support Fund (PSF) according to the quantity. This is then paid to the OMCs by the

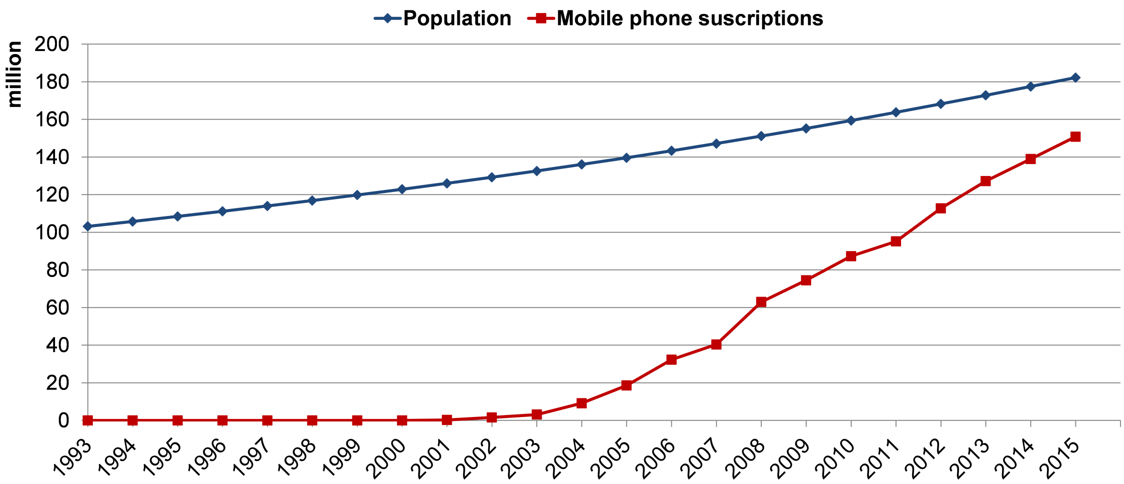


Figure 4.7.: Historical development of population and mobile cellular subscriptions in Nigeria. The indicator includes the number of postpaid subscriptions, and the number of active prepaid accounts. Author's own diagram, source data from International Telecommunication Union, World Telecommunication/ICT Development Report and database, licensed CC-BY 4.0.

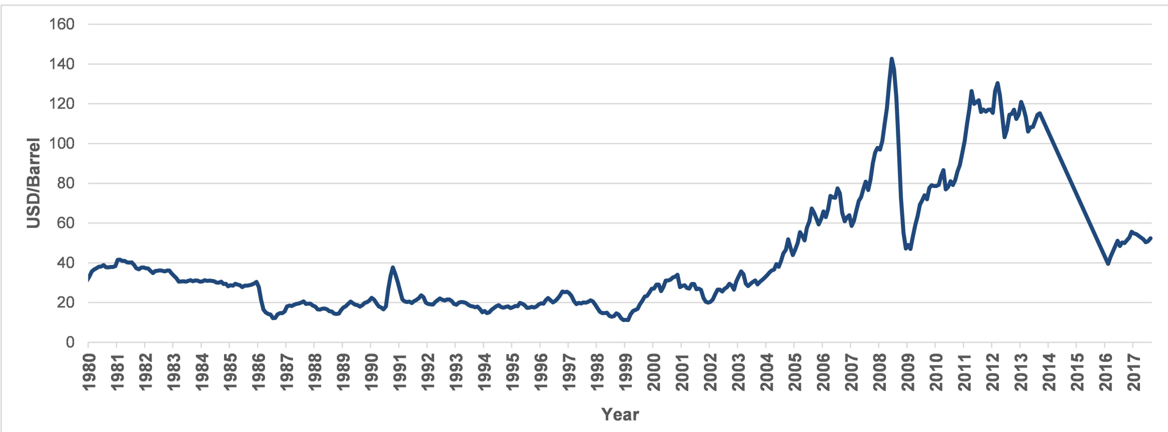


Figure 4.8.: Crude oil price fluctuations. Author's own diagram, based on U.S. Landed Costs of Nigeria Crude Oil (EIA, 2017).

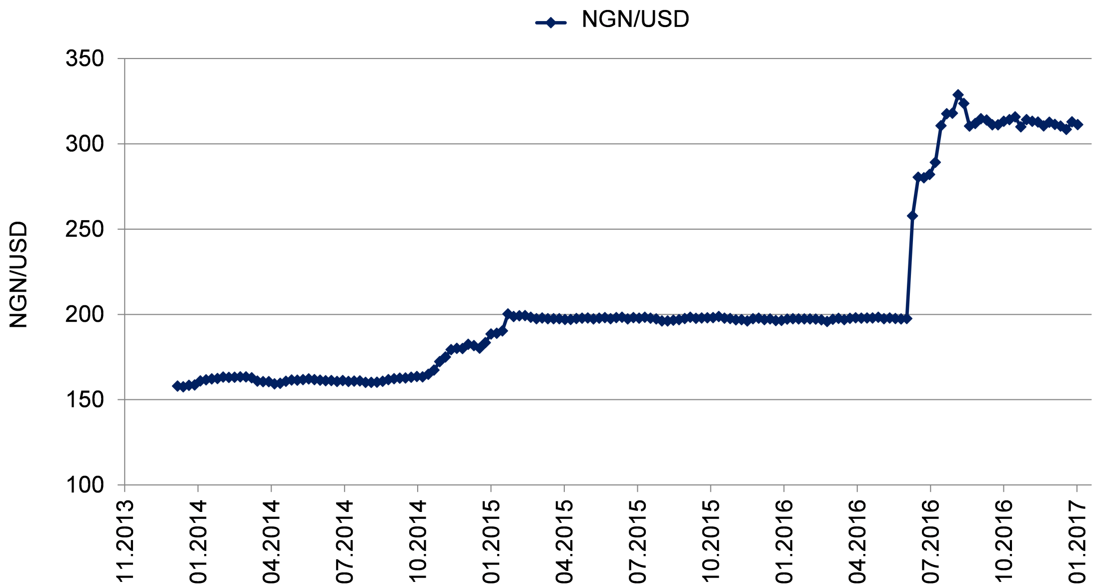


Figure 4.9.: Historic currency exchange rate of NGN/USD. Author's own diagram, data based on OANDA (2016).

Central Bank of Nigeria (Stakeholder Democracy Network, 2015).

With an increasing amount of imported oil due to the national demand, the total amount of required subsidies increased the governmental expenditures heavily. At the same time, the country is highly dependent on the world market price for the import of refined products and the world market price of crude oil for the export. The subsidy scheme was justified by the government's official intention to support the poor population, however, the by far largest customer group of petroleum products is the middle and upper class of society while the consumption by the poor is marginal (Siddig, Aguiar, Grethe, Minor, & Walmsley, 2014; Soile & Mu, 2015).

To stabilize the economy, in the beginning of 2015 the government decided to fix the currency exchange rate of the Naira to the USD. The shortage of foreign currency in the country at that time, due to the much reduced export earnings, lead to a tremendous increase for the black market exchange rate. As a consequence, Nigerian importers of refined oil could not pay for the required imports, which led to a serious fuel shortage in May 2016. During that time, the regulation for pump prices allowed a price increase to almost double of the original price.

In June 2016, the Buhari government decided to abrogate the fixed exchange rate to allow a free trading of the currency (Fig. 4.9), also as a measure to prevent the black market exchange from flourishing. This resulted in a sudden strong devaluation of the Naira, which lasts until today. This is a negative development for businesses which rely on USD imports but it may have positive effects for foreign investors, who will get more for their money. However, inflation in the country is projected to increase significantly, putting even more pressure on the poorer parts of the society (BBC, 2016).

4.2. Nigeria's electric power sector

Nigeria's power sector is facing the great challenge of supplying electricity to more than 180 million people, of which more than half are currently under- or not at all supplied.
Historically, the development progress and transition of Nigeria's energy sector was related to technology which was available at a given point in time (Edomah, Foulds, & Jones, 2016): the first power plant in the former British Colony of Nigeria was built in Lagos in 1896 and generated the first electricity, mainly used to light the Government House and for street lighting in the area. Large infrastructure developments were planned and shaped by the British colonialists, while traditional rulers mainly worked at local community levels. Around the era of industrialization, the development of ports and the railway system was of high importance for economic development. "In 1950 the Electricity Corporation of Nigeria was created and made responsible for the generation and supply of electricity. Altogether, in 1963/63, there were 48 generating plants installed – three in Lagos, seven in Western Nigeria, five in Mid-Western Nigeria, eleven in Eastern Nigeria and twenty-two in Northern Nigeria" (Iloeje, 1965). This fact is not concerning in itself, but compared to today's situation, not too much has changed within the past 50 years (Fig. 4.10), despite the tremendous growth of the population which results in a much higher demand for electricity. In the early years of the 20th century, coal was discovered in Nigeria and started to be used for electricity generation but was phased out later. After the commercial discovery of oil in Nigeria in 1956, the resource was used for electricity generation, but was mainly replaced by gas later on. Today refined oil and diesel are important for the decentralized generation of electricity with generators as well as for the transport sector.
The national electrification rate in 2016 in Nigeria is stated at 61 % in the World Energy Outlook IEA (2017c). From 2009 to 2014, the number of people without access to electricity increased from 76 to 98 million people. This is a consequence of the high prevailing annual population growth, which increased the total number of Nigerians from almost 160 million inhabitants to more than 180 million inhabitants during the same period. The power sector development did not keep pace with this population growth over the last decades, leading to a stagnating and exacerbating energy access situation, especially in the rural areas of Nigeria. In these rural regions, the total electricity access is much lower (34 %) than in urban areas (86 %), as the supply companies mostly focus on providing energy access the densely populated urban areas (ibid).
Census data from 2006 reveals that the most dominant energy source (circa 60 %) for household lighting is still kerosene (National Bureau of Statistics, 2006). This points to the lack of electricity for domestic uses. With an installed capacity of only approximately 6,000 MW for the whole country, the electrification rate unveils how little electricity is available even for the population connected to the electrical power grid. By comparing the per capita electricity generation per year for several countries, the lack of supply and resulting consumption becomes obvious: in 2013, Nigeria consumed approximately 140 kWh per capita and year, which is less than Cameroon (280 kWh) and less than half of the consumption of Ghana (380 kWh) (Fig. 3.9). In addition, the power generation plants in Nigeria are in general very old and refurbishment is needed in the near future for many facilities (Akinwale,

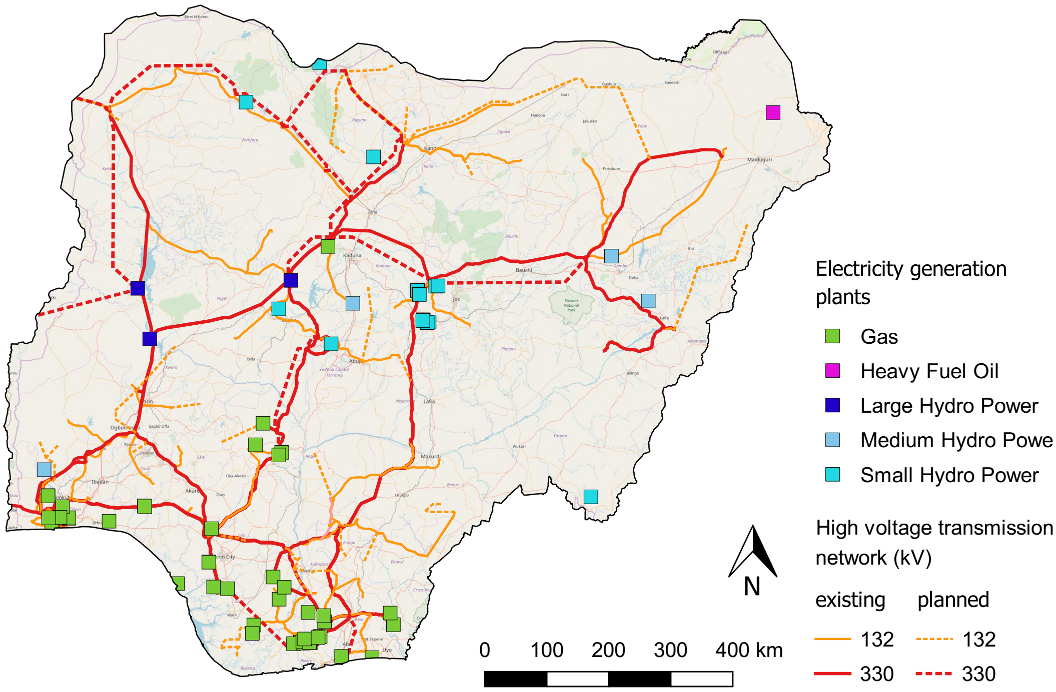


Figure 4.10.: Map of TCNs transmission line system connecting major large-scale power plants in Nigeria. Author's own map, based on data from West African Power Pool (WAPP) (2017) and ECREEE (2017).

2010). Installed capacity is not fully utilized and transmission losses are high (Oseni, 2011). Today, most of the electricity is produced by conventional energy sources, respectably by gas. With the global transition towards the exploitation of more and more renewable energy sources for electricity generation, this opportunity can present an attractive option to diversify the local economy. The only renewable energy resource which is used in Nigeria with a significant power generation capacity is hydro power. Today, almost 20 % large hydroelectric power plant capacity is installed (European Union Energy Initiative Partnership Dialogue Facility (EUEI PDF), 2016), the large-scale power plants are two large hydroelectric power plants, built on the Niger River in Kainji (1969, 760 MW) and Jebba (1984, 540 MW), another one in Shiroro (1990, 600 MW) on the Kaduna River (Aliyu, Ramli, & Saleh, 2013). This old and mature technology can put the large hydro power potentials in Nigeria to use within large-scale projects which contribute a significant share to the national power generation, but also with small village-level hydro power plants. Back in the 1970s, hydro powered electricity generation accounted for more than 80 % of the total generation, while today, due to an increase in generation capacity, the most dominant generation sources are gas and oil, which decreased the share of hydro power generation to less than 20 % (IEA, 2014a). This contrasts a projection dating back to the 1980s, where the authors forecasted

Table 4.1.: Trade statistics for diesel generator import in Nigeria in 2016. Data source (UN Comtrade, 2017).

Trade Flow	Diesel engine size	Quantity /units	Trade Value (US$)
Import	Output < 75kVA	15,061	102,348,028
Import	Output > 75kVA < 375kVA	3,881	73,198,662
Import	Output > 375kVA	n/a	115,875,933

hydro power as the main future power source with a potential generation capacity of more than 8 GW until the end of the 20th century (Sharma & Sharma, 1981).

Independent electricity generation with small generators plays a significant role for power supply in the country. Petrol and diesel fuel pump prices are slowly increasing, while still being cheap in international comparison (National Bureau of Statistics, 2018).

The quality of power supply is insufficient, leaving many regions in the dark for irregular time periods. As a result, businesses started to generate electricity independently with diesel generators. Consequently, the term "Diesel Generator Economy" emerged (Obadote, 2009; Odior & Oyawale, 2012). This term is supported by the fact, that in 2011, a survey of around 30,000 households showed that 26 % of Nigerian households own a generator (National Bureau of Statistics, 2011). The World Bank's Enterprise Survey World Bank (2017a), a survey of businesses, shows that the situation in the economic sector is even more profound, stating that access to electricity is the most hindering obstacle for doing business – in a typical month, more than 30 outages occur with a typical duration of 8 hours. Furthermore, they estimated that this led to economic losses of more than 10 % of the annual sales, which is only that low because more than 70 % of the interviewed companies own a generator. This number does not include the informal sector, which may even have a higher diesel generator use. Oyedepo (2012a) states that the poor electricity supply leads to an economic loss of almost a billion USD annually. From 2007 to 2014 the power outages in firms in a typical month increased from 25.2 to 32.8 outages (World Bank, 2017a), stressing the crucial role of diesel generators for Nigeria's economy (Steinbuks & Foster, 2010).

As a result of the heavy reliance on diesel generators of electricity generation due to the unreliable central power system in Nigeria, and the heavy reliance on decentralized diesel generators for electricity generation, trade statistics confirm the high prevalence of the decentralized electricity supply option: in 2016 alone, Nigeria yielded an official net import of diesel generators with a trade value of almost USD 300 million. In the medium size class, more than 3,500 units were imported during a single year, while in the smallest class (<75 kVA), more than 15,000 units have been imported. Table 4.1 provides an overview of the import and export statistics, showing the large numbers and values of imported diesel generators. The highest trade value can be observed for small diesel generators below 75 kVA, which are mainly used for private small-scale energy generation (UN Comtrade, 2017). Import duty for diesel generators is 5 % and 5 % VAT (Nigerian Customs Service, 2017). Electricity generation costs by decentralized diesel generation are found to be more expensive than the use of gas (Oladokun & Asemota, 2015).

Oyedepo (2012a) further discusses how high infrastructural investments in a diversified energy system with significant shares of renewable energy can be economically off-set with clean development mechanisms. However, electrification rates are still below acceptable levels and therefore, research has been carried out to identify solutions. One of the most recent studies (Ohiare, 2015), finds that expansion of the central grid may be the key measure to increase access to electricity, while Dada (2014) mentions benefits of decentralized electricity generation options.Ohunakin, Adaramola, Oyewola, & Fagbenle (2014) highlight the important role of solar energy for Nigeria's energy sector development, while solar energy is only utilized within small applications or in pilot projects today. They further state that until 2012, there existed no major off-grid hybrid or grid-connected solar projects in Nigeria, even though a large untapped potential exists (Fig. 4.2). To increase the attractiveness for solar products, these are exempted from value added tax, but there is still a 5 % duty on the import. However, batteries are subject to an import duty and a value added tax of 20 % and 5 % respectively for lithium and lead-acid batteries (Nigerian Customs Service, 2017). Increased access to clean electricity can reduce the dependency on fossil fuels eventually and Oyedepo (2012a) stresses the role of energy efficiency measures as an important step towards a sustainable future.

4.2.1. Political stakeholders, institutional bodies and legislative framework of Nigeria's power sector

By analyzing the actors related to the power sector of Nigeria they can be classified into two categories: political stakeholders and the private sector representatives.

A differentiation is necessary to distinguish between different motivations and missions. Between these two groups close relationships and dependencies exist. Therefore, this chapter provides a snapshot of the current situation of the political institutions related to energy provision and specifically rural electrification and its evolution from the 1950s until today. The progress of the evolution of the different institutions and resulting policy design is illustrated in Figure 4.11.

Historically, Nigeria's official power sector management began during colonial times. In 1950 the Electricity Corporation of Nigeria (ECN) was formed. After the independence, the National Electric Power Authority (NEPA) was founded in 1972 by merging the ECN and the Niger Dam Authority (NDA). One key policy development was the National Electric Power Policy (NEPP) of 2001, with the aim of overcoming the prevailing deficits in the energy sector.

The Electric Power Sector Reform (EPSR) Act of 2005 was a major mile stone for the energy sector: With this complex network of different stakeholders a regulating institution is required. Therefore, in 2005 the Nigerian Electricity Regulatory Commission (NERC) was initiated by EPSR Act. Its task is to monitor and regulate the electricity sector, provision of licenses and ensuring compliance with current rules (NERC, 2017b).

Furthermore, in 2006, Nigeria's Rural Electrification Agency (REA) was established as a consequence of the EPRA. Its mandate is the promotion of rural electrification by the coordination of rural electrification programs and the administration of a rural electrification fund. This fund is intended to support financing of rural electrification projects. One option

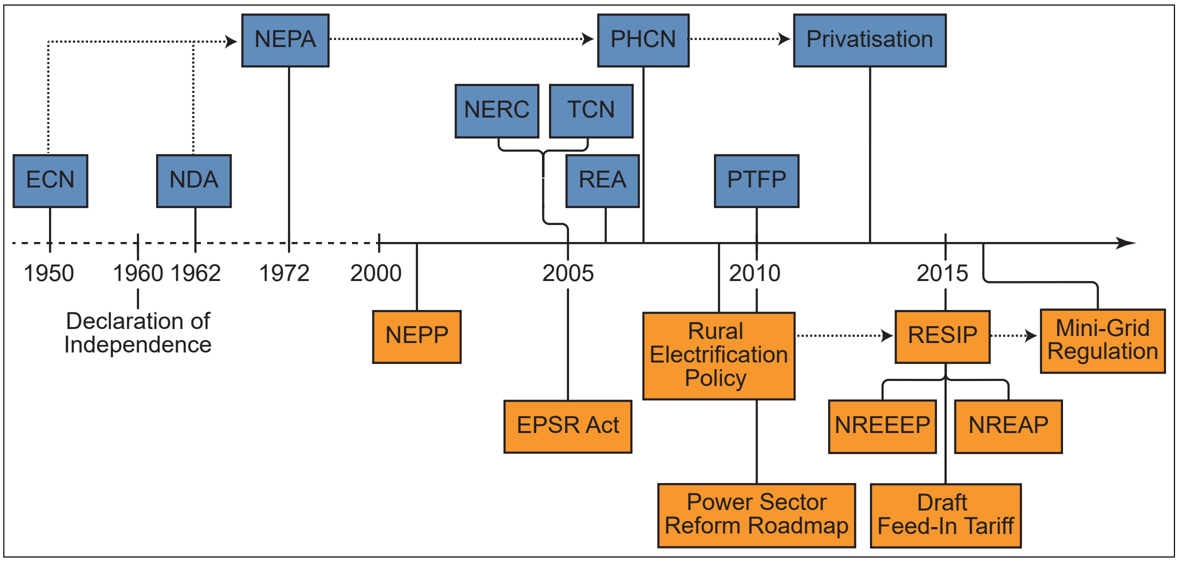


Figure 4.11.: Historical time line of the formation of different institutions and regulatory bodies (upper section), as well as respective policy documents (lower section). Source: Author's own diagram, data based on Olukoju (2004), NERC (2017b) and REA.

for achieving this is the splitting of assets: REA can provide subsidies or grants for the distribution grid of a village, while the capital expenditure for generation and project development costs will be covered independently. This measure can lead to lower resulting electricity costs and can mitigate risks for the project developer. Covering the costs for the distribution grid matches also in case a mini-grid becomes interconnected to a larger network, since in that case, the respective distribution company (DisCo) will be managing the new asset.

Main target groups for REA are villages in areas which are mostly located in a rural setting and difficult to access, often characterized by a low socio-economic development.

In 2007, NEPA was transformed to form the Power Holding Company of Nigeria (PHCN) as a result of Nigeria's EPSR Act. In 2013 PHCN was privatized. Due to the unreliable power supply with frequent blackouts in Nigeria, the informal, sarcastic paraphrase "Never expect power again" was created for NEPA (Williams & Shenley, 2012; Oxford Business Group, 2010; Olukoju, 2004) and with the transformation to PHCN the public created the backronym "Please Hold a Candle Now" (Ukegbu, 2018), illustrating the resignation of the public regarding Nigeria's unreliable energy sector.

Since the power sector has been faced with many challenges, in 2010 the government created a Presidential Task Force on Power (PTFP) under Goodluck Jonathan's administration, aiming at a substantial power sector reform in Nigeria; with the goal to tackle ongoing maladministration and unmet demand in electricity generation and supply. The main achievement of that task force was the creation of the Power Sector Reform Roadmap as legal framework, which mainly focuses on the capacity growth for electricity generation.

PHCN was unbundled to separate electricity generation, transmission and distribution: the Transmission Company of Nigeria (TCN) is responsible for the long distance high voltage power transport at 330 kV and 132 kV with a system frequency of 50 Hz. TCNs activities include electricity transmission, system operation and trading of electricity. The local DisCos

are responsible for the distribution of electricity to the end customers. In addition, they are in charge of tariff collection. Nigeria is divided into eleven distribution networks, run by different companies. Today, there are several electricity generation companies in operation.
NERC drafted a feed-in tariff-regulation in 2015 and regulations for mini-grids in 2016, which specify under which regulatory conditions mini-grids can be operated (Nigerian Electricity Regulatory Commission, 2016). With this regulation in place, a differentiation between isolated mini-grids and interconnected mini-grids is considered. Isolated mini-grids below 1 MW generation capacity are regulated under the mini-grid regulation and require a permit if the power generation system has a capacity > 100 kW. Smaller systems only require a registration. Interconnected mini-grids > 1 MW require licensing, while smaller systems require an agreement between the system operator, the responsible distribution company, and NERC.
In 2015, the Nigerian National Renewable Energy Action Plan (NREAP) was created with the aim of installing 30 GW capacity with a 30 % renewable energy share until 2030. Those objectives have become known as Nigeria's Vision 30:30:30. This plan is based on the National Renewable Energy and Energy Efficiency Policy (NREEEP). In 2016, the Rural Electrification Strategy & Implementation Plan (RESIP) was formulated based on the Rural Electrification Plan to increase access to electricity by strategic actions and planned implementation measures (Federal Ministry of Power, 2015). The Federal Government of Nigeria represents and governs the power sector through the FMPWH, established from the former Federal Ministry of Power (FMP). This ministry is responsible for publishing respective policies and regulation and supervises most of the above-mentioned institutions.
To increase the involvement of private participation within the power sector, the model of public-private partnerships (PPP) was developed. Guidelines for that include the private sector participation in the total costs and assistance by the federal states in site identification and land acquisition processes, as well as by supporting capital costs of projects. Power purchase agreements (PPAs) will guarantee the cost recovery and revenue gain for the investor. Independent power producers (IPPs) can be involved in the energy market, requiring clear guidelines on rights and duties for power generation and trading of electricity (Okoro & Chikuni, 2017). Private sector participation can therefore present a viable option for enabling economic growth while increasing access to electricity (Iyke, 2015).

4.2.2. Electricity pricing and tariff regulation

Tariff design is required for allowing the commercial entities to yield a certain rate of return on investments, allowing them to do business in an economic sustainable manner. At the same time, tariff design may include price caps to protect the consumers by supporting an affordable tariff. Electricity tariffs in Nigeria are regulated by NERC under the so-called Multi Year Tariff Order (MYTO) (Nigerian Electricity Regulatory Commission, 2017). This is a a long-term plan defining the development of electricity tariffs between 2015-2024. The underlying method is developed as a result from the EPSR Act of 2005. Tariffs are designed for each DisCo's concession area independently and customers are grouped in residential customers, commercial, industrial, and special customers. Residential electricity consumption describes the domestic electricity usage at household level and is the most dominant form of electricity usage in rural areas. Commercial customers are characterized by for-profit activities, while industrial customers use electricity for manufacturing processes including energy-intensive industries. Special customers are mainly social institutions, such as religious institutions, schools, teaching hospitals, and government facilities but also water boards and agricultural customers. Those customers are also common in rural areas. In addition, a separate tariff is charged for street lighting. Those categories are further sub-categorized according to low and high consumption, leading to fourteen different annual tariff categories for energy use in Naira/kWh. In Plateau, in 2017 prices were in average at 0.08 USD/kWh for residential customers, while commercial and industrial customers paid a higher tariff between 0.10 and 0.13 USD/kWh (NERC, 2017a).

This tariff order is supposed to guarantee that the tariff is cost-covering for the generation companies and the distribution companies, since in the past the electricity sector was characterized by non-cost-covering tariffs, which may be the reason for the decline of infrastructure and insufficient payment collection schemes and metering technologies.

Clear regulations for tariff design are important for private investors to guarantee that their investments will pay off over time and will create transparency for the customers as well as participants in the entire value chain from the generation of electricity, over the transmission and distribution, to the end customer.

Regulation is furthermore required to define who is allowed to generate electricity and to sell it to whom at which price(Oladokun & Asemota, 2015). Therefore, NERC specified also a MYTO for generation and transmission, defining the respective allowed tariffs for electricity wholesale generation prices and feed-in tariffs for the different technologies.

4.2.3. CO_2 emissions of Nigeria's power mix and energy-related climate goals

The highest share of primary energy consumption in Nigeria is covered by biomass sources used for cooking and heating. This is similar to most African countries, where solid biofuels, such as wood and charcoal are the dominant cooking fuels. Electricity production is still a minor contributor to the national energy demand, energy use, and CO_2 emissions. Considering fuel combustion, the transport sector is still the largest single CO_2 emitter in Nigeria, emitting 120 kgCO_2/capita compared to 71 kgCO_2/capita for electricity and heat production (IEA, 2016). However, this ratio might change in the future, due to limited biomass resources, negative environmental impacts – such as deforestation and emissions – and an increasing demand for electricity for industrialization. Liquid cooking fuels, such as liquefied petroleum gas, are much cleaner and burn with a higher efficiency. Therefore, the national and international agenda aims at accelerating the use of modern cooking fuels.

The responsible agency for the negotiations of the climate change mitigation actions is the United Nations Framework Convention on Climate Change (UNFCCC). UNFCCC and the UN defined one climate-related SDG: In SDG #13 (Take urgent action to combat climate change and its impacts) (United Nations, 2015b) the following targets are set:

- 13.1 Strengthen resilience and adaptive capacity to climate-related hazards and natural disasters in all countries

- 13.2 Integrate climate change measures into national policies, strategies and planning
- 13.3 Improve education, awareness-raising and human and institutional capacity on climate change mitigation, adaptation, impact reduction and early warning.

Due to the high share of fossil fuels for central electricity generation and the importance of decentralized electricity generation with diesel generators, the CO_2 emissions per capita are higher compared to countries with a similar electricity supply rate and development. Other countries with a comparable electric power consumption use more large-scale hydro power in their systems, which might have other social and environmental impacts on watersheds than climate impacts induced by CO_2 emissions. In Nigeria, the CO_2 emissions are mostly a consequence of the huge domestic oil resources and the former cheap price of electricity. In addition, natural gas resources are large in Nigeria, but the extraction of oil and gas is emitting GHGs. A major cause for these emissions is gas flaring in the context of crude oil extraction. The natural gas is a byproduct of the crude oil production, but no sufficient infrastructures are in place to economically use the gas instead of burning it (Anomohanran, 2012). In other words, by gas flaring natural resources are wasted while emitting GHGs in a country suffering from a severe shortage in energy supply. Current regulations in place, such as fines, are not sufficiently employed to change the ongoing practice.
Climate change impacts are already observed in Nigeria: the Nigerian Meteorological Agency (NIMET) published figures indicating climate change effects, such as a long-term increase in temperature of approximately 1.1°C and a shift in onset and cessation of the wet season with a decrease of 81 mm over the last 100 years (Akpodiogaga-a & Odjugo, 2010). Consequences are an increased risk of droughts, which is especially challenging for the agricultural sector. Sea level rise can lead to flooding of the Niger Delta region in Nigeria, where a theoretical sea level rise of 1 meter would lead to the loss of 2,600 km² affecting 3.7 million people (Low, 2005).
In Nigeria's Intended National Determined Contribution (INDC) (Federal Ministry of Environment, 2015), prepared in the framework of UNFCCC for the Conference of the Parties (COP) in Paris in 2015, the country includes the objective to install 13 GW off-grid solar capacity until 2030. Compared to its current capacity installments, this is a major contribution and would benefit the national GHG emission footprint. At the same time, the improvement of the electricity grid is set as a target to minimize transmission losses. Additional key measures are the objective to end gas flaring by 2030, efficiency improvements, shifting car transport to mass transit, and the focus on a climate-friendly agriculture and reforestation (Federal Republic of Nigeria, 2016).

4.3. Presentation of the five Nigerian federal states

The detailed analysis of electrification options in this thesis focuses on the five Nigerian federal states Cross River, Niger, Ogun, Plateau, and Sokoto. They are located in various

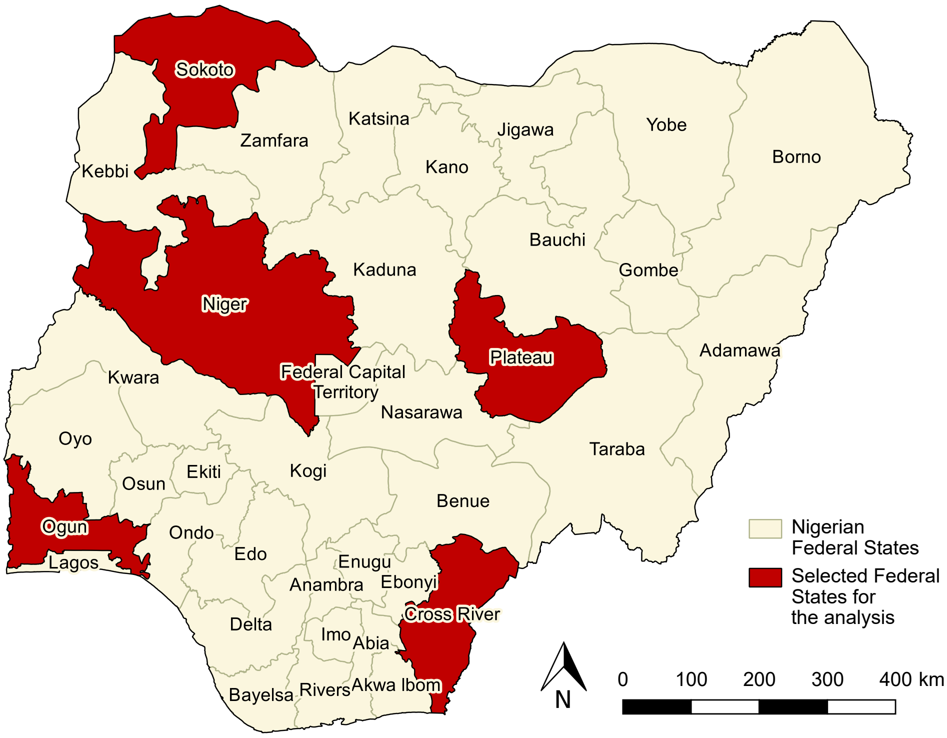


Figure 4.12.: Map of the five federal states (highlighted) in Nigeria. Author's own map, data based on United Nations Cartographic Section (2017).

regions (Fig. 4.12) all across Nigeria and are characterized by different topographies, population structures, natural resources, and existing infrastructure. The five states cover together around 20 % of Nigeria's country area or almost 50 % of the size of Germany. In total, more than 20 million Nigerians live in those five states, representing more than 10 % of Nigeria's population, which is more than the entire population of Burkina Faso (around 18 million inhabitants). In terms of religion, in Sokoto Islam is the major belief, while in the central states Niger and Plateau, as well as in Ogun, both Islam and Christianity are prevailing. In Cross River, the predominant belief is Christianity (Sampson, 2014).

By carrying out comparative analyses between the states, the different progress in regard to electrification planning become visible (Tab. 4.2, Fig. 4.13). The southern states are generally characterized by better electricity access than the northern states (Sanusi & Owoyele, 2016).

Spatial variations of climate in the different states are presented following the Köppen-Geiger climate classification as described by Peel, Finlayson, & McMahon (2007).

Cross River

Cross River is a state in the Southeast of Nigeria bordering Cameroon in the East and the Atlantic Ocean in the South. Its federal capital is Calabar. Cross River is home to the Cross-

Table 4.2.: Overview of the five federal states. Source data from Ohiare (2015).

State	Capital	Electrification rate (%)	Size (km²)	Population (million)
Cross River	Calabar	57	21,787	3.6
Niger	Minna	52	68,925	5
Ogun	Abeokuta	72	16,400	5
Plateau	Jos	37	27,147	4
Sokoto	Sokoto	39	27,825	4.6
Total			162,084	**22.2**

Table 4.3.: Socio-economic indications for the five federal states. Source data from National Bureau of Statistics (2017a) and National Bureau of Statistics (2017b).

State	GDP/cap (USD) 2007	Unemployment rate (%) 2017	Literacy rate (%) 2010
Cross River	3,150	15.6	70.4
Niger	1,480	8.1	60.1
Ogun	2,740	7.4	78.8
Plateau	1,587	19.6	55.1
Sokoto	1,274	14.3	73.4
Average	**2,046**	**12.9**	**67.6**

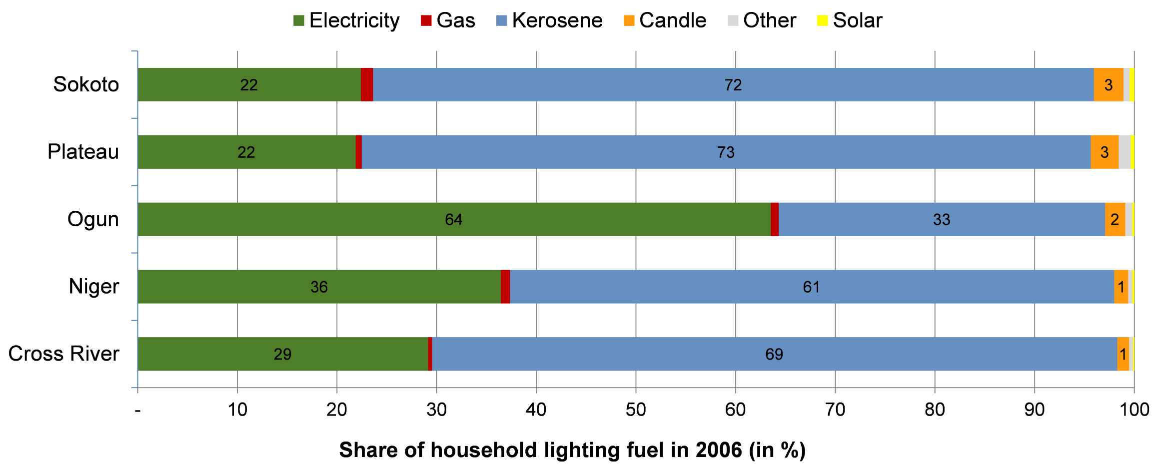


Figure 4.13.: Major lighting fuel sources in the five federal states in 2006. Author's own diagram, based on data from

River-National Park, which is one of the largest remaining rain forests in Nigeria. Forest land in Cross River is endangered by agricultural activities for both, food-crops and cash-crops (Osemeobo, 1988). With more than 3,000 USD per capita, Cross River yields the highest GDP of the five federal states. It is mainly located in the tropical/Savannah climate zone (Aw Köppen), whereas the very South is dominated by a tropical/monsoon climate (Am Köppen (Peel, Finlayson, & McMahon, 2007)). Cross River's electricity is supplied by the Port Harcourt Electricity Distribution company.

Niger

Niger is the largest Nigerian federal state with the capital Minna. It is located within the tropical/Savannah climate (Aw Köppen (Peel, Finlayson, & McMahon, 2007)) in the Central East region of the country. The river Niger runs through the state and two large dams with associated hydro power stations have been constructed, representing a significant share of Nigeria's installed electricity generation capacity (Aliyu, Ramli, & Saleh, 2013). Niger is the largest of the five federal states with a comparably low population density. A significant share of the workforce (circa 20 %) is employed in the manufacturing sector.
Niger is supplied with power by the Abuja Electricity Distribution Company.

Ogun

Ogun is a southern state just north of the former capital city Lagos. Therefore, its southern parts are influenced by diverse industries and high population densities. Compared to the other four federal states, Ogun has the highest electrification rate with 72 % and lowest unemployment rate with 7.4 %. In Ogun, comparatively the smallest proportion of the workforce is employed in agriculture (<10 %), the largest proportion in the tertiary sector (National Bureau of Statistics, 2010). In the West, the state is bordering Benin. The state capital Abeokuta is well known for Olumo Rock, a mountain within the city, where ancient inhabitants used its protecting caves as shelters. This state's climate is characterized by tropical/Savannah effects (Aw Köppen (Peel, Finlayson, & McMahon, 2007)). Ogun's electricity demand is supplied with power by the Ibadan Electricity Distribution Company.

Plateau

Plateau with the capital Jos is located in a tropical/Savannah climate (Aw Köppen (Peel, Finlayson, & McMahon, 2007)) in the central region of Nigeria. Resulting from its high altitude, temperatures are very moderate compared to other regions in this climate zone. Due to the mountainous landscape a significant hydro power potential exists and some dams have been constructed in the past. Plateau has the greatest potential for small hydroelectric power compared to the other federal states (Ohunakin, Ojolo, & Ajayi, 2011). Plateau is characterized by the highest unemployment rates of almost 20 % (Fig. 4.3). Electrification rates are the lowest with 32 %, while as a result, kerosene use is the highest in Plateau. Jos Electricity Distribution Company is supplying Plateau with electricity.

Sokoto

Sokoto is mainly dominated by an arid/steppe/hot climate (BSh Köppen (Peel, Finlayson, & McMahon, 2007)). This results in low precipitation and high solar irradiation throughout the year. Sokoto is also the name of the state's capital, once having been the capital of the Sokoto Caliphate, which was defeated by the British in 1903. Of the five federal states, Sokoto has the lowest GDP per capita with 1,300 USD, but a comparatively high rate of literacy (Fig. 4.3). In Sokoto, more than 50 % of the workforce works in the agricultural sector. Sokoto is currently supplied with electricity by the Kaduna Electricity Distribution Company.

5. Methodology

Improving energy access can be achieved by either additional decentralized or extended centralized electricity generation and supply or a combination of both. For understanding the impact of the different options and for recommending location-specific electrification strategies, in this thesis, a detailed grid extension model is created and the different electrification options are modeled by applying the developed grid extension model and combining it with a simulation of mini-grids. The modeling is embedded into five successive working steps (Fig. 5.1), each building on the results of the previous work step.

This chapter introduces the technical modeling background of this thesis and discusses existing software models with their scopes and limitations. Subsequently, the database for electrification planning is presented. Data requirements, data availability and data collection efforts are analyzed and the suggested working steps to create and obtain missing data by using secondary datasets will be introduced. Building on that, the modeling of electrification options and their related costs are proposed with a subsequent analysis of CO_2 emissions of the different electrification approaches. Decentralized options and grid extension modeling are introduced in order to understand and identify the most economic electrification solution for the individual locations. The chapter concludes with a validation of the model by analyzing sensitivities of the input parameters and through stakeholder workshops, in which the methodology and the input values have been discussed in detail.

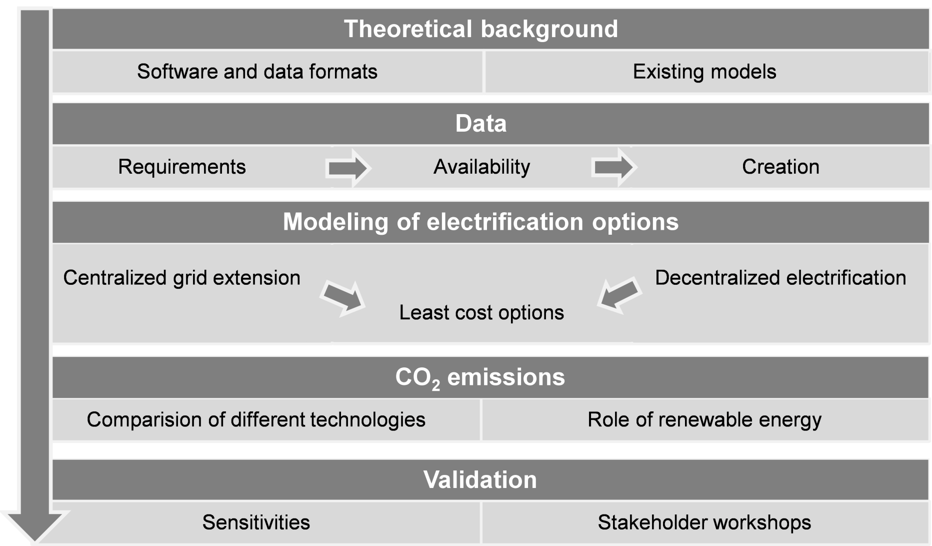


Figure 5.1.: Methodology of the modeling split in successive working steps. Author's own diagram.

5.1. Technical modeling background and definitions

This chapter introduces the technical framework in which the modeling takes place and discusses data requirements and necessary pre-processing steps in order to obtain these datasets for the modeling. Software usage and data formats are introduced accordingly.
Modeling of electrification options requires an understanding of the status quo of the energy access situation and infrastructure in place, but also the current processes and official plans for widening access to electrification. Therefore, information on the current status of electrification and on the methods to model different supply options is required. For modeling and comparing different options of providing access to electricity, some key questions need to be addressed at the beginning of the detailed analysis regarding the current situation:

- Where is electrification required and where is the power grid already developed?
- Which areas are already supplied with electricity?
- How much electricity is required in these unelectrified locations?
- What are the locally available energy resources and costs?
- Which other factors are important for electrification planning?

With regard to the application of the methodology for assessing the different electrification options the following questions must be addressed first:

- Which modeling capacities are required?
- Which software tools can be used?
- Which data is required?

This chapter aims at providing an understanding of the geospatial modeling context and the available and utilized data in the further analysis.

5.1.1. Existing tools and modeling requirements

GIS-based techniques and data formats representing spatial data are used for the modeling. In the following, it is described which software was used, what data formats and which system boundaries and level of depth are assumed.
Existing tools are discussed regarding their applicability for comprehensive electrification planning of rural areas (Cader, Blechinger, & Bertheau, 2016). Three existing tools (HOMER Energy, Network Planner, and GEOSIM) are compared by different criteria (Tab. 5.1): the first criterion is the consideration of geospatial planning, the second the consideration of energy system modeling, and the third criterion is the inclusion of load projections. In addition, it is analyzed if hybrid systems, grid extension modeling, and stand-alone systems are included in the respective tool. The three tools output a mini-grid configuration with a different level of detail: HOMER carries out a detailed energy system optimization, also including the option of solar-powered mini-grids and batteries, while GEOSIM uses a cost-benefit optimization for diesel mini-grids. The Network Planner calculates the system dimension based

on a statistical analysis for diesel-based mini-grids only. Spatial grid extension is only modeled by GEOSIM and the Network Planner. Some models, such as the Network Planner of Columbia's Earth Institute, are based on spatially explicit planning, reflecting specific locations and considering the shortest distance (straight-line Euclidean distance) between locations. However, one hypothesis is that this approach leads to an underestimation of the real length of the grid, as obstacles and resistance on the ground are not considered. HOMER Energy only calculates the break-even grid distance based on cost-assumptions without investigating any spatial relations (also see Fig. 5.18). Furthermore, another modeling tool is the Open Source Spatial Electrification Tool (OnSSET) (Division of Energy System Analysis KTH Royal Institute of Technology, 2017). This open-source tool aims at carrying out a preliminary area planning in order to propose the first recommendation for an electrification strategy.

To account for all criteria, a method is developed to meet the requirement of a detailed energy system simulation including hybrid solar mini-grids and spatially explicit grid extension planning, considering local spatial characteristics. It was found that those different tools represent certain criteria differently, and none of the tools combines all listed criteria within their functional range: the introduced existing tools do not consider topographical characteristics, such as steep slopes or land cover (e.g. large water bodies, national parks). In consequence, a detailed grid extension path model is developed to account for topographic aspects and reflect spatial characteristics such as land cover, accessibility, and existing infrastructure.

For the electrification modeling and the previous data processing, open-source software is used to easily share the methodology and reproduce the findings without restrictions from commercial software.

The data preparation and the applied methodology require a geographical/spatial perspective and are based on the use of geographic information systems.

Since much data needs to be processed in repeating steps, and because of the desire to create an easily applicable method, it is developed to be in line with the principles of reproducible research. The software must be able to process large datasets, since the analysis is conducted in a high spatial resolution. In consequence, for the grid extension model, the open-source programming language R (R Core Team, 2016) is used to develop scripts which document each processing step and make an automation of the working steps possible.

R is developed with a core functionality extendable by additional libraries which can be developed by a large user community and made available within independent packages. This expands the functional range to be much larger than the standard version. Especially the option to utilize R as a software to process geospatial data is accelerated significantly by different libraries focusing on the use of spatial data. Those libraries implement functions which can be used instead of the need to be programmed again from scratch. For the programming routines developed for this study, the library packages "rgdal" (Bivand, Keitt, & Rowlingson, 2017) and "sp" (Pebesma & Bivand, 2005; Bivand et al., 2013) are used for general geo-data processing, while "raster" (Hijmans, 2015) is used for raster data processing, "gdistance" (Etten, 2015) is used for spatial distance calculations, and "fossil" (Vavrek, 2011) for identifying the shortest connecting pathways between a set of points.

Table 5.1.: Comparison of existing electrification planning tools, adapted from Cader, Blechinger, & Bertheau (2016).

Criteria	HOMER Energy (Lambert, Gilman, & Lilienthal, 2005)	Network Planner (Sustainable Engineering Lab, Columbia University, 2015)	GEOSIM (Innovation Energie Développement (IED), 2013)
Geospatial planning	no - only local solar irradiation is used	yes	yes
Energy system modeling	yes	no - only statistic analysis	yes - cost-benefit optimization
Load projections	yes - loads are created based on input, also deferrable loads are possible	no - loads need to be provided	yes - detailed projection builds on different user classes and surveys
Hybrid mini-grid	yes	yes - but no solar-diesel mini-grids	yes - but no solar-diesel mini-grids
Grid extension	no - only calculation of break-even grid distance	yes - the method is built on a modified Kruskal's algorithm finding the shortest path between locations (Kruskal, 1956) which ought to be connected to the grid, but no topographic details are considered	yes - considering constraints such as distance to substations, investment budgets, available energy on the grid, but no topographic details are considered
Stand-alone systems	no	yes	yes
Case study	Sen & Bhattacharyya (2014)	Kemausuor, Adkins, Adu-Poku, Brew-Hammond, & Modi (2014) and Akpan (2015)	BENIN ENERGIE (2017)

For visualizing the input data and the results, the open-source software QGIS (Team, 2016) is used. This software allows simple visual inspections, interactive presentation of data processing steps and cartographic map making.
For the calculation of the mini-grid system design, the capacities, and costs the open-source software Python (Python Software Foundation, 2018) is used in the development of RLI's mini-grid model.

5.1.2. Data formats

The requirements for location-specific modeling of electrification options are accordingly the use of spatially high-resolution data: geo-data is characterized by its unique location information, which can be either geo-coordinates (latitude, longitude) of points or several coordinates describing lines or polygons. In addition, raster data are characterized by a spatial extent covering a certain area divided into equal sized cells, also referred to as pixel. For the GIS-related calculations, standardized data formats are used.
Geospatial datasets represent geospatial characteristics either in vector formats (.shp) or raster data formats (.tiff). Vector formats represent spatial features with points, lines, or polygons, whereas raster representations divide a surface into rows and lines and allocate a value to each cell. Both conceptualizations have their advantages, however, when mathematical operations on superimposed datasets are required, the use of the raster format is recommended (Couclelis, 1992). Some required datasets are available in vector formats, such as point or polygon locations of villages and spatial lines for existing transmission and distribution lines. Other data, such as land use, solar irradiance or elevation data are raster datasets representing respective characteristics of land surfaces.
Distance calculations require the use of a projected coordinate reference system (CRS) in metric units. Such a systems projects the concave earth surface (three-dimensional) in a two-dimensional system. Therefore, for this analysis, the Universal Transverse Mercator (UTM) system covering Nigeria at UTM32N is used. N implies that the CRS region is north of the equator.

5.1.3. Investigation level

Modeling is a method to represent a reality within a simplified modeling process, minimizing the distortion of the studied effects. Models are a useful tool to analyze different development scenarios and an appropriate option to understand the effects of certain actions over a given time period. Models are a common tool to assist in decision-making and for projecting future development for all kinds of applications: a model is the representation of an original, which can be a concrete or abstract representation. Models aim to solve tasks or test behavior for an object (the original) with the use of function, structure, or behavior analogy, which is not possible or very time-consuming on the original. Models are intentionally no exact copies of the original, they emphasize certain characteristics and omit others (Kastens & Büning, 2014). It is important to have in mind that models reflect the reality in a simplified way – that requires certain assumptions and generalizations to be made. Creating a model is based on the trade-off between the technical feasibility due to complex conditions and a reasonable reflection of reality. Too much complexity would complicate the design, prolong the computing time, and complicate the interpretation of results. Too much simplified models, on the other hand, are useless as they omit too many decisive parameters, such that the results would not be usable.

Finding the optimal level of detail also depends on available data. If data quality is very weak, data needs to be handled with care. Very detailed data also holds the challenge of differentiating between the relevant information and irrelevant information, and the risk of false translation of the detailed information to other locations with fewer available information. Therefore, it is crucial to check the comparability and transferability of disposable datasets. Often, nationwide strategies for electrification access are developed which lack the spatial resolution on a local level. For example, national policy goals often mention a goal for a certain level of access to electricity to be reached until a certain year, such as 100 % electrification until 2030 (United Nations, 2015b). However, those goals neither include a specification of the electrification options – if it shall be achieved via grid extension or decentralized systems – nor are they presented with detailed spatial connotations. Only nationally aggregated final goals are specified. The absence of such a connotation prohibits the structured implementation of electrification options and impedes the participation of the private sector, since there is an unforeseeable risk due to the lack of information.

This challenge can be solved by referring back to the multi-level perspective developed by Rauch (2009), introduced in Chapter 2.3. This approach showcases how a problem can be approached on different investigation levels to achieve the most sustainable outcome for a given question. In consequence, in the following assessment, a village level perspective is chosen to start with a village dataset of non-electrified locations. The results will suggest individual electrification options for each non-electrified location, considering their exact location and spatial attributes. Those results can be accumulated eventually to draw conclusions on LGA, federal state, or national level and also to design policies based on the detailed results. The analysis will not be downsized to a household level, nor will it address cross-border international energy sector planning. Five rural electrification plans for the respective case study federal states are created.

5.2. Overview on data requirements, availability and access

Modeling of electrification options requires input data to reflect the real world appropriately and hence, the modeling of these electrification pathways requires several different input datasets. Therefore, it was aimed at collecting as much detailed data on the current status of electrification, information on electrified and non-electrified locations and spatial characteristics as possible. Those datasets can be classified into natural environmental characteristics, infrastructural data, socio-economic data, and technical data (Tab. 5.2).

These datasets present the prerequisite on which the modeling is based, however, data availability and quality of those datasets differ greatly and huge data gaps are revealed during data collection.

Data research revealed that for some of these aspects detailed information is available, whereas for some other datasets the availability is very limited. Questionnaires and official requests

Table 5.2.: Required datasets for the modeling and their respective type and use case.

Type	Data	Use case
Socio-economic	Village location (lat/long)	Geographical location of each village / spatial relations (To assess distance to the grid and to neighboring villages)
	Administrative boundaries	Administrative categorization
	Village population	To estimate the electricity demand
	Status of village electrification	To define if electrification is required
	Economic activities	To estimate the electricity demand
	Social facilities	To estimate the electricity demand
Infrastructural	Existing electricity grid	To consider as starting point for grid extension
	Roads	To consider for grid extension planning
Natural environmental	Land cover	To consider forest and water bodies in grid extension modeling
	Elevation	To derive slope to consider in grid extension modeling
	Solar irradiation	To consider for solar mini-grid modeling
Technical data	Cost data	To calculate electrification cost of the different technologies
	System configuration	To simulate the electrification options

for data on the location of non-electrified regions and villages were created to identify existing datasets, but revealed quickly that major required information is not easily available (see Chap. 5.2.1). However, the achievement of the SDGs requires planning, monitoring, and tracking of the progress and this leads to the requirement of detailed base data. The challenge regarding data availability is not unique for Nigeria but is observable especially in developing countries (Tatem, 2017). Therefore, intensive efforts in data collection and data pre-processing have been required and workarounds were developed to compensate the lack of this data (see Chap. 5.2.2).

5.2.1. On-site data collection process

The acquisition of data was conducted within several different data gathering activities: the first step was to use questionnaires to get an understanding of data availability and data usage at the different Nigerian institutions. This was followed by working group meetings in each of the five Nigerian federal states, during which data availability and access have been

discussed intensively. In consequence, officially available datasets have been requested from the respective institutions.
Some data is available through global datasets available online, mostly derived from satellite imagery, which often has the disadvantage of low spatial resolutions and missing information on the data quality, while covering the full study area and make comparable analyses possible.

Questionnaires design

A detailed questionnaire with a Likert scale was developed (Appendix A) to find out which data is available for the local actors and how they rate the importance of the respective datasets for electrification planning, in order to learn how that data is managed and used today. Also, the questionnaire was created to understand the institutional set-up related to electrification planning with the mandates and activities of the different organizations. In detail, the questionnaire covered the following thematic areas:

- Background and mandate of the different Nigerian institutions in regard to electrification planning;
- Population data, such as information on the location of villages and towns, and the number of inhabitants or households of these;
- Infrastructural information, such as the existing power line network with transmission and distribution lines, location and capacity of transformer stations, and information on power plants and their respective locations;
- Topographical information such as data on land cover, land ownership, and elevation.

Furthermore, the capacities of the respective organization with regard to data management and visualization, knowledge of software and digital data formats and available hardware for digital data management and data processing have been inquired.
The questionnaire was distributed to more than 20 organizations and institutions and 17 respondents from national and federal state level institutions returned the filled-in document (Tab. 5.3).
For the majority of respondents, the results of the questionnaire revealed a large discrepancy between expected knowledge, capacity, and available data. If such a limited data availability had been known beforehand, the structure of the questionnaire would have been designed simpler with a more basic estimation of their tasks, data availability, and activities. Due to the limited number of respondents, no statistical analysis of the results was conducted.
The outcome of the questionnaire can be summarized as follows:

- The available data in the respective institutions is very limited. If data exist, most of it is in paper format mostly without any geo-references or identification except the name of the village. Those are mainly lists of electrified and non-electrified villages and lists with villages for which electrification is planned for the next financial period. Village names hold the disadvantage of ambiguity and are further complicated by local language and spelling variations.

Table 5.3.: Interviewed organizations that returned the questionnaire.

#	National institutions (n=3)	Cross River (n=5)	Ogun (n=2)	Plateau (n=5)	Sokoto (n=2)
1	Federal Ministry of Power, Works and Housing	Cross River Geographic Information Agency	Ogun State Geographic Information System	Plateau State Geographic Information System	Ministry of Lands, Housing & Surveys
2	Nigerian Electricity Regulatory Commission	Cross River Bureau of Statistics	Bureau of Electrical Engineering Services	Jos Distribution Company	Permanent Secretary of Sokoto
3	Rural Electrification Agency	Cross River State Electrification Agency		Ministry of Water, Resources and Energy	
4		Ministry of Lands and Housing		Bureau of Statistics Plateau State	
5		Port Harcourt Electricity Distribution Company		State Planning Commission	

- Digitized and geo-referenced data is still very uncommon, especially in government-related institutions. This is likely to be a result of unavailable hardware, such as computers and the related human capacities for the use of software. Most digital geospatial data and activity was found in the field of land management with tasks concerning cadaster/land register management, carried out by private companies as commercial activities.

- Local GIS agencies are well-equipped with modern computer and server infrastructure and internet access. They also have the human capacity to manage data, especially GIS data. Those agencies mainly work as commercial companies and need to be contracted by a respective institution, such as the government, in order to work on energy access planning and support respective institutions.

- Communication between different institutions tends to be very limited and often the knowledge about data and capacity in other institutions within the same state was not given due to the lack of exchange between key stakeholders.

The institutional set-up and the decision structure for electrification are different in all states, for example in Ogun, state villages interested in becoming electrified need to fill in an application (Fig. 5.2). In general, electrification projects strongly depend on yearly budget allocations for grid extensions and no common decision structures or planning processes, in order to succeed in structured electrification measures could have been identified.

(a) Folder containing village applications for electricity at the Bureau of Electrical Engineering Services in Ogun, Nigeria. Author's own photograph (January, 2015)

(b) Working group meeting Cross River Geographic Information Agency, Calabar, Nigeria. Author's own photograph (January, 2015)

Figure 5.2.: Data collection activities in Nigeria.

Since only a few of the required datasets are available, other sources and workarounds are needed. Due to the low capacity, planning tools are needed to improve electrification planning and ensure sustainability.

Data obtained from local stakeholders

Data on existing power grid infrastructure is essential for defining grid-connected and off-grid locations and are required as a starting point for grid extension modeling. Different datasets on the power grid in varying quality and level of detail could be obtained (Fig. 5.3).
For the whole country, only one power grid dataset of the high voltage network exists without detailed information on the line network on the ground; only point-to-point connections create artificially straight lines connecting different regions.
To carry out spatially explicit modeling considering local topography, the distortion from the exact location needs to be minimized. In two of the five states (Plateau and Niger), detailed medium voltage grid data could be obtained directly, for the other three states it was modeled with the information on connected villages by applying the developed grid extension algorithm (introduced in Chapter 5.3) and subsequent validation by the local experts. For Cross River, village lists with the status of electrification could be obtained.

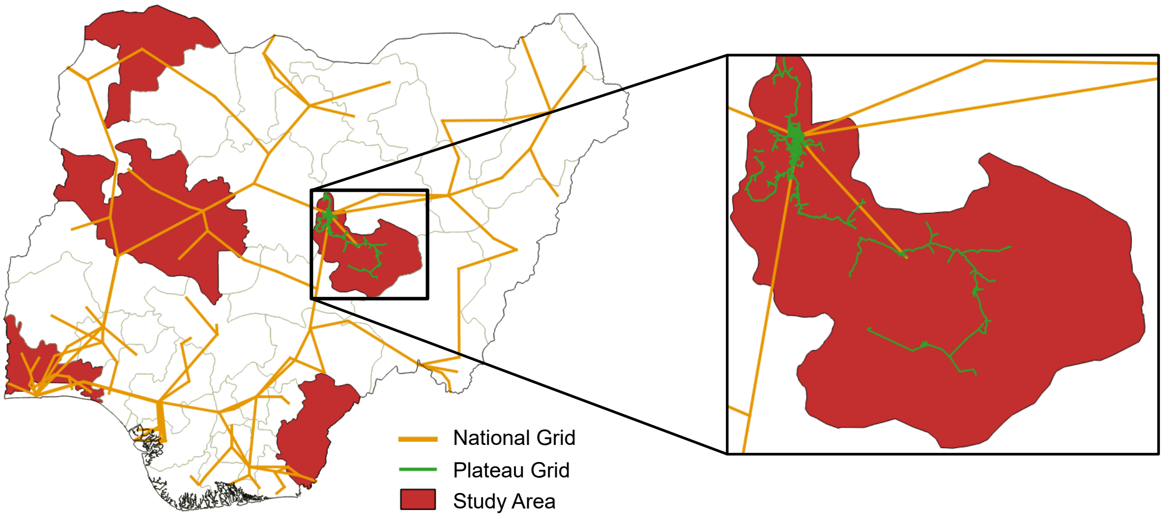


Figure 5.3.: Different level of detail for grid data quality along the example of Plateau. The national high voltage grid dataset (left) simplifies the course of the power grid significantly compared to state-level data of the medium voltage network (right). Author's own representation.

Publicly available datasets

The following required geospatial datasets are available online from public data bases:

- Socio-economic data
  - Administrative areas United Nations Cartographic Section (2017)
  - Population data: World pop data (Linard, Gilbert, Snow, Noor, & Tatem, 2012; Tatem, 2017; Lloyd et al., 2017)
  - Census data and polling units(Independant National Electoral Commission, 2018)
  - School locations and size and status of electrification: Nigeria MDG Information System (Center of Sustainable Development, 2014)
- Natural environmental
  - Land cover data for Nigeria is extracted from a global land cover dataset with a 30 m spatial resolution using satellite data from 2000-2010 developed by Chen, Chen, Liao, Cao, Chen, Chen, He, Han, Peng, Lu, Zhang, Tong, & Mills (2015)
  - Elevation SRTM (Jarvis, Reuter, Nelson, & Guevara, 2008)
  - Solar irradiation (Stackhouse & Whitlock, 2008)

5.2.2. Data creation by using secondary data

Data collection revealed a gap between available and needed data. In consequence, three methods are developed for creating the datasets, which are required but not available and presented in the following section:

1. Identification of villages: to account for the lack of geo-referenced village data with information of the respective number of inhabitants, secondary datasets, such as census data and global population data, are used to derive the required information.

2. Definition of the status of electrification of the identified villages: power grid information, night light emissions, and information on electrified schools are combined to classify the villages accordingly.

Identification of village or population cluster (output: cluster)

In order to achieve SDG#7, it is essential to understand the spatial context to conclude where exactly access to electricity is required. More precisely, it is required to know where the people are located in order to analyze if they have or do not have sufficient access to electricity. The information on the location of people and villages is available in population datasets stemming from national census or through local administrations. Very often, in official databases, the spatial connotation is lost and only national level data exists, which holds no information on the detailed location and distribution of people within a certain administrative area. This data gap presents a huge challenge, especially in rural areas and also for the rural-urban distinction. For spatial infrastructure planning the exact location of villages is required if spatial modeling are to be applied considering distances between different locations.

To identify these locations, different datasets are combined: population raster datasets derived from satellite imagery include the spatial distribution of population across a region. The population dataset contains spatially referenced demographic data as an answer to the often prevailing low-quality outdated census datasets available in poor countries (Tatem & Linard, 2011): a high-resolution spatial dataset with the number of people in each 100 m x100 m pixel disaggregates census data by combining it with land use data drawn from satellite data (Linard, Gilbert, Snow, Noor, & Tatem, 2012; Stevens, Gaughan, Linard, & Tatem, 2015). If the population value in a pixel exceeds a threshold value, a polygon cluster is formed to define a settlement and extended by a buffer zone to account for surrounding settlements (Fig. 5.4). Those are combined with the location of polling units, village coordinates obtained from administrative lists provided by the federal governments, and schools which are point data buffered in a radius of 500 m to account for nearby villages (Fig. 5.5). For each of the identified village clusters, the population is calculated and aligned to match the official statistics.

For the validation of the cluster locations 718 villages with geo-coordinates, obtained from the village list of Cross River, are compared to the modeled cluster locations. The vast majority (circa 80 %) of village points are located in a village cluster, the others are in close distance to the location of the list. 92 % are within a distance of 1 km (Tab. 5.4). The findings show a high conformity with the modeled results of the settlement locations.

In addition, in Niger State, a survey of the number of inhabitants per village was conducted in 36 villages and compared to the modeled results to validate the assigned cluster population. This analysis revealed that there is a tendency to underestimate the number of inhabitants for small villages, while for large population clusters, the respective population tends to be

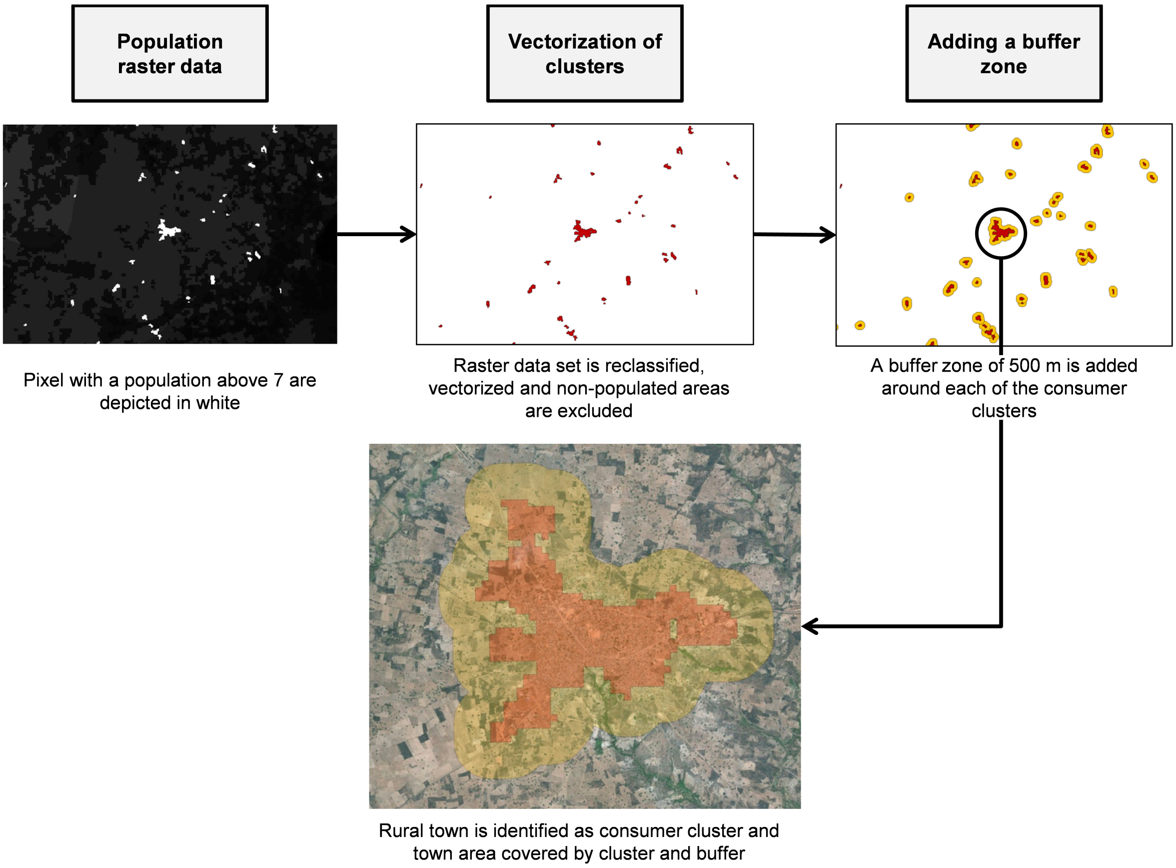


Figure 5.4.: Process of extracting village clusters from the population raster with population values > 7 inhabitants per pixel as vector polygons and adding a buffer zone to account for the outskirts of the villages. Author's own diagram.

Table 5.4.: Results of the validation of the cluster location with provided information on village locations in Cross River.

Cluster location	# of Cross River villages
Covered within cluster	586
Closer than 100 m	15
Closer than 500 m	33
Closer than 1,000 m	26
Closer than 2,500 m	40
Closer than 5,500 m	18
Total	718

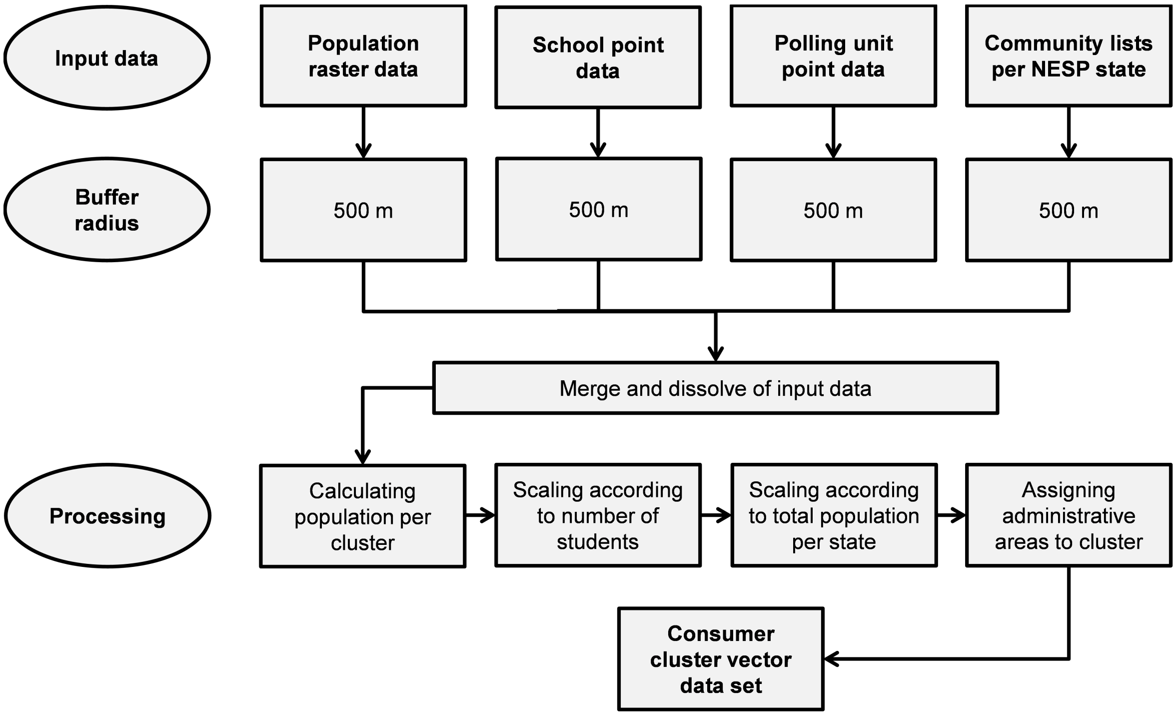


Figure 5.5.: Method and input data to identify and define village cluster population. Author's own diagram.

overestimated. Furthermore, the total population of all clusters within each state was calculated and compared to official statistics on the respective state population. That comparison reveals a strong underestimation of the total population figures. Here it is assumed that 10 % of the population live in very sparsely populated regions or a nomadic life which cannot be accounted for in the population dataset. For the remaining missing population, the number of each cluster was scaled up to match with the official statistics minus 10 % in total. This process considers the spatial distribution of population, while being in line with the official statistics. For the scaling, large clusters are up-scaled less than small cluster to account for the deviation of the calculated values compared to the evaluated numbers from Niger. This methodology outputs a complete dataset of all village clusters and their exact location in the five federal states.

Identification of grid coverage and status of electrification (output: electrified and non-electrified cluster)

For assessing energy supply scenarios, it is necessary to know where electricity is already available and in which of the identified locations access to electricity is not provided. More specifically, to define where electrification measures are required, it is essential to know which locations are not connected to the existing power grid, since this is the predominant electrification type. In regions which are not grid-connected, there may exist an electricity supply based on decentralized diesel generators, however, those are not sufficient in most cases and therefore counted as non-electrified locations for further planning.
Data on the status of electrification on village level is not available throughout Nigeria. There-

fore, a method was developed to use other available data to assign the status of electrification from secondary data. Mainly two data sources are used (Fig. 5.6): the first dataset contains satellite imagery with spatial information on night light emissions, indicating where artificial light is emitted during nighttime. This is a good proxy for an electrified location and more specifically, for assessing the level of energy consumption. On the other hand, it is useful to identify communities without access, as already discussed by different researchers (Amaral, Câmara, Monteiro, Quintanilha, & Elvidge, 2005; Doll & Pachauri, 2010). One requirement for the detection of electricity use from space is that the source is of sufficient size, i.e. outdoor lighting, such as street lighting or installed security lights.

The second dataset is a detailed set of schools and their respective location with the attribute if electricity is supplied to that school or not. In addition, the number of students, teachers, and facilities such as toilets, are compiled.

The school dataset is comparably recent (2014) and the most complete dataset which could be obtained on a village level for all five federal states.

In addition, for the states Plateau and Niger, the medium distribution network dataset was provided, whereas in Cross River, some community lists with the status of electrification are available. Locations, defined as electrified in a list, covered by distribution lines, and emitting light at night are classified as electrified. By including data on electricity grid infrastructure, the differentiation needs to be made between villages with access to the power grid (a physical connection), villages connected to a grid which is currently underserved or out of order and villages “under the grid”. The latter refers to the specific challenge where electricity infrastructure, such as high voltage transmission lines, cross a certain region without connecting nearby villages, which could be the case if villages are too small to install transformers to down-step the electricity to connect a distribution grid or because households cannot afford the connection fee to become connected to an electricity network (Lee, Brewer, Christiano, Meyo, Miguel, Podolsky, Rosa, & Wolfram, 2016).

This information was combined and overlaid to identify the clusters which are either covered by night light emissions, contain a school which is supplied by electricity, are defined as electrified by state representatives, or are connected to a distribution line. Those are marked as grid-connected and hence, classified as grid-connected or non-grid connected clusters, respectively. This work step outputs the village cluster dataset of unelectrified villages for which electrification planning is required in order to achieve full access to electricity.

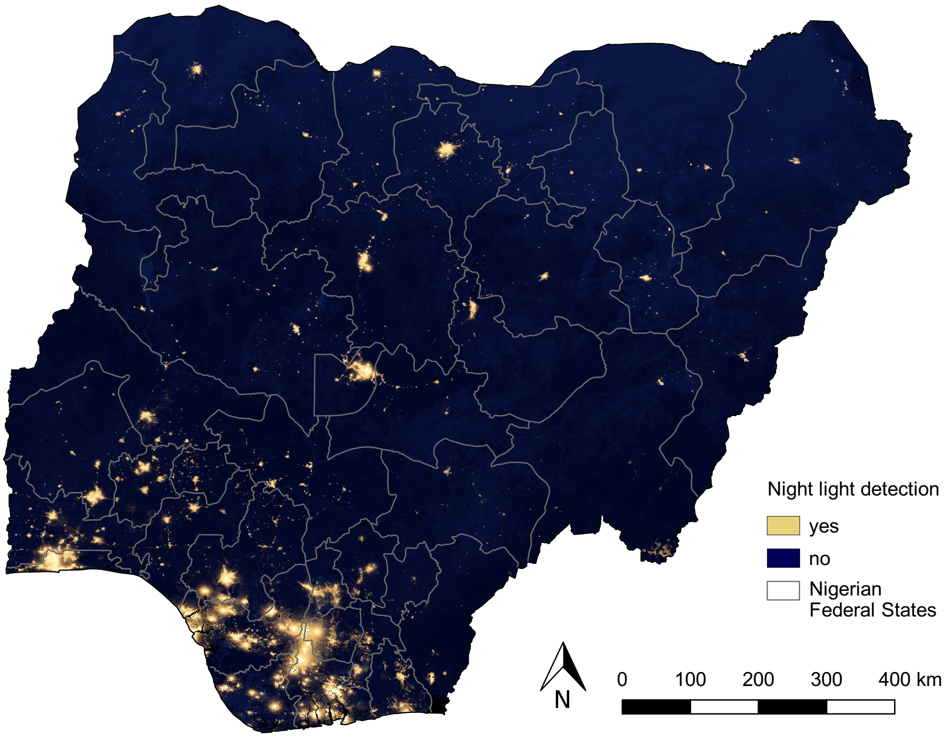


Figure 5.6.: Map of spatially resolved night light emissions in Nigeria. Author's own map, data based on NASA Earth Observatory (2016) and United Nations Cartographic Section (2017).

5.3. Modeling of electrification options: Local least cost electricity supply

This section describes the method developed to calculate and compare the different options for rural electrification in the five Nigerian federal states. The chapter is structured in four parts:

- electricity demand assessment in each village: information on village sizes and economic activity allowed the estimation of an individual energy demand in hourly time steps for each village cluster;
- spatial grid extension modeling for the estimation of the related costs for grid extension;
- modeling of decentralized energy supply systems for calculating the optimum technology composition and respective costs;
- comparison of the different options to identify the optimum electrification option by prioritization.

5.3.1. Estimation of local electricity demand (output: daily electricity demand)

To carry out planning for electricity infrastructure, electricity demand forecasting is required. This demand for electricity varies from location to location and depends on the population size of a village, economic development and economic activities such as productive use, climate, and cultural habits. In addition, energy demand is characterized by a daily variation, reaching the highest demand during the day in industrialized countries whereas in most cases developing countries reach a demand peak in the early evening hours. Energy demand is also changing over time, from an initial small demand increasing to a higher demand due to the use of additional appliances and the inclusion of productive use. Bhattacharyya & Timilsina (2010) find that the knowledge about accurate electricity demand is especially challenging in the context of developing countries, since data on livelihoods, ability to pay, and typical household appliances is often scarce. Furthermore, the electricity demand is often very location-specific and can vary highly. Also, the use of traditional energy sources, such as biomass, is still prevalent and a transition towards modern energy sources, such as electricity, is ongoing, making the demand for the latter hard to assess. In conclusion, the authors find that available tools to assess electricity demand are inadequate and require more detailed assessments.

To correctly size an energy system for a village, it is necessary to estimate the required amount of electricity as accurately as possible: the total demand per day, but also the distribution of demand over the day, and the peak demand. It is recommended to use hourly load profiles, where the energy demand is documented for each hour. A daily load profile can be extended to a yearly load profile by stringing together daily load profiles considering seasonal fluctuations and adding statistical variation. A yearly load profile allows simulating a whole year with the climatic variations of the renewable energy source. If this is not considered in detail, the systems and new infrastructure components can either be sized too small or too large. In the first case, it will not be possible to cover the total demand of electricity, leading to load shedding and furthermore endangering the whole functionality, as electric systems are vulnerable to changes in frequency and voltage levels. This results in consumer dissatisfaction and threatens payments. In the second case, there is an excess of electricity, which cannot be allocated and used. A consequence is an increase in costs, as electricity is provided but cannot be sold.

For rural areas, most of the demand for electricity occurs in the evening when the sun is setting down. This is especially challenging for the use of solar energy, as the consumption of electricity generated by using solar resources at night requires storage. In Nigeria, the time of sunset varies only slightly over the course of a year due to its proxy to the equator, and takes place between 6 PM and 7 PM in Abuja in the center of the country. For defining electricity demand, it is also important to consider the coincidence factor. This factor accounts for the fact that it is easier to forecast the demand for electricity for a larger customer group, due to a statistical balancing effect compensating fluctuations of the assumed demand. Considering this, electricity demand is easier to assess for larger settlements than for small villages due to a higher volatility of the load (Willis & Scott, 2000).

Table 5.5.: List of identified parameters ranked according to their impact on local electricity demand. Data collected in the stakeholder workshops.

Parameter	Comment	Impact (10 high - 0 low)
Household size	average household size per state	10
Population	number of inhabitants	10
Socio-economic level	e.g. gross domestic product per village	9
Economic activity	main sector of income generation	8
Type of household appliances	e.g. number of light bulbs, mobile phone charger, fan, fridge, iron, radio, TV in a typical household	8
Electricity tariff	different tariffs may lead to different consumption levels	7
Climate/season	dry/wet season, temperature	7
Social infrastructure	e.g. number of schools, hospitals, water wells	7
Cultural habits	e.g. specific load Sundays/Fridays reflecting religious behavior	5
Age structure	average age	3
Telecom towers	sites within villages	3

If electricity is already available in a location, the exact demand can be assessed by on-site measurements. If electricity is newly introduced in a region measurements are not possible. In those locations, it is possible to conduct surveys on the ability and willingness to pay for electricity as a proxy for the demand or to use load prediction modeling. In the past, village demand for electricity was analyzed by different researchers. Olatomiwa, Mekhilef, Huda, & Ohunakin (2015) defined different load profiles for domestic and social infrastructure consumers in Nigeria differentiating between dry and wet season. By specifying the use of all appliances and the hours of the day during which they run, an hourly electricity demand per villages is created. For Nigeria, typical appliances of a rural livelihood setting are considered, such as lighting, phone charging, fans, as well as radio and TV (Adeoti, Oyewole, & Adegboyega, 2001). Some appliances, such as large cold storage, air conditioning or electric cooking are not considered as they are mostly not in use in the rural context and have a strong influence on the required electricity. In detail, a set of 11 different significant parameters impacting on the local demand for electricity was defined and prioritized (Tab. 5.5). With the knowledge of village sizes and economic activity, load profiles can be modeled as illustrated in Figure 5.7.

In Nigeria, a significant demand increase on a national level is projected as response to urbanization, higher income, and overall population growth (Ouedraogo, 2017). This further worsens the stability of Nigeria's electricity, as it leads to additional suppressed demand, on-grid for the population which is affected by load shedding and black-outs and off-grid by having no access to electricity at all (also refer back to Chapter 3).

Due to the large sample of locations where the estimated energy demand is required, surveys at all locations are prohibitive in terms of cost and time. Therefore, a modeling routine is

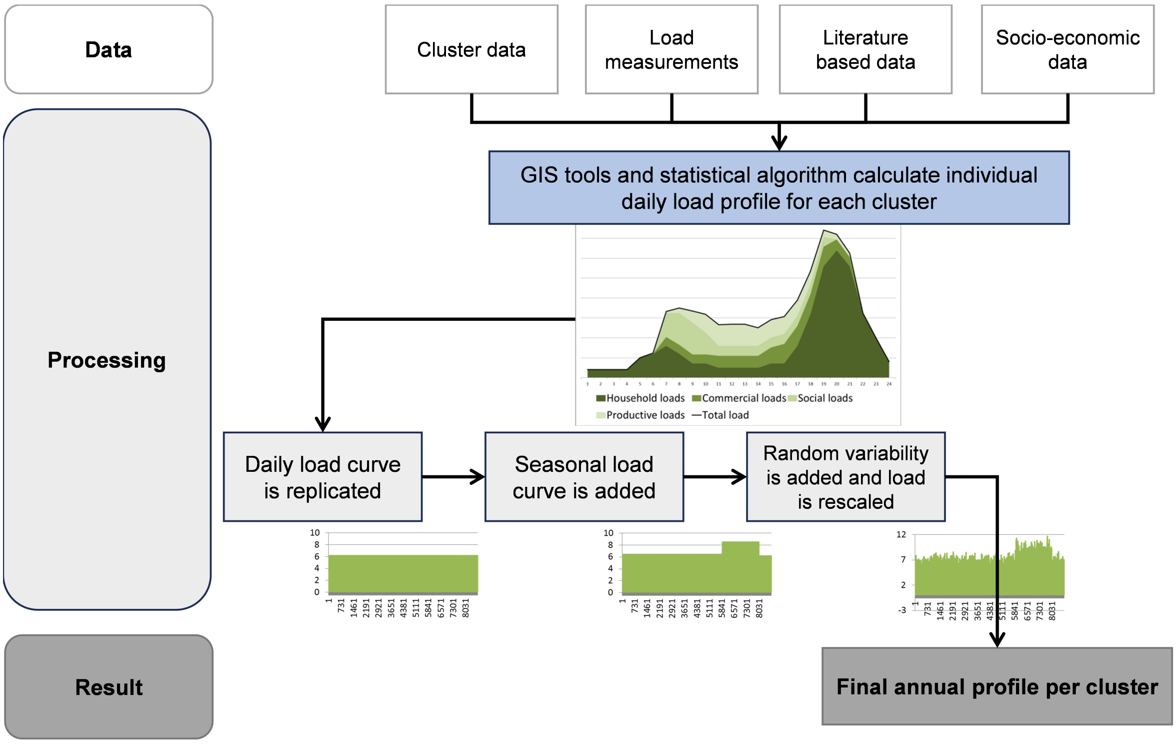


Figure 5.7.: Schematic overview of the method for the electricity demand projection. Author's own diagram.

developed using the open-source language Python.

The load modeling tool is based on the following steps:

- For each village the specific information on number of inhabitants (population and average household size), social infrastructure (schools, small and large healthcare centers considering hospitals, clinics, health posts, and dispensaries, water supply facilities) and economic activity (Ghosh, Powell, Elvidge, Baugh, Sutton, & Anderson, 2010) is collected (Tab. 5.6).
- For each customer segment, a certain use of electricity over the day is assumed. Specifically, it is defined how much electricity is used in each hour of the day and the different customer groups are accumulated for each village (Tab. 5.7).
- A daily load curve is modeled by overlaying the demand of electricity of the identified customer's appliances. This daily load curve with values for each hour is upscale to 365 days of the year resulting in 8,760 values, assuming the electricity demand for each hour of the year independently for each village.
- Climatic factors are considered to add a seasonal effect to the load curve: the demand for electricity to power agricultural appliances is added depending on the agricultural seasons of a typical year. As a simplification, Nigeria's agrarian seasonal calendar is divided into a south and a north region[5], accounting for diverse climate zones, assigning

[5] http://www.fews.net/west-africa/nigeria/seasonal-calendar/december-2013

Table 5.6.: Electricity demand of different customer segments per day.

Category	Electricity demand (kWh/d)
Households low consumption	0.74
Households medium consumption	2.35
Households high consumption	5.38
Commercial use	3.00
Productive use	12.00
Schools	3.00
Water pumps	1.00
Health low consumption	15.00
Health high consumption	150.00
Agricultural appliances	5.00

Table 5.7.: Description of the different influencing variables on the load modeling.

Input value	Value	Description
Share of households connected	80 %	Connection rate per consumer cluster. Value is applied for households with low consumption only
Commercial units per household	1 unit per 10 households	Value derives the number of commercial units from number of households
Productive units per household	1 unit per 50 households	Value derives the number of productive units from number of households
Agricultural appliances per household	1 unit per 20 households	Value derives the number of agricultural units from number of households
Day-to-day variability	10 %	Provided the range for selection of random values per day
Hour-to-hour variability	10 %	Provided the range for selection of random values per hour

different electricity requirements over the year taking into account the agricultural activities.

- Although a typical electricity demand is assumed for certain customer groups, an hour-to-hour and a day-to-day variance will occur. A random variability is added to account for those fluctuations and resulting uncertainties. This is important for identifying the correctly sized least cost electricity system. Therefore, a variation derived from a Gaussian distribution is used to create an hourly and a daily variation within a given threshold.

- Finally, the randomized loads are re-scaled to match the initial overall demand prior to the randomization:

$$L_{randomized} \times \frac{\sum L}{\sum L_{randomized}} \tag{1}$$

With this model, an hourly load for one year is assigned to each village not connected to the central power grid. By accumulating the demand, the additional required electricity

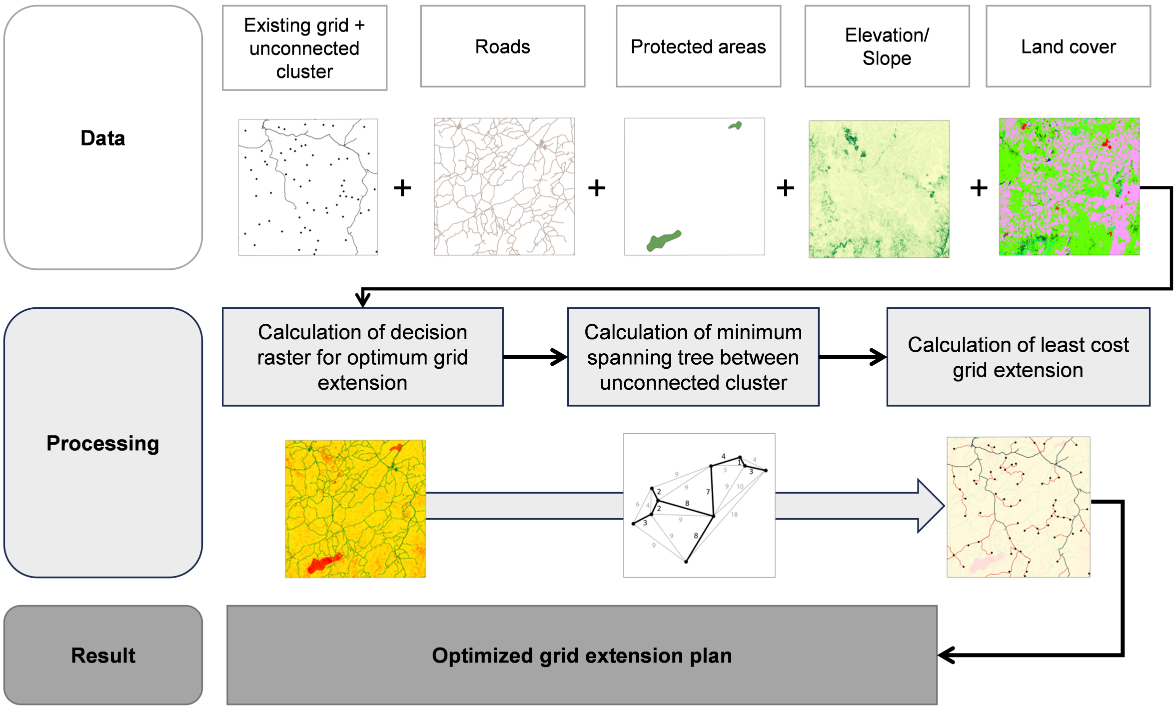


Figure 5.8.: Overview of the grid extension methodology under consideration of topographical characteristics. Author's own diagram.

generation capacity can be calculated for each administrative unit. The assumption of the electricity demand modeling are validated through a working group discussion with participants of all five Nigerian states. Resulting demand figures are in the range of the current averaged electricity demand per person as previously shown.

With the completion of this step, the necessary data for modeling the various electrification options are compiled and the data preparation is completed.

5.3.2. Grid extension of the existing power grid

As shown in Chapter 5.1.1, none of the existing modeling software for network expansion takes into account the corresponding topography and other geographical factors of rural areas, in which electrification options are to be proposed. It is estimated that grid extension results in a 30 % increase in power line lengths from the shortest route to the actual route on the ground, resulting from topographical characteristics (Deichmann, Meisner, Murray, & Wheeler, 2011). The developed algorithm identifies where those deviations from the shortest path to the optimum path occur.

Several key criteria are identified to distinguish the potential pathway of grid extension in reality. These datasets form the starting point for the generation of a combined dataset, which in turn forms the basis for the network extension calculation (Fig. 5.8). This allows the modeling of the optimal electricity network considering the given topography.

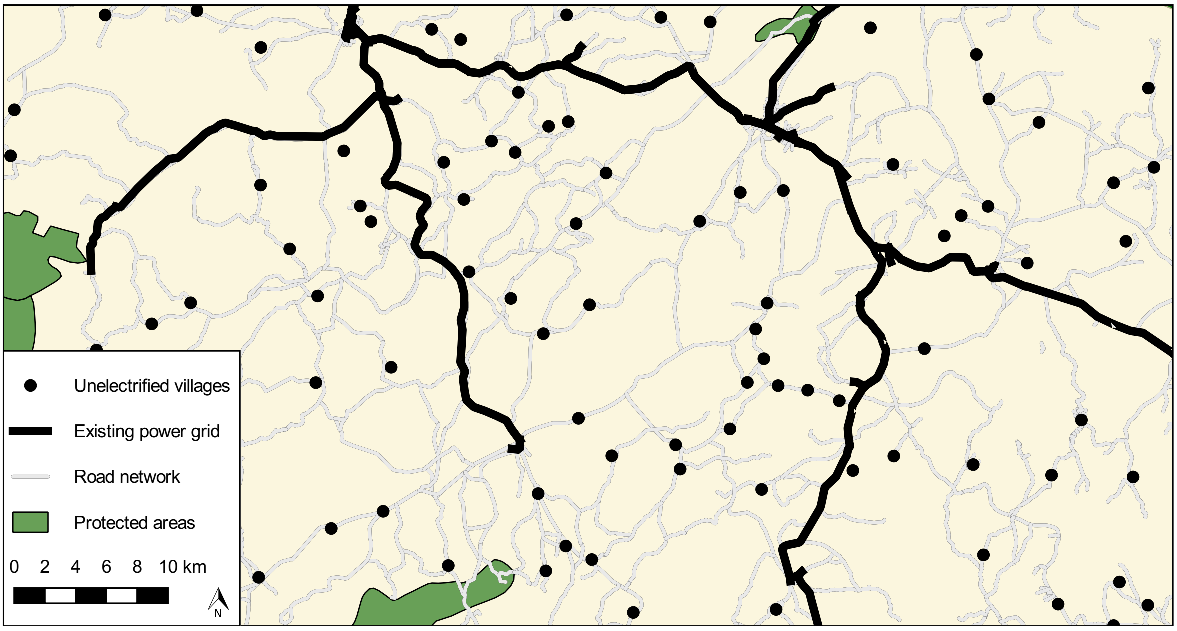


Figure 5.9.: Map of vector input datasets for the grid extension modeling: Roads, protected areas, the existing power grid and the unconnected locations. Author's own map, data resulting from the applied methods and described input data.

Creation of a decision raster topography

The developed model aims at reflecting topographic characteristics and other geographical factors.

Artificially created infrastructures also play a role (Fig. 5.9). Regions designated as nature reserves can be specified as exclusion areas for power grid extensions. On the other hand, proximity to roads can be regarded as an advantageous factor, since roads provide good accessibility and land rights are often on the state side, making it easier to decide on their use as an electricity grid corridor. Most villages in the sample region are located in close distance of the existing road network.

Grid extension is a spatial problem with is often discussed in line with other land-use planning issues: to define where the power lines are going to be constructed, it is important which other infrastructural and environmental features exist at the given locations. Only with this knowledge, reasonable decisions can be made on how and where exactly to install new power lines. In consequence, as a further dataset, the existing electricity grid is integrated in order to link the non-electrified locations to this existing grid network. Also, the spatial relation between different unelectrified clusters is of interest, since some are located close to each other, while others are separated from others by their location.

In addition to the existing infrastructural data in the area, a steep slope can make electricity grid construction considerably more difficult, so that this is also taken into account when evaluating the topography (Fig. 5.10). In order to facilitate the construction of electricity grids, they run along valleys or ridges and avoid very steep gradients.

Similarly, the land cover dataset categorizes the land surface into six discrete classes: Cultivated lands, forest, grassland, shrubland, water bodies, and artificial surfaces (Fig. 5.11).

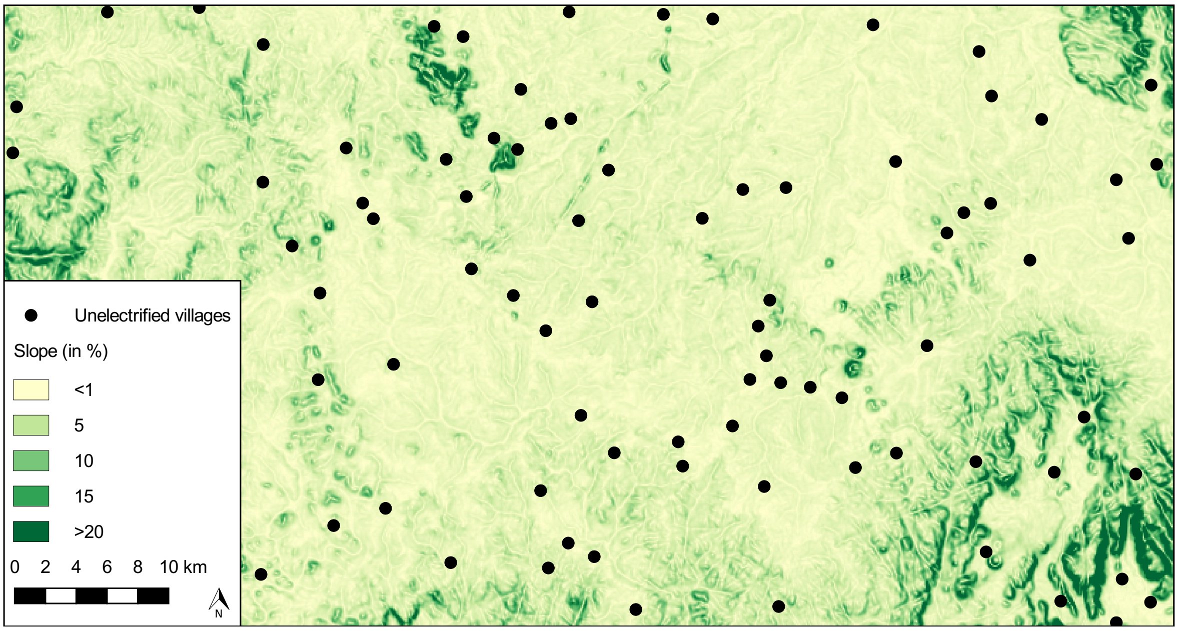


Figure 5.10.: Map of slope raster showing the variations in steepness of the surface as a result of the elevation. Author's own map, data resulting from the applied methods and described input data.

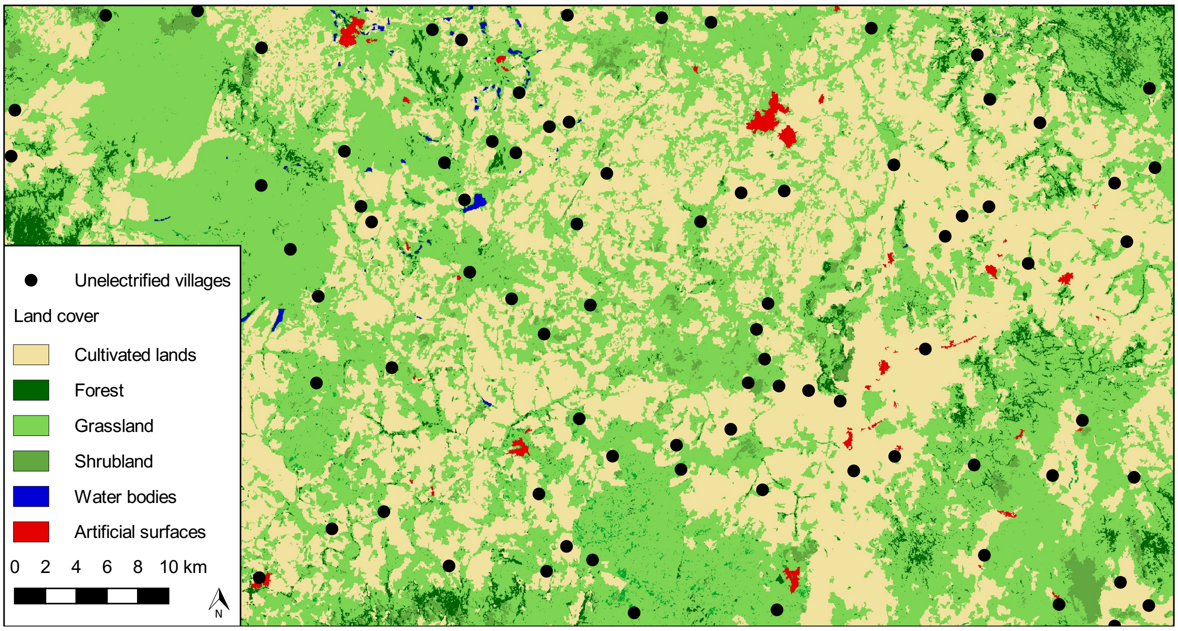


Figure 5.11.: Map of land cover data to account for increased costs on certain surface types, i.e. when passing water bodies and forests. Author's own map, data resulting from the applied methods and described input data.

Factors that complicate network expansions are forest cover and large water areas; they have been extracted from land cover datasets. The land use data show that the unelectrified villages are characterized by an unequal surrounding land cover.

The developed grid extension algorithm is based on pixel calculations. As a consequence, all vector datasets are transformed into raster datasets with the same cell size and dimension as

Table 5.8.: Spatial attributes and their default impacts for grid extension assessment.

Factor	Default impact value	Resulting raster
Grid value	0	gr**
Road impact	-75 %	Rr
Protected area impact	50 %	Pr
Forest impact	25 %	fr*
Water impact	50 %	wr*
Slope impact	Slope (in %)	Sr

the available raster datasets. For the cell dimension, a pixel size of 90 m x 90 m is used. This size is a compromise between spatial accurateness and computing time, as with smaller pixel size the time for the programming routine to calculate the optimum options is increasing exponentially in relation to the pixel size. Furthermore, a cell size that is too small might create the false impression of an accuracy which is not inherent in the data. At the same time, this chosen spatial resolution still represents the used geospatial characteristics adequately as discussed in Hengl (2006) as a requirement for defining the resolution of a given study area.These five described datasets are taken into account in network extension modeling with the percentage weighting factors listed in Table 5.8. The weighting factors have mainly been identified by literature analysis (Kumar, Mohanty, Palit, & Chaurey, 2009; Deichmann, Meisner, Murray, & Wheeler, 2011; Bhandari & Stadler, 2011) and in stakeholder interviews during workshops (Chap. 5.5), since the nature of commercialism of power construction companies makes it is very difficult to disclose detailed information on costs with regard to different landscape characteristics. Road availability is the only factor impacting on the resistance of the decision raster negatively, making it more likely that the grid will run in parallel to roads, while the other factors reflect areas where grid development is undesirable, leading to a higher resistance for transition through the respective pixel cells. Regions in which power grid infrastructure already exists are weighted with zero, as this allows a linkage of unconnected sites to any point of the already installed network since this holds zero resistance(Etten, 2015).
In order to implement this weighting, an algorithm was developed (Appendix B1) that combines these raster datasets into one dataset, taking into account the individual weighting of each individual dataset (Geiger & Cader, 2016).
As a starting point, input data will be tailored to the region of interest, vector data will be converted into raster data with 90 m x 90 m resolution and appropriate extent, and projections will be standardized to UTM32N. All datasets are buffered with a defined distance of 90 m to allow the algorithm to perform correctly at the borderlines of the investigation area. Rasterized vector data of the grid lines is also buffered to guarantee that the respective grid pixels have a continuous structure. Furthermore, for the categorical nominal data of the land cover dataset, the nearest neighbor reclassification method is used to extract the values for water bodies and forest areas; while for the elevation dataset in an ordinal scale, bi-linear interpolation is used as to compute the slope values in the projected dataset. Slope indicates how the altitude changes from one pixel to the next – in completely flat regions it would be

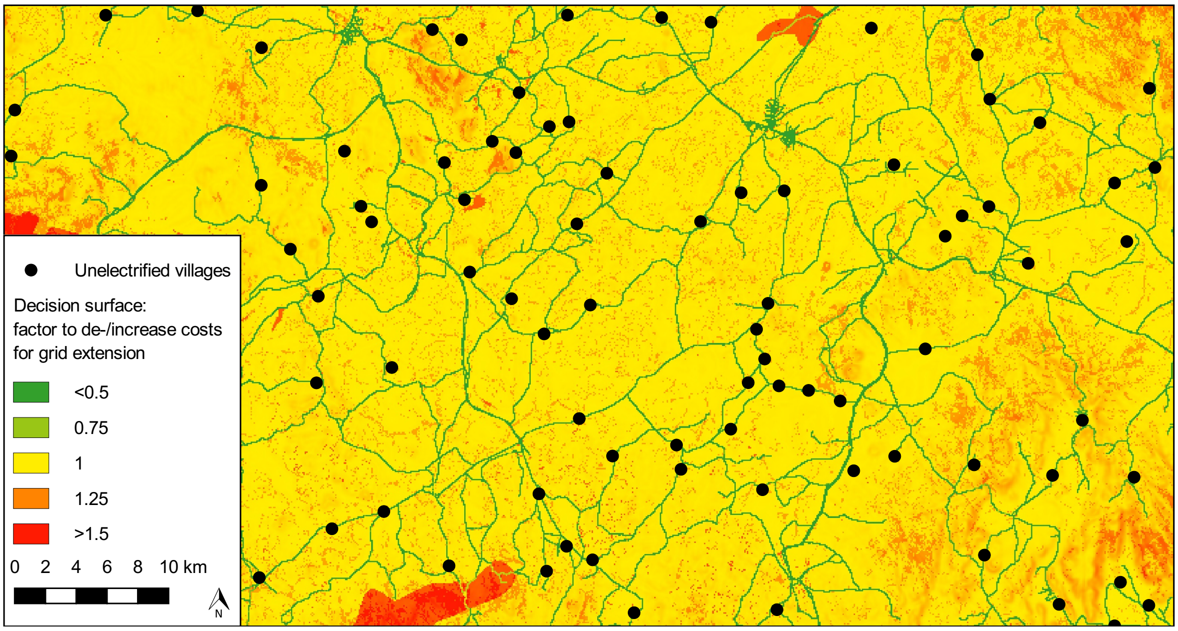


Figure 5.12.: Map of resulting decision surface raster displaying the scaling factors for finding the optimum grid extension pathways for the unconnected locations. Author's own map, data resulting from the applied methods and described input data.

zero.

Next, an empty raster dataset with the dimensions and resolution of the input data is created. By using a pixel-based calculation routine, mathematical operations, such as additions and multiplications, on each overlapping pixel of the variables $\boldsymbol{V}$ are carried out to combine the different data layers into the new decision raster layer $\boldsymbol{d}$ while accounting for their respective weighting (Eq. 2):

$$d = \left(1 + \frac{V_{slope}}{100} + V_{forest} + V_{protected} + V_{road} + V_{water}\right) \times V_{gr} \tag{2}$$

In case of an iterative network extension, by extending grid infrastructures in a phase-wise structure, an extended network can simply be used to update the decision raster to $\boldsymbol{d_{update}}$ by

$$d_{update} = d \times V_{gr}. \tag{3}$$

It is not necessary to recalculate the entire raster, but only to set the areas that are now crossed by a network to zero values in the decision raster (Eq. 3).

The output raster dataset combines the input datasets discussed above in one resulting raster data file, on which the grid extension calculation routine will be conducted (Fig. 5.12).

Identification of the optimum grid connections

The idea of the grid extension modeling is to consider heterogeneous geographic spaces in addition to distance. Those decision surfaces, which impact on the real path of grid extension on the ground, form the base layer on which the concept of minimum spanning trees is

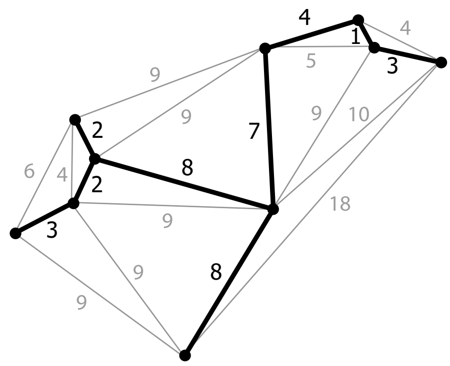


Figure 5.13.: Concept of a minimum spanning tree. The numbers reflect the values of the edges and correspond to the length of each. The black lines highlight the minimum spanning tree for this specific constellation of ten vertices.

applied to connect locations which are not connected to the existing power line network yet. A minimum spanning tree is a composite of edges connecting vertices on a surface with the aim of creating only those connections which are necessary to connect all vertices to one network (referred to as tree) by minimizing the total length/costs of the vertices. If the edges differ only by their lengths, the minimum spanning tree will be the tree connecting all vertices by the shortest connection (Fig. 5.13). In the case of rural electrification planning, the vertices represent the non-electrified locations and the edges the potential routes for power grid constructions to connect those to the existing grid.
For the calculation of the network paths, successive processing steps are necessary, which are based on Etten (2017)(Fig. 5.14). As a first step, a graph is created based on the previously calculated decision grid. This connects pixel centers with their neighboring pixels. Here, the Moore neighborhood is used, which considers eight adjacent cells of a pixel (Takeyama & Couclelis, 1997).
Weights must be added to the edges of this graph, such as the permeability or resistance from one cell to the next to represent the costs of the respective transition through the cell. For this analysis, the corresponding permeability is calculated, which indicates to what extent the landscape crossing for electricity network corridors is impeded by obstacles. In order to achieve this, the weighted edges of the graph are transformed into a transition matrix. Here, the reciprocal value of the resistance value, the conductance or permeability, is calculated for each pair of connected points (1/conductance). This allows to store the data in a sparse memory format, where the value zero is assigned to unconnected cells. To account for the different lengths between diagonal and orthogonal neighbors, a geo-correction for the values in the transition matrix is required. This grid must be adjusted to compensate for the distortion caused by diagonal and orthogonal traversing the pixels and different lengths of the meridians between the pole and the equator.
On the basis of this corrected dataset, a cost-distance matrix is calculated, which computes the path with the highest permeability, being equal to the least-cost option, between a given set of points (the locations to be connected to the power grid). As a final step, Dijkstra's algorithm (Dijkstra, 1959) is used to minimize the cost-optimized connection between all

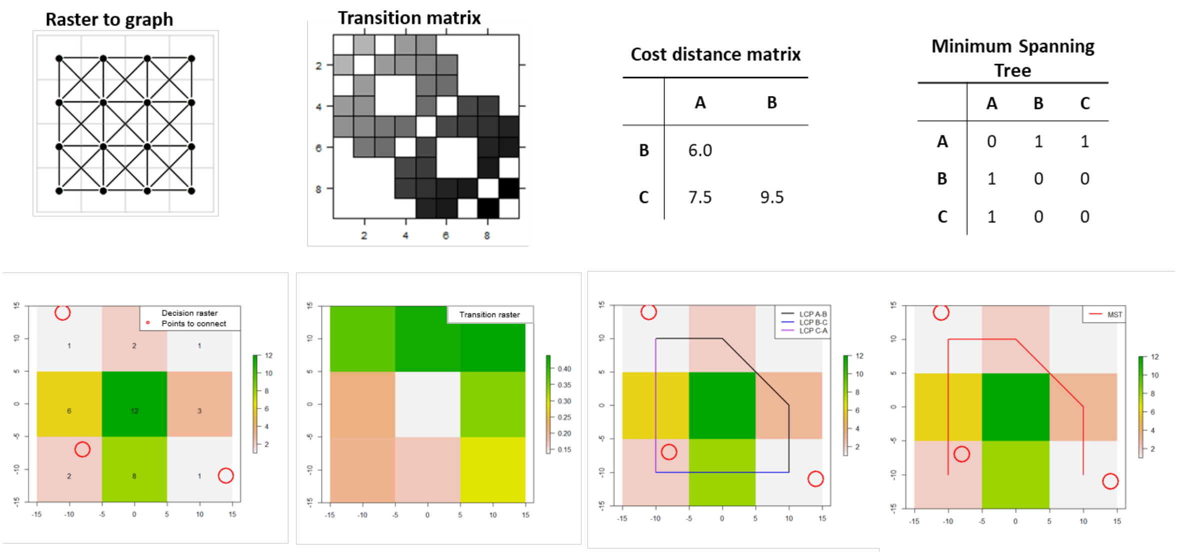


Figure 5.14.: Minimum spanning tree calculation based on a heterogeneous surface raster. The upper row shows schematically how the data is processed, while the lower row shows the corresponding spatial representation, in order to connect three example points A, B, and C on an example grid with 9 differently weighted pixels via the most cost-effective path. From left to right showing examples of graph design considering Moore's neighborhood, calculation of transition layer, computation of cost-distance matrix and finally, the derivation of the minimum spanning tree calculation based on Dijkstra's algorithm. Author's own diagram.

points based on the cost matrix. In this step, the connections are identified, which finally represent the optimal power network expansion path, depending on the topological influencing factors defined at the beginning (Fig. 5.15). The detailed implementation of the processing steps can be found in Appendix B2.

Resulting new network connections have to be processed further: since zero costs are assumed for pixels on which network infrastructure is already located, any networks that have been formed here must be subtracted from the result dataset. Furthermore, when the centroids are connected through the pixel structure, some staircase-like line structures have resulted, which artificially extend the network line length and therefore have to be smoothed out. With this formatted dataset, distances and network costs can now be determined for the suggested grid extension.

Identifying grid branches and assigning the grid extension costs

From an implementation point of view, it makes sense to look at network expansion at various points in their branches diverging from the main network. This prevents networks from being viewed individually without looking at their linkage to the existing electricity grid. By understanding the completely optimized grid network solution, respective grid lines and transformers can be sized correctly, even if the full grid branch would not be constructed in the first phase. These branches are derived from networks that branch off at one point from the existing network. This also prevents new networks from being recommended without considering nearby locations that are also included in the entire least-cost network.

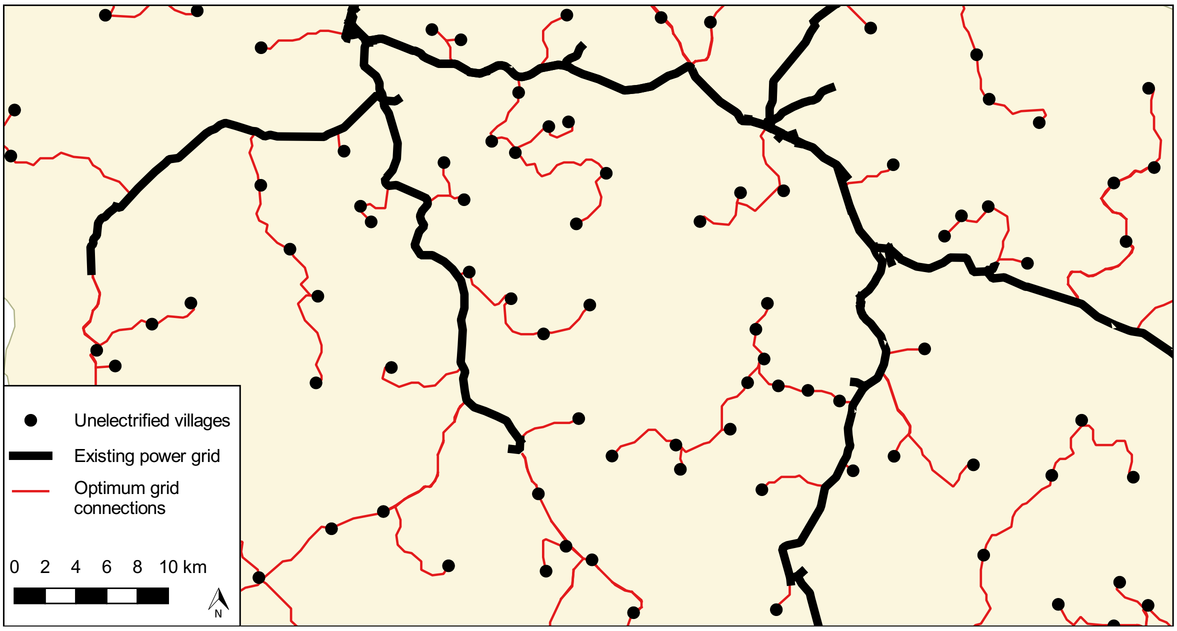


Figure 5.15.: Map of optimum grid connections to each locations considering the impacting factors of roads, slope, land cover and protected areas, as combined in the decision surface raster.

Table 5.9.: Assumed cost values for grid extension.

Cost parameter	Unit	Value
Project development	USD/project	20,000
Medium voltage grid	USD/km	20,000
Transformer	USD/kW	100
Distribution grid connection	USD/customer	400
Central power generation and transmission	USD/kWh	0.08

Grid extension costs are composed of transformer costs, grid costs, construction and maintenance cost, and operational costs. For the investment costs, financial parameters, such as the cost of capital, need to be considered. To assess the grid extension costs, several separate cost parameters are collected (Tab. 5.9).

5.3.3. Decentralized energy systems

Decentralized energy systems present a different approach of providing electricity in contrast to the extension of a centralized option, as described in the previous chapter. By using this option, there is no distinct spatial separation between generation, transmission, distribution, and consumption as in centralized systems. The consumption electricity is closer to the electricity generation and in many cases, those systems are run locally, e.g. within a village or a household. For decentralized electricity generation, it can be differentiated between very small systems on a household level, such as solar home systems or pico-solutions, or larger systems forming a mini-grid, supplying one or more nearby village clusters with electricity. Decentralized solutions can either be powered by fossil fuels or by renewable energy sources.

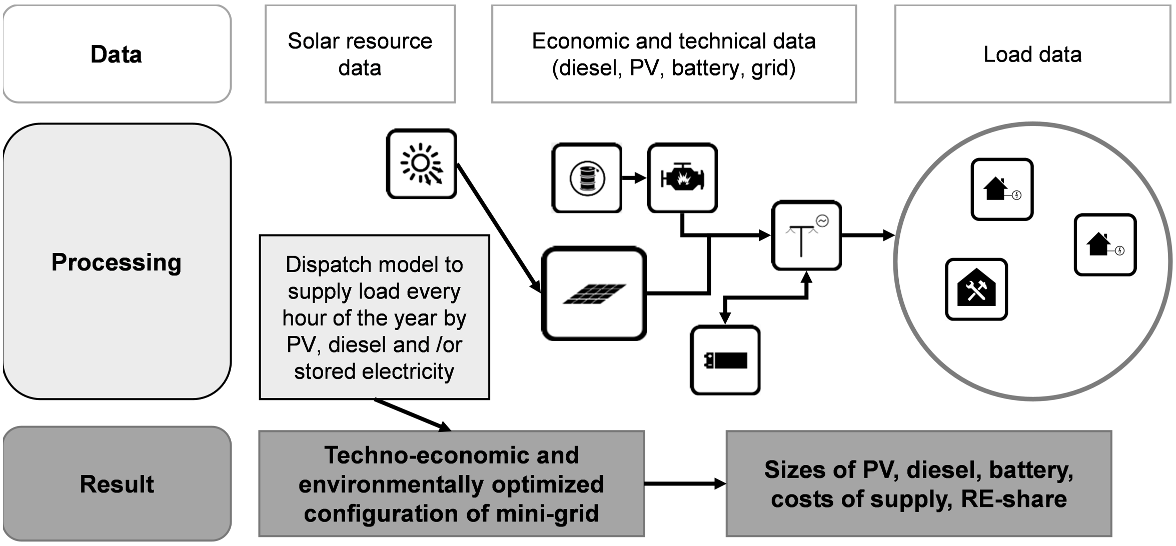


Figure 5.16.: Schematic description of input data, processing steps, and results of modeling a PV-diesel-battery mini-grid. Author's own diagram.

Mini-grids

Mini-grids is an electricity generation option which combines at least two different power generation plants and optional storage units, managed by a control system, and distributing the power to a small network of connected customers to cover the respective electricity demand (Fig. 5.16).

For this study, PV, diesel generator, and battery storage are simulated to identify the most economical mini-grid design with the lowest levelized cost of electricity for each unelectrified location. Therefore, different component sizes of the technologies are simulated to identify the most economic system configuration by defining the optimum size of each component for each specific location with a site-specific demand for electricity and site-specific solar irradiation. For all non-electrified locations, the costs (in LCOE) are calculated to have a metric that allows a comparison of the resulting costs for the grid extension for each of the locations.

For the mini-grids, capital expenditure, operational expenditure, a site-specific load and solar irradiation, and a specified lifetime of the components are assumed (Tab. 5.10).

With this input, the Python-based simulation tool, developed at RLI, optimizes the system to find the most economic system configuration with the lowest LCOE as described in Blechinger, Cader, Bertheau, Huyskens, Seguin, & Breyer (2016). By this calculation, the sizes of the different components, such as PV, battery storage, and diesel generator, are calculated to identify the least-cost configuration, the resulting required investment costs, the share of renewable energy in the system, and the amount of required fuel, as well as the resulting CO_2 emissions.

The comparison of grid extension with decentralized energy systems is based on a techno-economic comparison of the levelized cost of electricity (LCOE) both from electricity from the power grid and the decentralized options.

Renewable energy technologies are generally characterized by high initial investment costs

Table 5.10.: Overview on simulation parameters and costs for the mini-grid modeling.

Asset	Parameter	Unit	Value for Nigeria
PV	CAPEX	USD/kW	1,250
	OPEX	USD/kW/y	25
	Lifetime	y	25
Battery	CAPEX (Capacity)	USD/kWh	250
	CAPEX (Power)	USD/kW	500
	OPEX	USD/kWh/y	6.75
	Lifetime	y	15
	Maximum c-rate	kW/kWh	0.5
	Maximum depth of discharge	%	80
	Charging efficiency	%	97
	Discharging efficiency	%	97
	Number of cycles	#	4,900
	Initial state of charge	%	0
Diesel	CAPEX	USD/kW	820
	OPEX (fix)	USD/kW/y	0
	OPEX (var)	USD/kWh	0.05
	Lifetime	y	10
	Minimal Loading	% of max power	10
	Rotating mass	%	40
	Efficiency @ min loading	%	30
	Efficiency @ max loading	%	35
Other	Project development cost fix	USD	20,000
	Project development cost var	%	0
	Project lifetime	y	20
	Annual fuel price change	%	5
	WACC	%	16
	Connection costs	USD/customer	400
	Lifetime distribution grid	%	40
	OPEX distribution grid	%	1

for the technologies and low costs during operation, due to the free availability of renewable energy potentials of solar irradiation. During that phase, only the costs for maintenance occur. Fossil powered energy generation, on the other hand, need a constant supply of fossil fuels and are in consequence more expensive during operation. On the other hand, the initial investment costs are lower and therefore, such a system might be easier to afford.
To allow for electricity use at night from solar powered systems batteries are required. Those are characterized by a strong price decline and a steep technology learning curve over the last years. Lithium-ion batteries are chosen for the mini-grids due to their technical appropriateness (Bocklisch, 2015). Technological details for the battery storage and the diesel generator are also listed in Tab. 5.10.

Stand-alone solutions: Solar Home Systems

Stand-alone solutions are the smallest option to generate electricity on a household level and easiest to install and maintain. In most regions, different providers of such technologies are available at local markets, selling their products often combined with pre-payment schemes and service contracts. As these systems do not require complex infrastructure or high investments, they are easily purchasable by the local population, this electrification scheme is recommended in sparsely populated regions, with correspondingly low demand for electricity and low payment capacity.

One advantage of those stand-alone solutions is their modularity: they are available in many different sizes and price classes and households can choose a suitable application according to the household's demand for electricity services and ability to pay. Locations, where SHS are feasible are often not economically connectable to an existing grid due to the low purchasing power of customers and their expected low energy demand. Such a low energy demand and comparably high project development costs make electrification by mini-grids prohibitively expensive. Grid expansion is also not an option in these cases, since the costs for transformers and grids cannot be efficiently allocated due to the small number of customers. Often the required distances are also very large.

Although the capacities of stand-alone solutions may be modest, these systems still allow to power some household applications, such as lights and radios and allow the charging of mobile phones. Therefore, they play a crucial role in providing access to basic electricity services.

In this model, SHS are assigned to villages or settlements with an electricity peak demand smaller than 50 kW. Those locations are mostly rural farms or temporal settlements, where both, a grid connection and a mini-grid would exceed the costs in regard to the expected return of invest compared to providing power by independent solar home systems. For a typical household solar home system of 50 W, the cost of 100 USD is assigned.

5.3.4. Least-cost electrification option

In the previous work steps, the costs for the three considered electrification options are calculated independently for each location. In order to enable holistic planning, however, these options have to be implemented in terms of their spatial proximity and implementation over time. This requires identifying the least-cost energy supply options for an integrated development of all locations jointly, depending on the chosen electrification pathways of neighboring clusters. Therefore, the modeling results, considering existing infrastructure and renewable local energy resources and local demand for electricity for each location, are used as an input into a prioritization to find the optimum solution by minimizing the overall cost of electrification for all locations to be electrified (Fig. 5.17): by applying a small-scale prioritization, the village clusters with a demand lower than 50 kW are assigned to small-scale systems. The mini-grid prioritization identifies the most remote sites and socio-economic priority clusters. Grid prioritization outputs villages with the highest economic priority. The latter two electrification options can be synchronous, as sites can first be assigned to mini-grid electrification, having a high socio-economic priority, but can become grid-connected eventually in a later phase as an interconnected mini-grid.

To compare costs, both options, renewable energy based mini-grids and grid extension, need to be in a comparable unit. Therefore, LCOE are chosen as the decisive parameter. LCOE of the mini-grids are a direct output of the mini-grid model, while the grid extension LCOE need to

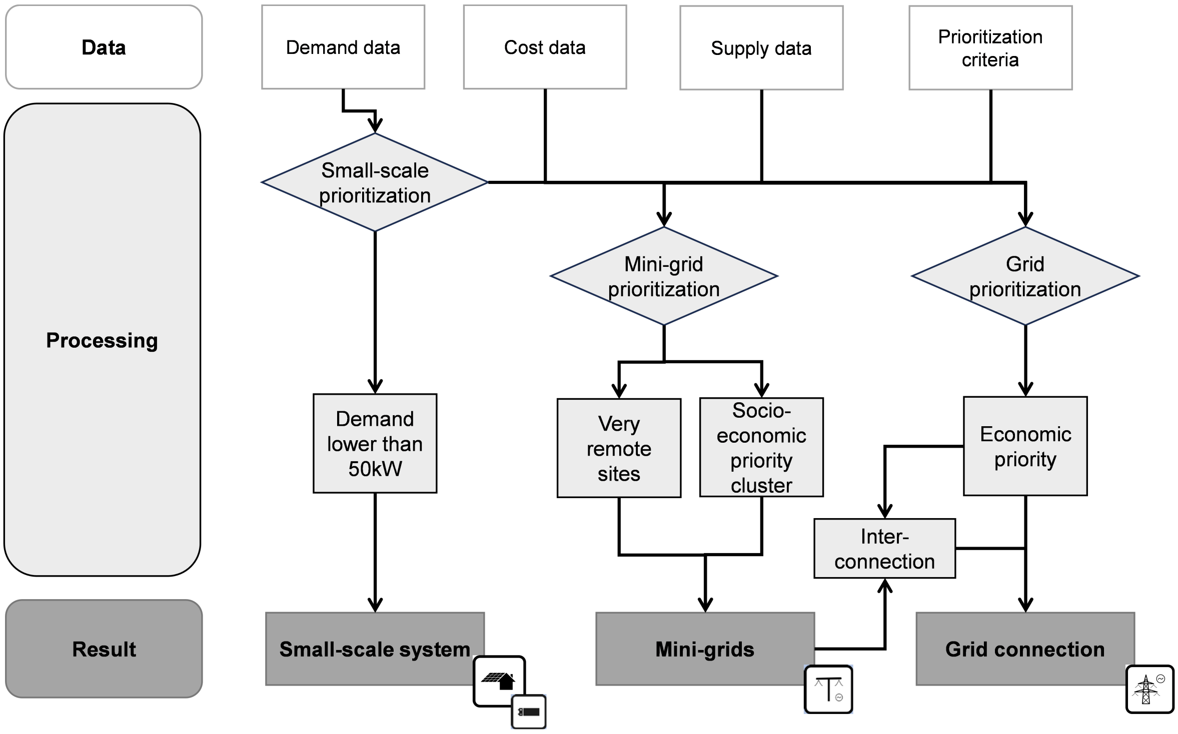


Figure 5.17.: Prioritization of sites and allocation of the non-electrified locations of the three electrification options. Author's own diagram.

be calculated by considering total required grid length and related costs for construction and operation as well as the cost of electricity. Those costs are structured in the respective OPEX, calculated as a fixed rate of the costs for each transmission grid infrastructure, transformers, and connection costs on the distribution and household level (Eq. 4). The total costs are subdivided into their annuities considering the weighted cost of capital $WACC$ and the project lifetime y in years by being multiplied with the cost recovery factor and shown in Eq. 5 (Jeynes, 1956).

$$opex_i = cost_i \times r \tag{4}$$

$$annuity_i = cost_i \times \frac{wacc(1 + wacc)^y}{(1 + p)^y - 1} \tag{5}$$

$$cost_{projectdev} = 20,000 \text{ USD} \tag{6}$$

$$cost_{grid} = 20,000 \text{ USD/km} \times length \tag{7}$$

$$cost_{transformer} = 2 \times 1.5 \times peak\ load * \frac{5,000 \text{ USD}}{50 \text{ kW}} \tag{8}$$

$$cost_{grid} = customers \times 400 \text{ USD} \tag{9}$$

The LCOE are composed of the sum of all cost annuities and the OPEX of each component divided by the total consumption plus the generation cost of the grid electricity (Eq. 10).

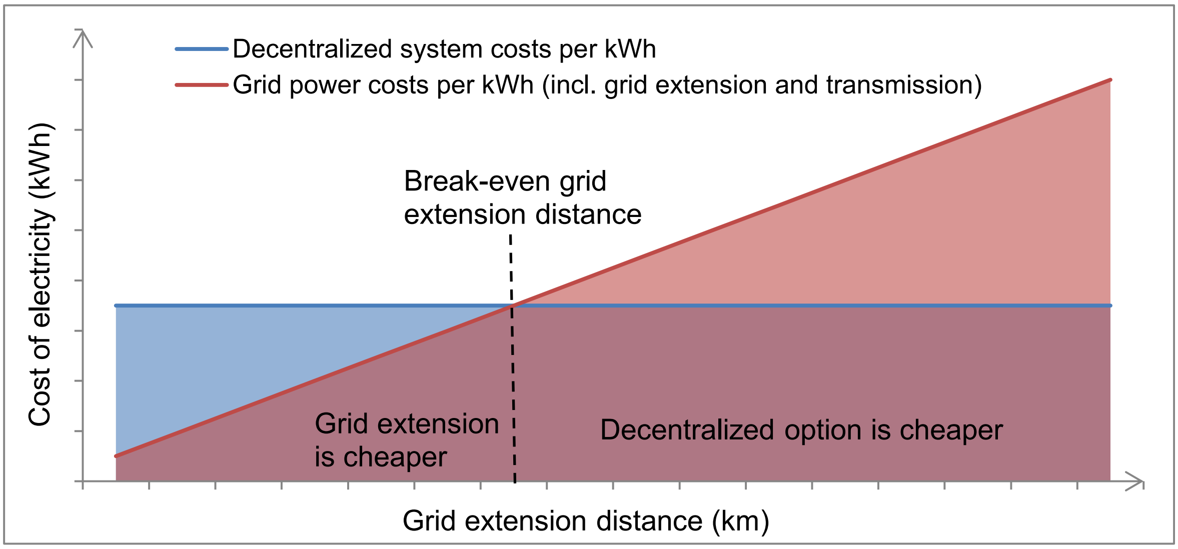


Figure 5.18.: Schematic representation of the break-even grid extension distance. This describes the length of a power line, which will provide electricity more economical than a decentralized energy supply option. Author's own diagram.

$$LCOE = \sum_{i \in \left\{ \substack{projectdev., \\ grid, \\ transformer, \\ connection} \right\}} \frac{opex_i + annuity_i}{consumption} + central\, power\, cost \qquad (10)$$

A set of subsequent working steps was developed and applied to each of the five states: all village clusters are connected separately to the existing grid by using the cheapest pathway on the defined topographical decision raster. The resulting length of separate lines is calculated and costs of the lines are calculated and compared to the mini-grid costs on the LCOE basis. For the cases where grid extension is already outperforming mini-grids, a minimum spanning tree considering the neighboring village clusters is compiled. A minimum spanning tree is created between those clusters where grid extension would be cheaper than mini-grids, even without considering the neighborhood of the location.

The next step is buffering the remaining clusters with the direct maximum distance which would lead to cheaper costs than a mini-grid solution. If a grid line is within reach at that distance, additional grid lines are simulated for that cluster. If clusters remained out of reach of existing grid lines with the maximum length of potential lines, those sites remain mini-grid clusters (Fig. 5.18). After that step, the final grid layout is reached, even though the last step can be repeated until it converges. The created networks are divided into the branches which are connected to the existing grid and the required distance of that grid is calculated. Also, the number and demand of connections for each branch can be assessed and hence, branches can be ranked according to their efficiency.

The prioritization has been translated into a three-step implementation plan. This allows a better understanding of a gradual electrification towards a 100% coverage. In order to do so, all village clusters which are out of economic reach to the next power line are assigned to mini-grids. From this selection of sites, priority mini-grid sites are chosen according to the following criteria:

- Size (weighted by 0.6);
- Social infrastructure (schools and health facilities, weighted by 0.4); and
- Distance (minimum distance to the grid 5 km).

To determine the priority locations for electrification through network expansion, village clusters along specific network branches are grouped together on the basis of the most cost-effective network expansion plan. Clusters that require the lowest number of kilometers of the grid line per kW of calculated electricity demand are prioritized in the least-cost plan for network electrification. If these clusters are already electrified by mini-grids, they are converted into interconnected mini-grids consecutively.

5.4. CO_2 emission of rural electrification

Independently of any technology choice, rural electrification increases the CO_2 footprint of any given region. $CO_2$and CO_2equivalents are emitted during the technology production and its transport to the project sites. In addition to those indirect emissions, direct emissions occur during the operation of power generation plants, depending on the type of fuel use. For the latter, renewable sources are emission free, while fossil fuel based generation emits different greenhouse gases. Therefore, the climate impact differs from technology to technology and an increasing electricity consumption on non-renewable electricity leads to higher CO_2 emissions. For renewable energy technologies, the carbon footprint is comparably low in contrast to fossil fuel technologies (Amponsah, Troldborg, Kington, Aalders, & Hough, 2014). Fossil fuel-powered technologies emit the by far largest share during operation. Consequently, complete life cycle analyses are excluded and only direct emission during operation of the electricity generation are considered.
To estimate the emission of the centralized grid systems, a respective emission factor can be calculated considering the currently installed power plants and the respective energy production. For Nigeria, UNFCCC (2012) assumed a grid emission factor of 0.63 $kgCO_2/kWh$. This will change if investments are made for a cleaner production portfolio with a higher share of renewable energy sources. The total grid emissions $CO_{2\text{ - grid}}$ are calculated by multiplying the grid emission factor *gef* with the electric power consumption from the grid kWh_{grid}

$$CO_{2-grid} = kWh_{grid} \times gef. \tag{11}$$

For diesel generators, the emissions can be calculated considering the system efficiency *eff* and the burning rate of the diesel fuel *b*. Diesel fuel has a heat value of 0.1 l/kWh_{th} and by assuming a generator efficiency of 0.3, a system efficiency of 0.33 l diesel fuel per kWh generated electricity is calculated. In consequence, the burning of one liter diesel fuel leads to 2.64 kg of CO_2 emissions.

For mini-grids consisting of a diesel generator plus a renewable source and battery storage, the respective renewable energy share *res* needs to be considered

$$CO_{2-mini-grid} = kWh_{mini-grid} \times (1 - res) \times eff \times b. \tag{12}$$

For solar home systems, zero CO_2 emissions are assumed, as solar irradiation is used as energy source.

5.5. Stakeholder workshops for the validation of the methodology

The validation is used to check if the developed approach and the modeling fulfills the intended purpose and represents the reality accurately, regarding the defined specifications.
The grid extension model is validated by replicating a known grid network. Parts of the existing grid lines are deleted and modeled by the algorithm. The output is compared to the existing structures and a comparison shows that the model results matches quite well with the known structures.
The developed method and the results have been presented and discussed intensively during stakeholder workshop in Abuja with participants of the federal rural electrification working groups of all five states. This workshop allowed unveiling limitations and concerns about the approach, as well as the validation of the assumed and estimated parameters.
In general, it was found that the participative approach during the workshop was very beneficial to unlock and understand concerns. Three workshops have been conducted, the first one (I) discussing the method to model the location of villages, their respective population size and their status of electrification and accordingly their connectivity to the power grid, the second one (II) to discuss the method to assess the demand for electricity and the last one (III) to verify the grid extension and mini-grid modeling (Tab. 5.11).
A key concern risen during the first workshop was that village names cannot yet be assigned to all locations considered within the modeling. This issue is a consequence of the lacking availability of digital and geo-referenced data, which is most likely to be overcome during the next years due to much cheaper availability of GPS trackers and mapping approaches, such as OpenStreetMap. Knowledge of exact village positions is not only required for energy sector related questions, but also for all cross-sector development issues such as land management, agricultural processes, and general market development. The Bureaus of Statistics also expressed a strong interest in such a dataset to monitor population development and track census information in detail.
The discussion during the second workshop on the validation of the assumed demand for electricity focused mostly on the role of agricultural activities and the division of the country into two sections. It was agreed that due to a lack of data the suggested classification is used as more detailed data was not available yet. The second workshop revealed very interesting figures about the demand for electricity in the regions which are already grid connected. Here, a suppressed demand was identified – as the delivered electricity was below the demand. This is most likely a result of the frequent blackouts and the overall unreliability

Table 5.11.: Key findings of the participative stakeholder workshops to validate the approach and the underlying assumed parameters.

Workshop	Limitation/Concern	Validation
I	Village names cannot be assigned to the defined villages due to the lack of required geo-referenced datasets.	With additional villages lists the participants agreed on the results to reflect a valid location and population dataset. With the limited knowledge of the status of electrification it was agreed that the developed method is the most suitable approach to assess the spatial distribution of electrification.
II	A concern was raised that the division of Nigeria into the North and the South for the estimation of the seasonal effects on the energy demand might simplify the real demand too much.	The load estimation was validated by discussions and agreements on the electricity demand of different appliances and the weighting of seasonal impacts of the agriculture. Due to the absence of higher resolved data the classification remained as suggested. The accumulation of the demand in each state helped the authorities to get a much clearer understanding of the electricity requirement in terms of additionally required electricity generation capacity.
III	The existing power grid is not correctly reflected.	In the cases that the modeled grid was incorrect, corrections are suggested during the workshop and additional digital data was made available after the workshop. By that it is guaranteed that the most up-to-date information is used in the modeling.
	Cross border power lines are not considered.	This limitation is inherent to the approach to model each federal state independently. To overcome it, data of the other states needs to be made available, which could be added at a later point in time to extend the modeling.
	Lithium ion battery storage technology is chosen, lead-acid batteries are neglected.	A discussion was started on which battery storage type to assume for the decentralized mini-grids. A clear result was that lithium ion batteries are preferred due to their higher environmental safety and their technical performance, even though costs are still higher and the respective market in Nigeria is not yet fully developed.

of the electricity supply from the central power grid. The estimated demand of electricity for the unelectrified villages presented an eye-opener for the workshop participants to understand the large challenge of supplying all households. Not only connections to energy infrastructure is required but also a significant amount of additional generation capacity.
The third workshop was very useful to correct some parts of the modeled grid. As a response to the presented results, it was possible to obtain more detailed digital data on the correct position of the existing power grid and mistakes in the dataset have been corrected. The workshop facilitated an enhanced understanding of the input data requirements for the modeling by presenting preliminary results. It was also made clear that the consideration of cross-border electricity transport would impact on the results, however that would require infrastructural data of the cross-border regions. A discussion on battery storage technology revealed a clear preference for lithium ion technology.

6. Electrification requirements and strategies for the five Nigerian federal states

This chapter presents the detailed results of the modeling conducted. It is structured in four parts: First, it pinpoints the exact locations of residences in the five federal states and their status of access to electricity. Based on these figures, the calculated electricity demand for the places without access to electricity is shown. In the second part, the results of decentralized and centralized electrification are presented in a three-phased expansion plan. In the following part, the climate impact of the proposed electrification scheme are illustrated, followed by the developed distribution strategy of the results. Key findings for each individual location are listed in Appendix C.

6.1. Overview on required electrification efforts

Due to the lack of conclusive detailed information on the distribution of villages and their respective status of electrification, the methods described previously are applied to identify the location of village population clusters, to derive detailed information on the number of inhabitants of said areas and to extract information on the respective status of access to electricity. These results are necessary input data for the subsequent working steps of assessing the optimum electrification options for each federal state.

6.1.1. Number of non-electrified clusters and number of people without direct access to electricity

In total, the analysis (as described in Chap. 5.2.2) reveals 8,048 village clusters in the five federal states Cross River, Niger, Ogun, Plateau, and Sokoto (Tab. 6.1). Niger is characterized by the largest number of villages, followed by Plateau and Sokoto, each correlated to the total size of the states.

The identified villages are populated by a total number of more than 20 million inhabitants, of which almost 50 % have no access to electricity on a household level (Tab. 6.2). This leaves more than ten million people without electricity access, an amount equivalent to the total population of Greece or Somalia. These findings show that the electrification rate in the five states varies between approximately 30 % in Sokoto and 75 % in Ogun, which is in line with the official national statistics (Tab. 4.2).

Table 6.1.: Total number of village clusters, grid-connected and electrified village clusters in the five federal states.

	# cluster	# electrified cluster	# grid-connected cluster	% electrified cluster
Cross River	818	160	274	20
Niger	2,694	74	456	3
Ogun	1,199	119	207	10
Plateau	1,834	26	189	1
Sokoto	1,503	25	255	2
Total	**8,048**	**271**	**1,381**	**3**

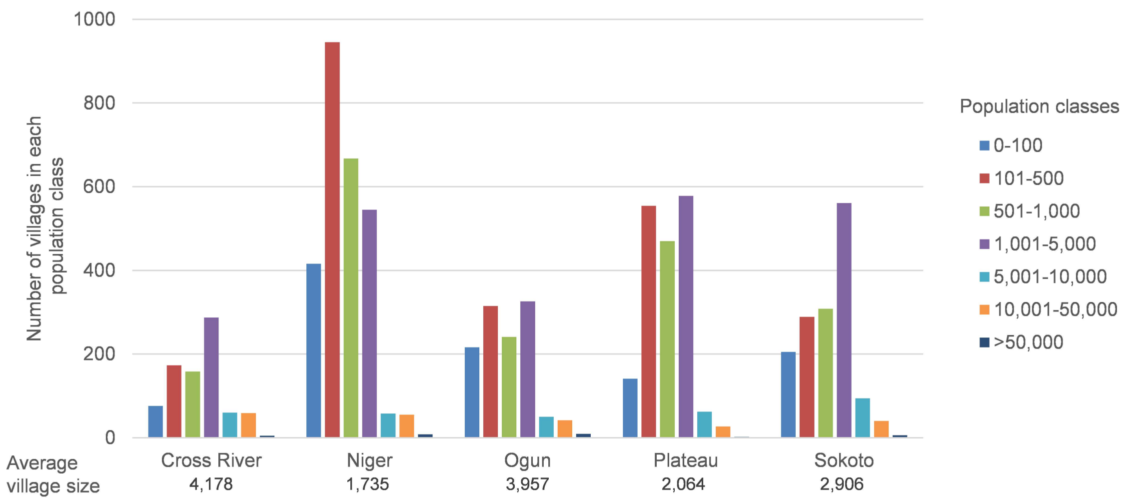


Figure 6.1.: Number of villages categorized according to population size for each state. Author's own diagram.

The population is more evenly distributed in the five states than the number of villages, since the population density in southern Nigeria is much higher than in northern Nigeria, while the northern states being larger in total size. In each state, there is a high disparity in village population as displayed in Figure 6.1. The majority are small villages with less than 5,000 inhabitants. Niger has the largest share of small villages between 100 and 500 inhabitants while the other four states are characterized by many larger villages between 1,000 and 5,000 inhabitants. This leads to an average village size in Niger and Plateau of around 2,000 inhabitants, in Sokoto approximately 3,000 inhabitants and in Ogun and Cross River around 4,000 inhabitants in average. Therefore, it can be concluded that the village clusters in the northern states are smaller in average compared to the clusters in southern Nigeria. This can be confirmed by Figure 6.2 - Figure 6.6, where the size and distribution of electrified and unelectrified clusters is displayed.

Only a small share of the village clusters are grid-connected, and not all of those have access to electricity, due to the lack of power supply in the power grid. These grid-connected clusters are generally those with a larger population, leading to a total electrification rate of almost

Table 6.2.: Population of the unelectrified and electrified village clusters and the resulting electrification rates in the five states.

	# population	# electrified population	% electrified population
Cross River	3,622,000	2,228,000	61.5
Niger	4,996,000	2,232,000	44.7
Ogun	4,935,000	3,680,000	74.6
Plateau	4,041,000	1,389,000	34.4
Sokoto	4,627,000	1,466,000	31.7
Total	**22,221,000**	**10,996,000**	**49.5**

50 % in the five states. In Sokoto, Plateau, and Niger, electrification rates are found to have the lowest rates significantly below 50 %, while Cross River and Ogun achieved much higher electrification rates of up to nearly 75 %.

The developed grid extension algorithm is used to reconstruct the existing grid in areas where the data was not available. Therefore, as electrified identified locations (by village information and night light emission), have been linked by the network expansion algorithm through the most probable connection corridor.

In Cross River, the existing transmission grid has its largest consumer site in Calabar in the south of the country. The grid network runs north on the western side of Cross River National Park. This protected area is also the reason for comparatively densely populated regions outside this area. In Niger, the grid network is the most dominant in the south-eastern region of the federal state, connecting the capital city Minna to Nigeria's Federal Capital Territory – Abuja. Parts of western Niger particularly lacks coverage of the existing power grid. Ogun's grid network is very strong in the south of the federal state, where several connections to the neighboring state of Lagos exist. This region is characterized by high population densities – as a result of the nearby megacity Lagos. Grid coverage in the very North and East is the weakest in this state. Plateau's existing power grid infrastructure has its largest consumer base in the north of the federal state, where the state capital Jos is located. From this point, a single power line departs in eastern direction, leaving the southeastern region without grid coverage. In Sokoto, the spatial location of the capital at the center of the federal state ensures that the network has developed in a relatively uniform manner in all directions. Nonetheless, due to the large size of the federal state, many regions and villages in between these grid corridors, are without grid connection.

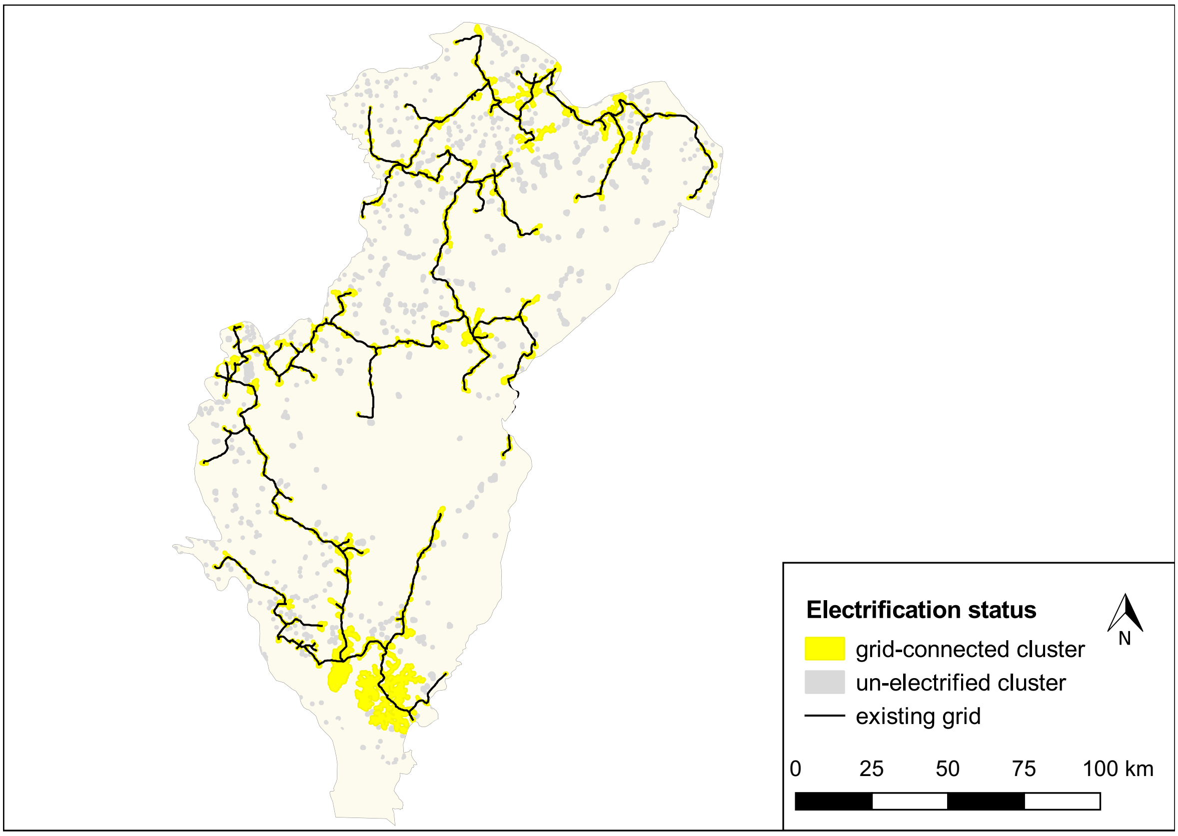


Figure 6.2.: Map of the existing powergrid and the current status of electrification in Cross River. Authors own map, data resulting from the applied methods and described input data.

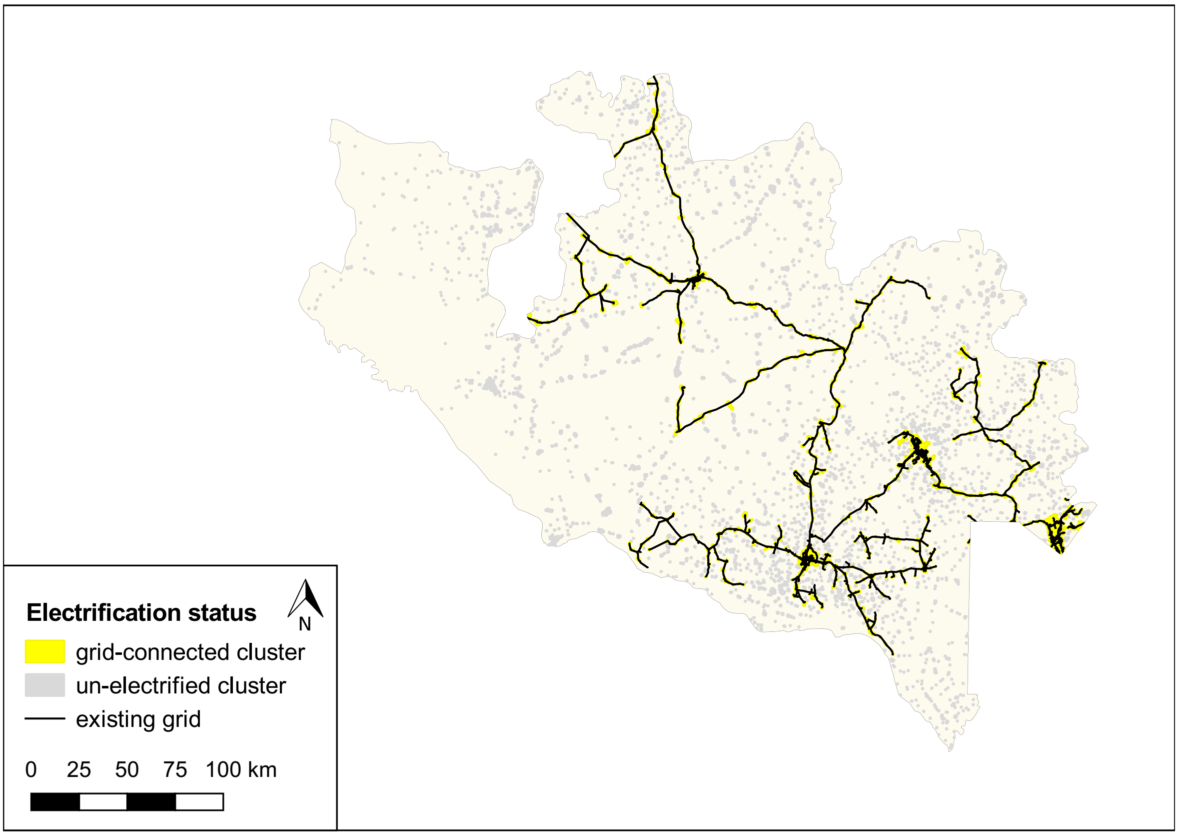


Figure 6.3.: Map of the existing powergrid and the current status of electrification in Niger. Author's own map, data resulting from the applied methods and described input data.

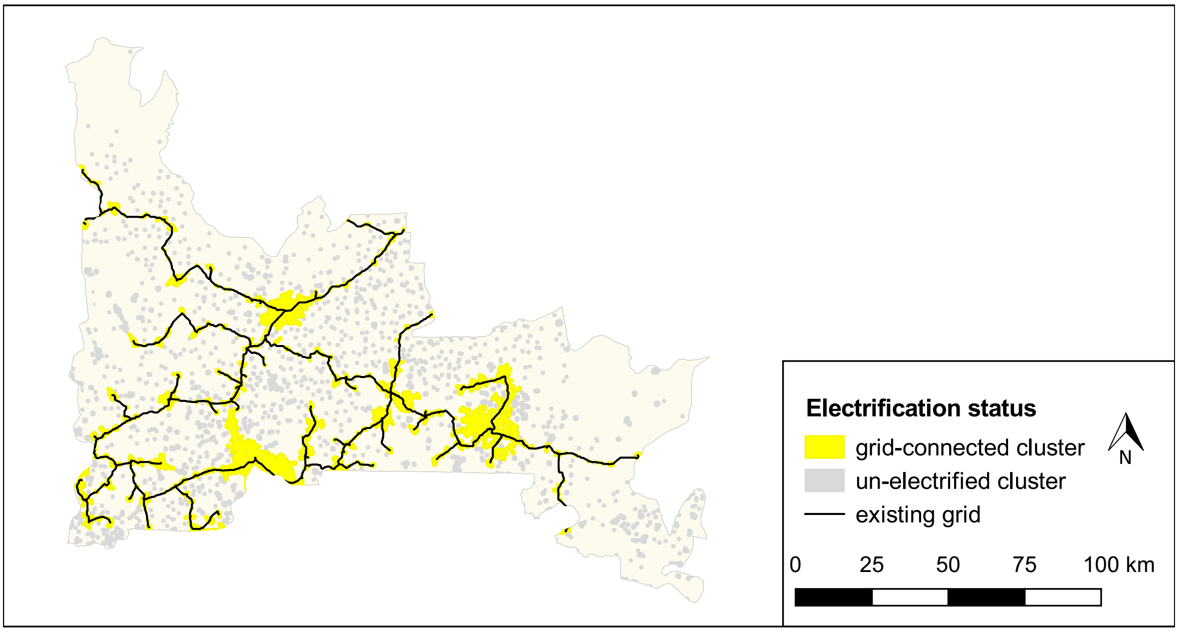


Figure 6.4.: Map of the existing powergrid and the current status of electrification in Ogun. Author's own map, data resulting from the applied methods and described input data.

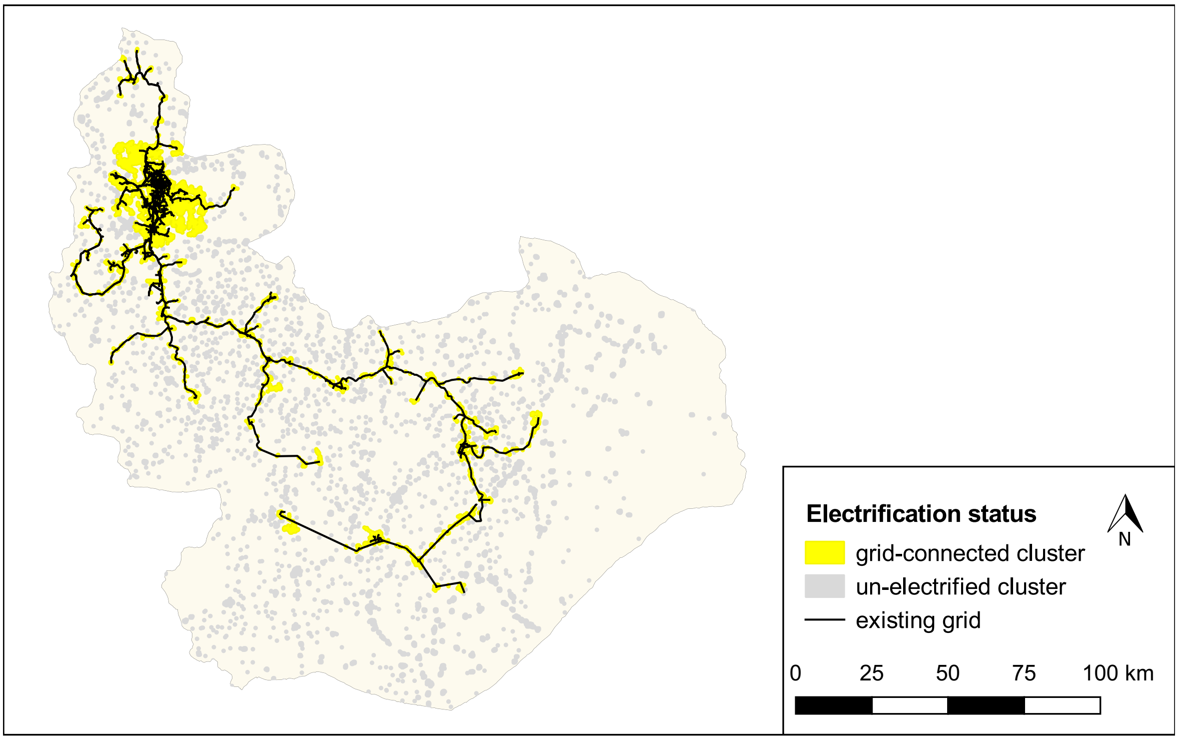


Figure 6.5.: Map of the existing powergrid and the current status of electrification in Plateau. Author's own map, data resulting from the applied methods and described input data.

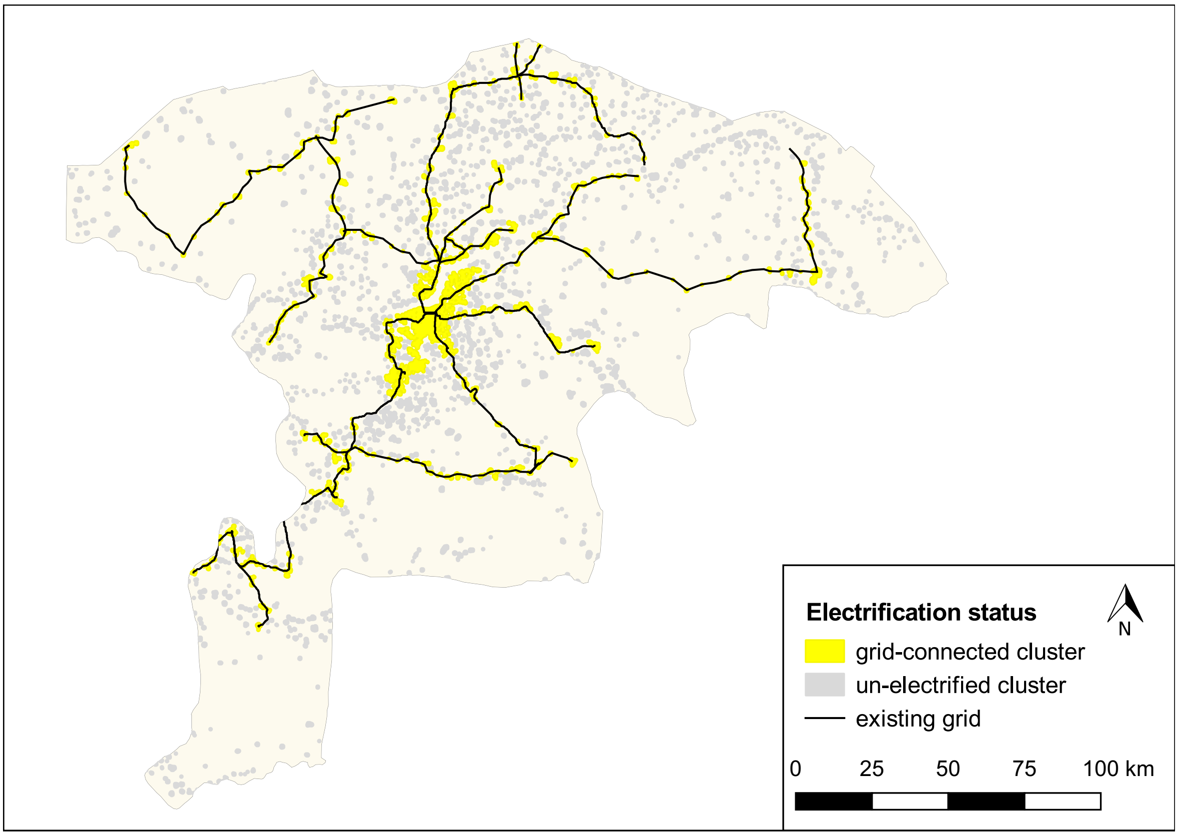


Figure 6.6.: Map of the existing powergrid and the current status of electrification in Sokoto. Author's own map, data resulting from the applied methods and described input data.

6.1.2. Predicted electricity demand in each state

To cover the basic energy needs by electricity, such as lighting and communication, the total energy demand per year in the five states ranges from 3.3 to 3.9 million MWh/a, depending on the chosen scenario (Tab. 6.3).

Two scenarios are differentiated: the first adopts a low tariff, reflecting the current electricity costs Nigeria, and a higher tariff, based on mini-grid electricity generation, resulting in higher costs (see Chapter 4.2.2).

This demand projection for five federal states equals to approximately 20 percent of the actual electric energy provided to all Nigerian federal states today, depicting the large gap between electricity generation as well as the supply versus the existing demand.

Depending on the high and low tariff scenario, a minimum peak demand of 1,441 MW is calculated for the high tariff, while a demand of 1,877 MW in the low tariff scenario is calculated for the fives states. The modeled total annual electricity demand would lead to an annual per capita electricity consumption between 150 and 180 kWh/capita/a. Although this is a significant increase compared to the per capita usage in 2013 (see Fig. 3.9), it is still very low, since national values consider industrial development and electricity usage in the different production sectors, and in this analysis, only household energy consumption and small commercial activities are accounted for.

The electricity demand is modeled in hourly time steps over one year to account for daily and seasonal fluctuations. The daily demand varies over the course of the day with the lowest values in the night forming the base load; and an increased demand over the day, with the peak demand in the early evening (Fig. 6.7).

In total, of the 8,048 identified village clusters without access to electricity, 2,051 are found to have a peak demand of 50 kW or higher and therefore qualify for either grid extension or mini-grid development. Ogun and Cross River have the smallest number of village clusters with a high demand, 260 and 303 sites, respectively. In the other three states, which are also characterized by overall lower electrification rates, more village clusters with a high demand are identified: 401 locations in Niger, 543 in Sokoto and 544 in Plateau. For the 2,051 village clusters, the detailed modeling of grid extension and mini-grids is carried out and results

Table 6.3.: Calculated electricity demand in the five federal states, assuming two different tariff schemes.

	high tariff		**low tariff**	
	peak demand	**annual consumption**	**peak demand**	**annual consumption**
	MW	**MWh/a**	**MW**	**MWh/a**
Cross River	353	831,000	455	957,000
Niger	268	628,000	352	729,000
Ogun	306	720,000	386	818,000
Plateau	229	535,000	307	624,000
Sokoto	285	633,000	377	745,000
Total	1,441	3,348,000	1,877	3,873,000

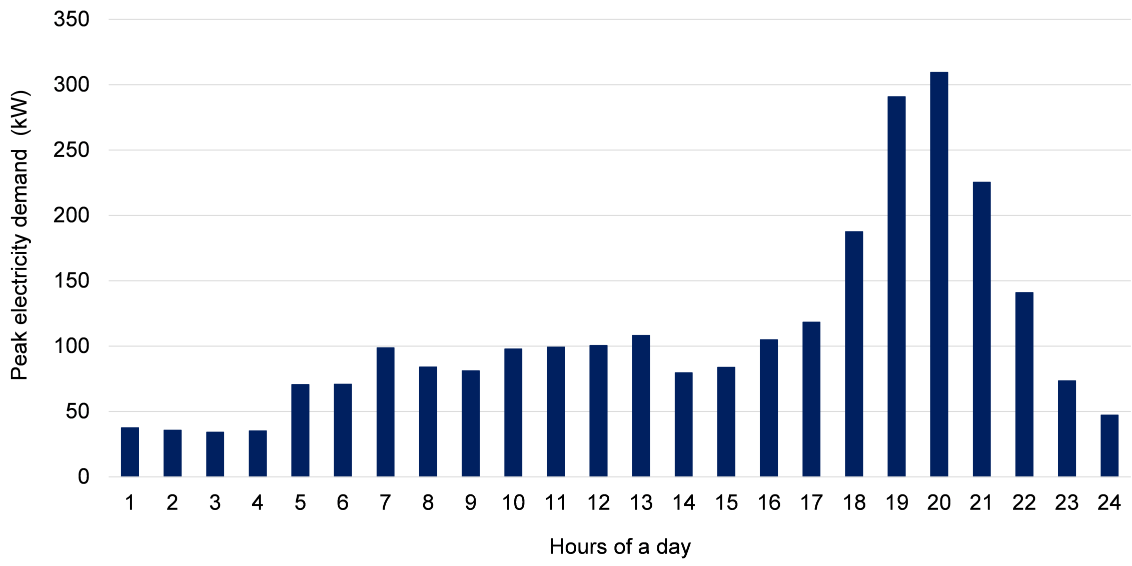


Figure 6.7.: Daily electricity demand in an example village in Plateau. The village has 4,000 inhabitants and requires approximately 800 household connections. The peak load per day is circa 320 kW and most electricity is consumed during evening hours. Author's own diagram, data resulting from the load modeling.

are presented in the next chapter. The villages with a peak demand of less than 50 kW are categorized for small-scale electrification measures by SHS.

6.2. Modeled electrification results for the five states

A phase-wise dynamic electrification approach is chosen which temporarily subdivides the electrification process in three subsequent steps; from the current status of electrification towards full electrification. Electrification options for each site are changing over the electrification process, meaning that locations with a proposed mini-grid solution can become interconnected to the grid once the grid is extended to a location which may have previously been electrified by a mini-grid.

Furthermore, the grid extension is suggested to be conducted in branches - since the location of certain village clusters imply a connection of several sites at once and it is required that certain sites are connected first in order to achieve the least-cost electrification grid layout. The spatial multi-criteria impacts lead to the following combined weighting layers as a starting point for the electrification planning. The impacts of existing grid infrastructure, water bodies and forests as well as protected areas influence the respective outputs. Indirectly, the total size of the respective area also has an impact, since larger states imply larger distances to be overcome.

Under the given assumptions, in all five federal states, grid extension is found to be the most dominant solution for achieving cost-efficient electrification. This can be justified by the fact that grid infrastructure is already installed over large areas, resulting in comparably short distances for the grid extension to connect unelectrified locations.

The following sub-chapters present the electrification phases for each state and its spatial extent. The required resulting electricity generating capacities and the number of supplied people in each phase are presented in the subsequent chapter.

6.2.1. Cross River

In Cross River, most of the inhabited areas are already covered by national power grid. Phase 1 is dominated by grid densification with the goal of meeting the suppressed demand and connecting unconnected households in previously connected clusters. 114 already grid-connected village clusters are supplied in this phase. In addition, 61 mini-grids are suggested to supply more than 300,000 people (Fig. 6.8). Most of the mini-grids sites are located near or in the Cross River National Park.

In phase 2, the grid supply is assumed to be stable without remaining suppressed demand, hence grid extension can successfully be initiated: in the second phase of electrification, 64 grid branches are suggested, extending the grid to 144 villages (Fig. 6.9). These are the most efficient grid extension measures, reaching the greatest number of people possible with the minimum length of new power lines. In total, in this phase, 470,000 people are reached by the suggested grid extension. For those connections, 38 of the mini-grids, which are developed in the first phase, become interconnected along the way. The longest grid branch is 35 km; and the total length is 450 km medium voltage grid extension during that electrification phase. In addition, 60 mini-grids are suggested to supply approximately 100,000 people in those locations.

In phase 3, the grid is extended further with 64 branches, connecting 158 village clusters of which 82 clusters are integrated mini-grid clusters (Fig. 6.10). The longest connecting branch is 76 km, doubling the length of the previous phase. In total, grid requirements for phase 3 are 833 km. Most of the grid development densifies the existing grid coverage and extends the grid into the forested national park area. In phase 3, no additional mini-grids are suggested for Cross River. This is a result of the dense rain forest without major settlements. The cluster with the largest direct distance to the grid is located within a distance of 35 kilometer to the existing power grid, while the average distance of all newly electrified locations is 9 km. The developed mini-grids of the first two phases have an average share of 67 % renewable energy-based electricity generation, with a minimum of almost 40 % and a maximum of 92 %. Figure 6.11 shows the layout of the electrification plan considering grid extension, mini-grids, as well as small-scale electrification with SHS. It can be observed that no grid lines cross through the center of the state. Investments of approximately 300 million USD for medium voltage and low voltage distribution infrastructure, mini-grids, and small-scale systems are required.

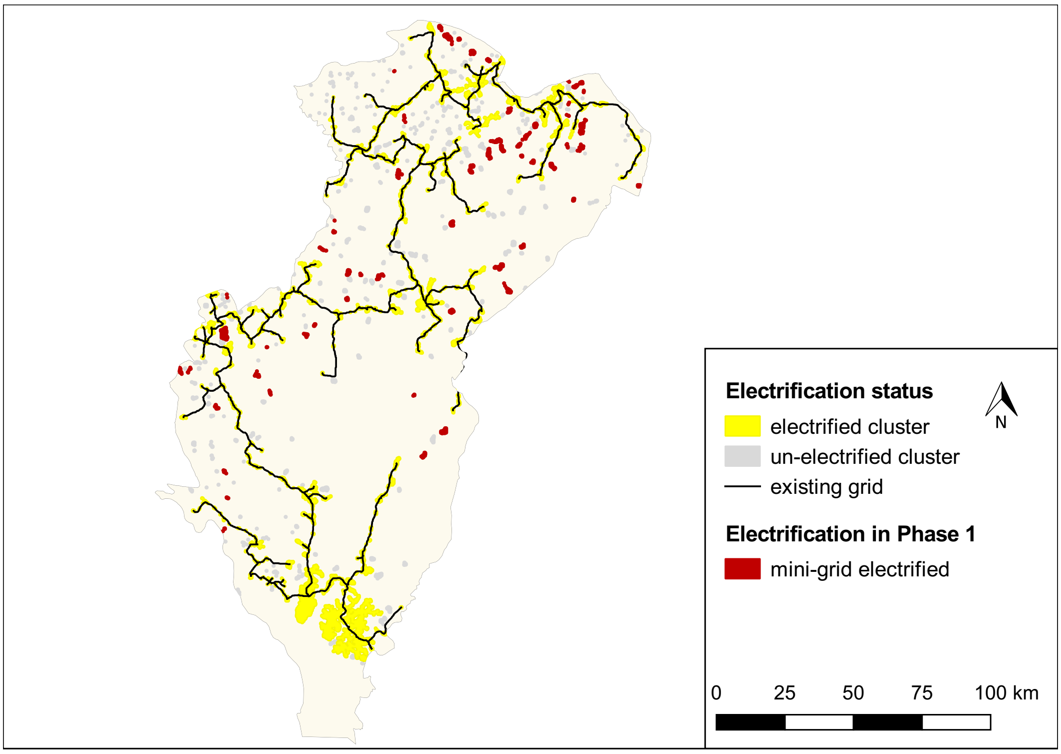


Figure 6.8.: Map of suggested electrification phase 1 for Cross River with mini-grid electrification. Author's own map, data resulting from the applied methods and described input data.

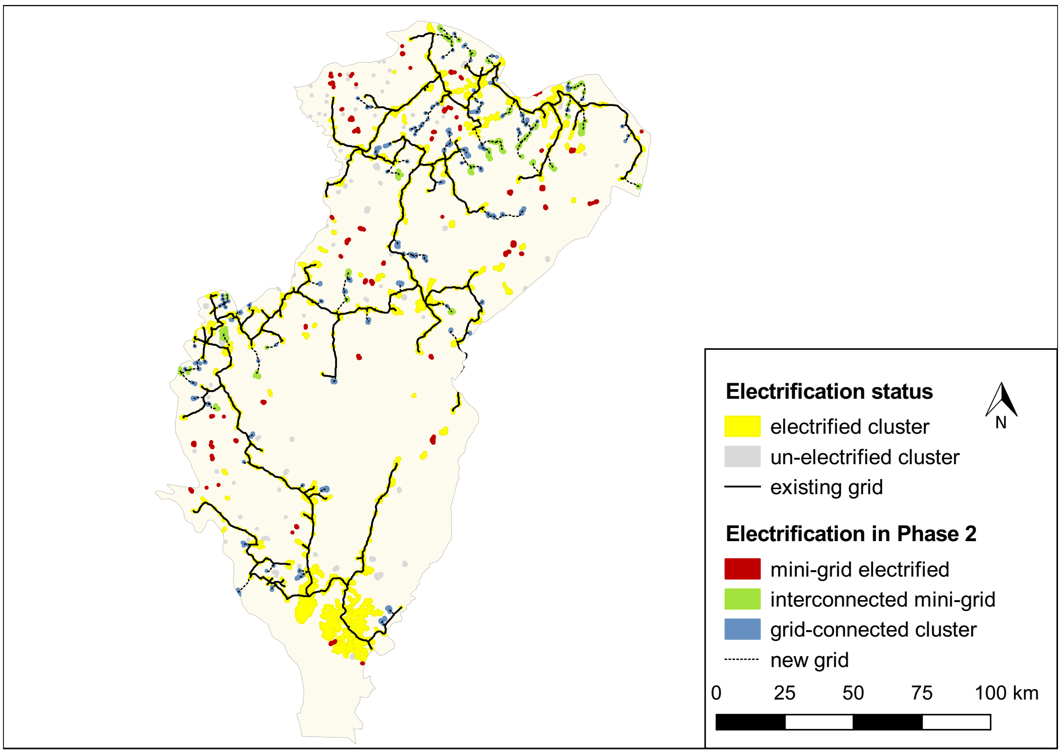


Figure 6.9.: Map of suggested electrification phase 2 for Cross River with mini-grid electrification, grid development and interconnected mini-grids. Author's own map, data resulting from the applied methods and described input data.

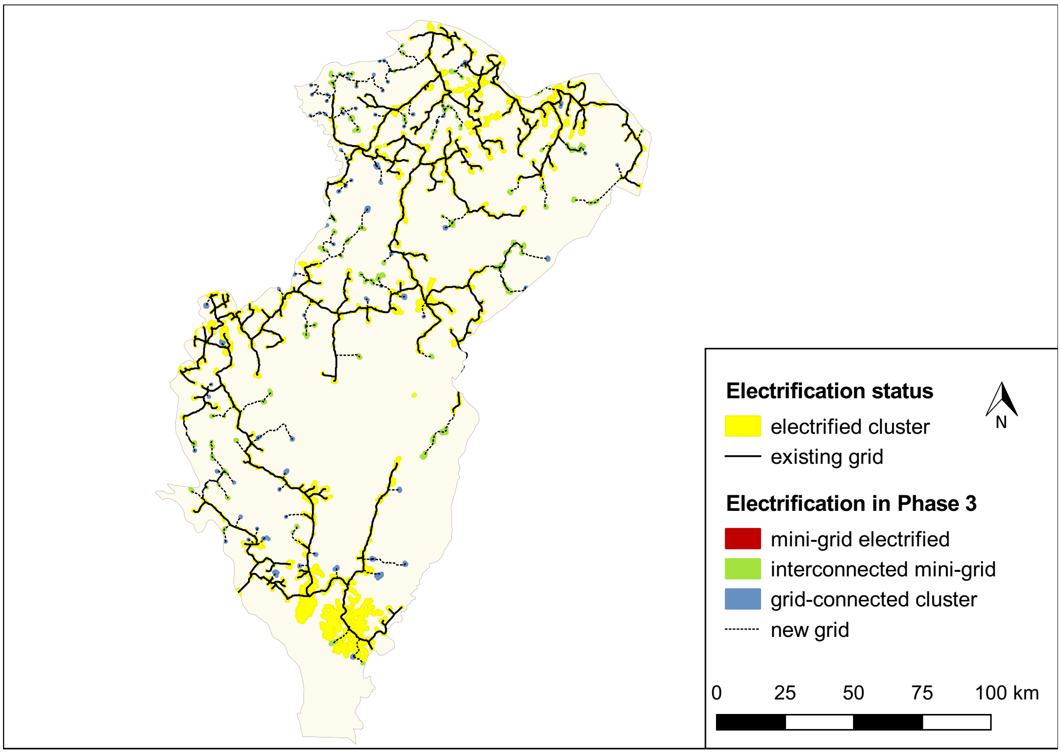


Figure 6.10.: Map of suggested electrification phase 3 for Cross River with mini-grid electrification, grid development and interconnected mini-grids. Author's own map, data resulting from the applied methods and described input data.

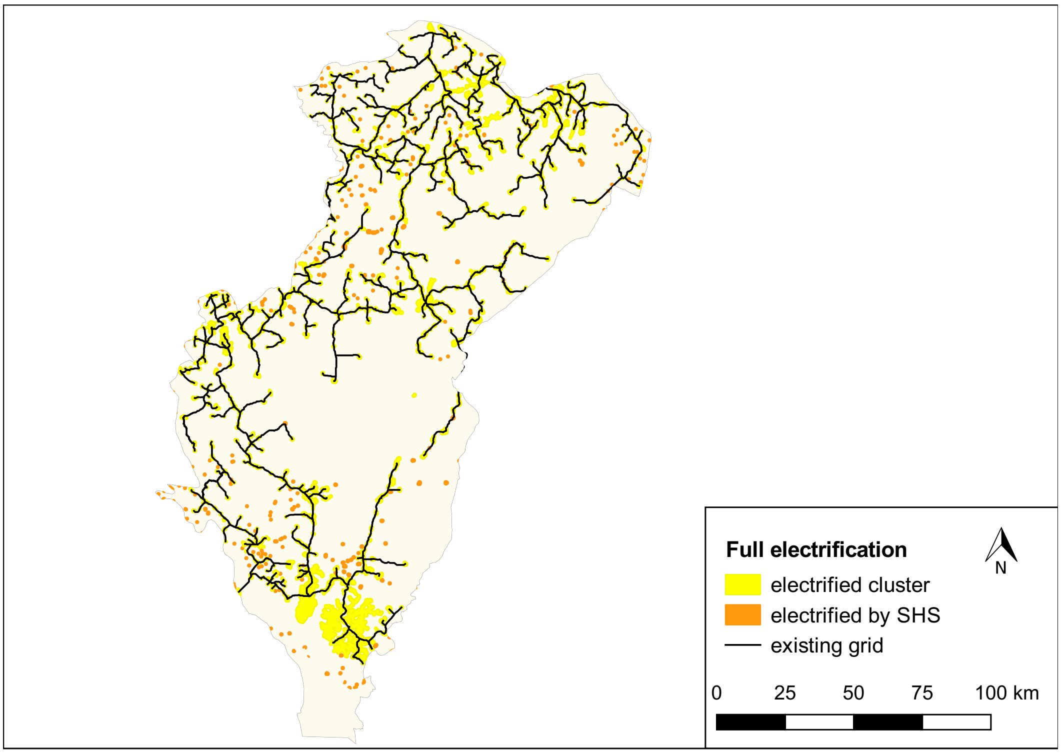


Figure 6.11.: Map of suggested full electrification layout for Cross River with mini-grids, grid extension and SHS. Author's own map, data resulting from the applied methods and described input data.

6.2.2. Niger

Niger's first phase of electrification (Fig. 6.12) is also dominated by grid stabilization to account for suppressed demand and unconnected households within the grid connected-clusters. In this stage, 382 already grid-connected, but not supplied, clusters are integrated into the supply system. Niger is the largest of the five investigated states and hence some of the population clusters have a much larger distance to the existing grid than in the other states. In Niger, the village cluster with the largest distance to the grid is located circa 180 km away from said infrastructure. On average, the locations that are electrified either by network expansion or by mini-grids are 25 km away from the existing power network infrastructure. 81 mini-grid sites are identified in phase 1, supplying more than half a million people.

In phase 2, 68 grid extension branches are suggested, connecting 22 mini-grids as interconnected mini-grids and an additional 115 unelectrified village clusters to the grid. Therefore, 926 km of new medium voltage grids are required, with the longest connection of 249 km. In addition, 68 mini-grids are suggested to supply almost 170,000 people (Fig. 6.13).

In phase 3, 69 additional grid extension branches are assigned, summing up to 2,340 kilometers of new medium voltage grids and connecting 227 village clusters, of which 103 sites are interconnected mini-grids. The longest single grid extension branch is 402 km. In phase 3, 12 additional mini-grids are developed in Niger, providing access to more than 15,000 people (Fig. 6.14). The developed mini-grids in all phases have an average share of 69 % renewable energy-based electricity generation, with a minimum of 44 % and a maximum of 87 %.

The full electrification scenario (Fig. 6.15) shows that, next to grid-connected and mini-grid clusters, many small clusters can eventually be electrified by small-scale systems such as SHS. To some extent, those sites are still quite remote, opening up decentralized options for mini-grid supply in future, if demand is increasing.

Investments of approximately 363 million USD for medium voltage and low voltage distribution infrastructure, mini-grids, and small-scale systems are required.

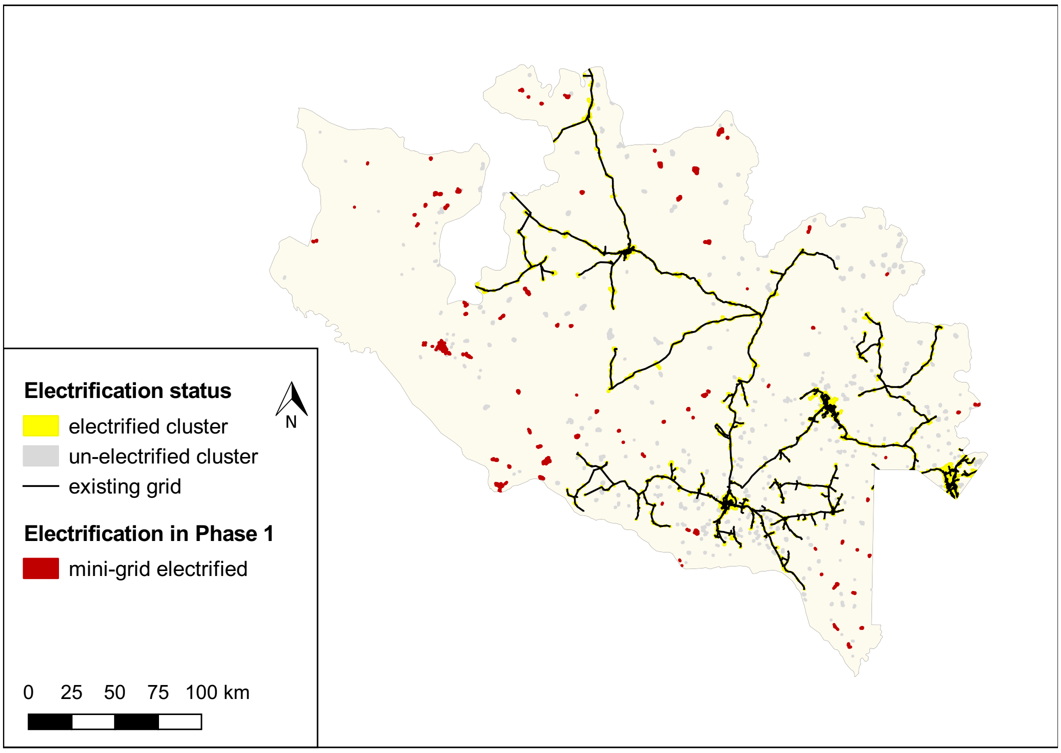


Figure 6.12.: Map of suggested electrification phase 1 for Niger with mini-grid electrification. Author's own map, data resulting from the applied methods and described input data.

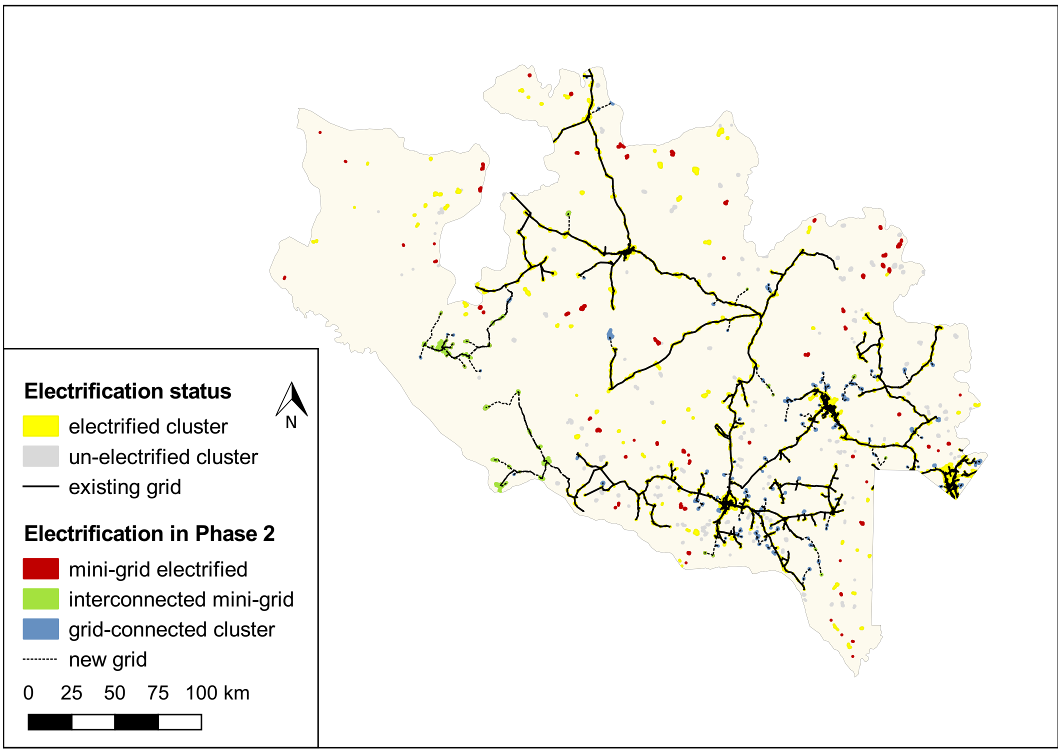


Figure 6.13.: Map of suggested electrification phase 2 for Niger with mini-grid electrification, grid development and interconnected mini-grids. Author's own map, data resulting from the applied methods and described input data.

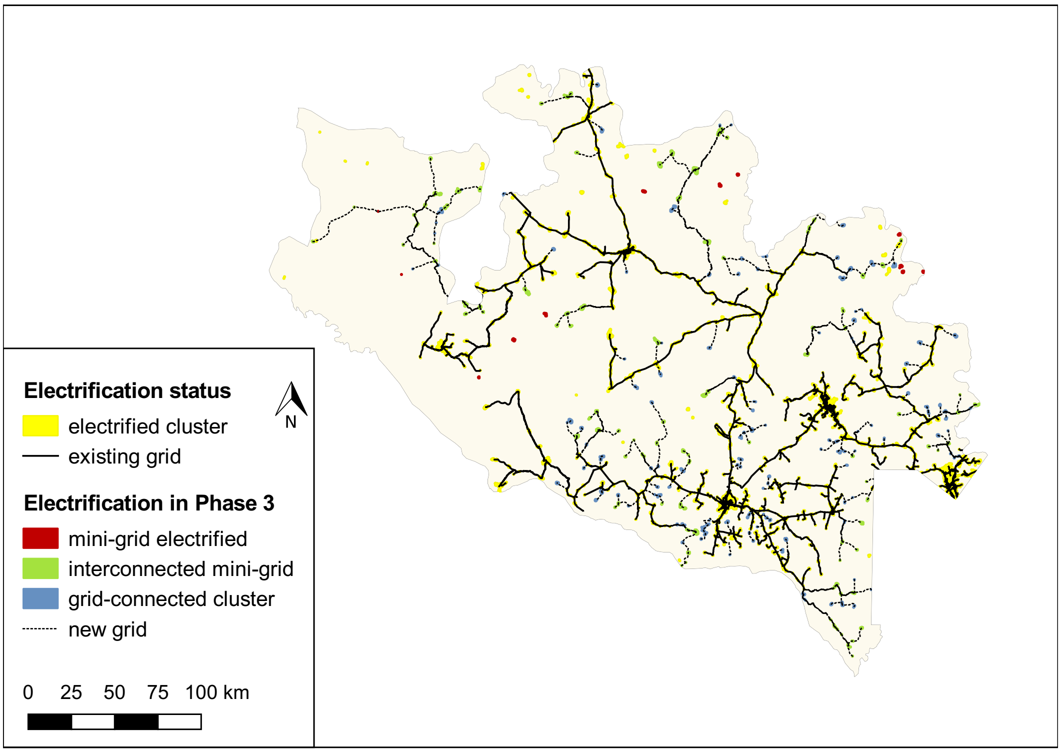


Figure 6.14.: Map of suggested electrification phase 3 for Niger with mini-grid electrification, grid development and interconnected mini-grids. Author's own map, data resulting from the applied methods and described input data.

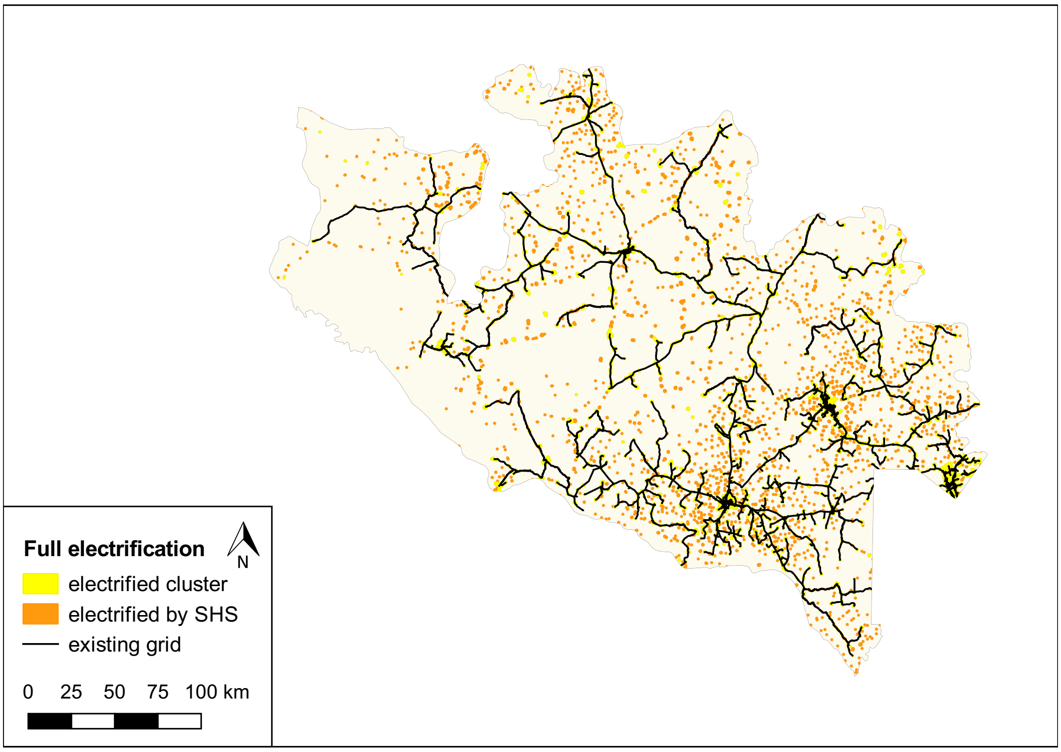


Figure 6.15.: Map of suggested full electrification layout for Niger with mini-grids, grid extension and SHS. Author's own map, data resulting from the applied methods and described input data.

6.2.3. Ogun

Ogun is the state with the most advanced power supply system resulting in the highest electrification rate (72 %) of the case study states. Specifically in the South, the grid infrastructure is already well-established. 119 of the 207 grid-connected village clusters are presently sufficiently supplied, leading to the requirement of supplying 88 additional sites by improvements in the existing grid system plus provision of additional on-grid generation capacity in phase 1. In addition, 52 mini-grid sites are suggested to supply more than 320,000 people, providing time for grid densification to account for suppressed demand and unconnected households within interconnected clusters (Fig. 6.16).

In phase 2, 47 grid extension branches are suggested, interconnecting 23 previously assigned mini-grids and 82 unelectrified clusters to the grid via 390 kilometer of grid lines (Fig. 6.17). The longest grid branch has a length of 43 km. For the decentralized electrification, 52 locations are identified for mini-grid development, supplying more than 100,000 people.

Phase 3 is characterized by the grid integration of the mini-grids via additional 46 grid extension branches, interconnecting 81 mini-grid sites and providing access to electricity to additionally 74 sites (Fig. 6.18). The length of those branches sums up to 969 km, while the longest single connection is approximately 200 km. In Ogun, mini-grid development is not suggested in the third phase anymore – the developed mini-grids of the previous two phases have an average share of 63 % renewable energy-based electricity generation, with a minimum of 38 % and a maximum of 85 %.

The full electrification layout (Fig. 6.19) shows that even in the areas already covered by the grid, small village clusters exist which are suggested to be electrified via small-scale solutions such as SHS. It is clearly observable that Ogun has the highest population density and cluster structure of the case study sites – nonetheless decentralized electricity generation is still of high importance. In Ogun, the location with the largest distance to the grid is located circa 60 km away from the closest grid infrastructure – in average all village sites are located in a distance of 13 km to the grid.

Investments of approximately 194 million USD for medium voltage and low voltage distribution infrastructure, mini-grids, and small-scale systems are required.

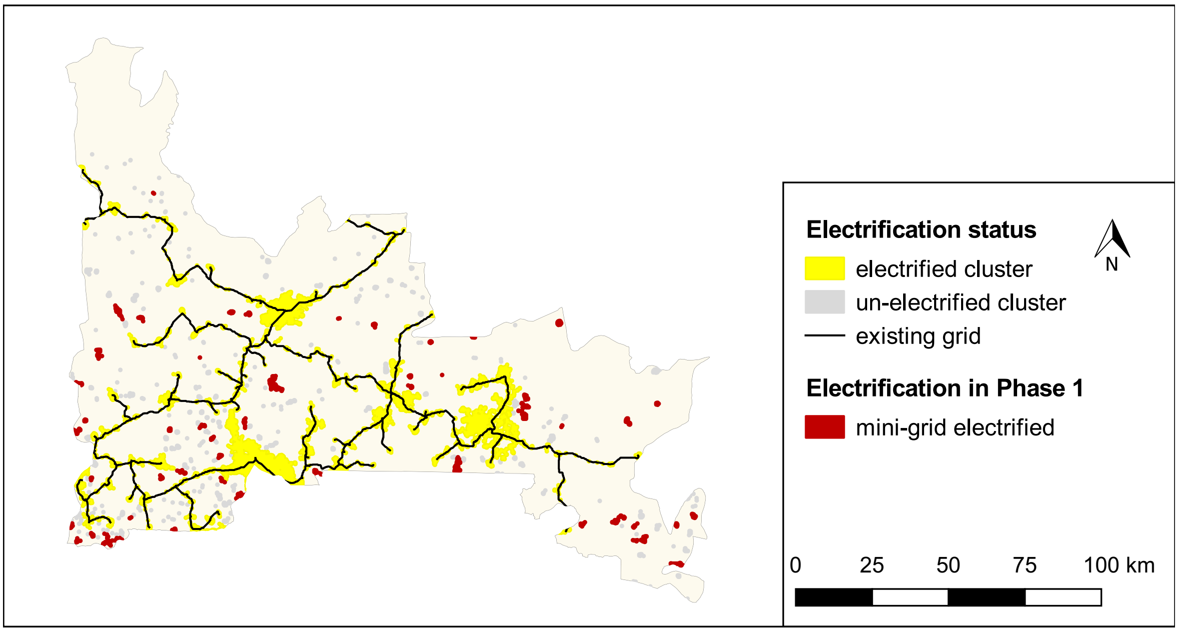


Figure 6.16.: Map of suggested electrification phase 1 for Ogun with mini-grid electrification. Author's own map, data resulting from the applied methods and described input data.

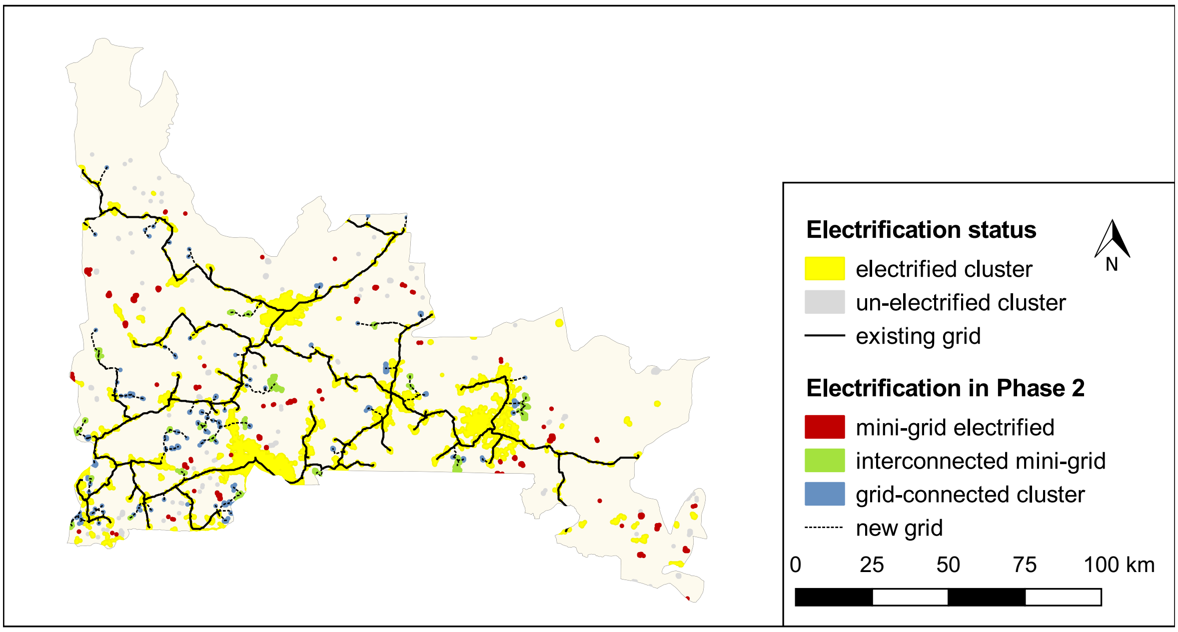


Figure 6.17.: Map of suggested electrification phase 2 for Ogun with mini-grid electrification, grid development and interconnected mini-grids. Author's own map, data resulting from the applied methods and described input data.

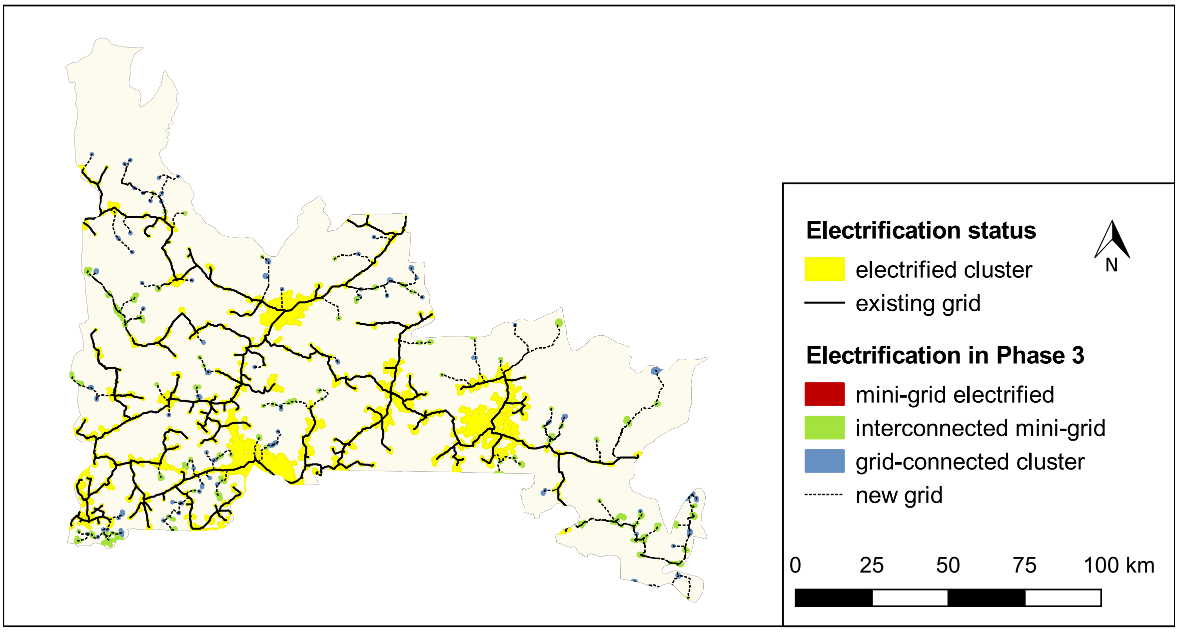


Figure 6.18.: Map of suggested electrification phase 3 for Ogun with mini-grid electrification, grid development and interconnected mini-grids. Author's own map, data resulting from the applied methods and described input data.

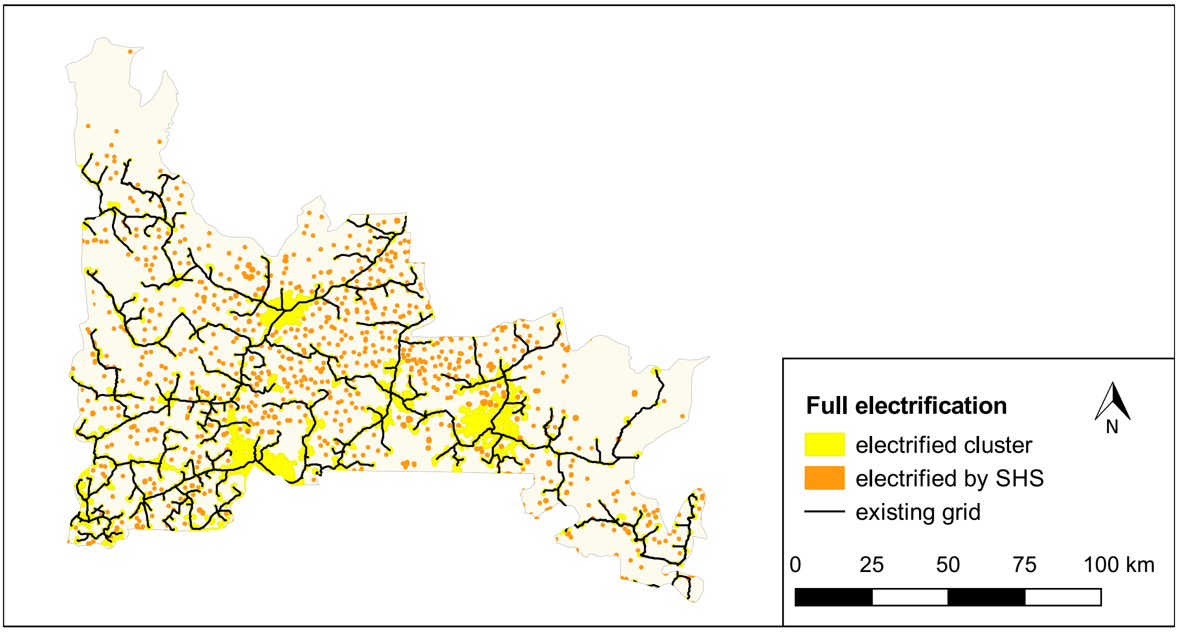


Figure 6.19.: Map of suggested full electrification layout for Ogun with mini-grids, grid extension and SHS. Author's own map, data resulting from the applied methods and described input data.

6.2.4. Plateau

Plateau state's electrification begins with improving the existing grid infrastructure in terms of generation capacity addition and grid densification for the unconnected households within grid-connected clusters. Of the 189 grid-connected clusters only 26 are supplied, requiring an increase to the supply of further 163 locations. At the same time, all across the federal state, mini-grid electrification is suggested for 109 clusters in phase 1, supplying more than half a million people with electricity (Fig. 6.20).

Phase 2 in Plateau is characterized by the first grid extension measures, suggesting 62 new grid branches to connect 149 unconnected clusters and interconnecting 29 previously electrified mini-grid clusters (Fig 6.21). This requires 625 kilometers of new grid lines, with the longest branch being 92 kilometers. In this phase 108 mini-grids sites are suggested for development, supplying more than 230,000 people.

The electrification phase 3 is dominated by grid extension (Fig. 6.22), where 175 unelectrified sites and 182 mini-grids are becoming interconnected to the grid by 65 branches with a total distance of 2,262 kilometers. The longest single branch in Plateau reaches 280 kilometer. In Plateau, 3 villages are suggested to be electrified by mini-grids, relating to a supply of almost 4,000 people. The developed mini-grids in all phases have an average share of 69 % renewable energy-based electricity generation, with a minimum of 45 % and a maximum of 93 %.

The full electrification layout for Plateau shows that decentralized small-scale solutions such as SHS are important. In the east of the state, the population density is low – therefore, this area is not covered by large village clusters, settlements are thus suggested being supplied by SHSs (Fig. 6.23). In Plateau, the largest distance from the existing grid to a village is 73 km, whereas in average, the villages are located in a distance of 15 km to the next grid infrastructure.

Investments of approximately 370 million USD for medium voltage and distribution grid infrastructure, mini-grids, and small-scale systems are required.

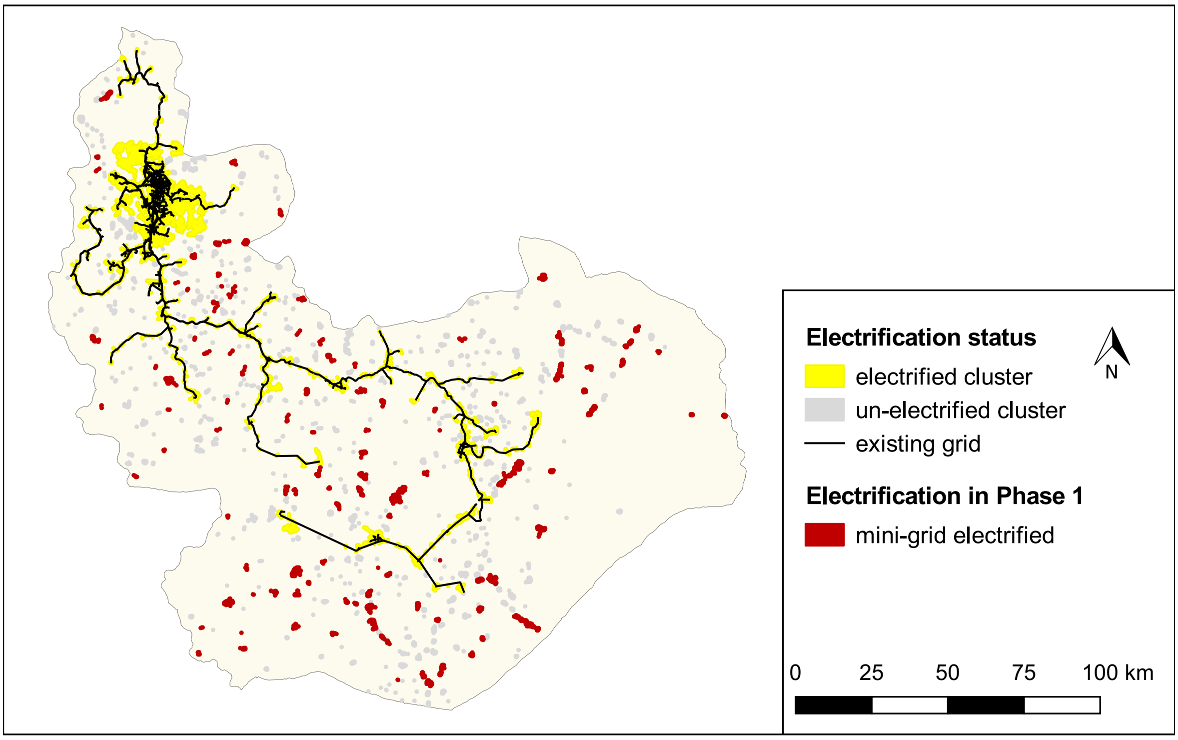


Figure 6.20.: Map of suggested electrification phase 1 for Plateau with mini-grid electrification. Author's own map, data resulting from the applied methods and described input data.

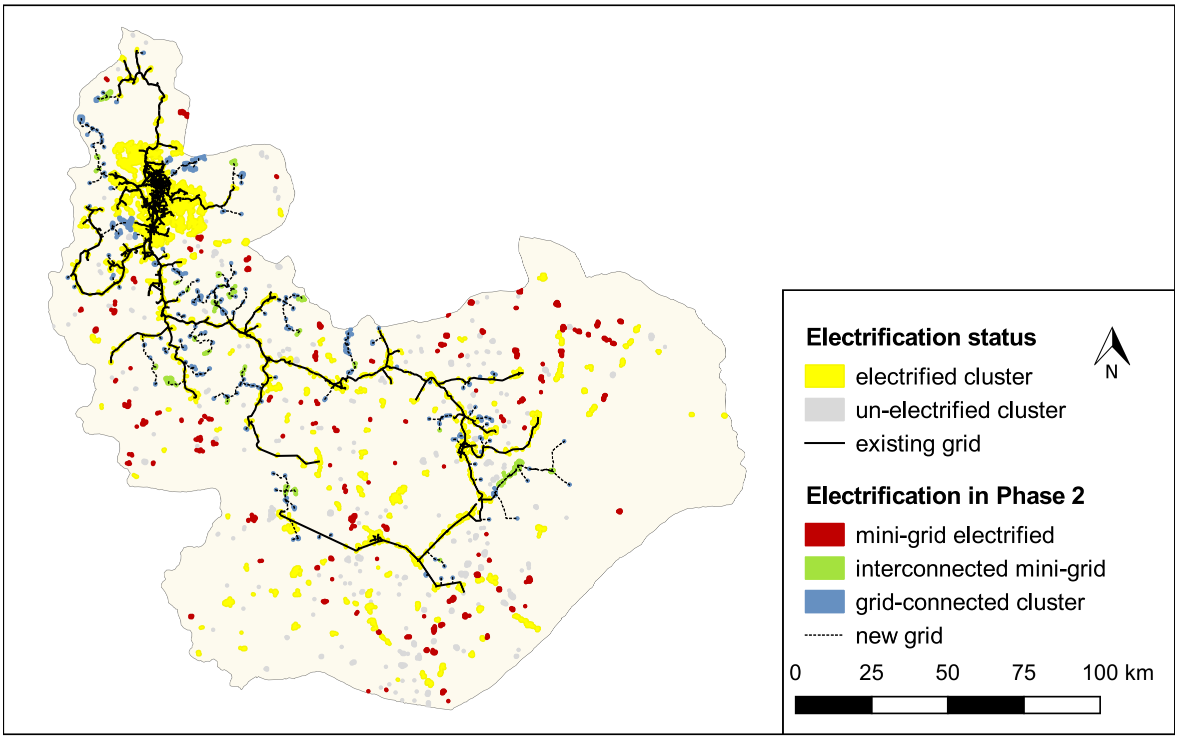


Figure 6.21.: Map of suggested electrification phase 2 for Plateau with mini-grid electrification, grid development and interconnected mini-grids. Author's own map, data resulting from the applied methods and described input data.

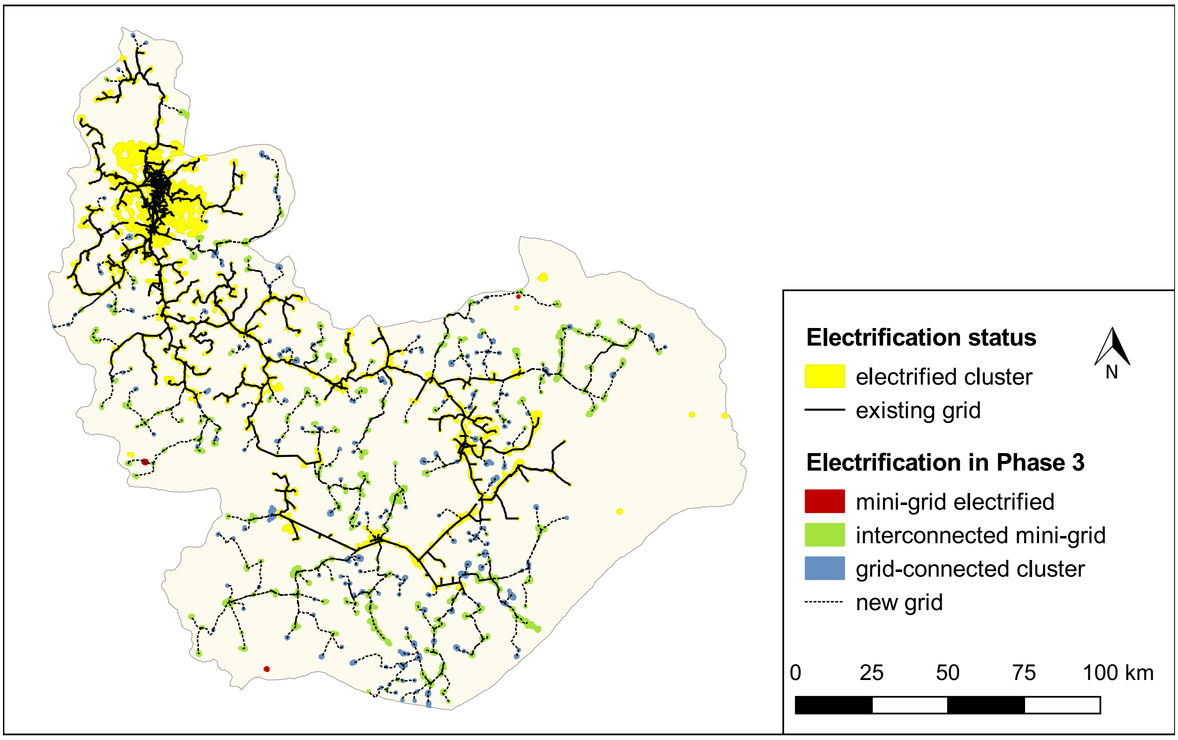


Figure 6.22.: Map of suggested electrification phase 3 for Plateau with mini-grid electrification, grid development and interconnected mini-grids. Author's own map, data resulting from the applied methods and described input data.

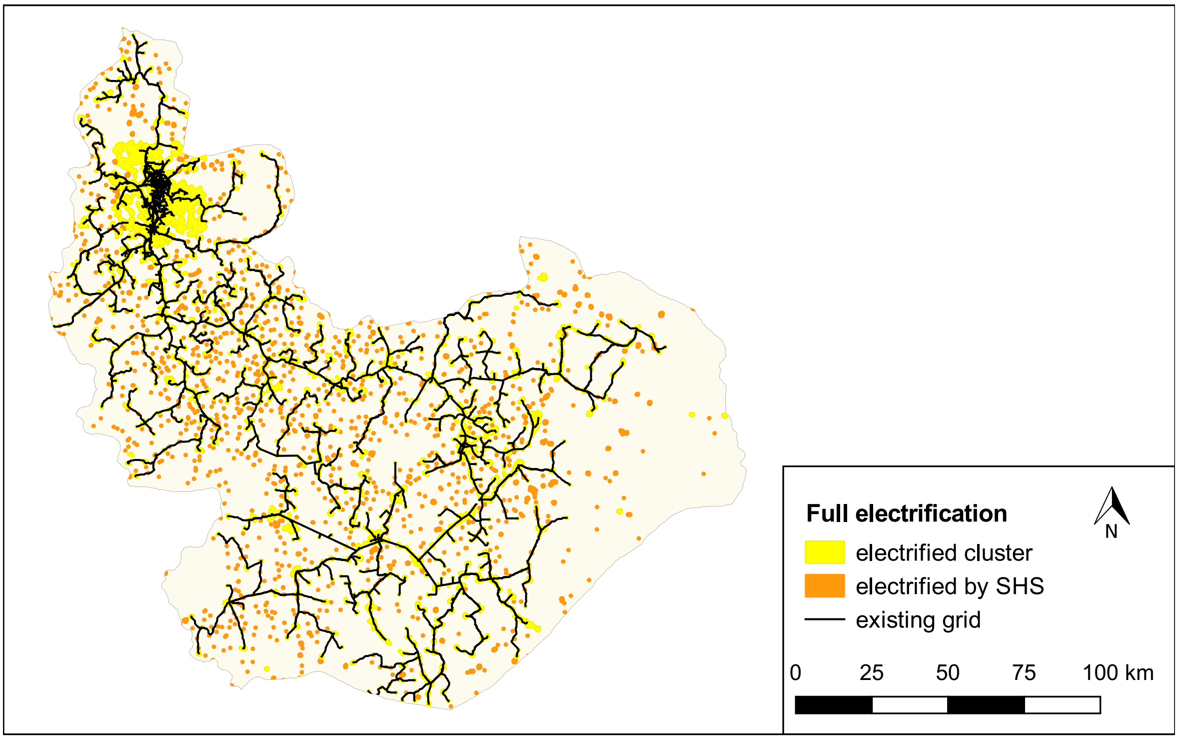


Figure 6.23.: Map of suggested full electrification layout for Plateau with mini-grids, grid extension and SHS. Author's own map, data resulting from the applied methods and described input data.

6.2.5. Sokoto

Sokoto's first electrification phase is likewise dominated by improving the existing grid to eliminate suppressed demand and incomplete household electrification in pre-established grid connected-clusters (Fig. 6.24). Of 255 grid-connected clusters, only 25 are supplied sufficiently, requiring additional capacity for 230 locations. Especially in Sokoto, this is challenging because majority of the electricity generation assets are located in the more industrialized South of the country, leaving the North with the largest infrastructural challenges. In addition to the improvements of the grid infrastructure, 109 mini-grids are suggested in phase 1, supplying 690,000 people in total.

Within phase 2, grid-extension is started in Sokoto. 145 clusters are directly connected to the grid while 54 mini-grids are becoming interconnected during the process (Fig. 6.25). 76 independent grid branches with a total length of 720 kilometers are required for that. The largest grid extension distance during this phase is 75 km. Additionally, 108 new mini-grids are suggested at this point, providing access to almost 250,000 people.

Phase 3 completes the electrification effort for reaching full electrification. This is achieved by 78 grid branches connecting 177 clusters with 2,075 kilometers of new grid lines, and interconnecting 156 mini-grids (Fig. 6.26) along the way. The longest branch sums up to 178 kilometers. In this phase, 4 additional mini-grids sites are identified, leading to an additional supply of more than 4,000 people in Sokoto. The developed mini-grids in all phases have the highest renewable energy shares compared to the other federal states, with an average share of 72 % renewable energy-based electricity generation, with a minimum of 46 % and a maximum of 97 %.

The full electrification layout shows that still a few parts of the state will still not be connected to the grid and decentralized electricity generation is of importance (Fig. 6.27). In Sokoto, the village with the largest distance to the grid is located 74 km away from the grid, whereas the average distance of locations in this federal state is circa 12 km from the existing grid.

Investments of approximately 351 million USD for medium voltage and low voltage distribution infrastructure, mini-grids, and small-scale systems are required.

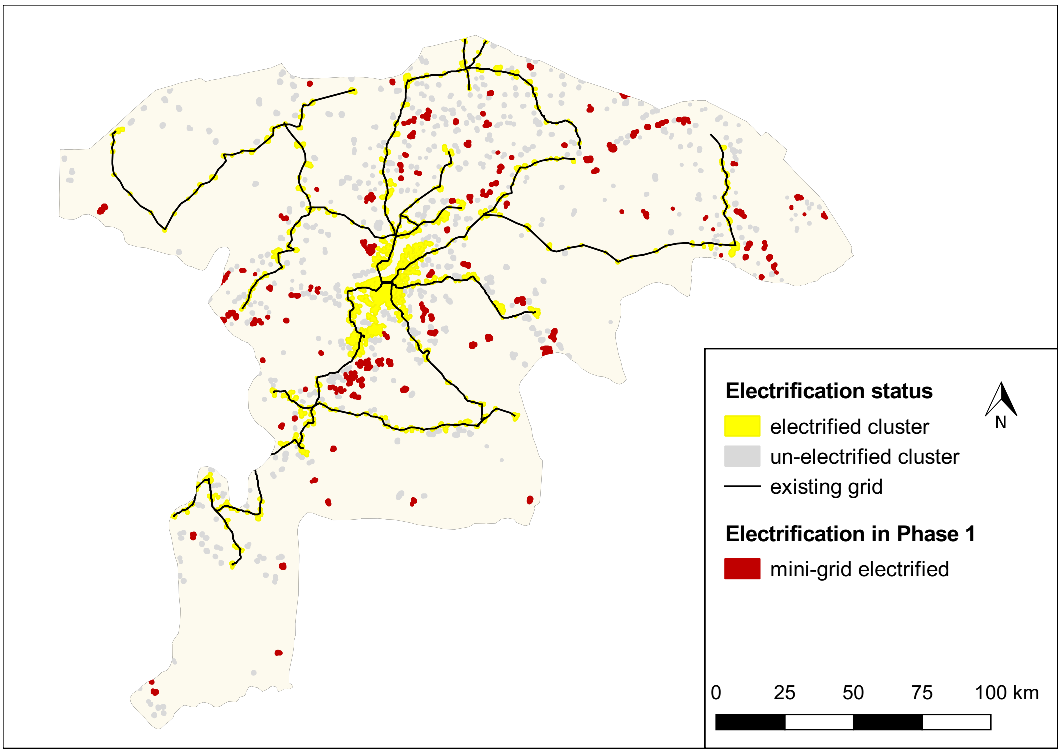


Figure 6.24.: Map of suggested electrification phase 1 for Sokoto with mini-grid electrification. Author's own map, data resulting from the applied methods and described input data.

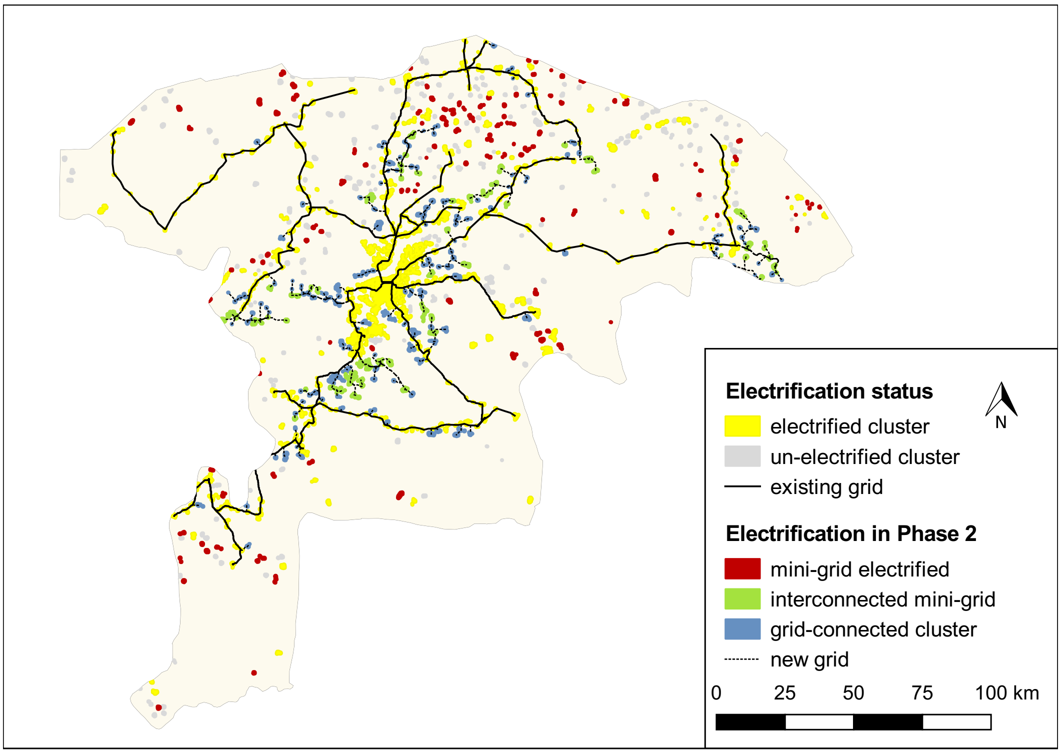


Figure 6.25.: Map of suggested electrification phase 2 for Sokoto with mini-grid electrification, grid development and interconnected mini-grids. Author's own map, data resulting from the applied methods and described input data.

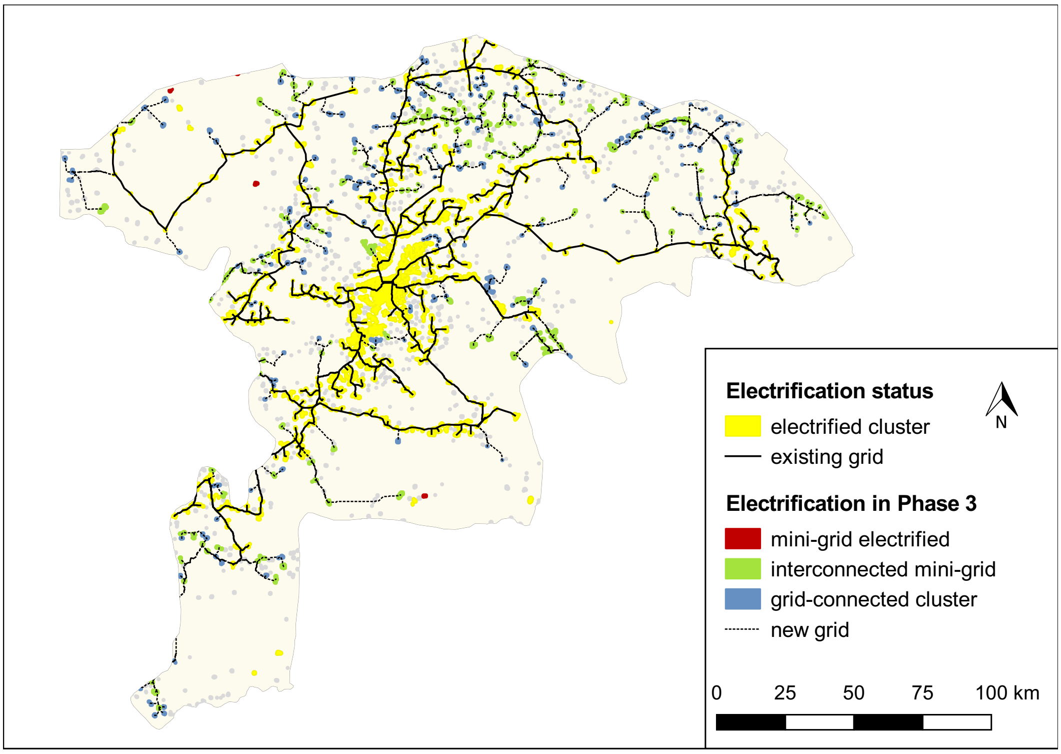


Figure 6.26.: Map of suggested electrification phase 3 for Sokoto with mini-grid electrification, grid development and interconnected mini-grids. Author's own map, data resulting from the applied methods and described input data.

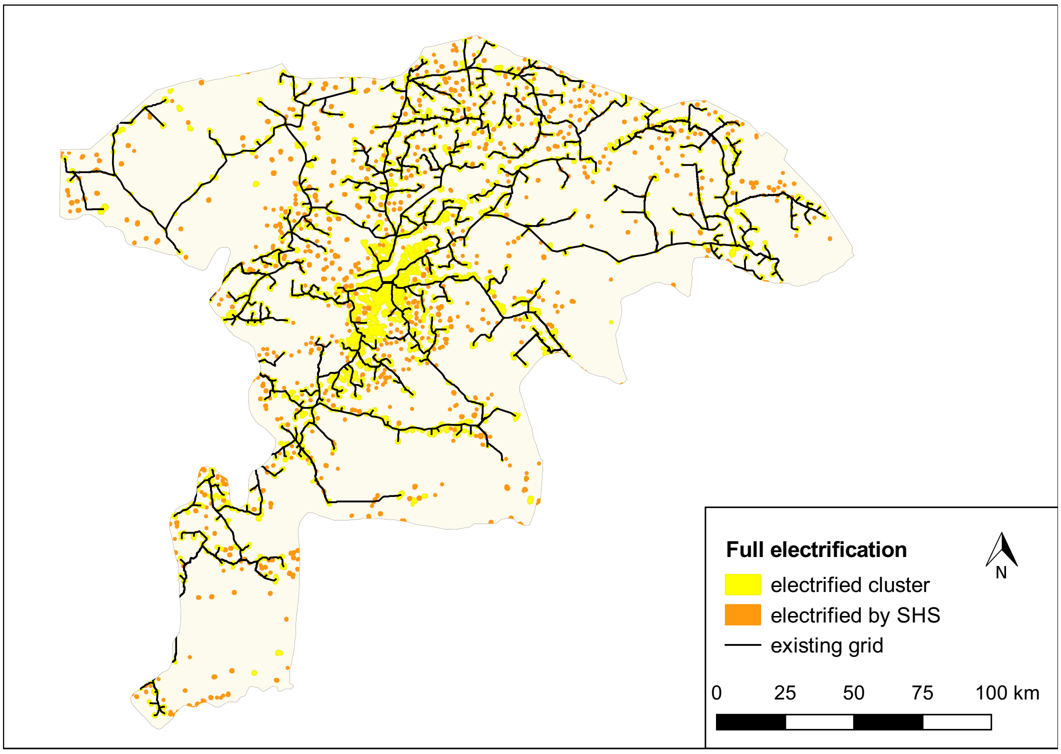


Figure 6.27.: Map of suggested full electrification layout for Sokoto with mini-grids, grid extension and SHS. Author's own map, data resulting from the applied methods and described input data.

6.2.6. Comparative results of the five states

Modeling the electrification options in the five different states allows for a comparison of the results between the five states. It is clearly observable that states with a higher initial grid coverage and a smaller overall size are most dominantly electrified via grid connection. In contrast, in larger states such as Sokoto and Niger, which are characterized by lower population densities and less initial grid infrastructure, off-grid solutions such as mini-grids and solar home systems are more important to achieve full electrification. During the first electrification phase (Tab. 6.4) mini-grid development is the most prominent electrification options in Niger, Ogun, Plateau and Sokoto, electrifying more than 2.4 million people in all five states. Only in Cross River are more people designated to grid densification than to mini-grid electrification during that phase. In all five states, approximately 2 million people are suggested to be supplied via grid densification. Solar home systems solutions are assigned to almost one million people in the five states. For supplying these electrified locations, in all five states more than 300 MW of generation capacity is required.

In phase 2 (Tab. 6.5) grid extension becomes the most dominant electrification scheme in the five states reaching more than 2.6 million people, most of them living in Sokoto. Of these, 1.3 million people are supplied by mini-grids in phase 1 and will become interconnected with the grid. Also, in terms of on-grid capacity development, interconnected mini-grids account for 87 MW of capacity for the five states, requiring an additional generation capacity of circa 230 MW. New mini-grid development falls back to approximately 0.9 million people in the five states, while SHS still supply up to one million people.

Table 6.4.: Phase-wise electrification results of all five states: people electrified by the different options and respective capacity requirements in phase 1.

Phase I	**Grid densification**		**Mini-grid**		**SHS**	
Unit	# people	MW	# people	MW	# people	MW
Cross River	552,000	75	307,000	30	88,000	1.3
Niger	76,000	6	583,000	33	348,000	3
Ogun	237,000	20	323,000	18	149,000	1.2
Plateau	481,000	43	517,000	28	246,000	2.3
Sokoto	606,000	87	690,000	39	156,000	1.6
Total	1,952,000	156	2,420,000	148	987,000	9

Table 6.5.: Phase-wise electrification results of all five states: people electrified by the different options and respective capacity requirements in phase 2.

Phase 2	**Grid extension**		**Int. mini-grids**		**Mini-grid**		**SHS**	
Unit	# people	MW	# people	MW	# people	MW	# people	MW
Cross River	469,000	58	233,000	22	100,000	9	88,000	1,3
Niger	623,000	48	369,000	23	208,000	10	348,000	3
Ogun	311,000	24	153,000	9	109,000	6	149,000	1.2
Plateau	464,000	34	165,000	9	232,000	12	246,000	2.3
Sokoto	789,000	65	392,000	24	250,000	13	156,000	1.6
Total	2,656,000	229	1,312,000	87	899,000	50	987,000	8

Table 6.6.: Phase-wise electrification results of all five states: people electrified by the different options and respective capacity requirements in phase 3.

Phase 3	**Grid extension**		**Int. mini-grids**		**Mini-grids**		**SHS**	
Unit	# people	MW	# people	MW	# people	MW	# people	MW
Cross River	255,000	32	174,000	17	0	0	90,000	1.3
Niger	610,000	41	378,000	18	15,000	0.7	386,000	3.0
Ogun	386,000	27	297,000	15	0	0	150,000	1.3
Plateau	865,000	63	576,000	31	4,000	0.2	250,000	2.3
Sokoto	835,000	63	536,000	28	4,000	0.2	213,000	2.2
Total	2,951,000	226	1,961,000	109	23,000	1	1,089,000	10

Table 6.7.: Progress towards full electrification in each of the five states.

			Phase 1		**Phase 2**		**Phase 3**	
	Unit	Initial el. rate	total	increase	total	increase	total	increase
Cross River	%	57	84	27	95	11	100	5
Niger	%	52	72	20	88	16	100	12
Ogun	%	72	86	14	95	9	100	5
Plateau	%	37	67	30	87	20	100	13
Sokoto	%	39	71	32	89	18	100	11
Average	%	51	76	25	91	15	100	9

The last phase towards full electrification (Tab. 6.6) is again dominated by grid extension and the interconnection of mini-grids. In Cross River and Ogun, no additional mini-grids are suggested since the grid coverage reached all large population clusters, excluding the small clusters with a low demand. Also, in the other three federal states, mini-grids are of subordinate importance. In particular the larger states, characterized by lower initial electrification rates (Niger, Plateau and Sokoto) require large-scale grid extension roll-out to be continued to achieve full electrification in phase 3.

The electrification effort towards full electrification varies across the five states, depending on the initial electrification rates (Tab. 6.7). Common in all states is the highest increase in electrification during phase 1. This correlates with the availability of large unelectrified village clusters nearby existing infrastructures, which can be interpreted as low-hanging fruits for an economic electrification. In the following phases, the efforts for electrification become more challenging, since the locations will be more remote and less densely populated, decreasing the number of people reached by either grid extension or mini-grids. Cross River and Ogun already achieve electrification rates of 95 % after phase 2.

6.2.7. Scenario analysis: Target-based modeling: Fixed decision criteria

In contrast to the calculation of the least cost electrification option, it is also possible to use the methodology to simulate certain electrification scenarios with fixed target figures. Those scenarios can, unlike the other cases, aim at fulfilling specific targets (e.g political goals), instead of merely aiming at minimizing the total costs of electrification.

Through intensive discussions with the rural electrification working groups, two major de-

Table 6.8.: Resulting distribution of the three different electrification options.

Option	Number of locations	Population
Grid extension	1,340	1,509,000
Mini-grid	132	330,000
Stand-alone	362	144,000

cision criteria are identified, which have been also used for an increase of electrification historically : The first one sets a goal to connect all major towns to the central power grid, so all locations with at least 5,000 people shall be considered for grid extension (Fig. 6.28). It is argued that grid electricity may enhance economic development through productive use of electricity, which would require not only a connection to the grid but also sufficient generation capacity in the grid. The second decision criteria is of spatial nature: grid connection shall be suggested to all locations within a ten kilometer radius of the existing grid network (Fig. 6.29). This process can be described as grid densification, as most of the additional grid lines will be low voltage distribution networks.

Furthermore, mini-grids can also be constructed in such a way that an interconnection to a larger grid infrastructure is possible. Those mini-grids can run in an independent island mode if the grid is not operational and can feed excess energy into the main grid if surplus electricity is available.

If those targets are applied to Plateau state, results are partly similar to the least cost option with an increased share of mini-grids. This is due to the fact in that particular example, the option of interconnected mini-grids is not included. It may be added to improve the state's power system. The similarity of the results between the target based and the least-cost based electrification approach shows that the targets, which are mainly defined by political stakeholders, consider costs of the different options appropriately. Connecting many people over short distances to the central grid remains a cost-efficient strategy (Fig. 6.30).

In the target based electrification plan, further future grid extension is not yet considered, and hence their attractiveness for each of the electrification is not assessed which may lead to missed opportunities. Also, since the grid extension is not structured in branches, the sizing does not consider future options as no foresight strategy is considered.

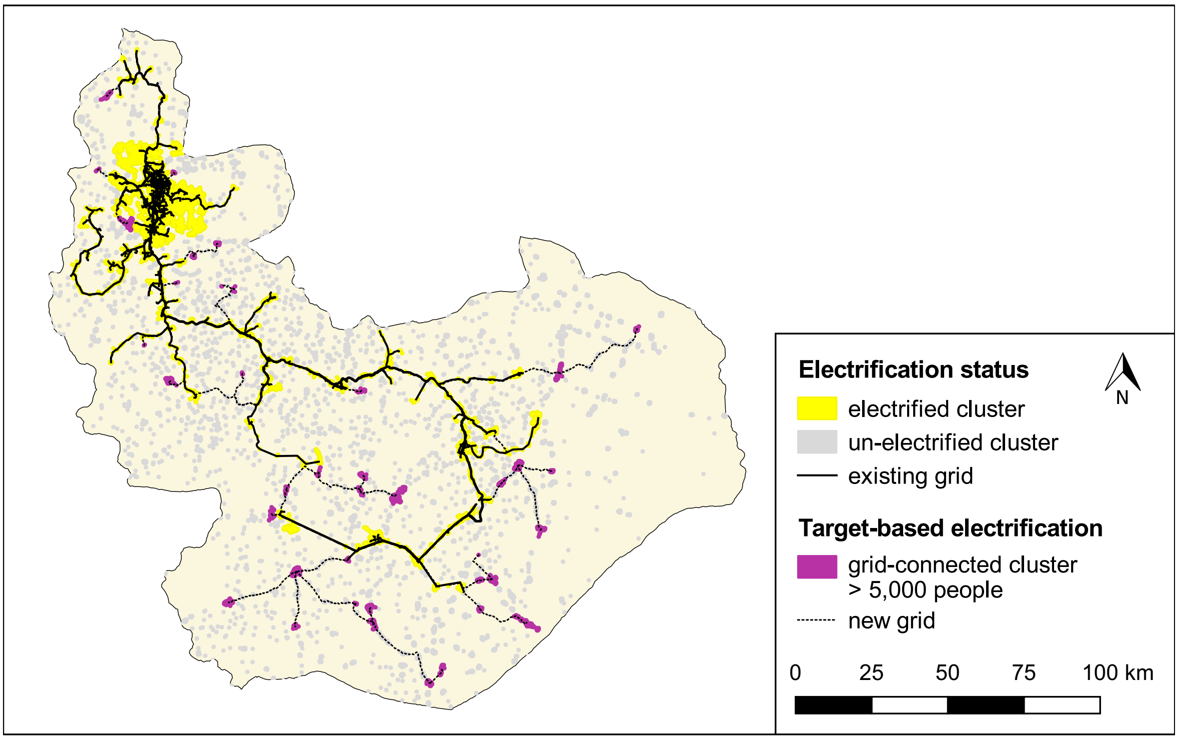


Figure 6.28.: Map of the composition of the target-based electrification plan: Optimized grid-connection to the towns with 5,000 people or more. Author's own map, data resulting from the applied methods and described input data.

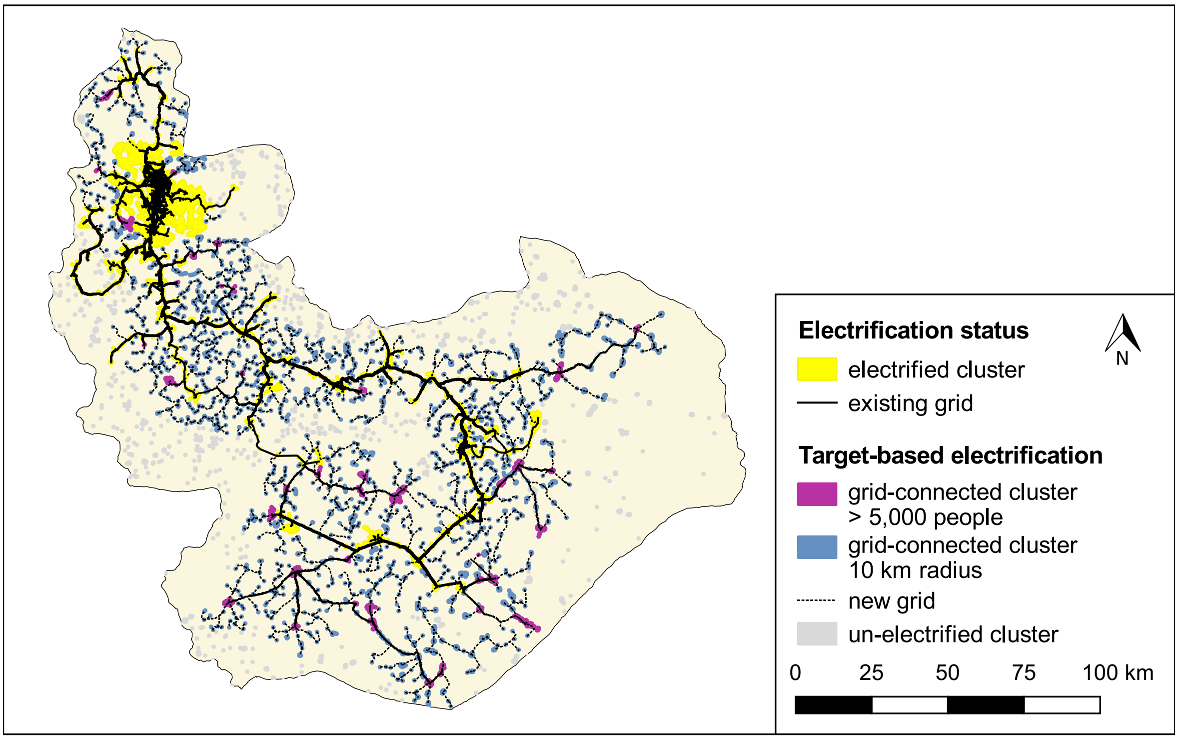


Figure 6.29.: Map of the composition of the target-based electrification plan: Optimized grid-connection to the towns in a 10 km radius around existing grid networks. Author's own map, data resulting from the applied methods and described input data.

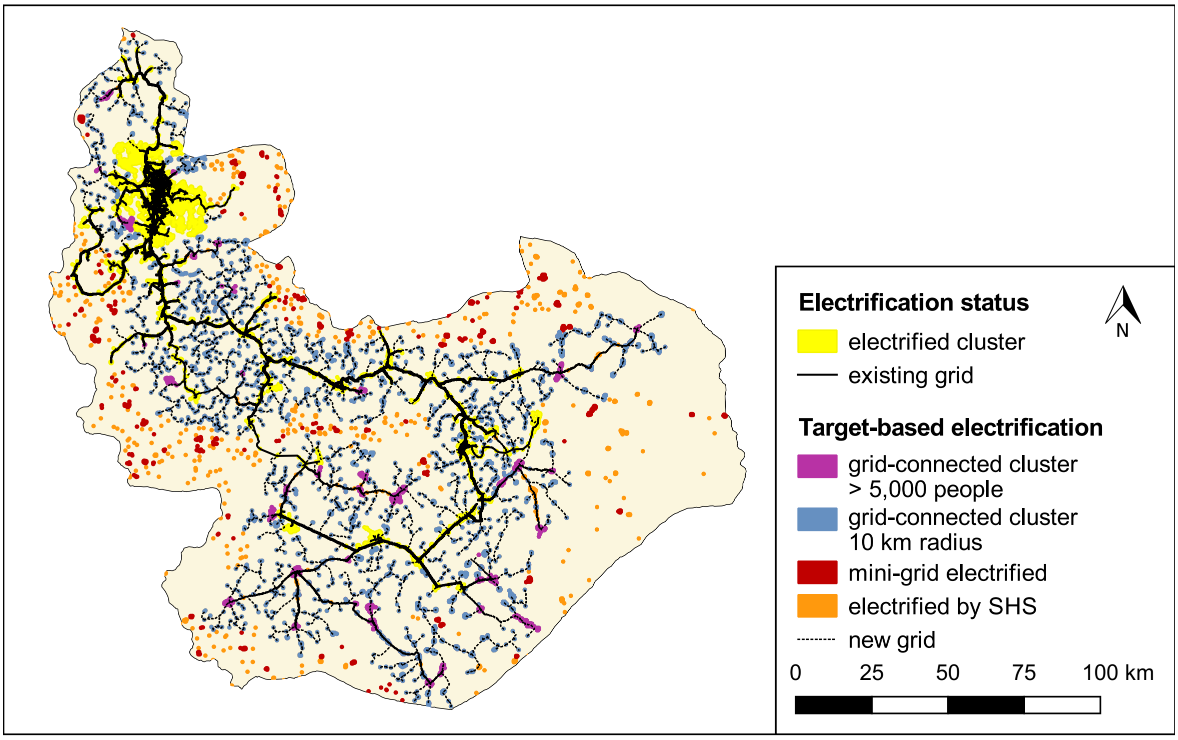


Figure 6.30.: Map of the electrification plan for Plateau reflecting based on defined political targets. Author's own map, data resulting from the applied methods and described input data.

6.3. Impacts of rural electrification on greenhouse gas emissions in Nigeria

Since energy systems require financial sustainability, this premise creates the challenge to find the most economic option, whereas the analysis also leads to the conclusion that the most economic options might not be the most ecological option today. Energy systems are not only required to be cost effective, but at the same time environmental and climate-related concerns are becoming of paramount importance. In consequence, the analysis of the related costs and environmental impacts becomes a requirement for energy system evaluation.

Due to the significance of energy for supplying basic needs, people use the technologies and options which are available for them, financially and practically. If no electricity is available, people will use kerosene or candles for lighting and diesel generators for productive use, depending on availability. Environmental concerns become a second priority due to the lack of alternative, cleaner options. Renewable energy sources have the potential to substitute greenhouse gas emitting energy technologies such as kerosene lamps and diesel generators. Kerosene lamps are a major emitter for black carbon, which also has a strong impact on climate change (Lam, Chen, Weyant, Venkataraman, Sadavarte, Johnson, Smith, Brem, Arineitwe, Ellis, & Bond, 2012).

With regard to Nigeria's INDCs, the official statement concerning specific national targets to combat climate change, infrastructure development and electrification planning need to be in line with defined climate-related objectives.

The resulting electrification options for the supply of the unelectrified locations in the five federal states lead to different forms of GHG emissions: mini-grids are composed of diesel generation, PV and battery storage and hence, CO_2 emission occur by burning diesel fuel in these mini-grids. For the locations which are assigned to grid extension, respective emissions are generated in the central energy system, as a higher generation capacity is required to cover for any additional demand. The mini-grids which are interconnected to the grid at a certain stage may become less energy intensive by using the grid electricity instead of the diesel-powered generation for peak and back-up electricity supply.

Table 6.9 shows that in total, the operation of the suggested electrification scheme leads to annual CO_2 emissions of more than 320 kt CO_2. The largest share of emissions are generated in the federal states with the lowest electrification rates, since both options, mini-grids and grid extension, lead to GHG emissions; as the optimized solutions are not supplied with solely 100 % renewable energy sources. As the most dominant electrification option will be grid extension, the focus is shifted towards the national grid emission factor which is estimated at around 0.63 kgCO_2/kWh. About 60 % of the GHG emissions result from grid-connected electricity supply. To reduce emissions in that case more electricity generation with renewable energy sources is needed in the central supply system. SHS supplied households do not emit CO_2 as no fossil fuel is required.

Three different emission scenarios are assessed in order to better understand electrification planning measures (Tab. 6.10): the first scenario assumes that interconnected mini-grids will be fully integrated into the centralized system, which allows the diesel generators to be switched off and the additional power required to be drawn from the grid. Under the given grid emission factor, the electricity from the grid is less CO_2 intensive than that produced by diesel generators, and thus leads to a reduction in overall CO_2 emissions. The second scenario considers the case that the mini-grid, instead of its average share of almost 70% renewable energies, would be operated as pure diesel grids. This shows that CO_2 emissions will increase by 264 kt CO_2 without the PV component. For the third scenario, it is assumed that no mini-grids will be built, instead electrification will take place solely through network expansion. Under the given electricity mix in the grid, this would mean a CO_2 increase of 155 kt $CO_2$for all five federal states.

Analyses show that if access to electricity is improved with hybrid mini-grids, emissions are cut compared to pure diesel grid - nonetheless the impact of the fossil fuel part of the mini-grids creates emissions. Therefore, the overall aim should be to increase the share of renewable energy for electric power generation as much as possible, on- and off-grid.

Table 6.9.: Resulting CO_2 emissions from the suggested electrification scenario.

	Hybrid mini-grids		**Grid connected sites**		**SHS**	**Total**
	kt CO_2	% of total	kt CO_2	% of total	kt CO_2	kt CO_2
Cross River	26	39.3	40	60.7	0	67
Niger	29	43.8	37	56.2	0	67
Ogun	18	46.4	21	53.6	0	39
Plateau	25	38.3	40	61.7	0	65
Sokoto	29	35.0	54	65.0	0	84
Total/Average	128	39.8	194	60.2	0	322

Table 6.10.: Additional CO_2 emission scenarios.

	Intercon. mini-grids		**Pure diesel mini-grids**		**Pure grid connection**	
	kt CO_2	Savings	kt CO_2	Increase	kt CO_2	Increase
Cross River	59	7	118	51	96	30
Niger	59	8	122	55	99	32
Ogun	34	5	70	31	57	17
Plateau	59	7	120	55	98	33
Sokoto	76	8	155	71	127	43
Total	287	35	585	264	477	155

6.4. Dissemination of the results - reaching visibility

In order to maximize the impact of the electrification modeling, the aim is to reach a large user group or as many interested stakeholders as possible. Those stakeholders may have academic backgrounds, be involved into the private sector, have governmental relations or be affected by local electrification measures. To make the results available to all of these groups, a dissemination strategy with an online web-mapping tool is developed where the results of the modeling are visualized online (Fig. 6.31 and Fig. 6.32). In such a framework, it is possible to interactively zoom into regions of interest and query attributes of villages. Attributes pop-up by clicking on the chosen village cluster and contain information such as population, demand for electricity, as well as suggested electrification options. Thereby a comparison of different sites and an understanding for the situation in a certain region can be reached. The three-phased electrification modeling towards full electrification is suggested as one scenario which can open up a discussion on alternative pathways. In addition to the three-phased electrification scenario, there is also and exploration mode where filters can be set to criteria of interest, e.g. distance to the existing grid network or minimum number of people. This allows stakeholders to identify the most interesting location in regard to different interest – for example sites which are specifically interesting for mini-grid development because of their large distance to the grid and sufficient customer market or sites which are very small for SHS distribution. Datasets can also be downloaded from this platform, either as spreadsheets containing all the information per village or in geospatial formats to allow further use and analysis in GIS.

Furthermore, an online tool also allows to share the information easily in a digitized way,

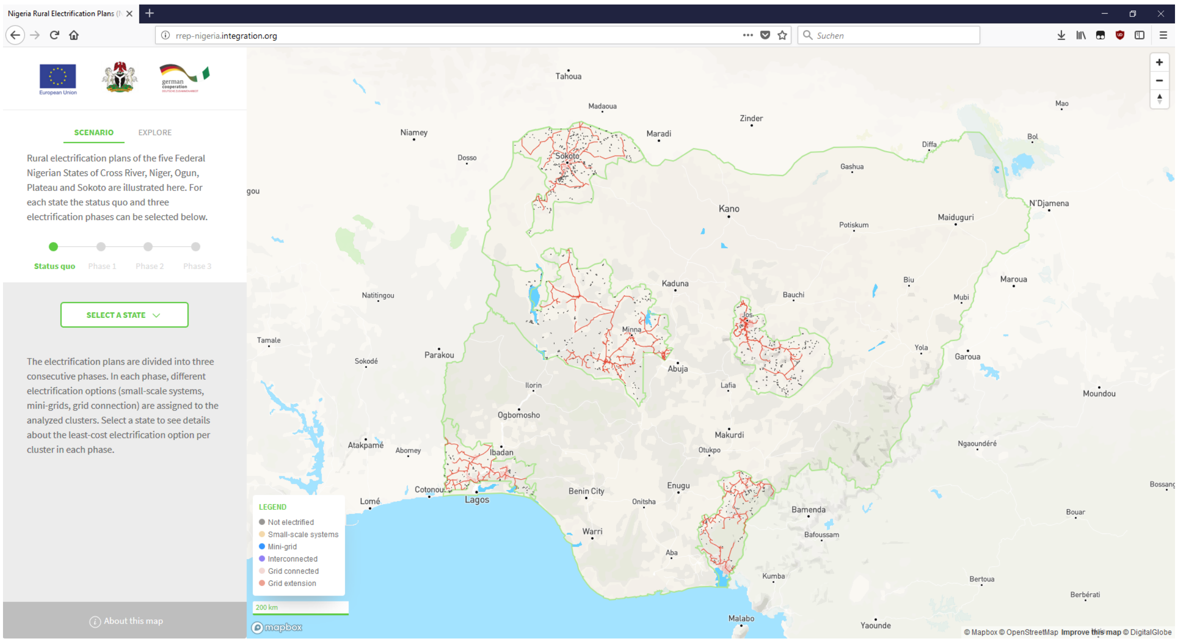


Figure 6.31.: Online visualization of the modeling results. Image source: http://rrep-nigeria.integration.org/ (accessed January, 23, 2018).

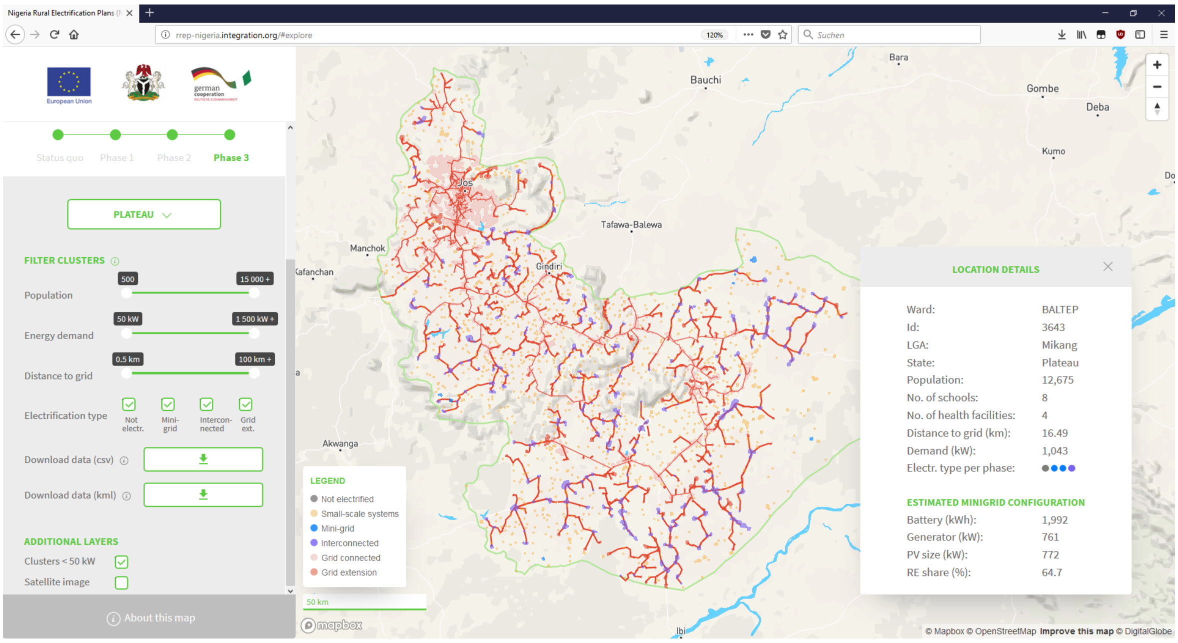


Figure 6.32.: Detailed, interactive interface allowing individual exploration of the modeling results, including the analysis of village level characteristics. A download function makes the results available in tabular format as well as geo-referenced data formats for further use in GIS. Image source: http://rrep-nigeria.integration.org/ (accessed January, 23, 2018).

without the requirement of map printing and physical transport to the interested party. This saves costs and time and makes the availability and accessibility for the recipients simple. The web-mapping-tool can be accessed here: http://rrep-nigeria.integration.org/ (accessed January, 23, 2018).

7. Discussion

This chapter discusses the results in order to address and answer the research questions formulated in Chapter 1.3. In doing so, an attempt is made to examine the results in the context of the theoretical concepts presented in Chapter 2. Furthermore, it is discussed how the implementation of the actual electrification can be initiated on the basis of the presented electrification planning. Limitations of the methodology and special challenges for Nigeria are highlighted. Subsequently, an outlook is given to provide perspectives on how electrification planning can be further enhanced to enable sustainable future electrification in Nigeria.

7.1. Energy access, renewable energy and climate change

With the size and population of Nigeria, this country's development can have significant impacts on the African economy, the market for decentralized energy systems, but also on greenhouse gas emissions.

With the ambitious national and international objectives declared in the SDGs, specifically on energy, and the temporal scale of reaching full access to electricity by 2030, the transformative process of increasing the access to electricity on the one hand and increasing the share of renewable energy on the other hand, is a massive task. Spatially explicit modeling of the status quo to understand the location-specific requirements for electrification is the starting point to ultimately create a specific spatial electrification planning tool, which can then subsequently form the basis for concrete actions.

The first research question poses the question of how non-electrified regions, which are unconnected to any grid, can be provided with electricity. The detailed modeling of electrification options results in a three-phased plan, considering a combination of grid extension of the centralized energy system to unconnected locations, mini-grid development, and small-scale solutions. Especially in the beginning of the electrification process, no grid extension can be recommended, as grid infrastructures need to be refurbished and additional generation capacities are required, since the available generation capacity is not adequate to supply the already connected locations sufficiently. To still allow for electrification in the first phase, PV-battery-diesel mini-grids are suggested in very remote locations, as well as in socio-economic priority clusters. In parallel, sparsely populated regions are suggested to be supplied by stand-alone SHS. With the progressing of the phases, grid extension measures are in the focus of attention – once the grid infrastructure is fully functional and generation capacity is added to the system, this measure is the most economic solution for many sites, even under the consideration of geographical characteristics such as slope, land cover, areas of avoidance

(e.g. protected areas), and existing infrastructure. The first grid extension measures are very efficient, reaching more people per km of grid line than the subsequent expansions, since in the second phase, the villages are located within a larger distance, requiring a longer grid extension to reach the same number of people. Previously developed mini-grid sites can become interconnected along the way. This has three benefits: first, available excess electricity can be fed into the grid, second, the diesel generator can reduce its operation to a backup function, minimizing the climate impacts of electricity generation, and third, the location still has an independent power supply opportunity in case the grid system is not operational. Furthermore, the modeling shows that cost-optimized mini-grids in the five Nigerian federal states are characterized by a high share of renewable energy based electricity generation in the system, on average for on- and off-grid supply at around 30 %, for the decentralized solutions approximately 70 % renewable energy share in the mini-grids and 100 % for the stand-alone solutions. These high shares of renewable energy in the decentralized systems also create independence of fuel supply, which may be influenced by shortages on the market, price fluctuations, and transport costs. If the suggested measures are implemented, it would have a significant impact of the national share of renewable energy in Nigeria, potentially stimulating local markets for PV technology and hybrid system development. The role of renewable energy is important for mitigating greenhouse gas emissions in both, decentralized and central power supply structures. The key finding here is that the total impact of electrification on greenhouse gas emissions varies in regard to the different supply option and needs different action to tackle those: for instance – if the decentralized supply option is suggested as electrification option of choice for a certain region, policy support is needed in order to make renewable-based mini-grids more attractive than diesel-based systems.
For the grid supply it is also decisive to include as much renewable energy as possible in the generation portfolio – but policies to achieve that are different compared to the decentralized options. Therefore, different measures are required, such as reliable feed-in tariffs for renewable energy generation, ambitious national goals for the development of the renewable energy sector, which can be realized by tendering or bidding schemes for renewable energy projects. The inclusion of significant amounts of volatile renewable energy sources requires stable, well-functioning powergrids – however, research has shown that the outdated grid infrastructure is in urgent need of replacements and repairs, before an ambitious grid extension is planned.
Even countries with a significant renewable energy share, such as Germany, need to consider more decentralized approaches for reaching its climate and energy goals (Kemfert, 2017). Considering that Germany is characterized by a well functioning, historically centralized energy system, that finding should support countries with not yet sufficient energy infrastructure to allow for novel structures which have not previously been rolled out in industrialized countries due to different technology options at that time. Clean technologies are required to account for SDG#7b and SDG#13 in particular. For the on-grid energy mix Nigeria could further develop its hydro power resources in the South and expand its efforts of solar based technologies in large scale power plants to increase to share of renewable energy. The second research question addresses the advantages and disadvantages of decentralized

and centralized electricity supply. Findings from the modeling show that much more people can be reached by a single grid extension measure, e.g. one new grid branch of an existing grid which supplies several village clusters, compared to a mini-grid, which is always an independent solution for each individual site. Grid-supplied sites can easier accommodate to an increase in demand, mini-grids are designed for a specific demand. Mini-grids are therefore limited in their additional supply capacities, while people in a grid-connected village cluster depend on the supply of the utility company. For external reason, the supply might be restricted, e.g. because of limited capacities or technical difficulties, and the customer can only wait passively for the utility to resolve this situation.

In the space-theoretical context, decentralized mini-grids have the advantage of being able to be developed independently of developments in the environment. An extension of the network, on the other hand, requires the previous development of the network to this location.

In terms of costs, for the majority of locations in the five federal states, grid extension is found to be the most economic solution. However, in total costs, this option is characterized by very large initial financial investments, which are only cost-competitive because the grid eventually reaches many people at once. Due to this required large up-front investment, private sector participation is difficult for the on-grid sector development. In contrast, mini-grids can present very attractive and manageable investment opportunities for investors, especially in regions which are located in a large distance to the existing grid, and in the case that a clear regulation exists which creates transparency on what happens in the case of a future grid-connection of that site and thereby reduces the risk for the mini-grid developer. Since the analysis found that grid extension is only feasible if the grid is functional and this is not given in many areas of the analyzed federal states, mini-grids can present a faster option to provide access to electricity. Also, the project implementation for small solutions will result in more timely electrification results than larger grid infrastructure expansion projects. Furthermore, efforts are required to raise awareness on energy efficiency from household to industrial level to reduce the overall energy requirements.

The third research question addresses the parameters which impact the decision between the different electrification options. Expert interviews in the five states revealed that in the past a strong focus put on grid extension as *ultima ratio* – however, over the last year this perception started to change to acknowledge the option and potential of mini-grids, specifically of PV-battery-diesel mini-grids as an equivalent electricity supply option. Two reasons for that are identified: first, the cost reduction for decentralized electricity generation, e.g. PV and battery storage, and second, the ongoing progress towards a clear regulatory framework which allows creating sustainable business models with mini-grid electrification. The regulatory framework also allows for an easier integration of the two different approaches, both technically and economically. In addition to that, it is found that spatial electrification planning presents a viable method to improve the knowledge on current status quo of electrification, its detailed spatial extents, and thereby creates transparency for all involved stakeholders, from governmental representatives responsible for large-scale planning, over regional governments to village heads, who apply for electricity supply. Private sector participants are thereby included as a new stakeholder in the energy sector landscape of Nigeria.

The fourth research question poses the question regarding the long-term sustainability of decentralized systems, although grid extension may be progressing over time and space. Here, the high renewable energy shares, which are quantified in the presented modeling, indicate very attractive business opportunities, since these installed mini-grid capacities can be integrated into a centralized system once that becomes available. Feed-in tariffs regulate the payment mechanism and with the predominant lack of generation capacity all across Nigeria and the continuous demand increase, there will be no energy surpluses in the foreseeable future. Another finding from the modeling is that the cost-optimized mini-grid configurations lead to lower CO_2 emissions than both, the current grid electricity mix and of course a supply by pure diesel generators, which is common practice in many places across Nigeria. The spatial explicit modeling also reveals the locations which are recommended to by supplied by mini-grids only, in very remote locations and in areas with a difficult accessibility, which are projected to remain decentralized supply systems.

Rural electrification from the perspective of location theory

Energy planning and rural electrification can be understood as one integral part of regional science - or spatial economics, posing the question on how to develop which regions best, considering their local resources as well their location in a superordinate space. For economic development there is a strong relation between productive use and energy demand, since usually productive use leads to higher electricity demand and ability to pay for electricity. In consequence, spatial analysis can support the identification of regions with potential growth centers, in which energy generation as business model or as state-managed supply of needs presents a great opportunity.

When prioritizing new electrification measures, either on-grid or off-grid solutions, existing spatial relations in terms of production centers, resource flows, and transport, as well as related distances to overcome, need to be considered in order to allow sustainable economic development.

In practice, one option is to suggest electrification via a large mini-grid or a connection to a larger T&D infrastructure for hierarchically more central places, while hinterland areas of that location will use independent solutions such as SHS on a household level supplying the basic household electricity needs. Productive use of electricity will be relocated and established at a more central place, which is still in acceptable distance. This would lead to the establishment of electricity supply as an “agglomeration factors” (Weber), increasing the overall economic performance of that location.

Electrification may grow from previously independently electrified hubs, considering local potentials and respective centers for commuters, describing the catchment area of central places.

Renewable energy-based electricity generation requires space – one resource which may be scarce in central places, due to the dense settlement structures and competitive land use, increasing the value of the hinterland for providing space for energy generation based on renewable energy sources. This brings together Brücher’s approach of *energy from space* with Christaller’s and von Thünen’s concept of land value: by generating electricity, hinterland areas might develop a new business segment to increase their economic attractiveness to either use their local resources to transport them to a more central place in a close proxy (transportation costs < price at central location), or attract new customers to rise up in the hierarchy of centrality in regard to other surrounding locations. Pay as go you solutions and mobile payment schemes support in making the remoter regions more attractive due to lower transaction costs, which was not given in the past. With the on-going digitization of the economy, physical accessibility may become of lesser importance for business development, however, it stresses the crucial role of electricity access for novel communication channels, such as via mobile phone technology or internet access.

Sustainable rural electrification: a way to mitigate global fragmentation

The decentralized use of renewable energy may open up a new perspective for fragmented places: If the installation of energy systems in an economic way, as a result of available technology and sufficient local resources, becomes possible, this has the potential to qualify those locations to overcome their development gap. Local energy access may spur its overall development, especially the participation in the globalized market may become a perspective due to the digitization of whole economies and education systems. As for the two development theories, the growth theory versus dependence theory, arguments for the cause of underdevelopment in the case of Nigeria exist for both theories: in favor for the first theory is the fact that Nigeria's economy is characterized by low internal processing power and refinement capacities of export products. A strong focus of the economy remains on the export of primary resources, which may be overcome by internal restructuring. A point that falls to the side of the latter theory is the fact that Nigeria was defined as one country by the colonialists, overrunning traditional functioning structures with the aim to maximize exports from the country. Colonialism is closely related to interests in natural resources and borders were defined on a map without considering local geographies or the conglomerations of different ethnic groups. As mainly raw materials, such as crude oil, are exported, no market diversion takes place, creating dependence on the import of foreign goods and products and failing to diversify the market risks to different product categories. Subsistence in the agricultural sector and a large informal economy, as seen in Nigeria, are also characteristics of a strong dependency.

As the results of the modeling show, consequences of Nigeria's lack of development are specifically prevailing in rural areas of the country, while urban areas are important as new centers within peripheries on a global scale. Particularly with regard to the challenge of electricity supply in rural areas, account must be taken of the geographical isolation and difficult accessibility of the areas to be supplied with electricity as a result of given environmental conditions and topographies. Results show that these unelectrified settlements are often located in mountainous or dense vegetation areas (such as forests), which complicates the supply with electricity for these places (Palit & Chaurey, 2011). Considering these facts, decentralized energy generation can establish a counter position to the lock-in of the resource curse, by opening up new economic opportunities, for the development and operation of mini-grids on the one hand, but also, on the other hand, by secondary economic activities which may result from having access to electricity. While this opportunity is mainly based on renewable energy sources, referring back to *energy from space*, this opportunity is specifically of interest in the periphery, since in those locations renewable energy potentials are high and demand for electricity is large. The resulting market potential and growth prospects in the renewable energy sector represent an opportunity to tackle the high unemployment in Nigeria.

7.2. Spatial electrification planning – from modeling to implementation

The modeling results are a useful indicator for understanding different electrification options regarding their appropriateness, requirements and costs.

However, to practically implement and use these theoretical results as recommended actions, they need to be translated into a phase-wise implementation approach supported by government regulation and policy development. Such a phase-wise implementation approach also needs to consider the temporal component which is inherent to infrastructural development. Financing strategies for these plans must be developed and also be reflected in national budget planning. Moreover, the consideration of the temporal component allows including revisions considering changes in the regulation or unforeseen challenges which may slow down the expected progress. A phase-wise implementation approach also makes it easier to track and monitor the progress of implementation. GIS-based tools have the functionality to include detailed implementation plans for each electrification phase to achieve the desired spatial resolution.

Risks and challenges are related to the resource curse: as pointed out before Nigeria has abundant fossil and renewable energy resources which can support the country's further development if managed well – but existing structures and value chains of the oil sector need to be considered.

Electrification planning and implementation needs to be understood as dynamic progress. Instead of one best solution for each not yet electrified location the solution might change over time. A clear example for that is the case of interconnected mini-grids: as the status quo of available power in the power network is insufficient, any additional grid extension would put even more demand on the grid which already cannot be satisfied. Therefore, mini-grids can be suggested for those locations which are generally recommended as grid-connected locations in the future. So a mini-grid can be planned and build quickly, and in case grid development is reaching that location, it can become interconnected to the grid to feed power into the grid in times with excess and can operate in island mode when generating an adequate amount of electricity. This guarantees an independent power supply for the respective location with related predictability of the quality and quantity of supply.

Also SHS act as an interim solution, to improve local livelihoods by the provision of low tier electricity supply for lighting and phone charging until other electrification options, such as mini-grids or grid extension, become feasible. Especially in terms of population growth, small settlements, which are suggested to be electrified by SHS, may reach a size and demand which makes them suitable sites for mini-grid development in the future.

By analyzing the time component also the multi level perspective (Rauch, 2009) needs to be considered for the overall planning: different institutional levels are responsible for time-bound measures which all need to be integrated, from a global level with the objective formulated within SDG#7, over national goals to regional and local levels, such as village electrification, planned and implemented by local communities.

On a global level, maps and spatial planning enhance a rough estimation of a current situation in a given region, also in contrast to other areas. For the case of Nigeria, this perspective unveils a weak energy sector which is not able to supply the total population sufficiently. To gain a deeper understanding of regional development in a given area of interest, a regional perspective is appropriate, including data collection and data management in a higher spatial resolution. For Nigeria, differences in the five states are analyzed, resulting in an understanding of state-level challenges and development pathways. These are further particularized to local level perspectives, as most accurate data needs to be sourced locally to capture relevant, site-specific information. This of importance for the implementation of the planned and suggested electrification option and a requirement before the actual implementation. For this analysis the local level is the village perspective, where for each village independently different electrification options are assessed. Those findings might be aggregated again to higher levels, e.g. for estimating the required investments, but at the same time, keeping a much higher accuracy that can be broken down again for implementation purposes. It is also possible to zoom into a sub-village level, which was done here only in parts during the demand estimation, as a way to gain more detailed input parameter for the calculation of the electric load, the village composition was analyzed including number of schools and number of health stations (e.g. dispensaries and hospitals).

By approaching only one of those different levels of spatial resolution, the outcome might be limited because all levels are interrelated. Spatial electrification planning can support these different spatial levels in developing concrete electrification implementation actions and tracking of the respective development progress.

7.3. Role of capacity building for spatial electrification planning

Capacity building for spatial electrification planning in Nigeria has the potential to expand knowledge of the spatial relations in the energy sector and also about the resource side: locations with renewable energy potentials can be overlaid with existing energy infrastructure and also with cross-sectoral information to enable integrated regional planning.

Modeling and the use of GIS for data management and scenario analysis can improve transparent decision-making. A precondition for that is a certain level of computer literacy, an understanding of data structures, attributes and formats and a familiarity in using certain software tools to handle digital data. The surveying of seventeen Nigerian organizations (Tab. 5.3) revealed that these preconditions are not always met yet and present a barrier to fully utilize such tools. An interesting observation for the five Nigerian states was that so-called GIS agencies emerged on a federal state level as private enterprise companies and that those entities have shown a much higher capacity in geo-data processing than governmental bodies. Governments need to know about the potentials of software-aided planning to request that information from planners to utilize it for decision-making support and also to carry out scenario analyses to understand the costs, effects, and requirements of certain developments for electrification planning and beyond. To leverage the impact of the GIS agencies for governmental planning purposes, more budget needs to be allocated to make use of the services of such companies. This in turn will only happen if the necessity of such interventions and the improvements and benefits for planning are clearly communicated and acknowledged by the government.

Capacity building for data management of spatial data and the use of modeling tools for infrastructure planning will not only improve electrification planning but will benefit also other spatially-related regional and infrastructure planning, such as road or water infrastructures, or the management of state-owned land such as protected areas or state-owned forests. Ongoing data collection and updating of data to track progress and change of local situations is another important perpetual task to be fulfilled to allow for applied planning schemes.

Capacity development can be set into the context of the multi-level perspective (Rauch, 2009) for different levels of intervention: from academic research on energy transition and development towards achieving full electrification to decision-support on governmental planning to influence regional policy development to the implementation of energy solutions on a local level.

The digital age provides several new options for information management and knowledge creation. To access those benefits not only electrical energy but also digital literacy is required. The consideration of spatial planning as such is also recommended as a component of the future education. Considering data-rich mapping tools in the context of the general scarcity in public data, even more in spatially-resolved information, which was one of the challenges of creating it, enhances its value for knowledge creation and decision support even more (Fig. 7.1).

Adding on to that, by visualizing a possible pathway towards full electrification, it enables all relevant stakeholders to scrutinize political agendas or policy development in a critical way. Furthermore, it allows people investigate in the detailed modeling and the results without specific background knowledge on spatial data infrastructures and GIS, as well as without the need to rely on experts to conduct and communicate a comparable analysis. This creates transparency and independence for all involved parties.

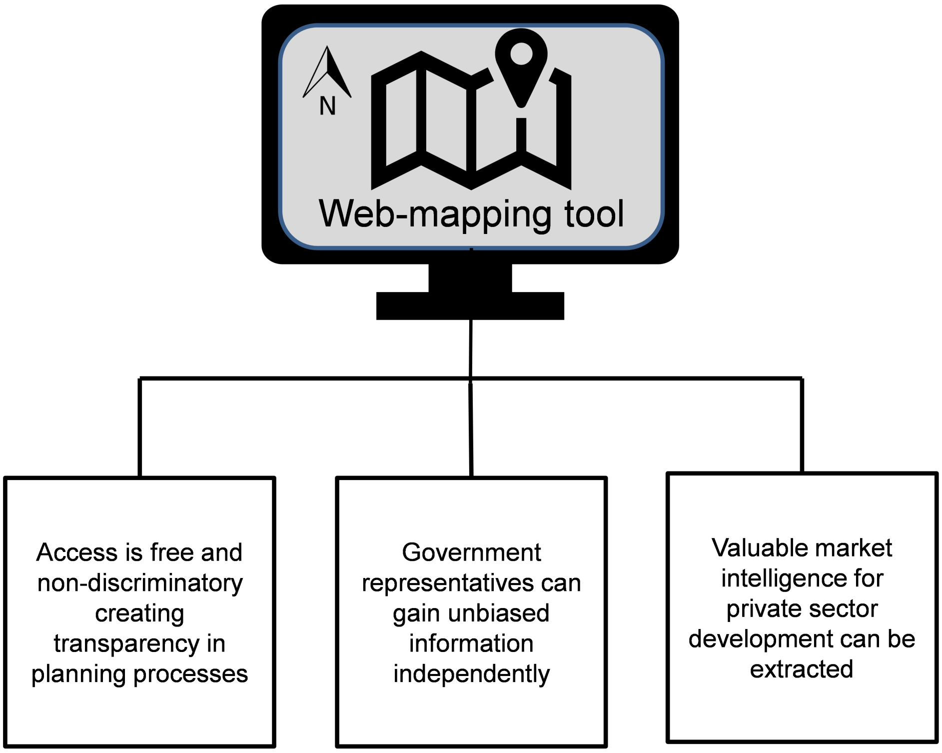


Figure 7.1.: Potential benefits of making electrification planning results available in an online web-map. Author's own diagram.

7.4. Limitations of the chosen method for the modeling of electrification options

For the modeling of the electrification planning some assumptions are made in order to focus on the geographical aspects of the electrification planning. In consequence, some limitations of the applicability of results for decision support on rural electrification pathways need to be considered.

Since the focus lies on the consideration of spatial relations of unelectrified villages in regard to their location, their distance to existing infrastructure, and their local resource potential, as well as their demand for electricity, no electro-technical modeling of the grid performance was included and grid extension projects require detailed assessments for an appropriate design and sizing prior to the construction. Technical feasibility studies on the ground are necessary to assess the current grid system and the local conditions to identify correct transformer station capacities and voltage levels for the planned power lines. In addition, it is of high importance to correctly represent the national power grid system for planning grid extension measures. Here, it is assumed that at all time the power availability in the grid is sufficient and that all extensions are technically feasible. However, more detailed analyses would illustrate the detailed required voltage levels and transformer sizes in each village. In addition, no analysis is conducted on power line losses over distances and voltage control in the grid. Also, the optimized grid topology results in many cases in single feeders, or branch lines, leading to so-called "dead ends", which are not optimal regarding voltage control and grid stability (Menck, Heitzig, Kurths, & Schellnhuber, 2014). In consequence, the grid topology development needs to favor meshed and circular layouts in order to maximize the local grid stability. However, this is a contradicting constraint to the cost-minimization, as it would require additional lengths of power lines for the connecting branches.

A different approach to solve the problem of how to connect several villages is a method called Steiner Tree problem, named after the Swiss mathematician Mr. Jacob Steiner. With this method, several points are connected by inserting additional vertices as crossings in which edges can be navigated. This method is complex because the definition of those so-called additional Steiner points creates infinite options to connect the desired locations and hence, it complicates the identification of the optimal solution (Hwang, Richards, & Winter, 1992: 52). Technological challenges also exists for the proposed interconnected mini-grids, specifically in old grid infrastructure: if the grid lines are build according to an expected voltage decline over distance, a feed-in of excess electricity at that end of line might result in a too large voltage increase which leads to a loss of stability in the grid by interconnecting mini-grids. Therefore, new or overhauled electricity infrastructure shall reflect that challenge by the installation of variable frequency converters.

Further, no *Nexus* perspective is considered – water and food productive use has different implications on household incomes, uptake of new technologies through subsidies, leading to difference in richer and poorer households to adopt new technologies (Mirzabaev, Guta, Goedecke, Gaur, Börner, Virchow, Denich, & Braun, 2015). In the modeling only PV-diesel-battery mini-grids are considered, neglecting the opportunities of other technology and resources, for example for small hydro power systems for village electrification.

An advanced accurateness of data can improve the level of detail of the resulted electrification planning, since some assumptions during identification of villages, deriving the electricity demand, and for spatial detail of existing infrastructure were made. Improving and refining these data can improve the accuracy of results. To keep the findings up-to-date, updates over time are required, since infrastructure planning is on-going and electrification planning needs to account for that.

System boundaries of rural electrification can also be a subject of discussion: neighboring national regions and cross-border regions are neglected for electrification in this modeling and need to be considered in future developments, as well as migration and urbanization patterns of population and related overall population growth.

The mini-grid modeling is based on an optimization of the LCOE, however, a multi-objective programming can allow to also minimize the share of diesel fuel and CO_2 emissions. This would allow identifying most climate-efficient solutions. The modularity of the model and the optional character of input parameters allows the application of the tool for other regions, however the methodology and the results are only validated for the case of the five federal states of Nigeria.

7.5. Outlook and further research

Geospatial modeling presents an option to simulate technology development and electrification planning. As digitization progresses, better data bases are created that can be used for planning purposes and, as a result, implementations can be adapted more precisely to requirements and thus become more efficient. This can be integrated into larger infrastructure planning schemes - considering other sectors, such as the mobility and transport sector, which is also very energy-intensive. Achieving the SDGs will eventually also require a decarbonization for this sector to reach sustainability. To cover the transportation and mobility needs, apart from energy efficiency measures, it will result in a shift to the usage of clean fuels and electricity, which then in turn has a much stronger link to the energy sector.

Furthermore, novel technologies may come to the foreground, such as hydrogen as energy storage medium and fuel. These technology developments but also societal transformations can impact on energy landscapes of the future: an emerging development is the idea of village cooperatives for electricity provision, which is based on the potentials of decentralized, smaller energy systems, creating a new independence of traditional utility structures.

8. Conclusion

Providing access to electricity in Nigeria is a challenging and dynamic task, a transformation process which will accompany the nation for the coming decades. The shaping of this development trajectory will distinguish the future of the respective regions, in terms of sustainability, economic growth, and ultimately, quality of life.

The energy supply situation in Nigeria and its existing infrastructure is characterized by under-supplied grids, differentiating the electrification task from countries where almost no initial infrastructure has been established. In those set-ups, exclusively new concepts, so called green-field approaches, can be developed, whereas in situations such as in Nigeria, the existing infrastructure needs to be integrated into the planning, limiting the available options.

The results of the analysis show that centralized electricity supply systems are a very efficient way to provide the citizens with affordable electricity. However, they require large-scale infrastructure projects, coupled to significant up-front investments. In addition, the installed infrastructure needs to be upgraded to allow for the integration of renewable energy-based generation plants.

The spatial electrification planning indicates the importance of small-scale renewable energy-based decentralized energy systems – as an efficient alternative to allow people to gain access to electricity in a much shorter time-frame with lower environmental impacts. Consequently, policymakers may consider decentralized energy supply systems an excellent solution for the current needs, which is in line with global development and climate goals as agreed upon in the SDG#7. As electrification is a very dynamic process, isolated decentralized solutions can be integrated into larger supply structures at a later time once the latter is ready for connection.

The following recommendations are summarized as a conclusion:

Regional and land-use planning can support energy infrastructure design and electrification planning. Using geospatial data allows stakeholders to gain a clear understanding of the status quo, the requirements, and the available options for the supply of electricity at a given location. Without a detailed mapping, these dimension often remain ambiguous and not location-specific. A distinctive understanding of localizing the different technology options is required if the planning shall lead to successful implementation measures. A requirement for successful planning is a complete base dataset. Geospatial techniques require digital and geo-referenced data. As this data was not fully available at the beginning of the investigation, an intensive process of data generation through digitization and geo-referencing was undertaken. This essential aspect created an awareness of how important and helpful data management is for planning processes; applicable beyond the energy sector for general land management,

water and agricultural planning and management processes. Data management and frequent updating is required to track and improve rural electrification measures.
Before the implementation of electrification options, the existing power grid must be stabilized to improve the quality of power supply. This requires the construction of additional large-scale generation capacities, which are recommended to be based on renewable energy sources to be in line with the targets of SDG#7 and SDG#13. In addition, old power grids and transformer stations need to be controlled and overhauled if necessary. This precondition must be met before a connection of additional customers to the grid can be recommended. Nationwide metering should be implemented to guarantee for fair payment schemes.
Decentralized energy supply systems hold a substantial potential to provide access to electricity in non-grid-connected areas in the five analyzed Nigerian federal states. These sites can be powered by mini-grids, based on renewable energy, or smaller stand-alone solutions, whereas mini-grids can potentially be connected to a larger grid system once it is in reach spatially. In this context, regulations are required to allow the private sector to invest safely into new projects without fear of losing their business case. Nigeria provided a substantial document on mini-grid regulation in 2016 which fulfills this requirement.
Least-cost grid extension does not necessarily imply the best option for electrification, if aspects such as project development, construction time and long-term sustainability are to be considered. From an economic point of view, logic suggests the least-cost solutions, however, the following questions must also be addressed when comparing different approaches for providing access to electricity:

- who is benefiting from electricity provision;
- how fast can electrification of a given region or population be achieved?

Since different electrification solutions are suggested for distinct locations, any existing dichotomy between centralized and decentralized solutions shall be overcome by innovative, integrated approaches. Network expansion and decentralized solutions are not mutually exclusive; on the contrary, the advantages of both approaches can be used through a smart combination. This is made possible by the advances in renewable energy and storage technologies, which have now reached market maturity through cost reductions.
Nigeria owns abundant potentials of renewable energy, especially solar resources. These can be the change agent towards the achievement of all SDGs, higher diversification in the economic sector, and a climate friendly future. For a giant nation like Nigeria, the impact of the large-scale uptake of solar energy will make a significant impact on a global level. In a huge and rapidly growing country like Nigeria, the global impacts regarding GHG emissions must be considered, while simultaneously fostering the future development of the country – both can be supported by integrated electrification planning.

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A. Questionnaire

Assessment of the partners' organisation, equipment, processes, staff and capacities in Plateau, Cross River, Ogun and Sokoto

-Questionnaire-

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Berlin, 05th January 2015

Introduction

Thank you for your participation in this questionnaire. We have identified you as one of the major experts regarding GIS and rural electrification planning in Nigeria. Therefore we very much appreciate your contribution to this study.
The study, commissioned by the Reiner Lemoine Institute, on behalf of INTEGRATION and GIZ is carried out by Catherina Cader.

This study sets out to explore the diverse structures and capacities regarding GIS (geographical information systems) to support rural electrification planning.
Within this project the Nigerian states Cross River, Ogun, Plateau, and Sokoto are visited.
Please indicate at the end of the questionnaire whether you would like to receive a copy of the final study.

Instructions

This questionnaire starts with the evaluation of the different aspects on a scale from 5 to 0 (highest importance to absolutely no importance) for each of them. If you have no opinion on a certain aspect, please state “Z” for “don’t know”.
The ranking will look like this:

Ranking scale						
5	**4**	**3**	**2**	**1**	**0**	**Z**
Highest importance	High importance	Moderate importance	Low importance	Very low importance	Absolutely no importance	Don’t know

Please make a careful selection. Each row will contain a comment section, in which we appreciate your thoughts/suggestions/ideas with respect to the question. Your ranking will serve to complete the first qualitative steps of the study, and is of special importance for its end-product, the rating matrix.
The questions will be followed by a set of statements and questions related to the topic. We will ask you to agree or disagree on a scale from 5 to 0 (strongly agree -strongly disagree).

To summarize the instructions:
1. Use the scale from “0” to “5”
2. Use “0”, when a criterion has absolutely no importance
3. Use “Z”, when you have no opinion on a certain criterion
4. Do not leave any blanks

For any questions, please do not hesitate to ask.

Confidentiality

Your response will be treated confidential and the results are used within the Nigerian Energy Support Program (NESP).

You may reserve your right to anonymity if you wish to do so. In case you provide me with your details, only the above mentioned researcher will see your response.

Expert Responder Data

Name: ______________________________________

Company/Ministry/Organis.: _______________________

Department/Position: ___________________________

Country: ____________________________________

Contact: ____________________________________

Email: ______________________________________

Phone: _____________________________________

Which one(s) of the following categories do you perceive to belong to? Please underline.
• Government, Utility, Private Sector, Researcher, Public Organisation, • Other (if yes, please state):

Topic	Question	Ranking (5 to 0 / Z)	Answer
1. Assessment of the institutional set-up			
• Mandate and function of the organization	Is the organization established within a ministry, independent or private?		
• General overview of activities of the organization	What is the core business? Is there a defined vision and mission?		
• Existence of work plans	Which structures are important for daily work?		
• Experience with planning	Planning of rural electrification, usage of renewable energy sources etc.		
• Other key state MDAs	Are there links to other state MDAs?		
2. Assessment of data availability			
Typ of data	Is the format of data analogue or digital		Please indicate for all data
2.1. Population			
• Villages and towns	Inhabitants, electrified and non-electrified regions, industries, trade, craft.		

Topic	Question	Ranking (5 to 0 / Z)	Answer
2.2. Infrastructure			
• Power line network	Transmission and distribution line data, voltage levels, operational status (planned, running, outdated)		
• Transformer stations	Location and capacities, operational status?		
• Power plant locations	Large scale power plants as well as independent power generation, renewable and fossil fuelled. Are small diesel gensets are used frequently?		

Topic	Question	Ranking (5 to 0 / Z)	Answer
2.3. Natural			
• Land cover and usage	With lands are cultivated, with are natural?		
• Land ownership	Is there a management system installed?		
• Water bodies	Rivers, lakes		
• Elevation			
3. **GIS capacities evaluation of staff of partner organization**			
• General GIS knowledge	GIS can be used as an interdisciplinary planning tool. How good would you describe your overall knowledge of the potentials of GIS?		
• Software experience	Are you familiar using GIS software? Which software? Do you use web-mapping applications?		
• Data types	Raster, vector, text format, asci, databases, import processes and transformation		
• Georeferencing of analogue information	CRS, GPS		
• Data modelling	Spatial calculations and queries, SQL, raster calculator		
• Visualization and mapping	Which maps currently exist?		
• Working example	Overall estimation of task		

Topic	Question	Ranking (5 to 0 / Z)	Answer
4. Assessment of hardware and software equipment			
4.1. Software			
• How important is GIS software for the business processes of the organization?	Is commercial or open source software in use?		
• Are there any security policies/measurements in place?	Is data securely backuped? Is there a data exchange between different organizations?		
• Other relevant software or license besides GIS	Is there any other relevant software or license besides GIS?		
• Is there a spatial data management system established?	Is the data stored in databases? Meta data management?		
4.2. Hardware			
• Computer infrastructure	How many computers are available (PC, laptop), which OS and version, processor speed (Mhz), RAM, storage spage, age, condition		
• Server	Producer, OS and version, processor speed (Mhz), RAM, storage space, virtualized, if yes, which virtual machines?		
• Internet	How reliable is the internet connection, which internet provider, which hardware (switches, bandwidth)		
• Printer/Plotter	Producer, type, black/white/colour, formats (A4-A0) age, condition		
• Scanner	Producer, format (A4-A0), resolution, age, condition		

Would you like to receive the final version of this study? Yes/No

And finally, thank you very much for your participation.

B. Program listings

B1: Function for the creation of the weighted decision raster layer

```
create_decision_surface= function (roipath,grid_buffersize,grid_
    impact,road_buffersize,road_impact,pa_impact,forest_impact,water
    _impact)
{
  #create decision surface
  #parameters:
  #roipath: path to inputfiles for roi
  #(grid/road)_buffersize: size of buffer around grid/roads

  #example:
  # path="C:\\Users\\Catherina\\Documents\\Grid_extension\\01_
      Grextool"
  # create_decision_surface(path,90,0,90,-0.75,0.5,c(0,11,0,
      11,20,0.25, 21,41,0, 41,60,0.5, 61,101,0))

    # define projection (in metric projection)
  proj_nigeria <- CRS("+proj=utm +zone=32 +datum=WGS84 +units=m +no_
      defs")

  #load raster slope
  slopepath<-file.path(roipath, "slope.tif")
  slope<- raster(slopepath)

  #load land cover (lc)
  lcpath<-file.path(roipath, "lc.tif")
  lc<-raster(lcpath)

  #reclassify lc
  # lc <-reclassify(lc, lc_costs)
  fi=0.25
```

```
wi=0.5
lc <-reclassify(lc, c(0,19.5,0, 19.5,29.5,forest_impact,
   29.5,49.5,0, 49.5,69.5,water_impact, 69.5,257,0)) #=1 oder 0?

#project and resample
slope<- projectRaster(slope, crs=proj_nigeria, res=90)
lc<- projectRaster(lc, crs=proj_nigeria, res=90, method="ngb")

# resample slope to lc
slope <- resample(slope, lc)

#load
roadpath<-file.path(roipath, "roads_clipped.shp")
roads<- readOGR(roadpath, "roads_clipped")
papath<-file.path(roipath, "pa_clipped.shp")
pa<- readOGR(papath, "pa_clipped")

#create empty Raster with slope as extent
emptyRaster<-setValues(slope,NA)

#rasterize PA
pa<-rasterize(pa,emptyRaster,update=TRUE)
pa[!is.na(pa)] <- pa_impact
pa[is.na(pa)] <- 0

#rasterize roads
rr<-rasterize(roads,emptyRaster,update=TRUE)

# buffer road
br<-buffer(rr,width=road_buffersize)
br[!is.na(br)] <- road_impact
br[is.na(br)] <- 0

#load and buffer grid if exists
gridpath<-file.path(roipath, "pg_clipped.shp")
if (file.exists(gridpath))
{
  grid<-readOGR(gridpath,"pg_clipped")
  rg<-rasterize(grid,emptyRaster,update=TRUE)
  bg<-buffer(rg,width=grid_buffersize)
  bg[!is.na(bg)] <- grid_impact
  bg[is.na(bg)] <- 1
```

```
  }else{
    bg←setValues(emptyRaster,1)
  }

  #calculate decision surface
  dc ← ((1+(slope/100))+lc+pa+br)*bg

  return(dc)
}
```

B2: Function for the minimum spanning grid extension calculation based on the weighted decision raster layer

```
create_mst=function(pts,ds)
{
  #create minimum spanning trees

  #required input: points to be connected, decision surface raster
     with same extent
  #output: spatial lines of suggested mst

  #transform projection of points
  proj_nigeria <- CRS("+proj=utm +zone=32 +datum=WGS84 +units=m +no_
     defs")
  pts<- spTransform(pts, proj_nigeria)

  #create transition layer
  T<-transition(ds, function(x) 1/mean(x), directions = 8)
  T<-geoCorrection(T)

  #calculate cost distance matrix between all points on the cost
     raster
  cd<-costDistance(T,pts)
  cdmat=as.matrix(cd)

  #calculate the minimum spanning tree based on the assigned costs
  mst_1=dino.mst(cd, random.start = TRUE, random.search = TRUE)

  #create list for the resulting shortest path
  pathlist=list()

  #list for the associated costs for each connection
  pathcostlist=c()

  #loop over the mst-list to get the correct points on which to
     carry out the spatial shortest path analysis
  for (i in 1:nrow(mst_1)) {
    for (j in 1:i) {
      if (mst_1[i, j] == 1) #points connected
      {
        pt1 <-
          SpatialPoints(
```

```
            coordinates(pts[i, ]),
            proj4string = proj_nigeria
          )
        pt2 <-
          SpatialPoints(
            coordinates(pts[j, ]),
            proj4string = proj_nigeria
          )
        #calculate path between those points and add to list
        pathlist = c(pathlist,
                     shortestPath(T, pt1, pt2, output = "
                       SpatialLines"))
        #add cost to list
        pathcostlist=c(pathcostlist,cdmat[i,j])
      }
    }
  }
  spatln= do.call(function(...) rbind(...,makeUniqueIDs=TRUE),
     pathlist)

  #make dataframe of costs
  dat=data.frame(pathcostlist)
  frame=SpatialLinesDataFrame(spatln, dat, match.ID = FALSE)
  return(frame)
}

#writeOGR(frame, getwd(), "linesandcost", driver="ESRI Shapefile")
```

C. Detailed results

C: Detailed results of the phase-wise electrification modeling for the five federal states

Table C.1.: Categories of the detailed electrification results.

Category	Unit	Explanation	Comment
LGA		Local Government Area	
Ward		Ward	
Lat.	°	Latitude	
Long.	°	Longitude	
Pop.	#	Population	
Demand	kW_p	Peak demand for electricity	
Phase 1,2,3	g	grid	Type of electrification in each phase
	m-g	mini-grid	
	ic-g	interconnected mini-grid	
	-	none	

Table C.2.: Detailed information on population and suggested phase-wise electrification of all village clusters > 50 kW peak demand in Cross River.

LGA	Ward	Lat. [°]	Long. [°]	Pop. #	Demand kW_p	Phase 1	Phase 2	Phase 3
Abi	Abayong	5.739	7.923	4,181	589	-	g	g
Abi	Biko Biko	5.788	8.750	982	109	-	-	g
Abi	Ebom	6.398	8.604	1,865	197	-	g	g
Abi	Ekureku II	5.934	8.119	1,641	236	-	-	g
Abi	Etam	5.774	8.180	2,527	255	-	g	g
Abi	Etam	6.571	8.661	2,384	259	-	g	g
Abi	Etam	6.854	8.826	2,297	238	-	g	g
Abi	Ndiagu Amagu II	5.968	8.918	692	84	-	g	g
Abi	Ndiagu Amagu II	6.586	8.689	1,057	125	-	g	g
Abi	Ndiagu Amagu II	5.957	8.057	5,618	568	m-g	ic-g	ic-g
Abi	Ndiagu Amagu II	6.681	8.352	6,891	692	m-g	ic-g	ic-g
Abi	Ndiagu Amagu II	6.584	8.563	2,527	259	-	g	g
Akamkpa	Awi	5.346	7.960	2,761	399	-	g	g
Akamkpa	Eku	5.408	8.044	2,302	369	m-g	m-g	ic-g
Akamkpa	Iko	5.620	8.043	2,288	328	-	m-g	ic-g
Akamkpa	Iko	5.668	8.219	1,185	139	-	g	g
Akamkpa	Ikpai	5.492	8.027	2,080	307	-	m-g	ic-g
Akamkpa	Ikpai	5.519	8.180	4,425	506	m-g	m-g	ic-g
Akamkpa	Ikpai	5.637	8.197	602	76	m-g	m-g	m-g
Akamkpa	Mbarakom	5.188	8.205	1,194	130	-	m-g	ic-g
Akamkpa	Mbarakom	5.827	8.239	910	107	-	-	g
Akamkpa	Oban	5.258	8.122	969	116	-	-	g
Akamkpa	Ojuk N	5.058	8.311	779	84	-	-	g
Akamkpa	Ojuk N	5.089	8.436	825	105	-	-	g
Akamkpa	Ojuk N	5.096	8.316	1,348	164	-	-	g
Akamkpa	Oniman-Kiong	5.081	8.208	1,378	153	-	m-g	ic-g
Akamkpa	Uyanga	5.348	8.645	689	72	-	g	g
Akamkpa	Uyanga	5.350	8.400	1,443	180	-	-	g
Akamkpa	Uyanga	5.514	8.756	1,580	181	-	-	g
Akamkpa	Uyanga	6.871	8.779	795	81	-	-	g
Akpabuyo	Eneyo	4.954	8.611	3,919	417	-	g	g
Akpabuyo	Idundu/Any.	5.073	8.238	855	92	-	-	g
Akpabuyo	Ikang Central	4.797	8.492	1,392	213	-	-	g
Akpabuyo	Ikang Central	5.177	8.072	956	101	-	m-g	ic-g
Akpabuyo	Ikot Eyo	4.917	8.591	3,337	397	-	g	g
Akpabuyo	Ikot Nakanda	4.844	8.426	1,339	192	-	m-g	ic-g
Bekwara	Afrike Ochagbe	6.572	8.486	8,301	973	-	g	g
Bekwara	Afrike Ochagbe	6.250	8.786	933	101	-	g	g
Bekwara	Beten	6.690	8.421	5,237	682	m-g	ic-g	ic-g
Bekwara	Gakem	6.656	9.101	758	94	-	g	g
Bekwara	Gakem	5.349	8.249	928	110	-	g	g
Bekwara	Ibiaragidi	4.776	8.524	946	118	-	g	g
Bekwara	Nyanya	6.777	8.966	1,286	166	-	g	g
Bekwara	Nyanya	6.781	8.949	1,148	135	-	g	g
Bekwara	Ugboro	6.667	8.889	1,075	133	-	m-g	ic-g
Bekwara	Ukpah	6.692	8.945	1,392	145	-	g	g
Bekwara	Ukpah	5.918	8.724	1,213	123	-	g	g
Biase	Abayong	5.727	8.176	1,057	153	-	g	g
Biase	Abayong	5.747	7.985	2,076	239	-	g	g
Biase	Agwagune/Okurike	5.528	8.160	2,389	258	-	m-g	ic-g
Biase	Agwagune/Okurike	5.541	8.792	3,434	351	m-g	ic-g	ic-g
Biase	Agwagune/Okurike	6.702	8.967	882	96	-	-	g
Biase	Agwagune/Okurike	6.522	8.696	1,190	117	-	-	g
Biase	Akpet/Abini	6.709	8.848	919	104	-	m-g	ic-g
Biase	Ehom	5.499	7.968	1,534	193	-	m-g	ic-g

Table C.2.: Cross River (cont.)

LGA	Ward	Lat. [°]	Long. [°]	Pop. #	Demand kW_p	Phase 1	Phase 2	Phase 3
Biase	Ehom	5.510	8.107	5,742	614	-	-	g
Biase	Ehom	5.515	8.291	1,286	189	-	g	g
Biase	Erei S	5.660	8.693	1,332	212	-	g	g
Biase	Erei S	5.707	8.429	3,795	530	m-g	ic-g	ic-g
Biase	Erei S	6.625	8.917	3,409	473	m-g	ic-g	ic-g
Biase	Erei S	5.654	8.017	781	78	-	g	g
Biase	Ikun/Etono	5.591	8.028	5,504	681	-	g	g
Biase	Ikun/Etono	5.631	8.016	4,709	584	-	g	g
Biase	Umon N	5.363	8.326	4,667	672	m-g	m-g	ic-g
Biase	Umon N	5.407	8.070	704	72	-	m-g	ic-g
Biase	Umon N	5.462	8.725	896	96	-	m-g	ic-g
Biase	Umon N	5.590	8.067	1,231	129	-	g	g
Biase	Umon N	5.742	7.953	919	108	-	m-g	ic-g
Biase	Umon S	5.747	7.939	4,199	495	m-g	m-g	ic-g
Biase	Umon S	5.440	8.133	753	80	-	-	g
Biase	Umon S	5.506	8.026	1,061	112	-	m-g	ic-g
Boki	Abo	5.977	8.472	3,842	572	m-g	m-g	ic-g
Boki	Abo	6.057	8.517	5,333	797	m-g	m-g	ic-g
Boki	Abo	6.083	8.974	919	108	-	-	g
Boki	Abo	6.116	8.728	1,443	216	-	m-g	ic-g
Boki	Abo	6.123	8.690	1,562	162	-	m-g	ic-g
Boki	Abo	6.128	9.047	2,283	284	m-g	m-g	ic-g
Boki	Abo	6.151	9.050	2,982	361	-	m-g	ic-g
Boki	Abo	6.605	8.500	583	68	-	-	g
Boki	Alankwe	6.406	8.882	4,092	473	m-g	ic-g	ic-g
Boki	Becheve	6.272	8.538	588	73	-	m-g	ic-g
Boki	Becheve	6.281	9.126	1,300	164	-	m-g	ic-g
Boki	Becheve	6.741	8.680	2,067	212	-	m-g	ic-g
Boki	Beebo/Bumaji	6.470	8.571	2,283	236	-	m-g	ic-g
Boki	Beebo/Bumaji	6.295	9.282	726	74	-	-	g
Boki	Boje	6.198	8.429	984	105	-	-	g
Boki	Boje	6.210	8.520	4,102	504	m-g	m-g	ic-g
Boki	Boje	6.212	8.795	1,626	206	-	g	g
Boki	Boje	6.225	8.818	1,414	206	-	g	g
Boki	Boje	6.251	8.955	919	95	-	g	g
Boki	Boje	6.257	8.938	2,859	352	-	g	g
Boki	Boje	6.299	9.294	2,132	279	-	m-g	ic-g
Boki	Boje	6.800	8.820	1,080	135	-	m-g	ic-g
Boki	Buentsebe	6.269	9.050	1,300	163	-	m-g	ic-g
Boki	Buentsebe	6.293	9.272	2,642	317	m-g	m-g	ic-g
Boki	Buentsebe	6.330	9.010	2,256	290	-	m-g	ic-g
Boki	Ekpashi	6.344	9.116	1,378	204	-	g	g
Boki	Kakwagom/Bawop	6.473	8.983	1,617	235	-	g	g
Boki	Kakwagom/Bawop	6.484	9.039	4,332	617	-	g	g
Boki	Kakwagom/Bawop	6.498	8.965	1,520	219	-	g	g
Boki	Oku/Borum/Njua	6.364	8.784	4,240	631	m-g	ic-g	ic-g
Boki	Oku/Borum/Njua	6.389	8.643	1,286	188	-	g	g
Boki	Oku/Borum/Njua	6.455	8.940	4,255	575	-	g	g
Boki	Oku/Borum/Njua	5.822	7.971	965	121	-	g	g
Etung	Abia	5.954	8.007	704	75	-	g	g
Etung	Ajassor	5.861	8.068	1,199	152	-	g	g
Etung	Ajassor	6.664	8.588	1,874	201	-	g	g
Etung	Etomi	5.909	8.091	7,575	762	m-g	ic-g	ic-g
Etung	Etomi	6.475	9.242	643	79	-	g	g
Etung	Ikom Urban I	6.015	9.059	850	91	-	-	g
Etung	Itaka	5.769	8.004	1,805	189	-	m-g	ic-g

Table C.2.: Cross River (cont.)

LGA	Ward	Lat. [°]	Long. [°]	Pop. #	Demand kW$_p$	Phase 1	Phase 2	Phase 3
Ikom	Akparabong	6.096	8.592	735	87	-	g	g
Ikom	Akparabong	6.110	9.133	4,314	666	-	g	g
Ikom	Akparabong	6.612	8.550	790	87	-	g	g
Ikom	Nde	6.010	9.001	1,292	153	-	g	g
Ikom	Nde	6.037	8.532	1,456	214	m-g	m-g	ic-g
Ikom	Nde	6.064	8.476	758	95	-	m-g	ic-g
Ikom	Nde	6.141	8.392	6,050	855	-	g	g
Ikom	Nde	6.543	8.844	547	70	-	-	g
Ikom	Nde	6.694	9.203	1,502	180	-	g	g
Ikom	Nnam	6.257	8.985	1,511	153	-	-	g
Ikom	Nta/Nselle	6.042	8.481	1,190	176	m-g	m-g	ic-g
Ikom	Nta/Nselle	6.157	8.639	2,168	320	-	m-g	ic-g
Ikom	Nta/Nselle	6.169	8.474	1,461	225	-	m-g	ic-g
Ikom	Ochon	5.766	7.980	832	88	-	m-g	ic-g
Ikom	Ofutop I	6.761	8.577	1,194	124	-	-	g
Ikom	Ofutop II	5.891	8.365	877	104	-	g	g
Ikom	Ofutop II	6.030	8.647	1,374	172	-	m-g	ic-g
Ikom	Ofutop II	6.578	8.833	606	80	-	-	g
Ikom	Yala/Nkum	5.971	8.080	964	112	-	-	g
Obanliku	Basang	6.534	8.503	23,140	2,376	m-g	ic-g	ic-g
Obanliku	Becheve	6.331	8.444	2,557	367	m-g	ic-g	ic-g
Obanliku	Becheve	5.923	8.330	671	81	-	-	g
Obanliku	Beebo/Bumaji	5.371	8.100	1,948	198	m-g	m-g	ic-g
Obanliku	Beebo/Bumaji	5.364	8.050	4,576	556	m-g	m-g	ic-g
Obanliku	Bendi I	5.955	8.802	2,182	308	m-g	ic-g	ic-g
Obanliku	Bishiri N	6.599	9.007	4,681	653	-	g	g
Obanliku	Bishiri N	6.596	8.893	3,487	432	m-g	ic-g	ic-g
Obanliku	Bishiri N	6.602	8.794	4,851	664	m-g	ic-g	ic-g
Obanliku	Bishiri N	6.762	8.593	2,738	342	m-g	ic-g	ic-g
Obanliku	Bishiri S	6.126	8.617	1,686	227	-	g	g
Obanliku	Bishiri S	5.977	8.536	2,853	337	m-g	ic-g	ic-g
Obanliku	Bisu	6.582	9.200	1,034	132	-	g	g
Obanliku	Bisu	6.638	9.248	3,868	541	m-g	ic-g	ic-g
Obanliku	Busi	6.661	9.252	4,213	425	m-g	ic-g	ic-g
Obanliku	Obudu Urban II	6.538	9.036	740	80	-	-	g
Obanliku	Utanga	6.602	9.199	2,628	281	-	g	g
Obanliku	Utanga	5.990	8.062	1,654	180	-	g	g
Obanliku	Utanga	6.580	8.789	2,113	216	-	g	g
Obanliku	Utanga	6.499	9.390	2,325	250	-	m-g	ic-g
Obubra	Ababene	6.732	8.612	547	68	-	-	g
Obubra	Iyamoyong	5.833	8.060	3,602	515	m-g	m-g	ic-g
Obubra	Iyamoyong	5.858	8.337	2,862	349	m-g	m-g	ic-g
Obubra	Iyamoyong	5.875	8.814	3,542	374	-	m-g	ic-g
Obubra	Obubra Urban	6.621	9.203	887	88	-	-	g
Obubra	Ochon	5.958	8.150	1,052	135	-	g	g
Obubra	Ochon	5.971	8.388	4,755	567	m-g	ic-g	ic-g
Obubra	Ochon	5.984	8.660	4,335	453	-	g	g
Obubra	Ochon	6.033	8.554	4,586	480	-	g	g
Obubra	Ochon	6.051	8.580	12,412	1,314	m-g	ic-g	ic-g
Obubra	Ofumbongha/Yala	6.004	8.465	1,577	231	-	g	g
Obubra	Ofumbongha/Yala	6.566	9.258	887	89	-	m-g	ic-g
Obubra	Ofutop II	6.029	8.383	1,360	144	-	m-g	ic-g
Obubra	Osopong I	6.130	8.999	4,700	642	m-g	m-g	ic-g
Obubra	Osopong I	6.160	9.021	1,897	269	m-g	m-g	ic-g
Obubra	Osopong I	6.548	9.379	827	81	-	-	g
Obubra	Osopong I	6.058	8.298	1,778	277	m-g	m-g	ic-g

Table C.2.: Cross River (cont.)

LGA	Ward	Lat. [°]	Long. [°]	Pop. #	Demand kW_p	Phase 1	Phase 2	Phase 3
Obubra	Osopong I	6.748	8.851	2,090	300	-	m-g	ic-g
Obubra	Osopong II	6.119	8.452	707	86	-	-	g
Obubra	Ovonum	6.157	8.427	822	99	-	-	g
Obudu	Alankwe	5.321	8.079	528	66	-	m-g	ic-g
Obudu	Alege/Ubang	6.432	8.670	1,773	209	m-g	ic-g	ic-g
Obudu	Alege/Ubang	6.469	8.792	5,633	881	m-g	ic-g	ic-g
Obudu	Alege/Ubang	6.549	9.093	2,628	319	-	g	g
Obudu	Alege/Ubang	6.551	9.249	1,757	218	-	g	g
Obudu	Alege/Ubang	6.235	8.431	1,498	185	-	g	g
Obudu	Alege/Ubang	6.219	8.405	997	119	-	g	g
Obudu	Alege/Ubang	6.010	8.247	960	113	-	g	g
Obudu	Alege/Ubang	6.554	9.061	1,553	204	-	g	g
Obudu	Alege/Ubang	6.526	9.041	3,533	373	m-g	ic-g	ic-g
Obudu	Buda	6.429	9.084	5,674	714	m-g	ic-g	ic-g
Obudu	Buentsebe	6.414	9.149	4,141	414	m-g	ic-g	ic-g
Obudu	Bunyia/Okubuchi	6.462	8.865	7,202	867	m-g	ic-g	ic-g
Obudu	Mbanyumangbagh	6.837	8.806	2,600	324	-	m-g	ic-g
Obudu	Ukpe	6.490	8.809	4,956	725	m-g	ic-g	ic-g
Obudu	Ukpe	6.530	8.808	9,738	1,182	m-g	ic-g	ic-g
Obudu	Ukpe	6.565	9.052	657	69	-	g	g
Obudu	Ukpe	6.502	9.050	1,309	197	-	g	g
Odukpani	Adiabo/Efut	5.064	8.576	1,045	152	-	-	g
Odukpani	Central Uruan II	5.011	8.116	1,259	130	-	g	g
Odukpani	Creek Town I	5.013	8.115	1,461	209	-	g	g
Odukpani	Creek Town II	6.616	9.176	2,031	298	-	g	g
Odukpani	Creek Town II	6.565	9.100	3,877	407	-	g	g
Odukpani	Eki	5.216	8.068	1,387	151	-	-	g
Odukpani	Isu	5.407	8.272	772	98	-	-	g
Odukpani	Ito/Idere/Ukwa	5.226	8.307	2,081	271	-	m-g	ic-g
Odukpani	Ito/Idere/Ukwa	5.454	8.029	749	90	-	-	g
Odukpani	Ito/Idere/Ukwa	5.476	7.970	2,040	314	-	m-g	ic-g
Odukpani	Ito/Idere/Ukwa	6.586	8.399	933	116	-	m-g	ic-g
Odukpani	Mbiase/Ayadehe	6.833	8.841	1,424	146	-	-	g
Odukpani	Obomitiat/Mbiabo	5.135	8.369	3,992	423	m-g	m-g	ic-g
Odukpani	Odot	5.120	8.556	734	86	-	-	g
Odukpani	Odot	6.540	9.080	3,110	442	-	g	g
Odukpani	Odot	6.813	8.653	827	85	-	-	g
Odukpani	Odot	5.694	8.024	965	116	-	-	g
Odukpani	Odukpani Central	5.022	8.226	1,410	192	-	g	g
Odukpani	Odukpani Central	5.064	8.577	1,934	285	-	g	g
Odukpani	Odukpani Central	5.066	8.327	2,389	359	-	g	g
Odukpani	Odukpani Central	5.080	8.317	1,012	146	-	-	g
Odukpani	Odukpani Central	5.104	8.663	1,122	119	-	-	g
Ogoja	Buda	6.469	9.215	2,761	330	-	g	g
Ogoja	Bunyia/Okubuchi	6.486	8.604	7,708	964	m-g	ic-g	ic-g
Ogoja	Ekajuk I	6.350	9.434	5,966	897	m-g	ic-g	ic-g
Ogoja	Ekajuk I	6.407	8.913	6,010	840	-	-	g
Ogoja	Ekajuk I	6.448	9.048	2,693	374	-	g	g
Ogoja	Ekajuk I	5.097	8.231	657	70	-	-	g
Ogoja	Ekajuk I	6.020	8.584	1,557	224	-	g	g
Ogoja	Ekajuk II	6.415	8.569	937	100	-	g	g
Ogoja	Ekajuk II	5.169	8.136	1,038	120	-	m-g	ic-g
Ogoja	Kakwagom/Bawop	6.468	9.114	1,148	166	-	m-g	ic-g
Ogoja	Mbube E I	5.207	8.293	749	78	-	g	g
Ogoja	Nkum Iborr	6.361	8.582	3,882	406	-	g	g
Ogoja	Nkum Iborr	6.507	8.751	1,576	233	-	g	g

Table C.2.: Cross River (cont.)

LGA	Ward	Lat. [°]	Long. [°]	Pop. #	Demand kW_p	Phase 1	Phase 2	Phase 3
Ogoja	Nkum Iborr	6.583	8.985	1,075	163	-	g	g
Ogoja	Nkum Iborr	6.552	8.717	956	121	-	-	g
Ogoja	Nkum Iborr	6.543	8.694	1,066	131	-	g	g
Ogoja	Nkum Iborr	6.538	8.682	2,026	325	-	m-g	ic-g
Ogoja	Nkum Iborr	5.866	8.878	827	100	-	g	g
Ogoja	Nkum Iborr	6.592	8.730	574	70	-	g	g
Ogoja	Nkum Iborr	5.991	8.076	818	97	-	g	g
Ogoja	Nkum Irede	6.480	8.917	8,389	1,033	-	g	g
Ogoja	Ogoja Urban II	6.586	9.049	3,178	452	-	m-g	ic-g
Ogoja	Ogoja Urban II	6.562	8.769	799	101	-	g	g
Ogoja	Ogoja Urban II	6.572	8.738	1,626	204	-	m-g	ic-g
Ogoja	Ogoja Urban II	6.687	8.501	956	116	-	-	g
Ogoja	Ogoja Urban II	6.351	8.466	5,899	604	-	g	g
Ogoja	Ogoja Urban II	5.966	8.069	2,426	246	-	-	g
Ogoja	Oku/Borum/Njua	6.482	9.198	1,746	273	-	m-g	ic-g
Ogoja	Okuku	6.368	8.485	1,024	147	-	-	g
Ogoja	Utugwang S	6.568	9.066	3,919	562	m-g	ic-g	ic-g
Ogoja	Wanihem	6.610	8.810	1,204	155	-	-	g
Yakurr	Ajere	5.886	8.336	1,368	171	-	g	g
Yakurr	Ediba	5.818	8.208	10,488	1,479	m-g	ic-g	ic-g
Yakurr	Iko	5.650	7.970	3,427	502	m-g	m-g	ic-g
Yakurr	Imabana II	5.906	8.542	10,483	1,134	-	g	g
Yakurr	Imabana II	5.936	8.817	12,022	1,291	-	g	g
Yakurr	Mkpani/Agoi	5.700	7.968	15,790	2,234	m-g	ic-g	ic-g
Yakurr	Mkpani/Agoi	5.787	8.511	3,372	412	m-g	ic-g	ic-g
Yakurr	Mkpani/Agoi	6.530	8.758	2,766	332	-	g	g
Yakurr	Mkpani/Agoi	6.247	8.422	4,700	484	-	g	g
Yala	Echumofana	6.678	9.225	1,818	298	-	m-g	ic-g
Yala	Ekajuk I	6.604	8.455	795	82	-	-	g
Yala	Ekajuk I	6.609	8.906	1,043	156	-	-	g
Yala	Ezza Inyimagu	6.703	8.475	781	95	-	-	g
Yala	Ezza Inyimagu	6.650	8.355	1,084	131	-	-	g
Yala	Gabu	6.790	8.885	15,994	2,130	m-g	ic-g	ic-g
Yala	M-Gbalaku In. II	5.951	8.072	809	106	-	m-g	ic-g
Yala	M-Gbalaku In. II	6.623	8.770	822	86	-	-	g
Yala	M-Gbalaku In. II	6.441	8.469	827	93	-	-	g
Yala	M-Gbalaku In. II	5.355	8.010	579	69	-	-	g
Yala	M-Gbalaku In. II	6.693	8.605	753	76	-	-	g
Yala	Mbawar	6.764	8.938	2,655	358	m-g	ic-g	ic-g
Yala	Mbawar	6.766	8.879	1,521	167	-	g	g
Yala	Mbayegh/Mbaikyer	5.977	8.063	1,038	128	-	g	g
Yala	Ndieze Inyimagu	6.531	9.443	680	84	-	-	g
Yala	Ndieze Inyimagu	6.610	8.537	662	79	-	-	g
Yala	Nnam	6.776	8.788	588	69	-	-	g
Yala	Nnam	6.546	8.659	671	83	-	-	g
Yala	Oboru/Oye	6.757	8.861	1,476	217	-	m-g	ic-g
Yala	Oboru/Oye	6.815	8.859	5,871	597	m-g	m-g	ic-g
Yala	Oboru/Oye	6.517	9.399	685	80	-	-	g
Yala	Oboru/Oye	6.590	8.380	666	83	-	-	g
Yala	Oboru/Oye	6.650	8.405	2,490	264	-	m-g	ic-g
Yala	Oboru/Oye	6.719	8.474	1,103	109	-	-	g
Yala	Oboru/Oye	6.629	8.404	1,378	140	-	-	g
Yala	Okpoma	6.540	9.246	1,263	167	-	m-g	ic-g
Yala	Okpoma	6.129	8.658	965	103	-	-	g
Yala	Okpoma	6.641	8.507	634	79	-	g	g
Yala	Okpoma	6.581	8.350	574	72	-	-	g

Table C.2.: Cross River (cont.)

LGA	Ward	Lat. [°]	Long. [°]	Pop. #	Demand kW_p	Phase 1	Phase 2	Phase 3
Yala	Okuku	6.612	8.753	2,233	316	m-g	m-g	ic-g
Yala	Okuku	5.258	8.271	1,374	200	-	g	g
Yala	Okuku	6.104	8.733	3,675	484	-	g	g
Yala	Osopong I	6.304	9.219	620	76	-	-	g
Yala	Owo	6.674	9.202	1,557	237	-	m-g	ic-g
Yala	Owo	5.981	8.077	2,132	265	-	m-g	ic-g
Yala	Owo	6.728	8.627	3,303	350	-	m-g	ic-g
Yala	Owo	6.468	8.450	2,770	331	-	m-g	ic-g
Yala	Owo	6.678	8.427	1,833	224	-	m-g	ic-g
Yala	Owo	6.718	8.448	2,076	252	-	m-g	ic-g
Yala	Owo	6.635	8.898	845	108	-	-	g
Yala	Owo	6.427	8.849	1,208	128	-	-	g
Yala	Owo	6.457	9.257	965	115	-	-	g
Yala	Ugboro	6.689	9.244	1,681	234	-	-	g
Yala	Ugboro	6.727	8.819	8,977	1,088	m-g	ic-g	ic-g
Yala	Ugboro	6.718	8.486	1,038	134	-	g	g
Yala	Ugboro	5.219	8.176	873	91	-	g	g
Yala	Ugboro	5.183	8.148	1,245	154	-	-	g
Yala	Wanakom	6.788	8.655	4,100	633	m-g	ic-g	ic-g
Yala	Wanakom	6.588	8.458	1,236	134	-	m-g	ic-g
Yala	Wanihem	6.716	8.559	556	68	-	-	g
Yala	Wanihem	6.677	8.502	643	75	-	-	g
Yala	Wanikade	6.717	8.418	786	102	-	g	g
Yala	Yache	6.515	9.065	2,221	272	-	m-g	ic-g

Table C.3.: Detailed information on population and suggested phase-wise electrification of all village clusters > 50 kW peak demand in Niger.

LGA	Ward	Lat. [°]	Long. [°]	Pop. #	Demand kW_p	Phase 1	Phase 2	Phase 3
Agaie	Baro	8.554	6.688	4,756	340	-	-	g
Agaie	Baro	8.618	6.617	1,869	120	-	g	g
Agaie	Boku	9.003	6.242	2,109	139	-	g	g
Agaie	Dauaci	8.882	5.782	3,483	209	-	-	g
Agaie	Dauaci	8.937	6.168	5,923	376	-	g	g
Agaie	Etsugaie	9.126	5.440	937	66	-	g	g
Agaie	Kutiriko	9.189	5.358	1,330	94	-	g	g
Agaie	Magaji	8.842	6.308	1,815	112	-	g	g
Agaie	Magaji	8.902	6.326	1,681	105	-	g	g
Agaie	Tagagi	8.624	6.685	9,055	584	m-g	ic-g	ic-g
Agaie	Tagagi	8.661	6.590	1,311	99	-	g	g
Agaie	Tagagi	8.699	6.420	1,928	142	-	g	g
Agaie	Tagagi	8.947	5.809	1,845	122	-	g	g
Agaie	Tagagi	9.593	7.294	3,339	195	-	g	g
Agaie	Tagagi	11.003	3.840	2,316	151	m-g	ic-g	ic-g
Agwara	Agwata	10.754	5.962	1,033	85	-	m-g	m-g
Agwara	Dugga	10.575	6.462	2,152	134	-	-	g
Agwara	Dugga	10.527	4.363	1,259	79	-	-	g
Agwara	Gallah	10.664	5.993	13,033	833	m-g	m-g	ic-g
Agwara	Kashini	10.695	4.816	10,074	673	m-g	m-g	ic-g
Agwara	Kashini	9.958	4.529	2,450	146	-	-	g
Agwara	Kokoli	10.593	4.477	5,208	319	m-g	m-g	ic-g
Agwara	Mago	10.830	5.832	3,099	195	m-g	m-g	ic-g
Agwara	Papiri	10.541	6.812	2,378	169	m-g	m-g	ic-g
Agwara	Papiri	10.579	4.347	1,605	102	-	-	g
Agwara	Papiri	10.604	4.491	4,890	308	m-g	m-g	ic-g
Agwara	Rofia	10.708	5.231	4,160	240	-	m-g	ic-g
Borgu	Babanna	8.587	6.428	7,614	462	m-g	m-g	ic-g
Borgu	Babanna	8.776	5.800	1,379	101	-	m-g	m-g
Borgu	Babanna	9.622	6.156	5,241	322	m-g	m-g	ic-g
Borgu	Dugga	8.960	6.538	11,582	694	m-g	m-g	ic-g
Borgu	Dugga	8.853	6.480	1,307	75	-	-	g
Borgu	Dugga	10.431	3.814	2,964	196	-	m-g	ic-g
Borgu	Kabe/Pissa	10.844	4.094	8,743	523	m-g	m-g	ic-g
Borgu	Kabe/Pissa	10.853	3.978	1,489	92	-	-	g
Borgu	Kaoje/Gwamba	11.271	5.307	1,941	118	-	m-g	m-g
Borgu	Karabonde	9.872	6.434	4,266	253	-	g	g
Borgu	Karabonde	10.484	4.456	4,319	358	-	ic-g	ic-g
Borgu	Karabonde	10.430	4.453	2,325	147	-	g	g
Borgu	Karabonde	9.373	7.125	1,883	121	-	g	g
Borgu	Konkoso	10.539	4.463	1,657	110	m-g	m-g	m-g
Borgu	Konkoso	9.890	4.551	1,643	115	-	m-g	m-g
Borgu	Malale	9.955	4.561	4,261	261	-	g	g
Borgu	New Bussa	9.556	6.399	76,744	7,134	m-g	ic-g	ic-g
Borgu	Riverine	9.938	7.025	4,453	361	-	g	g
Borgu	Riverine	10.296	4.343	3,017	244	-	g	g
Borgu	Riverine	9.892	4.451	1,355	120	-	g	g
Borgu	Riverine	9.836	4.389	3,132	199	-	g	g
Borgu	Riverine	9.846	4.526	4,641	375	-	g	g
Borgu	Riverine	9.799	6.164	24,705	2,093	m-g	ic-g	ic-g
Borgu	Shagunu	10.068	4.493	5,717	447	-	m-g	ic-g
Borgu	Shagunu	10.614	4.029	1,605	96	-	-	g
Borgu	Shagunu	10.594	4.155	4,645	286	-	m-g	ic-g
Borgu	Shagunu	10.338	4.461	1,979	129	-	-	g
Borgu	Shagunu	9.354	6.783	1,292	89	-	-	m-g

Table C.3.: Niger (cont.)

LGA	Ward	Lat. [°]	Long. [°]	Pop. #	Demand kW_p	Phase 1	Phase 2	Phase 3
Borgu	Wawa	10.317	4.477	3,800	235	m-g	ic-g	ic-g
Borgu	Wawa	10.421	4.290	1,600	94	-	g	g
Borgu	Wawa	9.300	5.060	23,145	1,579	m-g	ic-g	ic-g
Bosso	Beji	9.613	7.339	1,024	73	-	g	g
Bosso	Beji	9.614	7.320	10,266	695	-	g	g
Bosso	Beji	9.423	6.764	1,355	80	-	g	g
Bosso	Garatu	9.483	6.985	1,326	85	-	g	g
Bosso	Kampala	9.791	4.622	1,177	81	-	g	g
Bosso	Kampala	9.834	4.572	3,531	215	-	g	g
Bosso	Kato	9.636	6.366	1,739	115	m-g	ic-g	ic-g
Bosso	Kodo	9.873	4.483	1,239	79	-	g	g
Bosso	Kodo	9.627	6.346	1,643	143	-	g	g
Bosso	Maikunkele	9.692	5.530	1,148	107	-	g	g
Bosso	Maitumbi	9.613	5.613	1,379	85	-	g	g
Bosso	Maitumbi	9.628	6.314	3,795	222	-	g	g
Bosso	Shata	9.653	5.890	2,109	183	-	g	g
Bosso	Shata	9.699	6.528	2,152	183	-	g	g
Bosso	Shata	9.709	6.638	1,907	123	-	g	g
Bosso	Shata	9.705	6.227	4,208	282	-	g	g
Bosso	Shata	9.432	6.840	2,075	135	-	g	g
Chanchaga	Limawa B	9.441	7.038	1,763	151	-	g	g
Edati	Busu/Kuchi	9.015	6.223	2,335	192	-	g	g
Edati	Busu/Kuchi	8.975	5.785	1,974	124	-	-	g
Edati	Doko	9.098	6.634	1,648	101	-	g	g
Edati	Etsu Tasha	9.165	4.814	1,499	119	-	-	g
Edati	Etsu Tasha	9.660	6.252	3,339	208	m-g	m-g	ic-g
Edati	Fazhi	9.147	6.319	1,552	117	-	-	g
Edati	Gaba	8.901	5.880	4,540	328	-	g	g
Edati	Gaba	9.346	6.795	1,191	95	-	g	g
Edati	Gaba	8.907	6.006	1,206	83	-	g	g
Edati	Gazhe I	8.788	6.498	1,663	115	-	m-g	ic-g
Edati	Gazhe I	8.934	6.134	1,115	90	m-g	m-g	ic-g
Edati	Gazhe I	9.499	6.213	1,547	112	-	-	g
Edati	Gazhe II	8.958	6.281	1,062	84	-	-	g
Edati	Ja Agi	9.060	5.792	2,330	152	-	m-g	ic-g
Edati	Jima	8.913	6.177	1,034	80	-	-	g
Edati	Jima	8.936	5.853	3,742	278	-	-	g
Edati	Jima	8.963	6.245	4,256	259	-	-	g
Edati	Kusotachi	8.976	5.753	1,428	89	-	-	g
Edati	Mambe	8.720	6.513	889	69	-	g	g
Edati	Mambe	8.815	5.942	1,191	95	-	g	g
Edati	Mambe	8.890	6.622	2,056	127	-	-	g
Edati	Mambe	9.341	5.808	1,273	88	-	-	g
Edati	Mambe	8.950	6.085	961	82	-	g	g
Edati	Rokota	9.059	6.192	1,350	84	-	m-g	ic-g
Edati	Rokota	9.744	6.510	1,052	79	-	-	g
Edati	Sakpe	9.084	5.671	2,046	128	-	-	g
Edati	Sidi Saba	8.870	6.225	1,633	106	-	g	g
Gbako	Batagi	9.112	6.755	3,151	277	-	g	g
Gbako	Batako	9.268	5.612	3,488	236	-	-	g
Gbako	Batako	9.280	6.084	1,220	86	-	-	g
Gbako	Batako	9.304	5.813	1,403	124	-	-	g
Gbako	Batako	10.212	6.110	2,267	137	-	g	g
Gbako	Edokota	9.231	6.235	1,494	120	-	g	g
Gbako	Edokota	9.071	5.495	3,392	295	-	g	g
Gbako	Edozhigi	9.050	6.418	1,004	72	-	g	g

Table C.3.: Niger (cont.)

LGA	Ward	Lat. [°]	Long. [°]	Pop. #	Demand kW$_p$	Phase 1	Phase 2	Phase 3
Gbako	Edozhigi	9.062	5.425	8,541	697	-	g	g
Gbako	Edozhigi	9.131	5.632	1,191	75	-	g	g
Gbako	Etsu Audu	9.212	5.034	1,816	136	-	g	g
Gbako	Etsu Audu	8.819	6.031	1,235	92	-	g	g
Gbako	Gogata	9.126	5.656	1,619	128	-	g	g
Gbako	Nuwankota	9.512	5.675	2,162	134	-	g	g
Gbako	Sammajiko	9.389	5.271	3,079	185	-	m-g	ic-g
Gbako	Sammajiko	9.417	6.590	1,292	81	-	-	g
Gbako	Sammajiko	9.435	6.084	1,845	115	-	-	g
Gbako	Sammajiko	9.451	7.125	3,881	246	-	-	g
Gurara	Diko	9.083	5.885	2,003	135	-	-	g
Gurara	Diko	9.221	6.041	1,883	160	-	-	g
Gurara	Kabo	9.394	7.074	3,339	208	-	m-g	ic-g
Gurara	Kabo	9.334	6.848	1,513	89	-	-	g
Gurara	Kurmin Sarki	10.098	6.685	1,470	121	-	g	g
Gurara	Kwaka	9.269	4.864	2,282	149	-	g	g
Gurara	Lambata	9.335	7.212	2,440	147	-	g	g
Gurara	Lambata	10.240	3.666	1,326	96	-	g	g
Gurara	Shako	9.360	5.782	1,797	118	-	m-g	ic-g
Gurara	Shako	9.423	6.552	3,521	211	-	-	g
Gurara	Shako	9.357	7.192	1,662	102	-	-	g
Gurara	Shako	10.266	4.284	975	68	-	m-g	ic-g
Katcha	Badeggi	9.052	5.970	1,566	117	-	g	g
Katcha	Badeggi	9.102	5.850	3,541	240	-	g	g
Katcha	Bakeko	8.954	5.890	2,633	155	-	g	g
Katcha	Bakeko	8.978	5.914	1,435	98	-	-	g
Katcha	Bakeko	9.116	6.587	1,850	112	-	g	g
Katcha	Bisanti	9.305	4.787	2,388	155	-	g	g
Katcha	Bisanti	9.288	7.021	2,753	176	-	g	g
Katcha	Dzwafu	8.929	5.902	2,479	165	-	g	g
Katcha	Dzwafu	8.990	6.725	1,236	72	-	-	g
Katcha	Dzwafu	9.208	6.748	1,826	116	-	-	g
Katcha	Dzwafu	9.476	7.177	1,206	73	-	-	g
Katcha	Dzwafu	8.693	6.688	1,350	99	-	g	g
Katcha	Edotsu	8.749	6.450	2,076	151	-	g	g
Katcha	Edotsu	8.832	6.263	1,153	80	-	-	g
Katcha	Essa	9.186	5.119	1,201	81	-	-	g
Katcha	Essa	9.258	6.199	1,263	80	-	-	g
Katcha	Essa	8.966	6.174	1,220	79	-	-	g
Katcha	Etsugaie	9.143	5.352	1,402	84	-	g	g
Katcha	Gbakogi	8.829	5.899	2,018	118	-	g	g
Katcha	Gbakogi	8.850	6.701	2,546	156	-	g	g
Katcha	Gbakogi	8.877	6.184	1,854	127	-	-	g
Katcha	Gbakogi	8.893	6.154	1,071	77	-	g	g
Katcha	Gbakogi	9.416	5.520	1,302	82	-	g	g
Katcha	Kodo	9.527	6.318	1,297	81	-	-	g
Katcha	Sidi Saba	8.925	6.071	970	76	-	-	g
Katcha	Sidi Saba	8.992	6.016	1,364	83	-	-	g
Katcha	Tutungo Jedna	9.666	7.239	1,547	96	-	-	g
Kontagora	Nagwamatse	9.032	6.207	1,528	102	-	-	g
Lapai	Arewa/Yamma	9.924	5.662	2,642	159	-	g	g
Lapai	Birnin M/Tashibo	8.828	5.814	1,182	101	m-g	m-g	ic-g
Lapai	Birnin M/Tashibo	8.978	6.540	1,872	129	-	m-g	ic-g
Lapai	Birnin M/Tashibo	9.081	5.442	3,834	323	m-g	m-g	ic-g
Lapai	Birnin M/Tashibo	9.194	6.229	6,356	389	-	-	g
Lapai	Bonu	9.121	5.962	2,796	176	m-g	ic-g	ic-g

Table C.3.: Niger (cont.)

LGA	Ward	Lat. [°]	Long. [°]	Pop. #	Demand kW_p	Phase 1	Phase 2	Phase 3
Lapai	Ebbo/Gbacinku	6.419	9.362	19,158	1,226	m-g	m-g	ic-g
Lapai	Ebbo/Gbacinku	11.318	4.945	975	75	-	-	g
Lapai	Ebbo/Gbacinku	9.168	6.204	1,336	86	-	m-g	ic-g
Lapai	Ebbo/Gbacinku	10.295	5.473	1,955	118	-	m-g	ic-g
Lapai	Evuti/Kpada	8.347	6.661	1,926	140	-	-	g
Lapai	Evuti/Kpada	8.440	6.727	1,513	129	-	-	g
Lapai	Evuti/Kpada	8.564	6.568	6,831	410	m-g	m-g	ic-g
Lapai	Evuti/Kpada	9.839	5.467	1,196	72	-	-	g
Lapai	Gulu/Anguwa V	8.444	6.589	1,206	99	-	-	g
Lapai	Gulu/Anguwa V	8.565	6.625	1,355	83	-	m-g	ic-g
Lapai	Gulu/Anguwa V	8.615	6.421	12,250	866	m-g	m-g	ic-g
Lapai	Gupa/Abugi	6.614	8.787	4,549	295	m-g	m-g	ic-g
Lapai	Gupa/Abugi	8.997	6.634	1,153	87	-	m-g	ic-g
Lapai	Gurdi/Zago	8.874	6.456	2,738	171	m-g	m-g	ic-g
Lapai	Gurdi/Zago	8.482	6.565	1,336	107	m-g	m-g	m-g
Lapai	Gurdi/Zago	8.405	6.622	1,105	77	-	m-g	ic-g
Lapai	Lefu	9.344	7.235	1,902	122	-	m-g	ic-g
Lapai	Muye/Egba	6.533	8.701	8,186	506	m-g	m-g	ic-g
Lapai	Muye/Egba	8.371	6.680	3,737	241	-	m-g	ic-g
Lapai	Takuti/Shaku	8.819	6.765	2,282	140	-	-	g
Lapai	Takuti/Shaku	8.794	6.611	2,215	141	-	-	g
Lapai	Takuti/Shaku	8.293	6.680	1,134	93	-	g	g
Lapai	Takuti/Shaku	9.039	6.179	1,340	80	-	g	g
Lapai	Yaba	10.713	4.594	1,302	82	-	-	g
Lavun	Dabban	9.266	5.258	808	64	-	-	g
Lavun	Dabban	9.376	5.021	1,301	106	-	m-g	ic-g
Lavun	Dassun	9.239	5.996	2,186	156	-	-	g
Lavun	Dassun	9.326	6.212	841	68	-	m-g	ic-g
Lavun	Dassun	9.320	5.222	2,277	152	m-g	m-g	ic-g
Lavun	Dassun	9.328	5.476	2,176	164	m-g	m-g	ic-g
Lavun	Dassun	9.400	5.642	1,215	73	m-g	m-g	m-g
Lavun	Dassun	9.456	4.968	1,614	143	m-g	m-g	ic-g
Lavun	Egbako	9.223	6.392	3,885	251	-	-	g
Lavun	Egbako	9.290	6.068	1,316	91	-	m-g	ic-g
Lavun	Egbako	9.340	6.675	2,120	178	-	m-g	ic-g
Lavun	Egbako	9.123	6.676	1,230	90	-	m-g	ic-g
Lavun	Etsu Tasha	9.061	5.862	5,784	348	-	m-g	ic-g
Lavun	Gbangban	9.154	6.112	1,201	76	-	-	g
Lavun	Lagun	9.562	6.918	2,666	185	m-g	m-g	ic-g
Lavun	Lagun	9.661	4.907	2,168	164	-	-	g
Lavun	Lagun	11.311	5.248	1,681	126	-	m-g	ic-g
Lavun	Tukunji/Yamigi	9.498	6.579	1,624	137	m-g	m-g	ic-g
Lavun	Tukunji/Yamigi	9.610	7.134	2,256	179	-	-	g
Magama	Auna Central	10.011	5.108	10,497	656	m-g	ic-g	ic-g
Magama	Auna SE	10.076	4.718	4,540	273	-	m-g	ic-g
Magama	Auna SE	10.104	6.618	1,081	88	m-g	m-g	ic-g
Magama	Auna SE	10.101	4.700	2,123	162	-	g	g
Magama	Auna South	10.011	6.460	5,059	306	-	g	g
Magama	Auna South	10.067	5.047	1,552	97	-	m-g	ic-g
Magama	Ibelu North	10.549	6.615	2,196	141	-	g	g
Magama	Ibelu North	10.683	5.745	1,553	92	m-g	m-g	m-g
Magama	Ibelu West	10.630	4.403	2,298	135	-	-	g
Magama	Nasko	10.380	6.587	970	61	-	-	g
Magama	Nassarawa	9.908	4.558	1,215	73	-	g	g
Magama	Nassarawa	10.053	6.678	1,605	100	m-g	m-g	ic-g
Magama	Riverine	9.824	7.092	8,128	739	m-g	ic-g	ic-g

Table C.3.: Niger (cont.)

LGA	Ward	Lat. [°]	Long. [°]	Pop. #	Demand kW_p	Phase 1	Phase 2	Phase 3
Mariga	Bangi	10.623	4.514	4,674	427	m-g	m-g	ic-g
Mariga	Bangi	10.718	4.693	12,514	1,066	m-g	m-g	ic-g
Mariga	Bobi	10.214	6.223	3,939	303	-	-	g
Mariga	Bobi	10.341	6.827	2,364	146	-	m-g	ic-g
Mariga	Galma/Wamba	10.598	5.159	1,573	105	-	-	g
Mariga	Galma/Wamba	10.629	5.715	2,493	148	-	m-g	m-g
Mariga	Galma/Wamba	10.707	4.577	1,326	89	-	-	m-g
Mariga	Gulbin - Boka	10.690	4.466	1,009	74	-	-	m-g
Mariga	Igwama	10.395	6.835	4,223	273	m-g	m-g	ic-g
Mariga	Kakangi	10.717	5.560	1,182	87	-	-	m-g
Mariga	Kakihum	10.810	6.056	2,741	195	m-g	m-g	ic-g
Mariga	Kontokoro	10.916	5.202	3,819	234	m-g	m-g	ic-g
Mariga	Kontokoro	10.931	5.613	9,497	661	m-g	m-g	ic-g
Mariga	Kontokoro	8.916	6.091	2,224	133	-	-	g
Mariga	Kontokoro	8.999	5.922	1,441	90	-	-	g
Mariga	Kumbashi	10.857	5.643	1,965	142	-	m-g	ic-g
Mariga	Maburya	10.837	4.703	1,499	94	-	m-g	m-g
Mariga	Maburya	10.899	5.466	1,691	113	m-g	m-g	m-g
Mariga	Warari	10.920	5.707	1,200	75	-	m-g	m-g
Mashegu	Auna SE	10.115	4.623	2,856	185	m-g	m-g	ic-g
Mashegu	Auna South	9.871	6.420	1,624	111	-	g	g
Mashegu	Bokani	9.536	7.125	1,009	70	-	m-g	ic-g
Mashegu	Dapangi/Makera	9.475	5.244	1,785	117	-	-	g
Mashegu	Dapangi/Makera	8.867	5.964	1,672	110	m-g	m-g	m-g
Mashegu	Dapangi/Makera	11.066	5.958	1,105	80	-	-	g
Mashegu	Ibbi	9.431	5.220	4,929	431	m-g	ic-g	ic-g
Mashegu	Ibbi	9.577	7.162	3,862	227	-	g	g
Mashegu	Ibbi	9.658	6.623	8,008	686	m-g	ic-g	ic-g
Mashegu	Kaboji	10.073	5.160	2,691	225	-	m-g	ic-g
Mashegu	Kaboji	11.070	6.018	2,858	170	-	g	g
Mashegu	Kasanga	10.106	5.242	2,071	125	-	g	g
Mashegu	Kulho	9.933	5.636	1,232	72	-	-	m-g
Mashegu	Kulho	10.012	6.631	3,276	217	m-g	m-g	ic-g
Mashegu	Kwatachi	9.722	6.670	951	65	-	-	m-g
Mashegu	Kwatachi	9.794	6.945	17,241	1,521	m-g	ic-g	ic-g
Mashegu	Kwatachi	9.647	5.215	1,297	78	-	g	g
Mashegu	Mashegu	9.734	4.699	1,139	102	-	-	g
Mashegu	Mashegu	9.901	5.914	2,147	147	-	m-g	ic-g
Mashegu	Mashegu	9.777	6.514	1,451	85	-	-	g
Mashegu	Mazakuka/Likoro	9.974	7.214	1,191	113	m-g	m-g	ic-g
Mashegu	Mazakuka/Likoro	10.020	4.767	1,038	87	-	-	m-g
Mashegu	Mazakuka/Likoro	10.052	4.816	1,518	116	-	m-g	ic-g
Mashegu	Rabba/Ndayako	9.362	6.605	2,402	177	m-g	ic-g	ic-g
Mashegu	Saho-Rami	9.923	4.630	6,663	565	-	g	g
Mashegu	Saho-Rami	8.760	5.778	1,902	120	-	-	g
Mokwa	Bokani	9.403	5.463	12,106	781	m-g	m-g	ic-g
Mokwa	Bokani	9.459	6.100	3,999	295	-	m-g	ic-g
Mokwa	Bokani	9.466	5.332	2,044	129	-	-	g
Mokwa	Etsu Tasha	9.026	6.129	2,360	183	-	m-g	ic-g
Mokwa	Gbajibo/Muwo	9.253	5.905	5,073	436	m-g	ic-g	ic-g
Mokwa	Gbajibo/Muwo	9.308	7.322	10,276	869	m-g	ic-g	ic-g
Mokwa	Gbajibo/Muwo	9.504	5.168	5,380	331	-	g	g
Mokwa	Gbajibo/Muwo	10.261	5.247	1,153	82	-	g	g
Mokwa	Gbara	8.858	6.234	1,163	86	-	-	g
Mokwa	Gbara	8.910	6.441	10,100	727	m-g	m-g	ic-g
Mokwa	Ja Agi	9.190	7.239	2,520	152	-	-	g

Table C.3.: Niger (cont.)

LGA	Ward	Lat. [°]	Long. [°]	Pop. #	Demand kW_p	Phase 1	Phase 2	Phase 3
Mokwa	Ja Agi	9.194	7.251	4,575	296	m-g	ic-g	ic-g
Mokwa	Ja Agi	9.770	4.706	2,046	179	m-g	ic-g	ic-g
Mokwa	Jebba North	9.099	5.324	13,754	1,189	m-g	ic-g	ic-g
Mokwa	Kpaki/Takuma	9.260	5.778	1,585	99	-	-	g
Mokwa	Kpaki/Takuma	9.317	5.346	1,753	126	-	g	g
Mokwa	Kpaki/Takuma	9.365	6.631	1,129	98	-	-	g
Mokwa	Kudu	9.316	7.343	1,928	115	-	-	g
Mokwa	Kudu	9.320	6.083	1,605	102	-	-	g
Mokwa	Labozhi	9.074	5.770	1,405	85	-	-	g
Mokwa	Labozhi	9.129	6.122	2,675	160	-	-	g
Mokwa	Labozhi	9.172	5.710	3,381	208	-	g	g
Mokwa	Muregi	9.244	4.919	1,268	85	m-g	m-g	m-g
Mokwa	Muregi	10.237	6.222	1,441	104	-	m-g	ic-g
Mokwa	Patigi IV	9.994	6.008	2,748	192	m-g	m-g	ic-g
Mokwa	Rabba/Ndayako	9.608	6.495	77,625	6,662	m-g	ic-g	ic-g
Mokwa	Rokota	9.112	6.214	1,591	98	-	-	g
Muya	Fuka	9.638	6.638	1,192	81	-	-	g
Muya	Guni	9.758	6.678	4,713	284	-	g	g
Muya	Guni	9.789	6.770	2,005	146	-	-	g
Muya	Kabula	9.761	5.657	2,580	157	-	g	g
Muya	Kuchi	9.904	4.752	2,834	206	-	-	g
Muya	Sarkin Pawa	9.932	4.881	2,360	166	-	-	g
Muya	She	9.532	6.076	1,207	87	-	m-g	ic-g
Pailoro	Adunu	9.572	7.074	4,448	327	-	-	g
Pailoro	Bishini	9.578	4.739	1,878	116	m-g	m-g	ic-g
Pailoro	Bishini	11.238	4.903	994	71	-	-	g
Pailoro	Chimbi	9.463	5.439	2,156	138	-	g	g
Pailoro	Chimbi	10.435	3.831	1,922	129	-	g	g
Pailoro	Garatu	9.473	6.143	1,206	93	-	g	g
Pailoro	Gwam	9.230	4.890	3,603	214	-	g	g
Pailoro	Gwam	9.182	4.847	1,379	85	-	-	g
Pailoro	Gwam	9.287	6.962	3,651	223	-	g	g
Pailoro	Ishau	9.535	5.830	2,974	231	m-g	m-g	ic-g
Pailoro	Ishau	9.600	7.065	9,829	606	m-g	m-g	ic-g
Pailoro	Ishau	8.788	5.767	3,363	217	-	m-g	ic-g
Pailoro	Jere	9.939	6.677	1,201	73	-	-	g
Pailoro	Kafin Koro	9.510	6.408	1,502	102	-	g	g
Pailoro	Kwagana	9.511	5.186	1,187	89	-	-	g
Pailoro	Kwagana	9.527	5.286	3,742	229	-	-	g
Pailoro	Kwagana	9.576	6.146	1,088	79	-	-	g
Pailoro	Kwagana	9.579	5.804	1,893	134	-	-	g
Pailoro	Kwakuti	9.673	5.910	1,504	88	-	-	g
Pailoro	Nikuchi T/Mallam	9.327	5.359	4,530	270	-	m-g	ic-g
Pailoro	Nikuchi T/Mallam	9.341	5.565	1,110	67	-	-	g
Pailoro	Nikuchi T/Mallam	9.434	6.761	1,585	102	-	-	g
Pailoro	Nikuchi T/Mallam	9.502	6.773	3,108	185	-	-	g
Pailoro	Tutungo Jedna	9.331	5.574	3,228	229	-	-	g
Pailoro	Tutungo Jedna	9.410	7.180	2,364	148	-	-	g
Pailoro	Tutungo Jedna	9.409	6.128	1,912	120	-	-	g
Pailoro	Tutungo Jedna	9.479	6.478	1,193	102	-	g	g
Rafi	Inkwai	10.272	6.613	1,681	101	-	-	g
Rafi	Kagara Gari	10.132	5.931	2,447	206	-	g	g
Rafi	Kagara Gari	9.005	6.079	1,263	84	-	g	g
Rafi	Kakuri	9.965	5.388	4,535	280	m-g	m-g	ic-g
Rafi	Kakuri	9.368	6.686	1,321	87	-	-	g
Rafi	Kusherki North	10.455	5.898	6,413	415	m-g	m-g	ic-g

Table C.3.: Niger (cont.)

LGA	Ward	Lat. [°]	Long. [°]	Pop. #	Demand kW_p	Phase 1	Phase 2	Phase 3
Rafi	Kusherki North	10.526	6.434	3,262	193	-	m-g	ic-g
Rafi	Kushirki South	10.309	7.042	2,248	143	-	-	g
Rafi	Kushirki South	10.336	6.923	1,379	89	-	-	g
Rafi	Kushirki South	10.370	6.082	1,001	70	-	-	g
Rafi	Kushirki South	9.185	7.138	1,201	74	-	g	g
Rafi	Manta	9.826	6.956	1,874	112	-	m-g	ic-g
Rafi	Manta	9.846	4.641	5,698	337	-	m-g	ic-g
Rafi	Tegina West	8.900	6.216	1,614	101	m-g	ic-g	ic-g
Rijau	Danrangi	11.203	4.940	1,337	85	-	-	g
Rijau	Dukku	11.170	5.010	1,018	73	m-g	m-g	m-g
Rijau	Dukku	11.209	5.145	1,212	116	m-g	m-g	m-g
Rijau	Dukku	11.224	5.166	1,643	116	-	m-g	m-g
Rijau	Genu	10.874	4.428	1,734	113	-	m-g	ic-g
Rijau	Manga/Ushe	11.034	5.333	3,368	257	m-g	m-g	ic-g
Rijau	Manga/Ushe	11.178	5.384	1,023	83	-	m-g	ic-g
Rijau	Senchi	9.470	6.702	1,446	86	-	g	g
Rijau	Shambo	10.955	5.433	1,234	72	-	-	g
Rijau	T/Magajiya	11.034	5.960	1,953	137	-	g	g
Rijau	T/Magajiya	9.293	6.644	1,412	101	-	g	g
Rijau	Ushe	11.002	5.998	1,840	160	m-g	m-g	ic-g
Shiroro	Allawa	10.141	4.853	1,674	119	-	-	g
Shiroro	Allawa	10.187	4.946	1,261	79	-	m-g	ic-g
Shiroro	Allawa	10.308	6.934	2,733	211	-	-	g
Shiroro	Allawa	10.340	6.888	1,819	129	-	-	g
Shiroro	Allawa	10.351	6.771	1,280	97	-	-	g
Shiroro	Bassa/Kukoki	10.065	4.624	6,356	386	-	m-g	ic-g
Shiroro	Egwa/Gwada	9.749	6.047	1,922	138	-	g	g
Shiroro	Egwa/Gwada	9.376	6.507	2,959	190	-	g	g
Shiroro	Egwa/Gwada	9.985	6.494	2,618	218	-	g	g
Shiroro	Erana	10.009	5.181	1,532	118	-	-	g
Shiroro	Erana	11.147	5.312	1,115	67	-	-	g
Shiroro	Erana	9.802	6.823	1,345	78	-	-	g
Shiroro	Gayam	10.503	6.914	1,811	130	-	-	g
Shiroro	Gurmana	9.927	4.525	6,019	401	-	m-g	ic-g
Shiroro	Gussoro	9.759	6.791	1,907	137	-	-	g
Shiroro	Gussoro	10.295	6.849	1,287	76	-	-	g
Shiroro	Kushaka/Kurebe	10.374	5.984	1,898	127	-	m-g	m-g
Shiroro	Kushaka/Kurebe	10.384	6.204	2,192	144	-	m-g	m-g
Shiroro	Kushaka/Kurebe	10.409	5.085	4,213	253	-	m-g	ic-g
Shiroro	Kushaka/Kurebe	10.448	6.911	1,488	90	-	-	m-g
Shiroro	Kushaka/Kurebe	10.472	6.923	1,278	82	-	m-g	m-g
Shiroro	Kwaki/Chukwuba	10.285	6.723	1,519	98	-	-	m-g
Shiroro	Kwaki/Chukwuba	10.284	5.909	856	60	-	-	m-g
Shiroro	Kwaki/Chukwuba	10.290	6.064	2,222	138	-	m-g	m-g
Shiroro	Kwaki/Chukwuba	10.316	6.860	3,287	199	-	-	g
Shiroro	Kwaki/Chukwuba	10.321	6.656	2,037	118	-	-	m-g
Shiroro	Kwaki/Chukwuba	10.316	6.166	1,940	145	-	m-g	ic-g
Shiroro	Kwaki/Chukwuba	10.109	6.717	2,013	126	m-g	m-g	m-g
Shiroro	Pina	9.695	6.716	1,201	75	-	g	g
Shiroro	Pina	9.707	6.543	1,456	91	-	g	g
Shiroro	Pina	9.736	6.196	6,135	378	-	g	g
Shiroro	She	9.672	6.966	5,044	304	-	g	g
Tafa	Dogon Kurmi	9.278	5.650	3,665	256	-	g	g
Tafa	Garam	9.295	7.105	12,380	1,081	-	g	g
Tafa	Zuma East	9.168	6.253	3,963	331	-	g	g
Tafa	Zuma East	9.171	5.646	1,303	105	-	g	g

Table C.3.: Niger (cont.)

LGA	Ward	Lat. [°]	Long. [°]	Pop. #	Demand kW_p	Phase 1	Phase 2	Phase 3
Wushishi	Akare	9.633	6.329	1,954	140	m-g	m-g	ic-g
Wushishi	Akare	9.958	6.666	4,141	265	m-g	m-g	ic-g
Wushishi	Kasanga	9.853	4.613	2,075	127	-	-	g
Wushishi	Kodo	9.573	7.231	1,547	102	-	-	g
Wushishi	Kwata	9.729	6.502	1,220	88	-	-	g
Wushishi	Sabon Gari	9.308	6.052	1,023	76	-	-	g
Wushishi	Tukunji/Yamigi	9.540	7.167	1,513	96	m-g	m-g	m-g
Wushishi	Tukunji/Yamigi	9.563	5.322	1,346	95	m-g	m-g	m-g
Wushishi	Zungeru	9.712	6.468	3,502	249	-	g	g
Wushishi	Zungeru	8.641	6.777	7,009	445	-	g	g

Table C.4.: Detailed information on population and suggested phase-wise electrification of all village clusters > 50 kW peak demand in Ogun.

LGA	Ward	Lat. [°]	Long. [°]	Pop. #	Demand kW_p	Phase 1	Phase 2	Phase 3
Abeokuta N	Ibara Orile	7.020	2.800	2,295	201	m-g	ic-g	ic-g
Abeokuta N	Ido Foi	6.584	3.024	1,040	74	-	g	g
Abeokuta N	Ido Foi	7.220	3.574	3,868	218	-	g	g
Abeokuta N	Ido Foi	6.819	4.119	937	65	-	-	g
Abeokuta N	Ilugun/Iberekodo	6.897	2.881	1,385	110	-	-	g
Abeokuta N	Imala Idiemi	7.229	3.449	2,088	124	-	g	g
Abeokuta N	Isaga Ilewo	7.081	3.908	2,518	183	m-g	ic-g	ic-g
Ado-Odo/Ota	Agbara/Ejila A	6.491	2.874	2,062	171	-	g	g
Ado-Odo/Ota	Agbara/Ejila A	6.530	4.392	1,368	108	-	g	g
Ado-Odo/Ota	Agbara/Ejila A	6.541	3.012	1,146	94	-	g	g
Ado-Odo/Ota	Alapoti	6.549	2.876	2,071	183	m-g	m-g	ic-g
Ado-Odo/Ota	Atan	6.626	4.122	6,531	554	m-g	ic-g	ic-g
Ado-Odo/Ota	Atan	6.630	3.204	1,559	132	-	m-g	ic-g
Ado-Odo/Ota	Atan	7.247	3.660	1,487	124	-	-	g
Ado-Odo/Ota	Atan	7.256	3.291	1,342	114	-	m-g	ic-g
Ado-Odo/Ota	Atan	7.263	2.766	1,065	91	-	-	g
Ado-Odo/Ota	Ere	6.632	3.111	2,143	187	-	g	g
Ado-Odo/Ota	Ere	6.709	3.077	3,229	272	-	g	g
Ado-Odo/Ota	Ere	6.685	3.085	4,703	319	m-g	ic-g	ic-g
Ado-Odo/Ota	Ere	6.657	3.134	1,517	128	-	g	g
Ado-Odo/Ota	Ere	6.638	3.156	1,491	118	-	-	g
Ado-Odo/Ota	Ere	6.710	3.147	1,001	87	-	m-g	ic-g
Ado-Odo/Ota	Ere	6.732	3.123	1,525	89	-	-	g
Ado-Odo/Ota	Ere	6.726	3.195	1,849	124	-	g	g
Ado-Odo/Ota	Iju	9.577	9.838	6,558	579	m-g	ic-g	ic-g
Ado-Odo/Ota	Iju	6.533	4.515	3,116	263	-	g	g
Ado-Odo/Ota	Iju	6.532	4.237	2,610	213	-	m-g	ic-g
Ado-Odo/Ota	Iju	6.560	4.566	1,376	111	-	g	g
Ado-Odo/Ota	Iju	6.558	4.410	8,772	736	m-g	m-g	ic-g
Ado-Odo/Ota	Iju	7.262	2.790	1,142	97	-	-	g
Ado-Odo/Ota	Iju	7.285	3.722	1,082	87	-	-	g
Ado-Odo/Ota	Ilogbo	6.674	3.049	1,861	158	m-g	m-g	ic-g
Ado-Odo/Ota	Ilogbo	7.300	3.297	1,057	84	-	-	g
Ado-Odo/Ota	Ilogbo	6.534	3.026	1,014	81	-	-	g
Ado-Odo/Ota	Ilogbo	7.332	3.063	2,727	225	-	m-g	ic-g
Ado-Odo/Ota	Ilogbo-Araromi	6.382	4.522	8,316	693	m-g	m-g	ic-g
Ado-Odo/Ota	Ilogbo-Araromi	7.226	3.617	1,491	125	-	m-g	ic-g
Ado-Odo/Ota	Ketu-Adie-Owe	6.565	2.926	1,896	156	-	g	g
Ado-Odo/Ota	Ketu-Adie-Owe	6.545	2.909	1,069	88	-	-	g
Ado-Odo/Ota	Ketu-Adie-Owe	6.537	2.900	1,363	109	-	m-g	ic-g
Ado-Odo/Ota	Ketu-Adie-Owe	6.560	2.961	1,619	131	-	-	g
Ado-Odo/Ota	Ketu-Adie-Owe	6.529	2.998	1,095	88	-	-	g
Egbado N	Afon	7.015	3.990	1,253	88	-	g	g
Egbado N	Ebute Igbooro	6.867	3.599	3,843	221	-	g	g
Egbado N	Ebute Igbooro	6.581	3.050	2,684	225	-	g	g
Egbado N	Ebute Igbooro	6.618	3.087	997	70	-	g	g
Egbado N	Ebute Igbooro	6.552	3.043	1,129	79	-	-	g
Egbado N	Ebute Igbooro	7.200	3.569	2,424	173	-	g	g
Egbado N	Ebute Igbooro	7.042	2.996	3,783	322	-	g	g
Egbado N	Ebute Igbooro	7.154	2.930	1,321	111	-	g	g
Egbado N	Ibese	6.616	3.104	1,346	91	-	g	g
Egbado N	Ibese	7.511	2.899	2,863	188	-	g	g
Egbado N	Iboro/Joga	6.578	3.068	1,227	83	-	-	g
Egbado N	Idi Ayin	7.473	2.947	1,623	100	-	g	g
Egbado N	Idi Ayin	7.541	2.971	1,457	97	-	g	g

Table C.4.: Ogun (cont.)

LGA	Ward	Lat. [°]	Long. [°]	Pop. #	Demand kW$_p$	Phase 1	Phase 2	Phase 3
Egbado N	Ido Foi	7.352	3.005	1,304	73	-	-	g
Egbado N	Idofa	7.119	4.031	1,483	89	-	g	g
Egbado N	Igua	6.949	2.724	2,578	177	-	m-g	ic-g
Egbado N	Igua	6.988	4.450	4,043	243	m-g	m-g	ic-g
Egbado N	Ijoun	6.988	3.650	22,363	1,836	m-g	m-g	ic-g
Egbado N	Ijoun	7.114	3.614	2,228	154	-	m-g	ic-g
Egbado N	Ijoun	7.147	3.191	2,799	227	-	m-g	ic-g
Egbado N	Ijoun	7.186	2.904	1,670	118	-	-	g
Egbado N	Imasai	6.782	4.277	2,177	154	-	g	g
Egbado N	Iwoye	7.310	3.062	1,355	125	-	m-g	ic-g
Egbado N	Kajola/Agberiodo	6.715	3.991	1,325	82	-	-	g
Egbado N	Kajola/Agberiodo	7.496	2.925	1,512	89	-	-	g
Egbado N	Kajola/Agberiodo	7.592	2.886	1,551	92	-	-	g
Egbado N	Ohunbe	6.886	3.371	1,402	78	-	-	g
Egbado N	Ohunbe	6.897	3.148	2,957	202	m-g	m-g	ic-g
Egbado N	Ohunbe	6.900	2.897	2,198	138	-	m-g	ic-g
Egbado N	Ohunbe	6.924	3.092	8,461	509	m-g	ic-g	ic-g
Egbado N	Ohunbe	6.553	2.820	1,312	74	-	g	g
Egbado N	Sunwa	7.108	2.878	3,012	202	-	m-g	ic-g
Egbado N	Sunwa	7.127	4.162	2,458	173	-	m-g	ic-g
Egbado N	Sunwa	7.608	2.772	1,295	78	-	-	g
Egbado S	Ajilete	6.748	3.496	1,431	130	-	g	g
Egbado S	Asa/Yobo	6.851	3.107	1,040	85	-	-	g
Egbado S	Ilobi/Erinja	6.707	4.055	1,879	106	-	g	g
Egbado S	Ilobi/Erinja	6.720	3.882	2,058	144	-	g	g
Egbado S	Ilobi/Erinja	6.936	2.856	1,278	103	-	g	g
Egbado S	Iwoye	6.748	3.038	1,236	100	-	g	g
Egbado S	Iwoye	6.785	4.142	3,519	270	m-g	ic-g	ic-g
Egbado S	Iwoye	6.575	3.151	967	67	-	-	g
Egbado S	Iwoye	6.549	2.787	2,122	148	-	g	g
Egbado S	Iwoye	7.057	3.109	1,483	127	-	g	g
Ewekoro	Asa/Yobo	6.906	4.065	929	72	-	m-g	ic-g
Ewekoro	Elere/Onigbedu	6.918	3.454	1,947	160	-	-	g
Ewekoro	Elere/Onigbedu	6.841	3.010	1,133	91	-	m-g	ic-g
Ewekoro	Elere/Onigbedu	6.931	2.973	5,432	340	m-g	m-g	ic-g
Ewekoro	Itori	6.973	2.864	1,858	140	-	g	g
Ewekoro	Itori	6.886	2.796	1,704	136	-	g	g
Ewekoro	Itori	7.016	3.026	1,427	121	-	g	g
Ewekoro	Mosan	6.741	3.002	950	65	-	g	g
Ewekoro	Papalanto	6.851	3.071	1,517	123	-	g	g
Ewekoro	Papalanto	6.889	2.932	1,044	89	-	g	g
Ewekoro	Sunren	6.932	3.239	1,491	124	-	m-g	ic-g
Ewekoro	Wasimi	6.774	3.064	1,734	109	-	-	g
Ifo	Abalabi	6.819	3.096	1,428	117	-	g	g
Ifo	Abalabi	6.822	3.158	1,491	114	-	g	g
Ifo	Coker	6.727	3.853	3,779	305	m-g	ic-g	ic-g
Ifo	Coker	6.988	3.113	1,772	148	-	g	g
Ifo	Coker	7.012	3.099	1,278	103	-	g	g
Ifo	Ibogun	6.759	3.319	1,027	86	-	g	g
Ifo	Ibogun	6.775	3.139	1,270	102	-	g	g
Ifo	Ibogun	6.773	3.002	7,051	596	m-g	ic-g	ic-g
Ifo	Ibogun	6.791	2.740	1,133	94	-	g	g
Ifo	Ibogun	6.792	3.035	1,287	107	-	g	g
Ifo	Ibogun	6.811	3.250	1,534	119	-	g	g
Ifo	Ibogun	6.857	3.175	1,760	144	-	g	g
Ifo	Oke-Aro/Ibaragun	6.694	2.793	2,036	171	-	m-g	ic-g

Table C.4.: Ogun (cont.)

LGA	Ward	Lat. [°]	Long. [°]	Pop. #	Demand kW_p	Phase 1	Phase 2	Phase 3
Ifo	Oke-Aro/Ibaragun	6.722	3.939	1,344	105	-	-	g
Ifo	Ososun	6.743	3.022	2,019	165	-	m-g	ic-g
Ifo	Ososun	6.771	2.771	1,491	120	-	g	g
Ifo	Ososun	6.793	3.123	5,185	416	m-g	ic-g	ic-g
Ifo	Sunren	6.925	3.294	1,274	102	-	-	g
Ijebu E	Ajebandele	6.778	3.278	3,779	264	m-g	m-g	ic-g
Ijebu E	Ajebandele	6.835	3.123	3,408	209	m-g	m-g	ic-g
Ijebu E	Ajebandele	6.487	2.859	2,509	146	-	m-g	ic-g
Ijebu E	Imewiro/Ododeyo	6.765	3.149	1,253	78	-	m-g	ic-g
Ijebu E	Imobi II	6.533	3.183	1,368	85	-	-	g
Ijebu E	Itele	6.726	4.034	3,303	284	-	m-g	ic-g
Ijebu E	Itele	6.504	4.397	1,329	113	-	m-g	ic-g
Ijebu E	Osun	6.936	3.321	2,983	178	-	-	g
Ijebu E	Owu	6.810	3.109	1,278	72	-	-	g
Ijebu E	Owu	6.986	3.262	4,141	280	m-g	m-g	ic-g
Ijebu E	Owu	7.022	3.204	1,427	83	-	-	g
Ijebu N	Ako-Onigbagbo	6.759	3.107	1,278	96	m-g	m-g	ic-g
Ijebu N	Anlugbua	6.968	3.125	9,371	554	m-g	m-g	ic-g
Ijebu N	Mamu/Etiri	6.932	2.744	4,414	324	m-g	m-g	ic-g
Ijebu N	Omen	6.796	3.333	1,316	97	-	-	g
Ijebu N	Omen	6.871	3.289	1,402	118	-	m-g	ic-g
Ijebu N	Oru/Awa/Ilaporu	7.438	3.592	1,095	77	-	-	g
Ijebu N	Osun	6.876	3.319	1,108	84	-	g	g
Ijebu NE	Igede/Itamarun	6.837	4.368	1,087	90	-	g	g
Ijebu NE	Imewiro/Ododeyo	6.809	3.161	2,752	208	m-g	ic-g	ic-g
Ijebu NE	Imewiro/Ododeyo	6.822	2.763	7,823	478	m-g	ic-g	ic-g
Ijebu NE	Imewiro/Ododeyo	6.859	4.028	14,712	1,057	m-g	ic-g	ic-g
Ijebu NE	Odosimadegun	6.855	4.058	8,284	671	-	g	g
Ijebu ode	Itamapako	6.651	3.170	983	77	-	m-g	ic-g
Ijebu ode	Itamapako	6.682	3.988	1,636	103	-	m-g	ic-g
Ijebu ode	Itamapako	6.827	3.140	2,531	214	-	m-g	ic-g
Ijebu ode	Odoragunsin	6.604	3.161	2,748	223	-	m-g	ic-g
Imeko-Afon	Imala - Idiemi	6.315	4.550	1,900	111	-	m-g	ic-g
Imeko-Afon	Imeko	6.822	4.173	1,696	98	-	-	g
Imeko-Afon	Iwoye/Jabata	6.602	4.287	1,653	97	-	-	g
Imeko-Afon	Oke A/Moriwi	6.833	4.135	1,159	70	-	-	g
Imeko-Afon	Oke A/Moriwi	6.351	4.439	1,777	111	-	-	g
Imeko-Afon	Oke A/Moriwi	7.021	3.912	1,956	114	-	g	g
Imeko-Afon	Oke A/Moriwi	7.005	3.507	1,823	108	-	-	g
Imeko-Afon	Olorunda/Gbomo	7.372	2.785	1,704	105	-	-	g
Imeko-Afon	Olorunda/Gbomo	7.387	2.932	1,346	83	-	-	g
Imeko-Afon	Olorunda/Gbomo	7.496	2.956	2,650	164	-	m-g	ic-g
Imeko-Afon	Olorunda/Gbomo	7.434	3.705	1,346	80	-	-	g
Imeko-Afon	Otapele	6.964	4.062	4,763	288	m-g	m-g	ic-g
Imeko-Afon	Otapele	6.969	3.817	2,318	137	-	-	g
Imeko-Afon	Otapele	6.873	4.141	1,627	93	-	-	g
Ipokia	Agada	8.733	9.183	2,007	167	m-g	m-g	ic-g
Ipokia	Agada	6.417	4.518	5,138	361	m-g	m-g	ic-g
Ipokia	Agada	6.562	2.795	1,265	100	-	-	g
Ipokia	Agosasa	7.472	2.979	2,071	169	-	g	g
Ipokia	Ajegunle	6.551	2.750	1,619	128	-	g	g
Ipokia	Ifonyintedo	6.722	3.162	2,252	163	-	g	g
Ipokia	Ifonyintedo	6.749	3.299	6,105	420	m-g	ic-g	ic-g
Ipokia	Ifonyintedo	6.798	3.013	1,756	150	m-g	ic-g	ic-g
Ipokia	Ihunbo/ Ilase	6.554	3.197	1,853	153	m-g	ic-g	ic-g
Ipokia	Ihunbo/ Ilase	6.657	2.989	4,583	393	-	g	g

Table C.4.: Ogun (cont.)

LGA	Ward	Lat. [°]	Long. [°]	Pop. #	Demand kW_p	Phase 1	Phase 2	Phase 3
Ipokia	Ihunbo/ Ilase	6.519	2.807	2,377	169	-	g	g
Ipokia	Ijofin/Idosa	6.466	2.844	2,684	219	m-g	ic-g	ic-g
Ipokia	Ijofin/Idosa	7.496	2.980	3,719	263	-	g	g
Ipokia	Ijofin/Idosa	7.441	2.991	3,050	174	-	m-g	ic-g
Ipokia	Ijofin/Idosa	7.398	2.957	1,610	134	-	g	g
Ipokia	Ijofin/Idosa	7.369	2.945	1,806	143	-	g	g
Ipokia	Ijofin/Idosa	6.535	2.865	1,649	139	-	g	g
Ipokia	Ipokia I	7.361	2.854	1,487	105	-	-	g
Ipokia	Ipokia I	7.438	3.050	1,321	87	-	g	g
Ipokia	Ipokia II	6.511	2.727	1,662	120	-	-	g
Ipokia	Ipokia II	7.377	2.889	2,445	145	-	g	g
Ipokia	Ipokia II	7.321	2.896	1,478	105	-	g	g
Ipokia	Mauni I	8.598	9.131	3,732	307	m-g	m-g	ic-g
Ipokia	Mauni I	6.611	2.776	1,483	133	-	-	g
Ipokia	Mauni I	6.524	2.753	1,466	119	-	-	g
Ipokia	Mauni I	6.494	2.748	9,769	781	m-g	m-g	ic-g
Ipokia	Mauni I	6.539	2.745	1,355	117	-	-	g
Ipokia	Mauni II	6.442	4.411	1,368	111	-	-	g
Ipokia	Mauni II	6.527	2.728	1,917	155	-	m-g	ic-g
Ipokia	Mauni II	6.469	4.507	1,998	176	-	m-g	ic-g
Ipokia	Tube	6.591	2.998	1,968	150	-	g	g
Ipokia	Tube	6.571	2.816	1,645	112	-	g	g
Obafemi-Owode	Egbeda	6.500	2.820	1,619	143	-	g	g
Obafemi-Owode	Ipara	6.919	2.779	1,578	127	-	g	g
Obafemi-Owode	Itori	6.891	4.455	19,301	1,375	m-g	ic-g	ic-g
Obafemi-Owode	Kajola	6.483	2.830	2,769	194	m-g	m-g	ic-g
Obafemi-Owode	Kajola	6.478	2.805	1,189	78	-	g	g
Obafemi-Owode	Mokoloki	6.848	4.181	2,698	184	-	m-g	ic-g
Obafemi-Owode	Mokoloki	6.487	2.775	1,027	85	-	-	g
Obafemi-Owode	Moloko-Asipa	7.548	3.029	1,099	79	-	-	g
Obafemi-Owode	Obafemi	6.964	3.722	4,546	316	m-g	ic-g	ic-g
Obafemi-Owode	Ofada	6.500	2.832	1,785	138	-	m-g	ic-g
Obafemi-Owode	Owode	6.888	4.034	773	63	-	m-g	ic-g
Obafemi-Owode	Sunren	6.949	3.249	1,244	98	-	m-g	ic-g
Odeda	Alabata	7.119	3.565	2,578	175	-	m-g	ic-g
Odeda	Alabata	7.214	3.727	1,355	81	-	-	g
Odeda	Alagbagba	7.195	2.828	1,589	95	-	-	g
Odeda	Alagbagba	6.894	3.463	1,086	73	-	-	g
Odeda	Alagbagba	7.054	3.428	2,169	134	-	m-g	ic-g
Odeda	Alapako-Oni	7.066	3.781	2,663	223	-	g	g
Odeda	Alapako-Oni	6.491	2.847	1,968	160	-	m-g	ic-g
Odeda	Alapako-Oni	6.652	2.772	1,065	72	-	-	g
Odeda	Balogun Itesi	6.867	3.341	1,010	79	-	m-g	ic-g
Odeda	Balogun Itesi	7.064	3.750	1,619	99	-	-	g
Odeda	Erinwusi/Koguo	6.528	4.353	1,866	106	-	g	g
Odeda	Ilugun	7.133	3.509	1,393	81	-	-	g
Odeda	Ilugun	6.588	4.567	1,278	77	-	g	g
Odeda	Obete	7.150	3.751	1,269	91	-	-	g
Odeda	Obete	7.214	2.974	1,406	100	-	-	g
Odeda	Obete	7.198	3.756	1,316	83	-	m-g	ic-g
Odeda	Odeda	7.125	2.924	3,413	201	-	m-g	ic-g
Odeda	Odeda	7.143	3.241	1,555	106	-	-	g
Odeda	Odeda	6.635	2.780	1,108	80	-	-	g
Odeda	Odeda	6.364	4.392	1,329	79	-	-	g
Odeda	Osiele	7.144	2.857	1,261	100	-	g	g
Odogbolu	Ala/Igbile	6.651	2.783	1,022	84	-	g	g

Table C.4.: Ogun (cont.)

LGA	Ward	Lat. [°]	Long. [°]	Pop. #	Demand kW_p	Phase 1	Phase 2	Phase 3
Odogbolu	Isiwo	6.677	3.450	1,845	148	-	g	g
Odogbolu	Jobore/Ibido	6.613	4.551	15,224	1,223	m-g	ic-g	ic-g
Odogbolu	Jobore/Ibido	6.703	3.865	1,500	126	-	g	g
Odogbolu	Okun-Owa	6.881	4.062	1,329	113	-	g	g
Ogun w/s	Abigi	7.188	3.561	6,535	375	m-g	m-g	ic-g
Ogun w/s	Abigi	7.188	3.561	1,427	104	-	m-g	ic-g
Ogun w/s	Abigi	6.625	4.564	1,491	86	-	-	g
Ogun w/s	Aheri	6.486	4.393	1,904	109	-	m-g	ic-g
Ogun w/s	Ayede/Lomiro	6.547	4.343	2,203	127	-	-	g
Ogun w/s	Ayede/Lomiro	7.255	3.738	1,389	82	-	-	g
Ogun w/s	Ayede/Lomiro	7.234	3.699	1,862	116	-	m-g	ic-g
Ogun w/s	Ayede/Lomiro	7.375	3.610	1,632	99	-	-	g
Ogun w/s	Ayede/Lomiro	7.309	3.495	1,018	70	-	-	g
Ogun w/s	Ayesan	6.490	4.419	1,103	105	m-g	m-g	ic-g
Ogun w/s	Ayila/Itebu	8.689	9.518	4,184	312	-	m-g	ic-g
Ogun w/s	Ayila/Itebu	6.607	3.221	1,150	81	-	-	g
Ogun w/s	Ayila/Itebu	6.510	4.555	6,489	445	m-g	m-g	ic-g
Ogun w/s	Efire	9.093	9.959	7,157	454	m-g	m-g	ic-g
Ogun w/s	Efire	6.459	4.544	2,680	156	-	m-g	ic-g
Ogun w/s	Lukogbe/Ilusin	6.468	2.745	8,525	592	m-g	m-g	ic-g
Ogun w/s	Lukogbe/Ilusin	6.485	2.788	10,634	863	m-g	m-g	ic-g
Ogun w/s	Lukogbe/Ilusin	6.526	4.459	2,138	128	-	m-g	ic-g
Ogun w/s	Lukogbe/Ilusin	7.202	3.651	2,450	164	-	-	g
Ogun w/s	Mahin IV	8.454	9.612	9,011	638	m-g	m-g	ic-g
Ogun w/s	Makun/Irokun	9.689	9.074	1,943	111	-	-	g
Ogun w/s	Makun/Irokun	9.101	9.591	5,219	370	-	m-g	ic-g
Ogun w/s	Ode-Omi	7.324	3.565	2,365	137	-	-	g
Ogun w/s	Ode-Omi	7.312	3.280	2,471	148	-	-	g
Ogun w/s	Oni	6.504	3.029	7,064	400	m-g	m-g	ic-g
Ogun w/s	Oni	6.609	4.574	3,323	201	-	m-g	ic-g
Remo N	Akaka	6.912	3.769	4,301	370	m-g	ic-g	ic-g
Remo N	Ilara	6.896	3.099	2,808	241	m-g	ic-g	ic-g
Remo N	Orile-Oko	6.934	3.723	2,759	202	m-g	m-g	ic-g
Remo N	Orile-Oko	6.572	4.408	1,747	106	-	m-g	ic-g
Shagamu	Ipakodo	6.582	3.185	19,008	1,522	m-g	ic-g	ic-g
Shagamu	Ogijo/ Likosi	6.691	3.060	2,263	189	-	g	g
Shagamu	Simawa / Iwelepe	6.821	3.234	4,288	335	-	g	g

Table C.5.: Detailed information on population and suggested phase-wise electrification of all village clusters > 50 kW peak demand in Plateau.

LGA	Ward	Lat. [°]	Long. [°]	Pop. #	Demand kW_p	Phase 1	Phase 2	Phase 3
Barikin Ladi	Barakin Ladi	9.181	9.786	2,534	177	-	g	g
Barikin Ladi	Butura	10.059	8.714	4,651	319	m-g	ic-g	ic-g
Barikin Ladi	Butura	9.140	9.140	1,619	109	-	g	g
Barikin Ladi	Butura	9.355	8.744	2,514	174	-	g	g
Barikin Ladi	Fursum	9.240	9.022	966	68	-	-	g
Barikin Ladi	Fursum	9.542	8.634	1,050	78	-	-	g
Barikin Ladi	Gindin Akwati	8.815	9.710	6,076	411	-	g	g
Barikin Ladi	Jol/Kwi	9.486	9.012	2,112	134	-	-	g
Barikin Ladi	Kadunu	9.451	9.445	1,999	135	-	g	g
Barikin Ladi	Lobiring	9.250	8.883	2,005	132	-	g	g
Barikin Ladi	Lobiring	9.414	8.859	1,112	75	-	g	g
Barikin Ladi	Mangu Halle	9.953	8.723	1,537	100	-	g	g
Barikin Ladi	Manguna	9.429	9.028	957	72	-	m-g	ic-g
Barikin Ladi	Manguna	9.932	8.677	1,520	105	-	-	g
Barikin Ladi	Manguna	9.101	8.868	4,930	321	-	m-g	ic-g
Barikin Ladi	Manguna	8.765	9.596	1,253	86	-	-	g
Barikin Ladi	Marit/Mazat	9.427	9.954	3,632	239	-	g	g
Barikin Ladi	Marit/Mazat	10.180	8.699	2,095	142	-	g	g
Barikin Ladi	Marit/Mazat	9.383	8.800	4,080	283	m-g	ic-g	ic-g
Barikin Ladi	Marit/Mazat	10.240	8.728	1,692	111	-	g	g
Barikin Ladi	Marit/Mazat	9.989	8.720	1,633	105	-	g	g
Barikin Ladi	Marit/Mazat	9.440	8.900	1,408	97	-	g	g
Barikin Ladi	Rafan	9.552	8.749	1,304	101	-	g	g
Barikin Ladi	Rafan	9.550	9.078	2,817	181	-	g	g
Barikin Ladi	Rafan	10.191	8.728	2,920	194	-	g	g
Barikin Ladi	Rafan	9.507	8.570	2,396	160	-	-	g
Barikin Ladi	Tafan	9.519	10.266	6,915	459	m-g	ic-g	ic-g
Barikin Ladi	Tafan	9.591	9.008	3,148	228	m-g	ic-g	ic-g
Barikin Ladi	Tafan	8.427	9.563	5,710	376	m-g	ic-g	ic-g
Barikin Ladi	Tafan	8.423	9.510	13,231	882	m-g	ic-g	ic-g
Barikin Ladi	Tafan	8.943	9.091	1,605	111	-	g	g
Barikin Ladi	Tafan	9.478	8.978	5,327	374	m-g	ic-g	ic-g
Barikin Ladi	Tafan	9.605	8.953	2,602	202	-	g	g
Barikin Ladi	Tafan	9.552	9.023	4,671	321	m-g	ic-g	ic-g
Barikin Ladi	Tafan	9.187	8.870	1,932	123	-	g	g
Barikin Ladi	Tafan	9.533	8.841	1,408	98	-	g	g
Barikin Ladi	Tafan	9.543	8.943	2,430	161	-	g	g
Barikin Ladi	Tafan	9.644	9.086	1,352	91	-	g	g
Barikin Ladi	Tafan	9.209	9.918	1,791	124	-	g	g
Barikin Ladi	Tafan	8.923	9.483	2,945	199	-	g	g
Barikin Ladi	Tafan	8.675	9.978	2,478	171	-	g	g
Barikin Ladi	Tafan	9.729	9.012	1,782	125	-	g	g
Barikin Ladi	Zabot	9.588	9.312	3,517	343	-	g	g
Barikin Ladi	Zabot	9.668	8.946	6,448	519	m-g	m-g	ic-g
Barikin Ladi	Zabot	9.626	9.073	3,362	213	-	m-g	ic-g
Barikin Ladi	Zabot	9.599	9.098	1,408	91	-	-	g
Barikin Ladi	Zabot	9.254	9.895	5,916	396	m-g	ic-g	ic-g
Bassa	Buhit	9.471	8.992	1,256	82	-	g	g
Bassa	Gabia	9.770	9.007	1,408	96	-	g	g
Bassa	Garu	9.984	8.965	2,431	193	-	g	g
Bassa	Gyel A	9.753	9.060	1,661	111	-	g	g
Bassa	Gyel A	9.757	9.145	5,429	446	-	g	g
Bassa	Jengre	9.599	9.098	1,982	138	-	-	g
Bassa	Kadamo	9.584	9.071	1,588	111	-	g	g
Bassa	Kakkek	9.617	9.110	8,945	618	m-g	ic-g	ic-g

Table C.5.: Plateau (cont.)

LGA	Ward	Lat. [°]	Long. [°]	Pop. #	Demand kW$_p$	Phase 1	Phase 2	Phase 3
Bassa	Kakkek	9.612	9.000	2,666	227	-	g	g
Bassa	Kakkek	9.617	8.971	2,624	202	-	g	g
Bassa	Kakkek	8.741	9.604	1,247	83	-	g	g
Bassa	Kakkek	9.022	9.235	1,642	120	-	g	g
Bassa	Kasuru	9.997	8.910	2,937	192	-	g	g
Bassa	Kasuru	10.004	9.004	6,203	413	m-g	ic-g	ic-g
Bassa	Kasuru	9.736	8.979	2,036	133	-	g	g
Bassa	Kishika	9.956	9.134	1,678	158	m-g	ic-g	ic-g
Bassa	Kishika	9.758	8.962	2,683	183	-	g	g
Bassa	Kishika	10.270	8.762	2,903	193	-	g	g
Bassa	Kishika	10.173	8.758	2,086	140	-	g	g
Bassa	Lazuru	9.637	8.938	2,796	189	-	m-g	ic-g
Bassa	Mafara	9.972	8.701	2,678	180	-	g	g
Bassa	Mafara	9.963	8.721	2,745	185	-	g	g
Bassa	Mafara	8.434	9.547	1,796	118	-	g	g
Bassa	Mafara	8.606	9.047	2,514	163	-	g	g
Bassa	Mafara	9.225	9.010	1,504	102	-	g	g
Bassa	Rimi	9.917	8.741	1,216	81	-	-	g
Bassa	Rimi	10.201	8.717	2,241	157	-	g	g
Bassa	Rimi	10.043	8.686	1,532	132	-	-	g
Bassa	TaAgbe	10.075	8.712	1,098	73	-	-	g
Bassa	Zabolo	10.000	8.914	1,695	167	-	m-g	ic-g
Bassa	Zobwo	8.828	9.840	1,870	172	-	g	g
Bokkos	Bokkos	10.105	8.669	1,425	123	-	-	g
Bokkos	Bokkos	10.076	8.670	1,408	98	-	g	g
Bokkos	Butura	9.286	9.969	5,949	480	m-g	ic-g	ic-g
Bokkos	Butura	8.496	9.562	1,197	106	-	g	g
Bokkos	Daffo	9.127	9.713	1,439	112	-	m-g	ic-g
Bokkos	Daffo	10.093	8.686	842	78	-	m-g	ic-g
Bokkos	Daffo	8.937	10.102	1,188	78	-	-	g
Bokkos	Damwai	10.349	8.846	3,294	230	m-g	m-g	ic-g
Bokkos	Kerang	9.559	9.287	2,241	148	-	g	g
Bokkos	Kwatas	10.319	8.838	1,689	127	-	g	g
Bokkos	Kwatas	9.315	9.030	2,568	198	-	g	g
Bokkos	Kwatas	9.293	9.049	1,664	116	-	g	g
Bokkos	Mangor	9.387	8.875	2,129	158	-	g	g
Bokkos	Manguna	9.233	9.846	1,677	136	-	m-g	ic-g
Bokkos	Manguna	9.382	9.036	935	72	-	-	g
Bokkos	Manguna	9.365	9.009	1,216	83	m-g	m-g	ic-g
Bokkos	Mbar/Mangar	9.209	8.819	1,222	116	-	m-g	ic-g
Bokkos	Mbar/Mangar	9.063	8.815	2,160	153	m-g	m-g	ic-g
Bokkos	Mbar/Mangar	9.864	8.677	1,115	87	-	m-g	ic-g
Bokkos	Mushere West	9.228	8.953	2,492	184	-	m-g	ic-g
Bokkos	Mushere West	9.260	8.914	2,264	160	-	m-g	ic-g
Bokkos	Mushere West	9.321	8.816	1,160	77	-	-	g
Bokkos	Mushere Central	9.101	9.870	1,374	105	-	m-g	ic-g
Bokkos	Mushere Central	9.385	8.989	1,596	131	m-g	m-g	ic-g
Bokkos	Mushere Central	9.336	8.874	1,275	89	-	-	g
Bokkos	Richa	9.346	8.755	2,376	166	m-g	m-g	ic-g
Bokkos	Richa	10.039	8.720	1,920	128	-	m-g	ic-g
Bokkos	Tangur	9.160	9.050	2,393	184	-	m-g	ic-g
Bokkos	Tangur	9.269	8.713	2,250	163	-	m-g	ic-g
Bokkos	Tangur	9.201	9.062	1,740	134	-	-	g
Bokkos	Tangur	9.173	9.056	1,478	111	m-g	ic-g	ic-g
Bokkos	Tangur	9.472	8.891	2,416	162	-	m-g	ic-g
Bokkos	Tangur	9.506	8.994	1,611	107	-	g	g

Table C.5.: Plateau (cont.)

LGA	Ward	Lat. [°]	Long. [°]	Pop. #	Demand kW$_p$	Phase 1	Phase 2	Phase 3
Bokkos	Toff	9.067	9.932	1,394	90	-	-	m-g
Bokkos	Toff	9.138	9.007	2,993	209	-	m-g	ic-g
Bokkos	Toff	9.173	9.004	1,053	94	-	m-g	m-g
Jos E	Federe	9.151	9.000	2,084	138	-	g	g
Jos E	Federe	9.140	8.901	2,858	201	-	g	g
Jos E	Fursum	9.677	9.151	1,729	117	-	-	g
Jos E	Fursum	9.684	9.244	5,299	483	m-g	m-g	ic-g
Jos E	Fursum	9.707	9.150	1,760	139	-	m-g	ic-g
Jos E	Fursum	9.596	9.114	1,585	107	-	-	g
Jos E	Fursum	9.643	9.001	1,444	111	-	-	g
Jos E	Jarawan Kogi	9.775	8.814	1,579	132	-	g	g
Jos E	Jarawan Kogi	9.271	9.006	4,356	352	m-g	ic-g	ic-g
Jos E	Jarawan Kogi	9.285	9.090	1,233	96	-	g	g
Jos E	Mai Gemu	9.974	8.986	1,732	113	-	-	g
Jos E	Mai Gemu	9.101	8.794	2,050	139	-	m-g	ic-g
Jos E	Mai Gemu	9.126	8.801	1,408	95	-	-	g
Jos E	Maijuju	9.693	8.873	4,429	396	m-g	m-g	ic-g
Jos E	Maijuju	9.840	9.132	4,854	321	m-g	m-g	ic-g
Jos E	Shere West	9.782	8.764	862	66	-	g	g
Jos E	Zabot	9.594	9.032	2,483	171	-	m-g	ic-g
Jos E	Zandi	9.772	8.797	4,834	332	m-g	m-g	ic-g
Jos E	Zandi	9.848	9.077	1,599	109	-	-	g
Jos E	Zandi	9.701	9.072	1,464	103	-	-	g
Jos N	Naraguta B	9.814	8.790	2,799	265	-	g	g
Jos N	Naraguta B	9.806	8.746	1,664	163	-	g	g
Jos N	Naraguta B	9.993	9.109	6,476	635	-	g	g
Jos N	Shere East	9.844	9.249	3,201	227	-	g	g
Jos S	Du	9.932	9.132	2,379	185	-	g	g
Jos S	Gyel A	9.716	8.988	1,607	146	-	-	g
Jos S	Gyel A	9.724	9.052	2,140	198	-	g	g
Jos S	Kuru A	9.651	10.034	1,110	103	-	g	g
Jos S	Vwang	9.759	9.088	3,525	320	-	g	g
Jos S	Vwang	9.913	9.233	1,394	97	-	-	g
Kanam	Birbyang	9.429	10.379	749	66	-	m-g	ic-g
Kanam	Birbyang	9.452	9.732	2,160	163	-	m-g	ic-g
Kanam	Dengi	9.314	9.327	1,715	128	-	m-g	ic-g
Kanam	Dengi	9.316	9.490	1,267	97	-	-	g
Kanam	Dengi	9.888	9.242	1,399	94	-	g	g
Kanam	Dengi	8.889	9.863	1,647	110	-	-	g
Kanam	Gagdib	9.511	10.197	4,055	275	-	m-g	ic-g
Kanam	Gagdib	9.577	9.819	2,706	188	-	m-g	ic-g
Kanam	Gagdib	9.578	8.990	1,391	99	m-g	m-g	m-g
Kanam	Gagdib	9.737	8.897	1,459	95	-	-	g
Kanam	Gagdib	9.654	8.746	1,605	109	-	-	g
Kanam	Gagdib	9.037	9.875	1,337	86	-	-	g
Kanam	Garga	9.419	9.353	2,956	210	m-g	m-g	ic-g
Kanam	Garga	9.413	9.398	1,718	160	m-g	m-g	ic-g
Kanam	Garga	9.469	10.085	1,016	78	-	-	g
Kanam	Garga	9.480	10.170	7,045	496	m-g	m-g	ic-g
Kanam	Garga	9.500	10.094	1,126	85	-	m-g	ic-g
Kanam	Garga	9.537	8.960	1,284	84	-	-	g
Kanam	Gumsher	9.690	8.704	2,576	180	-	g	g
Kanam	Gumsher	9.718	8.735	1,267	83	-	g	g
Kanam	Gumsher	9.365	9.887	1,402	90	-	g	g
Kanam	Gumsher	8.878	9.107	1,464	112	-	m-g	ic-g
Kanam	Gwamlar	9.443	8.962	957	78	-	-	g

Table C.5.: Plateau (cont.)

LGA	Ward	Lat. [°]	Long. [°]	Pop. #	Demand kW_p	Phase 1	Phase 2	Phase 3
Kanam	Gwamlar	9.462	9.883	2,253	163	-	-	g
Kanam	Gwamlar	9.473	10.358	2,478	169	-	m-g	ic-g
Kanam	Gwamlar	9.592	9.867	1,864	127	-	-	g
Kanam	Gwamlar	9.523	9.823	1,222	77	-	-	g
Kanam	Gwamlar	9.323	9.795	1,596	121	-	-	g
Kanam	Gwamlar	9.304	9.825	1,582	103	-	-	g
Kanam	Gwamlar	9.356	9.845	1,295	86	-	-	g
Kanam	Gwamlar	8.738	9.088	1,830	134	-	-	g
Kanam	Jarmai	9.294	10.216	7,439	584	m-g	m-g	ic-g
Kanam	Jom	9.397	10.271	2,464	189	-	m-g	ic-g
Kanam	Jom	9.432	9.449	2,430	210	m-g	m-g	ic-g
Kanam	Kanam	9.383	10.173	2,351	187	-	m-g	ic-g
Kanam	Kanam	9.431	9.868	1,318	92	-	m-g	m-g
Kanam	Kanam	9.395	9.856	1,149	79	-	-	m-g
Kanam	Kanam	9.431	9.637	2,405	160	-	m-g	ic-g
Kanam	Kantana	9.469	8.693	1,014	100	-	m-g	ic-g
Kanam	Kantana	9.478	9.745	1,532	121	-	m-g	ic-g
Kanam	Kantana	9.486	9.455	2,419	171	-	m-g	ic-g
Kanam	Kantana	9.496	8.696	1,554	107	-	-	g
Kanam	Kantana	9.497	10.315	1,549	104	-	m-g	ic-g
Kanam	Kantana	9.504	10.114	921	72	-	m-g	ic-g
Kanam	Kunkyam	9.242	10.478	1,321	108	-	m-g	ic-g
Kanam	Kunkyam	9.391	9.811	1,368	90	-	-	g
Kanam	Lusa A	8.911	9.464	2,624	175	-	m-g	ic-g
Kanam	Namaran	9.129	9.494	3,497	224	-	m-g	ic-g
Kanam	Namaran	9.239	10.575	898	81	m-g	m-g	ic-g
Kanam	Namaran	9.417	9.807	1,408	94	-	-	g
Kanam	Namaran	9.427	9.903	2,365	166	-	-	g
Kanam	Namaran	9.452	8.841	1,492	99	-	-	g
Kanam	Namaran	9.465	8.950	1,408	99	-	-	g
Kanke	Ampang-East	9.310	10.027	1,951	140	-	-	g
Kanke	Amper Chika A	9.560	9.954	2,055	134	-	g	g
Kanke	Amper Chika B	9.368	10.082	1,206	94	-	-	g
Kanke	Amper Chika B	9.594	9.960	1,126	77	-	-	g
Kanke	Amper Chika B	9.394	10.033	2,354	162	m-g	m-g	ic-g
Kanke	Amper Seri	9.426	10.089	966	89	-	m-g	ic-g
Kanke	Amper Seri	9.051	9.847	1,872	123	-	m-g	ic-g
Kanke	Gagdib	9.964	8.929	4,823	311	m-g	m-g	ic-g
Kanke	Gwamlar	9.468	9.792	3,092	247	-	m-g	ic-g
Kanke	Kabwir Pada	9.303	9.925	1,681	119	-	g	g
Kanke	Kabwir Pada	9.346	9.554	788	65	-	-	g
Kanke	Kabwir/Gyangyang	9.454	10.244	1,250	97	-	m-g	ic-g
Kanke	Kabwir/Gyangyang	9.334	9.814	1,126	83	-	-	g
Kanke	Kabwir/Gyangyang	9.349	9.552	1,549	108	-	-	g
Kanke	Kabwir/Gyangyang	8.545	9.958	1,408	94	-	-	g
Kanke	Langshi	9.255	10.179	3,486	290	m-g	m-g	ic-g
Kanke	Nemel	9.340	9.696	3,379	232	-	g	g
Kanke	Pankshin Chigw.	9.205	9.366	1,461	99	-	m-g	ic-g
Kanke	Tapshin	9.625	9.061	1,247	87	-	g	g
Kanke	Wokkos	9.280	9.554	5,527	368	m-g	m-g	ic-g
Langtang N	Funyalang	9.071	9.683	2,253	155	-	-	g
Langtang N	Gumsher	9.668	8.710	1,267	86	-	-	g
Langtang N	Jat	9.232	9.037	1,520	98	-	-	g
Langtang N	Jat	9.283	9.736	1,323	92	-	g	g
Langtang N	Jat	9.259	9.710	1,549	114	-	g	g
Langtang N	Keller	9.230	9.517	4,356	284	-	g	g

Table C.5.: Plateau (cont.)

LGA	Ward	Lat. [°]	Long. [°]	Pop. #	Demand kW$_p$	Phase 1	Phase 2	Phase 3
Langtang N	Keller	9.199	9.507	1,315	94	-	g	g
Langtang N	Keller	8.396	9.647	1,183	78	-	g	g
Langtang N	Keller	8.458	9.598	1,732	116	-	g	g
Langtang N	Kuffen	9.386	9.597	2,799	196	-	-	g
Langtang N	Kumbur	9.022	9.265	3,286	279	m-g	ic-g	ic-g
Langtang N	Kumbur	9.064	9.494	1,394	124	-	-	g
Langtang N	Kwande	9.105	8.843	1,560	116	-	-	g
Langtang N	Lalin	9.433	9.718	1,275	107	-	m-g	ic-g
Langtang N	Lashel	8.796	9.989	1,651	105	-	-	g
Langtang N	Lashel	9.229	9.878	2,444	169	-	m-g	ic-g
Langtang N	Lashel	9.090	9.917	1,580	119	-	-	g
Langtang N	Lashel	8.456	9.647	5,643	399	-	m-g	ic-g
Langtang N	Lipchok	9.012	9.888	1,287	84	-	-	g
Langtang N	Lipchok	9.443	10.398	985	81	-	g	g
Langtang N	Mban/Zamko	8.444	9.573	1,549	118	-	g	g
Langtang N	Mban/Zamko	9.299	9.087	1,267	84	-	-	g
Langtang N	Namaran	9.430	8.907	1,549	101	-	-	g
Langtang N	Nyer	8.818	9.400	1,085	87	-	-	g
Langtang N	Nyer	9.401	9.623	1,188	79	-	-	g
Langtang N	Nyer	9.435	9.670	2,019	145	-	-	g
Langtang N	Nyer	9.458	9.524	1,470	98	-	-	g
Langtang N	Nyer	9.250	9.817	1,915	128	-	g	g
Langtang N	Nyer	9.585	9.244	2,700	173	-	m-g	ic-g
Langtang N	Pajat	9.267	9.831	2,134	139	-	g	g
Langtang N	Pajat	8.697	9.349	2,272	146	-	g	g
Langtang N	Pil Gani	9.175	9.847	2,095	143	-	g	g
Langtang N	Pishe/Yashi	9.215	9.866	1,751	116	-	-	g
Langtang N	Reak	9.172	9.831	1,042	85	-	g	g
Langtang N	Reak	9.105	9.775	1,230	90	-	g	g
Langtang N	Talgwang	8.770	9.570	1,067	73	-	-	g
Langtang N	Talgwang	8.770	9.794	2,281	147	-	-	g
Langtang N	Waroh	8.907	9.851	3,970	264	m-g	ic-g	ic-g
Langtang N	Waroh	8.894	9.810	1,382	92	-	g	g
Langtang N	Waroh	8.871	9.815	1,901	132	-	g	g
Langtang N	Waroh	8.933	9.871	1,588	105	-	g	g
Langtang N	Wase Tofa	9.512	8.614	1,188	77	-	-	g
Langtang S	Dadin Kowa	8.666	9.940	2,331	151	-	-	g
Langtang S	Dadin Kowa	8.714	9.512	4,468	311	-	m-g	ic-g
Langtang S	Dadin Kowa	8.714	9.298	12,749	918	m-g	m-g	ic-g
Langtang S	Fajul	8.585	9.629	8,692	648	m-g	m-g	ic-g
Langtang S	Fajul	9.434	9.256	1,974	129	-	-	g
Langtang S	Gamakai	8.553	9.773	2,768	186	m-g	m-g	ic-g
Langtang S	Gamakai	8.623	9.524	2,869	191	-	m-g	ic-g
Langtang S	Gamakai	8.647	9.802	6,090	396	m-g	m-g	ic-g
Langtang S	Gamakai	9.171	9.767	3,111	211	-	m-g	ic-g
Langtang S	Gamakai	8.651	9.346	1,014	70	-	-	g
Langtang S	Kurungbau B	8.671	9.516	3,672	295	m-g	m-g	ic-g
Langtang S	Mabudi	8.620	9.728	2,027	138	-	-	g
Langtang S	Mabudi	8.684	9.472	2,886	204	-	m-g	ic-g
Langtang S	Mabudi	8.725	9.901	6,873	449	m-g	m-g	ic-g
Langtang S	Mabudi	9.666	9.112	1,126	71	-	-	g
Langtang S	Magama	9.858	4.538	3,734	250	-	m-g	ic-g
Langtang S	Magama	8.417	9.687	10,623	697	m-g	m-g	ic-g
Langtang S	Magama	8.526	9.952	2,852	190	-	m-g	ic-g
Langtang S	Magama	8.532	9.819	4,252	275	-	m-g	ic-g
Langtang S	Magama	9.236	9.864	3,829	254	-	m-g	ic-g

Table C.5.: Plateau (cont.)

LGA	Ward	Lat. [°]	Long. [°]	Pop. #	Demand kW$_p$	Phase 1	Phase 2	Phase 3
Langtang S	Sabon Gida	8.646	8.982	2,106	143	-	-	g
Langtang S	Sabon Gida	9.198	9.724	1,901	131	-	-	g
Langtang S	Sabon Gida	9.593	9.265	1,993	134	-	g	g
Langtang S	Talgwang	8.752	9.989	3,291	221	-	m-g	ic-g
Langtang S	Talgwang	8.778	9.295	4,975	327	-	-	g
Langtang S	Timbol	8.500	9.612	2,055	137	-	-	g
Langtang S	Timbol	8.509	9.465	4,240	307	m-g	m-g	ic-g
Langtang S	Timbol	8.537	9.615	1,107	72	-	-	g
Langtang S	Timbol	9.218	9.723	1,267	88	-	-	g
Langtang S	Turaki	8.551	9.136	1,436	104	-	-	g
Langtang S	Turaki	8.583	9.267	3,291	217	-	m-g	ic-g
Langtang S	Turaki	8.607	9.706	2,393	164	-	m-g	ic-g
Langtang S	Turaki	8.626	9.982	3,044	213	m-g	m-g	ic-g
Langtang S	Turaki	9.235	9.732	2,354	170	-	m-g	ic-g
Mangu	Ampang West	9.241	9.749	1,301	87	-	g	g
Mangu	Ampang West	8.585	9.865	1,968	139	-	m-g	ic-g
Mangu	Ampang West	8.812	9.871	1,056	75	-	-	g
Mangu	Chanso	9.572	10.077	4,815	377	m-g	ic-g	ic-g
Mangu	Chanso	8.862	9.866	1,757	128	-	g	g
Mangu	Chanso	8.709	9.690	2,579	194	-	g	g
Mangu	Chanso	8.936	9.956	1,222	90	-	g	g
Mangu	Gindiri II	8.555	9.430	1,374	94	-	g	g
Mangu	Gindiri IV	8.711	9.467	1,306	91	-	g	g
Mangu	Jannaret	8.542	9.794	1,298	90	-	g	g
Mangu	Jipal/Chakfem	8.646	9.677	1,495	107	-	g	g
Mangu	Jipal/Chakfem	9.284	9.192	1,568	113	-	m-g	ic-g
Mangu	Jipal/Chakfem	9.293	9.216	1,292	86	-	-	g
Mangu	Jipal/Chakfem	10.088	8.699	1,247	88	-	-	g
Mangu	Kadunu	9.609	9.966	2,388	184	-	m-g	ic-g
Mangu	Kadunu	9.661	9.063	749	67	-	m-g	ic-g
Mangu	Kadunu	9.273	9.138	1,492	110	-	g	g
Mangu	Kangshu	9.491	9.853	2,436	199	-	g	g
Mangu	Kardam B	9.645	8.810	1,477	120	-	-	g
Mangu	Kerang	9.579	9.262	1,253	86	-	g	g
Mangu	Kerang	9.598	9.294	1,751	126	-	g	g
Mangu	Kerang	9.528	9.265	1,112	73	-	g	g
Mangu	Kerang	9.070	9.227	1,309	88	-	g	g
Mangu	Kerang	9.181	9.255	1,422	102	-	g	g
Mangu	Kombun	9.167	9.240	3,826	312	m-g	ic-g	ic-g
Mangu	Kombun	9.695	9.101	5,153	343	m-g	ic-g	ic-g
Mangu	Kombun	9.350	9.139	1,121	73	-	-	g
Mangu	Kombun	9.309	9.119	4,575	312	m-g	m-g	ic-g
Mangu	Kombun	9.331	9.165	1,222	81	-	-	g
Mangu	Kombun	9.334	9.148	1,977	130	-	g	g
Mangu	Kwatas	10.371	8.806	2,745	187	m-g	ic-g	ic-g
Mangu	Langai	9.325	9.184	3,646	248	-	-	g
Mangu	Langai	9.336	9.129	1,290	94	-	g	g
Mangu	Mangu Halle	9.509	9.367	2,070	171	-	g	g
Mangu	Mangu Halle	9.367	9.134	1,216	79	-	g	g
Mangu	Mangu Halle	9.449	9.151	1,140	79	-	g	g
Mangu	Mangu Halle	9.431	9.101	1,011	94	-	g	g
Mangu	Mangun	9.382	9.141	2,109	141	-	g	g
Mangu	Pan Yam	9.447	9.125	1,343	92	-	-	g
Mangu	Pan Yam	9.459	9.046	3,652	240	-	g	g
Mangu	Pushit	9.361	10.242	1,147	90	-	-	g
Mangu	Pushit	9.627	9.215	1,335	91	-	-	g

Table C.5.: Plateau (cont.)

LGA	Ward	Lat. [°]	Long. [°]	Pop. #	Demand kW$_p$	Phase 1	Phase 2	Phase 3
Mangu	Pushit	9.618	9.144	1,642	114	-	-	g
Mangu	Pushit	8.952	9.506	1,287	80	-	-	g
Mikang	Baltep	8.909	9.563	2,804	197	m-g	m-g	ic-g
Mikang	Baltep	8.953	9.397	12,675	1,043	m-g	m-g	ic-g
Mikang	Baltep	8.801	9.474	2,604	171	-	-	g
Mikang	Derteng	9.429	9.835	1,892	132	-	-	g
Mikang	Koenoem A	9.202	9.146	3,567	241	m-g	m-g	ic-g
Mikang	Koenoem B	9.548	9.108	1,464	102	-	-	g
Mikang	Lalin	9.054	9.889	4,392	369	m-g	m-g	ic-g
Mikang	Lalin	9.074	9.362	1,282	83	-	-	g
Mikang	Pangshom	8.944	9.574	2,810	195	m-g	m-g	ic-g
Mikang	Pangshom	9.167	9.874	2,041	133	-	-	g
Mikang	Pangshom	8.811	9.189	1,825	129	-	-	g
Mikang	Piapung A	9.017	9.487	5,375	396	m-g	m-g	ic-g
Mikang	Piapung A	9.489	9.023	1,095	97	-	m-g	ic-g
Mikang	Piapung B	8.970	10.011	5,561	384	m-g	m-g	ic-g
Mikang	Piapung B	9.579	9.137	1,912	129	-	m-g	ic-g
Mikang	Poeship	9.042	9.909	5,164	409	m-g	m-g	ic-g
Mikang	Shendam Central	9.745	9.002	2,320	153	-	-	g
Mikang	Tunkus	9.464	9.216	1,132	75	-	-	g
Pankshin	Chanso	8.394	9.748	1,295	90	-	g	g
Pankshin	Chip	9.356	9.234	2,317	162	m-g	m-g	ic-g
Pankshin	Chip	9.422	9.246	1,349	110	-	-	g
Pankshin	Chip	9.439	9.272	1,585	105	-	-	g
Pankshin	Chip	8.758	9.728	1,157	79	-	m-g	ic-g
Pankshin	Dok-Pai	9.027	9.394	1,723	132	-	m-g	ic-g
Pankshin	Dok-Pai	8.768	9.363	1,005	73	-	g	g
Pankshin	Fier	9.376	10.041	1,283	104	-	m-g	ic-g
Pankshin	Fier	9.397	9.759	3,230	263	m-g	m-g	ic-g
Pankshin	Fier	9.406	9.295	3,331	224	-	g	g
Pankshin	Fier	8.744	9.456	1,352	89	-	-	g
Pankshin	Garram	9.247	9.988	2,168	146	-	m-g	ic-g
Pankshin	Garram	9.307	9.908	2,447	165	m-g	m-g	ic-g
Pankshin	Jiblik	9.024	9.441	1,154	85	-	-	g
Pankshin	Jiblik	9.043	9.511	3,725	264	m-g	m-g	ic-g
Pankshin	Kadung	9.491	10.138	1,605	106	-	m-g	ic-g
Pankshin	Kadung	9.053	9.428	3,655	251	m-g	m-g	ic-g
Pankshin	Kadung	8.970	9.622	1,647	118	-	g	g
Pankshin	Kadung	9.595	9.055	1,619	111	-	g	g
Pankshin	Kangshu	9.193	9.346	1,627	117	m-g	ic-g	ic-g
Pankshin	Koenoem A	9.083	9.992	2,365	164	-	m-g	ic-g
Pankshin	Lankang	9.274	8.790	2,207	210	m-g	m-g	ic-g
Pankshin	Lankang	8.960	9.563	1,746	113	-	m-g	ic-g
Pankshin	Lankang	8.423	9.654	1,464	99	-	-	g
Pankshin	Pankshin Chigw.	9.143	9.425	2,317	165	m-g	ic-g	ic-g
Pankshin	Pankshin Chigw.	9.224	9.623	3,190	251	-	g	g
Pankshin	Pankshin South	9.106	9.675	1,774	139	-	m-g	ic-g
Pankshin	Pankshin South	9.462	9.370	3,584	239	-	g	g
Pankshin	Pankshin South	9.287	9.263	1,943	130	-	m-g	ic-g
Pankshin	Pankshin South	9.234	9.269	1,467	97	-	-	g
Pankshin	Tal	9.076	10.059	4,502	373	m-g	m-g	ic-g
Pankshin	Tal	9.467	9.446	1,605	103	-	-	g
Pankshin	Tapshin	9.467	10.223	1,968	173	-	g	g
Pankshin	Tunkus	9.501	9.543	1,143	79	-	m-g	ic-g
Pankshin	Wokkos	9.489	9.302	1,492	105	-	-	g
Qua'an Pan	Bwall	8.882	9.831	3,514	240	-	m-g	ic-g

Table C.5.: Plateau (cont.)

LGA	Ward	Lat. [°]	Long. [°]	Pop. #	Demand kW$_p$	Phase 1	Phase 2	Phase 3
Qua'an Pan	Bwall	9.403	9.522	1,078	73	-	m-g	ic-g
Qua'an Pan	Bwall	8.397	9.611	1,439	96	-	-	g
Qua'an Pan	Bwall	9.232	9.692	1,549	106	-	-	g
Qua'an Pan	Doemak-Goechim	10.139	8.959	2,526	179	m-g	m-g	ic-g
Qua'an Pan	Doemak-Goechim	8.780	9.486	1,937	126	-	-	g
Qua'an Pan	Doemak-Koplong	8.901	10.025	8,520	559	-	-	g
Qua'an Pan	Dokan Kasuwa	9.392	9.471	1,233	84	-	g	g
Qua'an Pan	Kurgwi	8.746	9.332	14,430	1,373	m-g	m-g	ic-g
Qua'an Pan	Kwa	8.975	9.420	5,493	506	m-g	ic-g	ic-g
Qua'an Pan	Kwa	9.371	9.456	1,304	86	-	g	g
Qua'an Pan	Kwa	8.888	9.399	1,154	79	-	g	g
Qua'an Pan	Kwalla Moeda	8.819	9.484	2,768	247	-	g	g
Qua'an Pan	Kwalla Moeda	8.881	9.363	1,999	137	-	g	g
Qua'an Pan	Kwalla YitlaAr	9.280	9.358	2,258	169	-	g	g
Qua'an Pan	Kwande	8.421	9.733	1,087	70	-	-	m-g
Qua'an Pan	Kwande	8.564	9.646	1,515	99	-	-	g
Qua'an Pan	Kwande	8.599	9.541	10,933	1,054	m-g	m-g	ic-g
Qua'an Pan	Kwande	8.690	9.380	4,820	380	m-g	m-g	ic-g
Qua'an Pan	Kwande	8.695	9.760	3,931	295	m-g	m-g	ic-g
Qua'an Pan	Kwande	8.717	9.230	1,661	128	m-g	m-g	ic-g
Qua'an Pan	Kwang	9.161	9.468	2,711	195	m-g	ic-g	ic-g
Qua'an Pan	Namu	8.524	9.660	1,126	110	m-g	m-g	ic-g
Qua'an Pan	Namu	8.537	9.004	3,427	230	m-g	m-g	ic-g
Qua'an Pan	Namu	8.616	9.292	1,639	115	-	m-g	ic-g
Qua'an Pan	Namu	8.667	9.844	10,792	843	m-g	m-g	ic-g
Qua'an Pan	Namu	8.769	9.836	1,760	148	m-g	m-g	ic-g
Qua'an Pan	Namu	9.134	9.466	1,929	136	m-g	m-g	ic-g
Qua'an Pan	Namu	9.285	9.464	1,225	92	m-g	m-g	ic-g
Qua'an Pan	Namu	8.965	9.479	2,115	156	-	m-g	ic-g
Qua'an Pan	Namu	8.710	9.601	1,239	88	-	-	g
Qua'an Pan	Namu	8.945	9.721	1,149	74	-	-	g
Qua'an Pan	Namu	9.164	10.096	1,126	74	-	-	g
Qua'an Pan	Namu	9.818	9.026	915	78	m-g	m-g	ic-g
Qua'an Pan	Namu	8.713	9.794	1,211	78	-	-	g
Riyom	Danto	8.931	9.152	1,492	104	-	g	g
Riyom	Danto	9.064	9.262	1,616	104	-	g	g
Riyom	Gidan Waya	10.010	8.700	1,492	99	-	-	g
Riyom	Jol/Kwi	8.992	9.265	1,183	82	-	-	g
Riyom	Rim	9.502	9.272	1,618	136	-	m-g	ic-g
Riyom	Rim	8.808	9.376	994	70	-	-	g
Riyom	Rim	8.968	9.289	1,484	106	-	m-g	ic-g
Riyom	Riyom	9.569	9.053	2,055	201	-	m-g	ic-g
Riyom	Riyom	9.017	9.292	1,839	126	-	g	g
Riyom	Riyom	8.613	9.013	1,416	93	-	-	g
Riyom	Sharubutu	9.453	10.290	3,209	255	m-g	m-g	ic-g
Riyom	Sharubutu	9.478	9.845	1,766	147	-	m-g	ic-g
Riyom	Sharubutu	9.609	9.045	935	71	-	-	g
Riyom	Sopp	8.711	9.167	2,064	151	-	m-g	ic-g
Riyom	Sopp	9.651	8.612	1,129	83	-	-	g
Riyom	Vwang	9.951	9.237	3,111	242	-	g	g
Riyom	Vwang	10.009	9.208	1,211	87	-	-	g
Shendam	Azara	10.019	9.193	2,971	207	-	m-g	ic-g
Shendam	Azara	9.281	9.309	2,993	210	m-g	m-g	ic-g
Shendam	Azara	9.205	9.313	2,100	143	-	-	g
Shendam	Azara	9.544	9.202	1,940	125	-	-	g
Shendam	Azara	8.744	9.441	1,633	111	-	-	g

Table C.5.: Plateau (cont.)

LGA	Ward	Lat. [°]	Long. [°]	Pop. #	Demand kW$_p$	Phase 1	Phase 2	Phase 3
Shendam	Azara	8.681	9.839	1,140	72	-	-	g
Shendam	Derteng	8.814	9.449	1,520	105	-	-	g
Shendam	Kalong	8.665	9.677	5,231	347	m-g	m-g	ic-g
Shendam	Kalong	8.677	9.658	3,658	294	m-g	m-g	ic-g
Shendam	Kalong	8.708	9.937	1,810	140	-	-	g
Shendam	Kalong	8.753	9.843	2,461	203	m-g	m-g	ic-g
Shendam	Kalong	9.624	8.632	2,275	150	-	m-g	ic-g
Shendam	Kalong	9.047	9.986	3,638	249	m-g	m-g	ic-g
Shendam	Kalong	8.890	9.061	1,098	73	-	-	g
Shendam	Kalong	8.420	9.591	2,072	140	-	-	g
Shendam	Kalong	9.090	9.737	2,064	143	-	-	g
Shendam	Kalong	9.370	8.777	1,380	96	-	-	g
Shendam	Kalong	9.097	9.830	1,464	103	-	-	g
Shendam	Kurungbau A	8.755	9.882	2,151	148	-	-	g
Shendam	Kurungbau A	9.133	9.848	4,674	325	m-g	ic-g	ic-g
Shendam	Kurungbau B	8.386	9.689	4,246	422	m-g	m-g	ic-g
Shendam	Kurungbau B	8.488	9.729	1,028	98	-	-	g
Shendam	Kurungbau B	8.540	9.706	1,489	120	-	-	g
Shendam	Kurungbau B	8.577	9.560	3,018	208	-	m-g	ic-g
Shendam	Kurungbau B	8.756	9.402	1,352	89	-	-	g
Shendam	Kurungbau B	8.760	9.762	1,070	70	-	-	g
Shendam	Kwalla Moeda	9.291	9.381	3,973	300	m-g	m-g	ic-g
Shendam	Kwande	8.490	9.206	1,903	133	-	-	g
Shendam	Kwande	8.572	9.705	2,174	179	m-g	m-g	ic-g
Shendam	Kwande	8.688	9.093	1,138	103	-	m-g	ic-g
Shendam	Kwande	8.908	9.140	1,920	128	-	-	g
Shendam	Kwande	9.315	9.833	1,492	103	-	-	g
Shendam	Kwande	8.941	9.547	1,943	125	-	-	g
Shendam	Kwang	8.765	9.428	1,625	121	-	g	g
Shendam	Moekat	9.909	4.501	1,858	122	-	-	g
Shendam	Moekat	9.905	4.409	11,857	823	m-g	m-g	ic-g
Shendam	Moekat	8.448	9.692	1,538	110	-	-	g
Shendam	Moekat	8.527	9.370	1,535	108	-	-	g
Shendam	Moekat	9.554	8.804	2,106	143	-	-	g
Shendam	Moekat	8.610	9.623	1,723	123	-	-	g
Shendam	Moekat	8.790	9.540	2,371	159	-	-	g
Shendam	Pangshom	8.878	9.301	1,570	132	-	m-g	ic-g
Shendam	Pangshom	8.937	9.464	1,175	83	-	-	g
Shendam	Pangshom	9.567	8.737	2,650	177	-	m-g	ic-g
Shendam	Pangshom	9.476	9.661	1,839	120	-	g	g
Shendam	Poeship	8.769	9.683	2,044	154	-	m-g	ic-g
Shendam	Poeship	8.790	9.847	6,651	525	-	-	g
Shendam	Poeship	8.790	9.358	1,889	125	-	-	g
Shendam	Poeship	8.800	9.807	1,090	93	-	m-g	ic-g
Shendam	Poeship	9.576	8.753	3,607	247	-	m-g	ic-g
Shendam	Poeship	9.035	10.112	1,408	95	-	-	g
Shendam	Poeship	9.159	9.929	1,506	98	-	-	g
Shendam	Poeship	9.539	9.751	1,746	116	-	-	g
Shendam	Poeship	8.816	9.536	1,689	115	-	-	g
Shendam	Poeship	9.453	9.346	2,030	136	-	-	g
Shendam	Poeship	9.362	10.051	1,126	79	-	-	g
Shendam	Sabon Gida	8.812	9.725	1,740	114	-	g	g
Shendam	Sarkin Kudu Ii	9.890	4.502	2,151	159	-	-	g
Shendam	Shendam Central	8.869	9.765	3,032	204	-	m-g	ic-g
Shendam	Shendam Central	9.628	9.091	1,971	131	-	-	g
Shendam	Shimankar	8.545	9.684	4,252	327	m-g	m-g	ic-g

Table C.5.: Plateau (cont.)

LGA	Ward	Lat. [°]	Long. [°]	Pop. #	Demand kW_p	Phase 1	Phase 2	Phase 3
Shendam	Shimankar	8.580	9.851	2,861	196	-	m-g	ic-g
Shendam	Shimankar	8.595	9.407	9,244	730	m-g	m-g	ic-g
Shendam	Shimankar	8.635	9.717	5,758	372	m-g	m-g	ic-g
Shendam	Shimankar	8.691	9.445	3,931	370	m-g	m-g	ic-g
Shendam	Shimankar	9.204	9.978	1,616	120	-	m-g	ic-g
Shendam	Shimankar	9.095	9.396	2,326	160	-	-	g
Shendam	Shimankar	8.669	9.137	1,971	132	-	-	g
Shendam	Talgwang	9.401	8.965	2,047	129	-	g	g
Shendam	Wuse	8.472	9.673	2,196	141	-	-	g
Shendam	Wuse	10.123	8.652	2,914	191	-	m-g	ic-g
Shendam	Yelwa	8.761	9.619	1,915	130	-	g	g
Shendam	Yelwa	9.218	9.349	1,808	128	-	g	g
Wase	Bashar	9.221	8.840	2,157	183	m-g	m-g	ic-g
Wase	Bashar	9.268	9.815	1,627	142	-	m-g	ic-g
Wase	Bashar	9.277	9.888	2,940	237	m-g	m-g	ic-g
Wase	Bashar	9.345	8.919	4,066	312	m-g	m-g	ic-g
Wase	Dadin Kowa	8.662	9.759	3,379	222	-	m-g	ic-g
Wase	Dadin Kowa	8.685	9.916	2,360	159	-	-	g
Wase	Fajul	9.888	8.721	1,025	76	-	m-g	ic-g
Wase	Gudus	9.350	10.029	2,787	227	m-g	m-g	ic-g
Wase	Jarmai	9.419	9.788	1,439	105	-	m-g	ic-g
Wase	Kadarko	8.832	9.858	5,733	408	m-g	m-g	ic-g
Wase	Kadarko	8.938	9.167	1,115	76	-	m-g	m-g
Wase	Kadarko	8.950	9.222	1,703	115	-	-	g
Wase	Kadarko	8.794	9.738	1,408	90	-	-	g
Wase	Kumbur	8.719	9.492	2,604	182	-	m-g	ic-g
Wase	Kumbur	8.791	9.146	1,267	83	-	-	g
Wase	Kumbur	8.956	10.261	3,097	209	-	g	g
Wase	Kumbur	9.004	9.599	9,061	643	m-g	ic-g	ic-g
Wase	Kumbur	8.874	9.286	2,467	165	-	-	g
Wase	Kumbur	8.781	9.968	1,301	88	-	g	g
Wase	Kumbur	9.222	9.931	25,005	2,049	m-g	ic-g	ic-g
Wase	Mavo	9.063	9.495	7,864	535	m-g	ic-g	ic-g
Wase	Mavo	9.622	8.767	1,216	82	-	g	g
Wase	Mavo	9.620	8.808	1,712	121	-	g	g
Wase	Mavo	8.656	9.476	2,396	170	-	g	g
Wase	Mavo	8.713	9.541	1,211	82	-	g	g
Wase	Nyalum/Kampani	9.231	9.912	2,348	156	m-g	m-g	m-g
Wase	Nyalum/Kampani	9.314	10.157	2,393	192	-	-	g
Wase	Saluwe	9.556	8.652	1,168	84	-	m-g	ic-g
Wase	Yola Wakat	9.200	9.414	1,785	173	m-g	m-g	m-g

Table C.6.: Detailed information on population and suggested phase-wise electrification of all village clusters > 50 kW peak demand in Sokoto.

LGA	Ward	Lat. [°]	Long. [°]	Pop. #	Demand kW_p	Phase 1	Phase 2	Phase 3
Binji	Gande E	13.094	5.165	1,345	100	-	-	g
Binji	Soro Gabas	13.094	4.753	2,054	175	-	m-g	ic-g
Binji	Soro Gabas	13.108	4.733	1,585	112	-	-	g
Binji	Soro Gabas	13.125	5.501	3,372	242	-	m-g	ic-g
Binji	Soro Yamma	13.096	4.714	1,876	159	-	m-g	ic-g
Binji	Gawazzai	13.166	6.358	3,336	263	-	g	g
Binji	Maikulki	13.100	5.188	1,026	75	-	-	g
Binji	Bunkari	13.092	4.956	4,014	333	-	-	g
Binji	Jammali	13.227	5.013	1,023	84	-	-	g
Binji	Jammali	13.254	6.291	2,691	198	m-g	m-g	ic-g
Binji	Inname	13.160	6.521	3,086	223	-	m-g	ic-g
Binji	Samama	13.129	4.952	1,096	76	-	-	g
Binji	T/Kose	13.270	5.464	1,008	81	-	-	g
Bodinga	Mazan G/Jirga M	12.710	5.063	2,360	171	-	g	g
Bodinga	Mazan G/Jirga M	12.779	5.204	1,435	119	-	g	g
Bodinga	Mazan G/Jirga M	12.799	5.704	1,647	145	-	m-g	ic-g
Bodinga	Mazan G/Jirga M	12.799	5.250	1,824	175	-	g	g
Bodinga	Mazan G/Jirga M	13.774	5.647	1,043	80	-	g	g
Bodinga	Tulluwa/Kulafasa	12.885	5.582	3,652	377	-	g	g
Bodinga	Dingyadi/Badawa	13.096	4.805	1,824	139	-	g	g
Bodinga	Kwacciyar Lalle	12.845	5.777	3,397	255	-	-	g
Bodinga	Kwacciyar Lalle	12.826	4.893	1,887	194	m-g	m-g	ic-g
Bodinga	Badau/Darhela	12.756	5.128	13,561	1,336	m-g	ic-g	ic-g
Bodinga	Bangi/Dabaga	12.701	4.952	922	82	-	g	g
Bodinga	Bangi/Dabaga	12.740	5.154	5,307	449	m-g	ic-g	ic-g
Bodinga	Danchadi	12.748	5.121	2,908	246	-	g	g
Bodinga	Danchadi	12.740	5.264	10,711	1,165	m-g	ic-g	ic-g
Bodinga	Kammata	12.924	4.771	2,505	175	-	g	g
Dange-Shuni	Ruggar Gidado	12.860	5.821	4,382	370	m-g	ic-g	ic-g
Dange-Shuni	Ruggar Gidado	12.880	5.759	1,686	139	-	g	g
Dange-Shuni	Ruggar Gidado	12.901	5.746	3,088	254	m-g	ic-g	ic-g
Dange-Shuni	Ruggar Gidado	12.925	4.794	1,289	130	-	-	g
Dange-Shuni	Tuntube/Tsehe	12.901	5.336	3,847	367	-	g	g
Dange-Shuni	Bangi/Dabaga	12.647	5.091	4,735	342	m-g	ic-g	ic-g
Dange-Shuni	Giere/Gajara	12.860	5.529	4,881	340	-	g	g
Dange-Shuni	Rudu/Amanawa	13.790	5.357	1,460	111	-	-	g
Dange-Shuni	Wababe/Salau	12.807	5.350	6,750	527	m-g	m-g	ic-g
Dange-Shuni	Wababe/Salau	12.800	4.824	2,484	262	-	g	g
Dange-Shuni	Bodai/Jurga	12.734	4.853	3,381	249	-	g	g
Dange-Shuni	Tsafanade	12.846	5.190	5,846	598	-	g	g
Dange-Shuni	Dange	12.793	5.153	5,745	585	-	g	g
Dange-Shuni	Shuni	13.779	5.709	1,738	170	-	g	g
Gada	Kadadin Buda	13.731	5.107	4,018	368	-	g	g
Gada	Dukamaje/Ilah	13.607	4.919	1,043	75	-	-	g
Gada	Dukamaje/Ilah	13.643	6.135	1,845	162	-	m-g	ic-g
Gada	Dukamaje/Ilah	13.651	5.622	9,565	698	m-g	m-g	ic-g
Gada	Dukamaje/Ilah	13.680	5.541	2,528	200	-	-	g
Gada	Dukamaje/Ilah	13.687	5.662	1,050	74	-	-	g
Gada	Dukamaje/Ilah	13.680	4.498	5,696	423	-	m-g	ic-g
Gada	Dukamaje/Ilah	13.708	5.659	4,067	300	-	m-g	ic-g
Gada	Dukamaje/Ilah	13.705	4.912	2,139	156	-	m-g	ic-g
Gada	Dukamaje/Ilah	13.718	5.328	5,120	368	m-g	m-g	ic-g
Gada	Dukamaje/Ilah	13.722	5.245	2,223	164	-	m-g	ic-g
Gada	Dukamaje/Ilah	13.797	5.726	3,962	290	-	m-g	ic-g
Gada	Kyadawa/Holai	13.675	5.570	1,919	158	-	-	g

Table C.6.: Sokoto (cont.)

LGA	Ward	Lat. [°]	Long. [°]	Pop. #	Demand kW_p	Phase 1	Phase 2	Phase 3
Gada	Kyadawa/Holai	13.683	5.508	1,410	104	-	-	g
Gada	Kyadawa/Holai	13.707	5.528	1,556	123	-	-	g
Gada	Kyadawa/Holai	13.801	5.702	1,008	79	-	-	g
Gada	Kadassaka	13.643	5.969	3,301	289	-	m-g	ic-g
Gada	Kadassaka	13.648	5.545	1,450	98	-	-	g
Gada	Kadassaka	13.651	4.481	1,156	87	-	-	g
Gada	Kadassaka	13.667	5.298	5,758	498	m-g	m-g	ic-g
Gada	Gilbadi	13.609	5.249	6,100	437	m-g	m-g	ic-g
Gada	Gilbadi	13.627	5.723	2,711	197	-	m-g	ic-g
Gada	Gilbadi	13.655	5.470	2,355	172	-	-	g
Gada	Shinaka	13.576	4.369	1,102	75	-	-	g
Gada	Kwarma	13.594	5.306	2,227	166	-	m-g	ic-g
Gada	Kwarma	13.797	5.343	973	80	-	-	g
Gada	Tsitse	13.483	5.293	1,647	122	-	m-g	ic-g
Gada	Tsitse	13.518	4.792	4,483	342	-	m-g	ic-g
Gada	Kaddi	13.573	6.247	14,924	1,022	-	-	g
Gada	Kaddi	13.609	5.512	1,536	110	-	-	g
Gada	Kaddi	13.666	6.032	972	88	-	m-g	ic-g
Gada	Kaffe	13.662	5.815	3,390	240	-	m-g	ic-g
Gada	Kaffe	13.670	5.994	2,130	149	-	g	g
Gada	Gada	13.680	5.442	1,449	105	-	-	g
Gada	Gada	13.718	5.553	4,014	339	-	g	g
Gada	Gada	13.712	4.967	1,253	124	-	g	g
Gada	Gada	13.717	4.867	2,320	163	-	m-g	ic-g
Gada	Gada	13.039	4.949	1,272	105	-	g	g
Gada	Kiri	13.608	6.196	4,733	342	m-g	m-g	ic-g
Gada	Kiri	13.613	5.034	3,175	232	-	m-g	ic-g
Gada	Kiri	13.622	5.552	2,808	203	-	m-g	ic-g
Gawabawa	Darna/ SabonG	13.468	4.988	1,965	146	-	-	g
Gawabawa	Darna/ SabonG	13.482	5.572	2,173	151	-	m-g	ic-g
Gawabawa	Darna/ SabonG	13.517	4.654	1,340	101	-	g	g
Gawabawa	Darna/ SabonG	13.555	6.041	1,174	102	-	g	g
Gawabawa	Darne/ Tsolawo	13.477	5.909	1,046	76	-	-	g
Gawabawa	Chimmola/Kudu	13.258	6.419	3,410	253	-	g	g
Gawabawa	Chimmola/Kudu	13.271	4.887	8,014	679	-	g	g
Gawabawa	Chimmola/Kudu	13.333	5.385	2,916	223	-	m-g	ic-g
Gawabawa	Chimola Arewa	13.302	5.862	4,220	352	-	g	g
Gawabawa	Chimola Arewa	13.333	5.427	2,492	177	-	m-g	ic-g
Gawabawa	Chimola Arewa	13.390	5.993	6,551	484	m-g	ic-g	ic-g
Gawabawa	Chimola Arewa	13.420	6.134	1,192	90	-	g	g
Gawabawa	Chimola Arewa	12.843	5.094	1,963	138	-	m-g	ic-g
Gawabawa	Asara Arewa	13.513	5.389	1,685	118	-	g	g
Gawabawa	Asara Arewa	13.522	5.502	9,029	671	m-g	ic-g	ic-g
Gawabawa	Asara Arewa	13.573	5.189	2,061	150	-	m-g	ic-g
Gawabawa	Asara Arewa	12.667	4.961	1,814	160	-	g	g
Gawabawa	Asara Kudu	13.388	5.170	5,272	440	m-g	ic-g	ic-g
Gawabawa	Asara Kudu	13.381	4.167	1,255	121	-	g	g
Gawabawa	Asara Kudu	13.406	5.279	2,177	192	-	g	g
Gawabawa	Asara Kudu	13.413	5.183	4,975	492	m-g	ic-g	ic-g
Gawabawa	Asara Kudu	13.439	5.932	5,680	438	-	g	g
Gawabawa	Asara Kudu	13.454	5.551	2,360	165	-	g	g
Gawabawa	Asara Kudu	13.449	5.277	3,937	379	m-g	ic-g	ic-g
Gawabawa	Asara Kudu	13.489	5.681	2,349	189	-	g	g
Gawabawa	Gidan Kaya	13.267	6.351	3,917	337	-	g	g
Gawabawa	Atakwanyo	13.308	5.365	14,690	1,055	m-g	ic-g	ic-g
Gawabawa	Atakwanyo	13.328	6.687	2,391	171	-	g	g

Table C.6.: Sokoto (cont.)

LGA	Ward	Lat. [°]	Long. [°]	Pop. #	Demand kW_p	Phase 1	Phase 2	Phase 3
Gawabawa	Atakwanyo	13.340	5.142	1,122	79	-	-	g
Gawabawa	Atakwanyo	13.384	5.820	1,727	124	-	-	g
Gawabawa	Atakwanyo	12.863	5.049	1,456	110	-	-	g
Gawabawa	Atakwanyo	13.102	6.472	1,571	112	-	-	g
Gawabawa	Gwadabawa	13.338	6.661	3,117	232	-	m-g	ic-g
Gawabawa	Gwadabawa	13.361	5.565	1,991	176	-	g	g
Gawabawa	Gwadabawa	13.365	5.326	3,058	297	m-g	ic-g	ic-g
Gawabawa	Mammande	13.396	4.956	4,236	308	-	-	g
Gawabawa	Mammande	13.431	5.279	2,246	167	-	m-g	ic-g
Gawabawa	Mammande	13.493	5.121	7,593	582	m-g	m-g	ic-g
Gawabawa	Gigane	13.414	5.702	1,612	119	-	-	g
Gawabawa	Gigane	13.491	5.837	2,130	155	-	g	g
Gawabawa	Gigane	12.926	5.297	1,929	138	-	g	g
Gawabawa	Gigane	13.021	4.704	1,897	131	-	g	g
Gawabawa	Salame	13.424	5.336	1,456	104	-	-	g
Gawabawa	Salame	12.873	5.297	1,112	78	-	-	g
Gawabawa	Salame	13.769	5.779	2,728	204	-	m-g	ic-g
Gawabawa	Salame	13.738	5.527	1,470	104	-	-	g
Gawabawa	Garu	13.589	5.427	7,937	567	m-g	m-g	ic-g
Gawabawa	Garu	13.591	5.497	833	67	-	-	g
Goronyo	Gari Dole/Dan	13.116	4.846	3,875	267	-	g	g
Goronyo	Gari Dole/Dan	13.259	5.155	1,693	146	-	m-g	ic-g
Goronyo	Gari Dole/Dan	13.297	6.343	4,531	387	m-g	ic-g	ic-g
Goronyo	Gari Dole/Dan	13.306	6.023	1,625	136	-	g	g
Goronyo	Gari Dole/Dan	13.315	4.949	5,877	486	m-g	ic-g	ic-g
Goronyo	Kwakwazo	13.445	5.313	3,847	283	m-g	m-g	ic-g
Goronyo	Kwakwazo	13.448	5.159	2,019	150	-	m-g	ic-g
Goronyo	Kwakwazo	13.512	5.203	3,881	282	-	m-g	ic-g
Goronyo	Kwakwazo	13.574	6.163	2,328	180	-	m-g	ic-g
Goronyo	Kwakwazo	13.122	5.387	997	83	-	-	g
Goronyo	Kwakwazo	13.202	5.463	2,356	176	-	g	g
Goronyo	Takakume	13.465	6.268	1,621	172	-	g	g
Goronyo	Takakume	13.486	5.623	4,587	369	m-g	ic-g	ic-g
Goronyo	Boyekai	13.405	5.101	1,425	104	-	-	g
Goronyo	Boyekai	13.442	5.186	1,556	107	-	m-g	ic-g
Goronyo	Goronyo	13.337	5.537	1,696	129	-	-	g
Goronyo	Goronyo	13.373	5.125	2,659	201	-	g	g
Goronyo	Goronyo	13.485	6.404	2,613	189	-	m-g	ic-g
Goronyo	Goronyo	13.848	5.584	2,627	224	-	g	g
Goronyo	Shinaka	13.446	5.406	2,329	165	-	m-g	ic-g
Goronyo	Shinaka	13.551	4.632	2,784	194	-	m-g	ic-g
Goronyo	Shinaka	13.186	5.402	1,710	122	-	m-g	ic-g
Goronyo	Kagara	13.344	5.512	5,572	399	m-g	ic-g	ic-g
Goronyo	Kagara	13.256	5.465	1,168	86	-	g	g
Goronyo	Kojiyo	13.393	5.593	7,194	515	m-g	ic-g	ic-g
Goronyo	Kojiyo	13.254	5.364	4,261	314	m-g	m-g	ic-g
Goronyo	Rimawa	13.350	6.281	1,091	107	-	-	g
Goronyo	Rimawa	13.390	5.140	5,598	405	m-g	ic-g	ic-g
Goronyo	Rimawa	13.444	6.287	18,353	1,486	m-g	ic-g	ic-g
Goronyo	Rimawa	13.455	5.241	2,838	219	-	g	g
Goronyo	Rimawa	13.508	5.700	2,166	150	-	g	g
Goronyo	Rimawa	13.205	5.355	1,612	122	-	-	g
Goronyo	Tsitse	13.534	6.036	901	76	-	-	g
Gudu	Daura/Sakkwabe	13.256	4.904	4,099	308	m-g	m-g	ic-g
Gudu	Maraken Bori	13.611	5.389	1,732	141	-	m-g	m-g
Gudu	Maraken Bori	13.643	5.912	1,733	132	-	-	g

Table C.6.: Sokoto (cont.)

LGA	Ward	Lat. [°]	Long. [°]	Pop. #	Demand kW_p	Phase 1	Phase 2	Phase 3
Gudu	Maraken Bori	13.667	4.917	1,075	74	-	-	m-g
Gudu	Maraken Bori	13.715	5.401	1,135	85	-	-	m-g
Gudu	Soro Yamma	13.123	4.819	1,062	90	-	-	g
Gudu	Awulkiti	13.614	5.643	1,571	113	-	-	g
Gudu	Bachaka	13.364	6.105	1,269	93	-	-	g
Gudu	Bachaka	13.380	4.790	1,755	137	-	-	g
Gudu	Bachaka	13.441	5.473	1,087	80	-	-	g
Gudu	Kurdula	13.563	6.062	1,524	122	-	-	g
Gudu	Kurdula	13.586	6.106	2,102	187	-	m-g	ic-g
Gudu	Balle	13.500	5.372	1,472	130	-	-	g
Gudu	Balle	13.541	6.010	1,167	83	-	-	g
Gudu	Balle	13.543	5.574	990	76	-	m-g	m-g
Illela	Darna/ SabonG	13.562	5.742	1,918	176	-	m-g	ic-g
Illela	Darna/ SabonG	13.592	6.268	3,773	276	-	m-g	ic-g
Illela	Darna/ SabonG	13.614	5.622	1,070	77	-	m-g	ic-g
Illela	Darne/ Tsolawo	13.497	5.877	1,103	86	-	-	g
Illela	Darne/ Tsolawo	13.544	6.415	1,387	103	-	m-g	ic-g
Illela	Asara Arewa	13.570	5.532	5,175	452	m-g	m-g	ic-g
Illela	Kadassaka	13.662	6.083	1,080	75	-	-	g
Illela	G/ Hamma	13.526	5.119	1,101	87	-	-	g
Illela	G/ Hamma	13.559	4.566	1,455	100	-	-	g
Illela	G/ Hamma	13.567	4.475	2,815	241	m-g	m-g	ic-g
Illela	G/ Hamma	13.586	5.604	3,038	222	-	m-g	ic-g
Illela	G/ Hamma	13.606	5.416	2,512	191	-	m-g	ic-g
Illela	G/ Hamma	13.649	5.686	1,022	88	-	m-g	ic-g
Illela	G/ Katta	13.616	5.363	1,116	84	-	m-g	ic-g
Illela	G/ Katta	13.613	5.076	1,020	104	-	-	g
Illela	G/ Katta	13.635	5.422	1,990	161	-	-	g
Illela	Kalmalo	13.669	5.379	4,357	311	-	-	g
Illela	Kalmalo	13.668	4.917	1,145	82	-	-	g
Illela	Kalmalo	13.690	5.576	3,434	318	m-g	m-g	ic-g
Illela	R. Gati	13.719	5.345	994	91	-	-	g
Illela	R. Gati	13.737	5.885	799	68	-	-	g
Illela	Illela	13.687	5.701	1,399	102	-	-	g
Illela	Illela	13.686	5.625	1,251	102	-	-	g
Illela	Araba	13.685	5.777	1,564	134	-	-	g
Illela	Araba	13.723	5.824	3,301	281	-	m-g	ic-g
Illela	Damba	13.522	6.218	1,345	98	-	g	g
Illela	Damba	13.548	5.314	996	86	-	-	g
Illela	Damba	13.599	6.369	1,123	105	-	-	g
Illela	Tozai	13.636	6.122	1,157	100	-	m-g	ic-g
Illela	Tozai	13.624	4.529	2,284	170	-	m-g	ic-g
Illela	Tozai	13.638	5.314	1,051	76	-	-	g
Illela	Tozai	13.650	4.798	1,066	75	-	-	g
Illela	Tozai	13.693	6.030	1,261	91	-	m-g	ic-g
Illela	Kiri	13.557	6.187	7,416	543	m-g	m-g	ic-g
Illela	Kiri	13.596	5.736	1,308	95	-	-	g
Isa	Tsabren Sarkin D	13.212	6.346	799	71	-	-	g
Isa	Tsabren Sarkin D	13.274	6.654	1,084	81	-	-	g
Isa	Tsabren Sarkin D	13.503	5.174	6,342	449	-	g	g
Isa	Isa S	13.105	6.530	3,823	265	-	g	g
Isa	Isa S	13.134	6.401	3,986	303	-	g	g
Isa	Gebe A	13.044	5.578	2,554	189	-	g	g
Isa	Gebe A	13.075	5.762	7,722	640	m-g	ic-g	ic-g
Isa	Gebe A	13.563	5.352	2,196	152	-	g	g
Isa	Gebe A	13.325	5.045	5,494	397	m-g	ic-g	ic-g

Table C.6.: Sokoto (cont.)

LGA	Ward	Lat. [°]	Long. [°]	Pop. #	Demand kW$_p$	Phase 1	Phase 2	Phase 3
Isa	Gebe B	13.117	5.409	12,149	1,025	m-g	ic-g	ic-g
Isa	Gebe B	13.138	5.375	8,625	722	m-g	ic-g	ic-g
Isa	Tidibale	13.151	4.538	2,909	210	-	m-g	ic-g
Isa	Tidibale	13.243	4.965	6,954	484	m-g	m-g	ic-g
Isa	Tidibale	13.277	5.756	7,447	552	m-g	m-g	ic-g
Isa	Bargaja	13.131	6.537	9,345	663	m-g	ic-g	ic-g
Isa	Bargaja	13.170	6.337	2,259	163	-	g	g
Isa	Bargaja	13.344	5.965	3,020	211	-	g	g
Isa	Bargaja	13.083	4.794	3,016	204	-	g	g
Isa	Bargaja	12.909	5.142	29,865	2,067	m-g	ic-g	ic-g
Isa	Shanawa	13.023	4.973	4,542	457	m-g	ic-g	ic-g
Isa	Shanawa	13.767	5.307	1,220	88	-	g	g
Isa	Yanfako	13.205	5.408	3,128	226	-	m-g	ic-g
Isa	Yanfako	13.223	5.686	2,054	147	-	-	g
Isa	Yanfako	13.242	4.989	6,116	445	m-g	m-g	ic-g
Isa	Yanfako	13.282	5.356	2,071	150	-	m-g	ic-g
Isa	Yanfako	13.299	6.704	2,881	204	-	m-g	ic-g
Isa	Yanfako	13.287	5.338	3,082	240	-	m-g	ic-g
Isa	Yanfako	13.357	6.335	1,689	118	-	-	g
Isa	Yanfako	13.036	4.918	2,120	153	-	m-g	ic-g
Isa	Yanfako	13.358	6.579	6,151	442	m-g	m-g	ic-g
Isa	Katuru	13.122	5.361	6,592	509	m-g	ic-g	ic-g
Isa	Tozai	13.199	6.504	2,052	145	-	g	g
Isa	Tozai	13.197	4.964	8,201	590	-	g	g
Isa	Tozai	13.225	6.428	1,303	98	-	g	g
Isa	Turba	13.161	6.441	6,252	450	-	g	g
Isa	Turba	13.217	5.037	3,958	270	-	-	g
Isa	Turba	13.422	5.652	6,759	470	m-g	m-g	ic-g
Isa	Turba	13.383	5.640	1,929	139	-	g	g
Isa	Turba	13.497	5.589	5,303	379	-	g	g
Isa	Turba	13.373	6.406	2,429	171	-	g	g
Isa	Turba	12.528	5.579	6,638	472	m-g	m-g	ic-g
Kebbe	Andarai/Kurunkwu	11.628	4.481	935	66	-	-	g
Kebbe	Jandutsi/Birnin	11.655	4.511	1,866	150	-	m-g	ic-g
Kebbe	Liba/Danwa	7.090	2.790	1,067	75	-	-	g
Kebbe	Liba/Danwa	7.581	2.869	2,196	210	m-g	m-g	ic-g
Kebbe	Alelu/Gehuru	11.667	4.465	1,151	82	-	-	g
Kebbe	Kebbe W	11.737	4.471	1,318	94	-	-	g
Kebbe	Margai - A	11.839	4.892	2,113	158	-	m-g	ic-g
Kebbe	Margai - A	12.124	4.903	3,270	240	-	g	g
Kebbe	Gayari	11.653	4.494	1,593	119	-	m-g	ic-g
Kebbe	Gayari	11.713	4.433	5,830	451	m-g	m-g	ic-g
Kebbe	Gayari	12.081	4.878	2,365	171	-	-	g
Kebbe	Girkau	11.704	4.481	1,358	117	-	-	g
Kebbe	Girkau	11.806	4.545	1,364	109	-	m-g	ic-g
Kebbe	Fakku	7.570	2.816	1,822	131	-	-	g
Kebbe	Fakku	7.240	3.073	899	75	-	-	g
Kebbe	Fakku	7.069	3.069	2,330	170	-	m-g	ic-g
Kebbe	Fakku	7.230	2.926	1,317	93	-	-	g
Kebbe	Fakku	6.910	2.850	1,009	71	-	-	g
Kebbe	Kuchi	7.217	3.340	8,997	753	m-g	m-g	ic-g
Kebbe	Sangi	6.896	2.867	1,145	90	-	m-g	m-g
Kebbe	Sangi	11.635	4.512	2,605	183	m-g	m-g	m-g
Kware	Birni/ G Karma	13.240	6.189	1,216	89	-	-	g
Kware	Bankanu/ R Kade	13.189	5.494	14,411	1,180	-	g	g
Kware	Bankanu/ R Kade	13.276	5.506	1,412	102	-	g	g

Table C.6.: Sokoto (cont.)

LGA	Ward	Lat. [°]	Long. [°]	Pop. #	Demand kW$_p$	Phase 1	Phase 2	Phase 3
Kware	Tsaki/ Walake E	12.987	4.815	1,070	93	-	g	g
Kware	Tsaki/ Walake E	13.010	5.394	1,498	157	-	g	g
Kware	Giere/Gajara	12.910	5.779	5,501	406	m-g	ic-g	ic-g
Kware	Kabanga	12.952	5.708	3,646	263	-	m-g	ic-g
Kware	Kabanga	12.958	4.843	2,150	157	-	-	g
Kware	Kabanga	12.982	4.781	748	69	-	-	g
Kware	Kabanga	13.369	5.193	3,062	246	-	g	g
Kware	Rikina	13.009	4.990	1,323	129	-	g	g
Rabah	Gwaddodi/GidanBW	13.005	4.743	4,507	449	-	-	g
Rabah	Gwaddodi/GidanBW	13.014	4.937	4,511	309	-	-	g
Rabah	Alkammu/Gyelgyel	13.750	5.816	1,251	84	-	g	g
Rabah	Riji/Maikujera	13.037	5.736	3,164	276	-	g	g
Rabah	Yar Tsakuwa	12.756	4.816	1,339	103	-	-	g
Rabah	Yar Tsakuwa	12.774	5.107	13,293	982	m-g	m-g	ic-g
Rabah	Yar Tsakuwa	12.800	5.217	1,943	142	-	m-g	ic-g
Rabah	Yar Tsakuwa	12.828	5.851	2,836	194	-	m-g	ic-g
Rabah	Gandi A	13.021	4.957	1,102	78	-	-	g
Rabah	Gandi B	12.848	5.320	4,826	363	m-g	m-g	ic-g
Rabah	Gandi B	12.870	5.395	1,564	147	-	m-g	ic-g
Rabah	Gandi B	13.364	5.177	1,209	91	-	m-g	m-g
Rabah	Gawakuke	13.030	5.317	1,877	163	m-g	ic-g	ic-g
Rabah	Gawakuke	13.071	4.696	2,524	249	-	g	g
Rabah	Gawakuke	13.087	5.473	821	81	-	g	g
Rabah	Nasarawa	12.743	5.068	1,436	108	-	-	g
Rabah	Nasarawa	12.743	5.197	4,097	298	-	m-g	ic-g
Rabah	Tsamiya	12.846	5.113	2,055	155	-	m-g	ic-g
Rabah	Tsamiya	12.862	5.088	1,205	104	-	-	g
Rabah	Tsamiya	12.899	5.394	3,540	299	-	g	g
Rabah	Kurya	12.953	5.243	5,849	570	m-g	m-g	ic-g
Rabah	Kurya	12.949	5.388	2,807	206	-	-	g
Rabah	Kurya	12.992	4.728	1,877	140	-	m-g	ic-g
Rabah	Rabah	13.083	5.138	9,828	1,011	m-g	ic-g	ic-g
Rabah	Rabah	13.118	5.637	2,594	214	-	g	g
Rabah	Tursa	13.076	5.582	1,410	101	-	-	g
Rabah	Tursa	13.161	5.179	935	86	-	-	g
Rabah	Rara	12.824	5.200	3,944	287	m-g	m-g	ic-g
Rabah	Rara	12.926	4.814	1,060	84	-	-	g
Sabon Birni	Tsabren Sarkin D	13.495	5.604	5,807	423	m-g	m-g	ic-g
Sabon Birni	Dukamaje/Ilah	13.628	5.449	3,788	294	-	m-g	ic-g
Sabon Birni	Unguwar Lalle	13.325	5.635	973	80	-	-	g
Sabon Birni	Unguwar Lalle	13.367	5.302	3,526	255	-	m-g	ic-g
Sabon Birni	Unguwar Lalle	13.530	6.386	6,218	478	m-g	m-g	ic-g
Sabon Birni	Unguwar Lalle	13.553	6.371	8,949	649	m-g	m-g	ic-g
Sabon Birni	Unguwar Lalle	13.592	5.645	3,529	267	-	-	g
Sabon Birni	Unguwar Lalle	13.624	5.335	2,320	197	-	-	g
Sabon Birni	Unguwar Lalle	13.411	5.391	2,287	165	-	-	g
Sabon Birni	S/Birni E	13.498	5.470	1,022	73	-	-	g
Sabon Birni	S/Birni E	13.513	5.303	2,011	159	-	m-g	ic-g
Sabon Birni	S/Birni E	13.514	5.461	917	77	-	-	g
Sabon Birni	S/Birni E	13.566	5.464	1,182	103	-	-	g
Sabon Birni	S/Birni E	13.598	6.153	1,484	122	-	-	g
Sabon Birni	S/Birni E	13.386	5.335	1,738	127	-	-	g
Sabon Birni	S/Birni E	13.431	5.235	1,039	73	-	-	g
Sabon Birni	S/Birni E	13.474	5.341	1,293	94	-	-	g
Sabon Birni	S/Birni E	13.475	5.363	1,216	85	-	-	g
Sabon Birni	Makuwana	13.526	5.289	2,377	173	-	-	g

Table C.6.: Sokoto (cont.)

LGA	**Ward**	**Lat.** [°]	**Long.** [°]	**Pop.** #	**Demand** kW$_p$	**Phase 1**	**Phase 2**	**Phase 3**
Sabon Birni	Makuwana	13.554	5.387	2,422	177	-	-	g
Sabon Birni	Makuwana	13.579	5.395	9,510	788	m-g	m-g	ic-g
Sabon Birni	Makuwana	13.588	5.566	1,182	95	-	-	g
Sabon Birni	Gangara	13.260	6.455	9,161	689	m-g	ic-g	ic-g
Sabon Birni	Gangara	13.306	6.422	5,539	393	-	-	g
Sabon Birni	Gangara	13.217	6.333	1,015	73	-	-	g
Sabon Birni	Lajinge	13.523	5.219	3,264	230	-	-	g
Sabon Birni	Lajinge	13.557	5.784	6,122	457	m-g	m-g	ic-g
Sabon Birni	Lajinge	13.609	5.536	1,049	74	-	-	g
Sabon Birni	Lajinge	13.621	6.096	2,701	191	-	-	g
Sabon Birni	Tsamaye	13.479	5.650	14,199	1,005	m-g	m-g	ic-g
Sabon Birni	Tsamaye	13.513	6.282	1,757	134	-	-	g
Sabon Birni	Tsamaye	13.516	5.721	2,631	279	-	-	g
Sabon Birni	Tsamaye	13.527	6.250	1,370	115	-	-	g
Sabon Birni	Tsamaye	13.531	5.856	1,268	96	-	-	g
Sabon Birni	Yanfako	13.288	4.278	2,801	202	-	m-g	ic-g
Sabon Birni	Yanfako	13.314	5.581	4,528	320	m-g	m-g	ic-g
Sabon Birni	Yanfako	13.524	5.656	7,416	551	m-g	m-g	ic-g
Sabon Birni	Yanfako	13.462	6.222	973	75	-	m-g	ic-g
Sabon Birni	Kuruwa	13.390	5.082	2,057	159	-	m-g	ic-g
Sabon Birni	Kuruwa	13.443	5.612	1,473	110	-	m-g	ic-g
Sabon Birni	Kuruwa	13.451	4.147	2,672	196	-	-	g
Sabon Birni	Kuruwa	13.475	5.274	1,001	88	-	-	g
Sabon Birni	Kuruwa	13.510	6.398	973	79	-	-	g
Sabon Birni	Kuruwa	13.288	6.305	1,237	89	-	-	g
Sabon Birni	Kalgo	13.303	5.191	1,116	81	-	-	g
Sabon Birni	Kalgo	13.336	6.404	1,675	142	-	m-g	ic-g
Sabon Birni	Kalgo	13.230	6.342	1,116	78	-	-	g
Sabon Birni	Turba	13.259	5.752	4,358	308	-	m-g	ic-g
Sabon Birni	Tara	13.389	5.210	1,477	110	-	-	g
Sabon Birni	Tara	13.445	6.394	5,164	388	m-g	m-g	ic-g
Sabon Birni	Tara	13.432	5.264	1,873	134	-	m-g	ic-g
Sabon Birni	Tara	13.468	6.399	6,126	449	-	-	g
Sabon Birni	Tara	13.638	5.487	1,025	73	-	-	g
Shagari	Dandin Mahe	12.579	4.936	6,707	699	m-g	ic-g	ic-g
Shagari	Dandin Mahe	12.627	4.936	3,781	277	m-g	ic-g	ic-g
Shagari	Dandin Mahe	12.695	5.326	16,118	1,539	m-g	ic-g	ic-g
Shagari	Jabo/Kagara	12.385	4.665	4,003	353	-	g	g
Shagari	Sanyinnawal	12.481	4.872	2,672	235	-	g	g
Shagari	Horo Birni	12.687	5.137	4,170	440	m-g	ic-g	ic-g
Shagari	Horo Birni	12.706	5.090	2,660	269	m-g	ic-g	ic-g
Shagari	Kambama	12.512	5.066	1,828	177	-	g	g
Shagari	Lambara	12.566	5.392	2,339	191	-	g	g
Shagari	Lambara	12.569	5.523	1,030	72	-	g	g
Shagari	Mandera	12.364	5.291	2,230	164	-	-	g
Shagari	Mandera	12.362	5.372	8,649	755	-	g	g
Shagari	Gangam	12.388	4.681	3,839	304	m-g	m-g	ic-g
Shagari	Jaredi	12.718	4.861	4,580	504	-	g	g
Shagari	Kajiji	13.551	6.081	1,738	146	-	g	g
Silame	Dundaye/Kwaido	12.968	5.361	2,249	166	-	m-g	ic-g
Silame	Dundaye/Kwaido	13.016	4.917	3,435	299	m-g	m-g	ic-g
Silame	Birnin T/Gudale	12.900	5.332	3,803	324	m-g	ic-g	ic-g
Silame	Katami N	12.942	4.839	1,988	149	-	g	g
Silame	Katami N	13.207	6.437	23,921	1,838	m-g	ic-g	ic-g
Silame	Katami S	12.875	5.010	2,317	193	-	g	g
Silame	Katami S	13.325	6.593	1,703	124	-	g	g

Table C.6.: Sokoto (cont.)

LGA	Ward	Lat. [°]	Long. [°]	Pop. #	Demand kW_p	Phase 1	Phase 2	Phase 3
Silame	Kubodu S	13.008	5.687	3,340	272	m-g	ic-g	ic-g
Silame	Kubodu S	13.007	5.713	7,173	553	m-g	ic-g	ic-g
Silame	Kubodu S	13.004	5.447	2,794	204	-	g	g
Silame	Kubodu S	12.996	4.645	2,033	155	-	g	g
Silame	Marafa E	12.932	4.901	903	75	-	-	g
Silame	Marafa E	12.931	4.691	1,330	94	-	g	g
Silame	Marafa E	13.286	6.594	1,067	75	-	-	g
Silame	Marafa W	12.976	5.315	2,996	279	-	g	g
Silame	Marafa W	12.991	5.070	1,656	119	-	g	g
Silame	Marafa W	13.036	5.355	1,133	83	-	g	g
Silame	Gande W	13.038	4.844	6,095	445	m-g	m-g	ic-g
Silame	Gande W	13.318	6.194	3,802	269	m-g	m-g	ic-g
Silame	Gande W	13.140	6.484	1,321	120	-	-	g
Silame	Soro Yamma	13.054	4.860	2,085	181	-	m-g	ic-g
Silame	Soro Yamma	13.095	6.495	766	74	-	-	g
Silame	Labani	12.872	5.201	6,642	495	m-g	ic-g	ic-g
Silame	Labani	12.887	5.237	3,541	263	m-g	ic-g	ic-g
Silame	Labani	12.897	5.798	3,433	259	m-g	ic-g	ic-g
Silame	Labani	12.911	5.434	2,412	177	m-g	ic-g	ic-g
Silame	Labani	12.918	5.728	2,627	213	-	g	g
Silame	Labani	12.918	5.387	1,786	129	-	g	g
Silame	Labani	12.929	5.168	1,491	106	-	g	g
Silame	Labani	12.918	4.718	1,442	102	-	g	g
Silame	Silame	13.015	5.076	15,430	1,334	m-g	ic-g	ic-g
Silame	Silame	13.021	5.351	1,929	143	-	g	g
Silame	Silame	12.942	5.990	1,168	81	-	g	g
Silame	Silame	13.661	6.248	1,077	82	-	g	g
Silame	Silame	13.034	5.004	1,251	88	-	g	g
Silame	Silame	13.232	6.359	1,300	86	-	g	g
Sokoto N	G Bubu/G Yaro	13.040	4.981	2,464	250	-	g	g
Tambuwal	Bakaya/SabonB	11.772	4.811	1,230	93	-	m-g	ic-g
Tambuwal	Bakaya/SabonB	12.140	4.817	1,269	97	-	-	g
Tambuwal	Bakaya/SabonB	12.153	4.677	2,518	190	-	m-g	ic-g
Tambuwal	Tambuwal/Shin.	12.225	4.631	1,517	109	-	m-g	ic-g
Tambuwal	Tambuwal/Shin.	12.320	4.621	1,682	135	-	-	g
Tambuwal	Tambuwal/Shin.	12.322	4.778	1,176	98	-	-	g
Tambuwal	Barkeji/Nabaguda	12.275	4.677	1,053	82	-	-	g
Tambuwal	Bagida/Lukkingo	12.094	4.846	2,224	167	-	m-g	ic-g
Tambuwal	Bagida/Lukkingo	12.190	4.785	1,758	125	-	g	g
Tambuwal	Bashire/Maikada	12.170	4.647	1,322	94	-	-	g
Tambuwal	Dogondaji/Sala	12.353	5.726	894	73	-	m-g	ic-g
Tambuwal	Dogondaji/Sala	12.372	4.789	1,625	128	-	g	g
Tambuwal	Faga/Alasan	12.181	4.686	2,260	190	-	g	g
Tambuwal	Jabo/Kagara	12.193	4.631	4,757	352	m-g	m-g	ic-g
Tambuwal	Jabo/Kagara	12.336	5.051	2,224	221	m-g	m-g	ic-g
Tambuwal	Jabo/Kagara	12.356	4.699	1,550	107	-	m-g	ic-g
Tambuwal	Romon Sarki	12.087	4.559	3,968	296	-	m-g	ic-g
Tambuwal	Romon Sarki	12.132	4.696	2,704	187	-	m-g	ic-g
Tambuwal	Romon Sarki	12.140	4.559	2,891	213	-	-	g
Tambuwal	Romon Sarki	12.152	4.832	4,396	310	m-g	m-g	ic-g
Tambuwal	Romon Sarki	12.154	4.894	1,867	133	-	-	g
Tambuwal	Saida/Goshe	12.580	5.492	839	73	-	-	g
Tambuwal	Kebbe W	12.070	4.572	1,450	108	-	-	g
Tambuwal	Dodoru	12.343	5.336	1,536	167	-	m-g	ic-g
Tangaza	Kwacce-Huru	13.177	5.174	1,519	116	-	-	g
Tangaza	Kwacce-Huru	13.163	5.027	1,578	111	-	m-g	ic-g

Table C.6.: Sokoto (cont.)

LGA	Ward	Lat. [°]	Long. [°]	Pop. #	Demand kW_p	Phase 1	Phase 2	Phase 3
Tangaza	Kwacce-Huru	13.212	5.372	1,310	138	-	m-g	ic-g
Tangaza	Kwacce-Huru	13.203	4.880	1,902	130	-	-	g
Tangaza	Atakwanyo	13.334	5.453	1,790	133	-	-	g
Tangaza	Ruwa-Wuri	13.614	4.857	3,230	251	-	m-g	ic-g
Tangaza	Ruwa-Wuri	13.682	5.348	2,132	160	-	m-g	ic-g
Tangaza	Ruwa-Wuri	13.689	5.817	3,142	245	m-g	m-g	ic-g
Tangaza	Ruwa-Wuri	13.694	5.263	1,743	129	-	-	g
Tangaza	Ruwa-Wuri	13.699	5.207	1,588	116	-	-	g
Tangaza	Ruwa-Wuri	13.713	5.873	1,706	119	-	-	g
Tangaza	Ruwa-Wuri	13.709	5.361	2,165	150	-	m-g	ic-g
Tangaza	Magonho	13.340	5.175	1,082	77	-	-	m-g
Tangaza	Magonho	13.442	5.332	1,441	105	-	-	g
Tangaza	Magonho	13.517	5.987	1,617	113	-	g	g
Tangaza	Sakkwai	13.588	5.346	1,206	89	-	-	g
Tangaza	Sakkwai	13.617	6.346	2,001	147	-	m-g	ic-g
Tangaza	Sakkwai	13.622	4.411	1,877	132	-	m-g	ic-g
Tangaza	Tangaza	13.299	6.103	2,784	245	-	g	g
Tangaza	Tangaza	13.365	6.281	1,708	126	-	m-g	ic-g
Tangaza	Tangaza	13.365	5.281	1,536	127	-	-	g
Tangaza	Gigane	13.508	6.418	1,289	100	-	-	g
Tangaza	Salewa	13.458	5.496	1,859	140	-	m-g	ic-g
Tangaza	Salewa	13.522	5.827	1,348	92	-	-	g
Tangaza	Salewa	13.609	6.228	2,101	145	-	-	g
Tangaza	Salewa	13.595	5.461	1,144	87	-	-	g
Tangaza	Sutti	13.342	6.646	3,885	289	m-g	m-g	ic-g
Tangaza	Sutti	13.647	6.300	1,119	82	-	-	g
Tangaza	Raka	13.359	6.618	1,619	115	-	-	g
Tangaza	Raka	13.365	4.997	1,496	106	-	-	g
Tangaza	Raka	13.409	4.174	2,460	181	-	m-g	ic-g
Tureta	Gidan Kare/Bim.	13.644	6.288	1,022	76	-	-	g
Tureta	Bangi/Dabaga	12.604	5.245	3,125	226	-	g	g
Tureta	Fura Girke	12.443	4.894	1,724	157	-	g	g
Tureta	Fura Girke	12.486	4.906	1,414	140	-	g	g
Tureta	Kambama	12.408	5.003	1,383	105	-	-	g
Tureta	Kwarare	12.213	4.645	2,618	199	m-g	m-g	m-g
Tureta	Lambara	12.219	4.601	3,187	236	-	m-g	ic-g
Tureta	Tsamiya	12.423	4.866	2,355	229	-	g	g
Tureta	Tsamiya	12.438	4.659	2,416	247	-	g	g
Tureta	Tsamiya	12.467	4.990	1,540	157	-	g	g
Tureta	Kuruwa	12.517	4.942	1,136	85	-	-	g
Tureta	Zauma	12.211	4.561	975	88	m-g	m-g	m-g
Tureta	Zauma	12.228	4.564	825	69	-	-	m-g
Wamako	G/Hamidu/G/Kaya	13.121	4.901	3,293	326	m-g	m-g	ic-g
Wamako	G Bubu/G Yaro	13.023	5.025	1,234	119	-	g	g
Wamako	G Bubu/G Yaro	13.034	5.298	1,232	129	-	g	g
Wamako	Kubodu N	13.019	5.435	8,486	645	m-g	ic-g	ic-g
Wamako	Kubodu N	13.086	6.563	5,105	366	m-g	ic-g	ic-g
Wamako	Gwamatse	12.955	4.787	1,482	120	-	g	g
Wamako	Gwamatse	13.006	5.039	1,122	98	-	g	g
Wamako	Gwamatse	13.012	4.760	3,473	255	-	g	g
Wamako	Bunkari	13.042	5.071	1,017	75	-	-	g
Wamako	Kammata	12.974	4.833	1,771	153	-	g	g
Wamako	Wamakko	12.993	5.658	1,524	133	-	g	g
Wurno	Gari Dole/Dan	13.281	5.470	1,067	89	-	g	g
Wurno	Alkammu/Gyelgyel	13.093	5.383	6,099	431	-	g	g
Wurno	Alkammu/Gyelgyel	13.118	5.444	3,037	321	-	g	g

Table C.6.: Sokoto (cont.)

LGA	Ward	Lat. [°]	Long. [°]	Pop. #	Demand kW$_p$	Phase 1	Phase 2	Phase 3
Wurno	Chacho/Marnona	13.127	4.785	2,686	263	-	g	g
Wurno	Chacho/Marnona	13.147	5.459	1,050	80	-	-	g
Wurno	Chacho/Marnona	13.216	5.396	1,189	88	-	-	g
Wurno	Chacho/Marnona	13.253	6.475	2,377	161	-	m-g	ic-g
Wurno	Chacho/Marnona	13.595	6.413	1,077	85	-	g	g
Wurno	Kwasare/Sisawa	13.167	5.833	1,261	109	-	-	g
Wurno	Kwasare/Sisawa	13.754	5.720	1,251	104	-	-	g
Wurno	Lahodu/G/Bango	13.148	4.835	1,782	132	-	-	g
Wurno	Lahodu/G/Bango	13.735	4.908	1,355	104	-	g	g
Wurno	Lahodu/G/Bango	13.745	4.874	1,255	95	-	-	g
Wurno	Kwargaba	13.239	5.437	1,265	102	-	g	g
Wurno	Kwargaba	13.250	5.206	4,198	312	-	g	g
Wurno	Kwargaba	13.254	6.612	1,704	147	-	g	g
Wurno	Dimbiso	13.295	4.906	3,051	300	m-g	ic-g	ic-g
Wurno	Dinawa	13.142	4.812	1,193	95	-	-	g
Wurno	Dinawa	13.167	5.450	3,482	299	m-g	ic-g	ic-g
Wurno	Dinawa	13.741	5.546	1,651	137	-	g	g
Wurno	Giyawa	13.324	6.653	5,240	374	m-g	ic-g	ic-g
Wurno	Huchi	13.299	6.216	7,534	638	-	g	g
Yabo	Saida/Goshe	12.685	5.079	1,410	115	-	-	g
Yabo	Saida/Goshe	12.723	5.158	1,536	111	-	m-g	ic-g
Yabo	Sanyinnawal	12.487	4.956	3,744	266	m-g	m-g	ic-g
Yabo	Sanyinnawal	12.541	5.280	3,853	375	m-g	ic-g	ic-g
Yabo	Sanyinnawal	12.565	5.476	1,854	199	-	g	g
Yabo	Ruggar Iya	12.585	4.891	1,376	104	-	g	g
Yabo	Ruggar Iya	12.672	4.832	3,948	289	m-g	ic-g	ic-g
Yabo	Ruggar Iya	12.693	4.994	17,162	1,487	-	g	g
Yabo	Birniruwa	12.828	5.665	5,267	366	-	g	g
Yabo	Birniruwa	13.766	5.633	1,439	101	-	m-g	ic-g
Yabo	Torankawa	12.711	5.302	8,643	612	-	-	g
Yabo	Torankawa	12.707	4.969	1,236	87	-	-	g
Yabo	Yabo A	12.576	5.416	1,948	140	-	g	g
Yabo	Yabo B	12.611	4.935	4,952	432	-	g	g
Yabo	Bingaje	12.641	5.194	1,233	95	-	g	g
Yabo	Bingaje	12.675	5.026	3,882	317	m-g	ic-g	ic-g
Yabo	Bingaje	13.742	4.721	2,353	175	-	g	g
Yabo	Kilgori	12.792	5.167	2,860	201	m-g	m-g	ic-g
Yabo	Bakale	12.827	5.020	1,587	118	-	-	g
Yabo	Binji	12.735	4.867	3,854	276	m-g	m-g	ic-g
Yabo	Binji	12.792	5.173	1,142	82	-	-	g

Statement of Authorship

I declare that I have completed this dissertation single-handedly without the unauthorized help of a second party and only with the assistance acknowledged therein. I have appropriately acknowledged and cited all text passages that are derived verbatim from or are based on the content of published work of others, and all information relating to verbal communications. I consent to the use of an anti -plagiarism software to check my thesis. I have abided by the principles of good scientific conduct laid down in the charter of the Justus Liebig University Giessen „Satzung der Justus- Liebig -Universität Gießen zur Sicherung guter wissenschaftlicher Praxis“ in carrying out the investigations described in the dissertation.
The PhD Thesis was not used in the same or in a similar version to achieve an academic grading.

Date Signature