Beyond costs: a governance-based approach to electricity access modelling for Sub-Saharan Africa

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7 AFFORDABLE AND CLEAN ENERGY

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Abstract

Private sector investment is crucial to reaching 100% electricity access by 2030 in Sub-Saharan Africa (SDG7), and a strong enabling environment is key to unlocking it. Amongst others, governance and regulatory quality are important enabling factors. To indicate which regions in Sub-Saharan Africa are most suitable for private sector investment, this report presents an Electricity Access Governance Index (EAGI) which uses 4 different governance indicators to assess the quality of governance related to electricity access investment for countries in Sub-Saharan Africa. The index is included in a spatial electrification model by modifying the discount rate for each country based on EAGI scores. The model produces results for the optimal, least-cost technologies for grid-cells in Africa to provide 100% electricity access and shows that private sector investment in mini-grid and standalone technologies is needed in large parts of Sub-Saharan Africa. In central Africa there is considerable potential for private sector investment in small-scale hydropower, while most of west Africa is dominated by central grid-expansion. A country case study of the DRC revealed that besides governance and regulatory quality, logistics and accessibility are key factors in determining private sector investment. For investment in Ghana a case study showed that the private sector should focus on investing in technologies to supplement the existing grid in countries with high levels of current electricity access and an unreliable grid. The results of this research can be used to inform investment strategies, and to suggest policy improvements in the countries studied.

Preface

The thesis presented here is the culmination of six months of work at Utrecht University, Shell New Energies, and The Netherlands Environment Assessment Agency (PBL). The research was undertaken as the final stage of the Energy Science MSc at Utrecht University. The aim was to explore how the private sector can best develop investment strategies to improve the electricity access levels in Sub-Saharan Africa towards reaching Sustainable Development Goal 7. The collaboration between PBL, Shell, and the University is not necessarily a traditional one, but it allowed for a truly multi-disciplinary approach to the research aim. The project was started with an extensive review of the current research themes in this field, after which it was decided to delve deeper in to the challenges of investing in Sub-Saharan Africa. The model used, developed previously by PBL, was a good starting point, and allowed for a quantitative approach to governance challenges in Sub-Saharan Africa to be included. The results of the model are the first to be produced using new data gathered during this research, and by the team at PBL. For this reason, there are still several inconsistencies that need to be addressed, and the analysis and discussion of the results in this report highlight what future research needs are. Nevertheless, a quantitative modelling project on Sub-Saharan Africa is still a delicate exercise, and there are simply factors that cannot be measured. Hopefully this thesis can be seen as a first step towards more clearly understanding the challenges and opportunities related to governance and electricity access in Sub-Saharan Africa, and a step towards universal electricity access for all.

Acknowledgements

The unwavering support and fruitful discussions with Anteneh Dagnachew (PBL) and Giacomo Falchetta (FEEM) were absolutely instrumental in the completion of this work, especially considering they were not obligated in any way to be involved. Dr. Katharina Gruenberg from the Shell New Energies department supervised fantastically throughout the process, and I am very thankful for her support. Throughout this research, Prof. Gert Jan Kramer has provided very enlightening and welcome feedback on the work, and I would like to thank him kindly for his commitment to supervising me for the last year. I would also like to thank my friends, family, and colleagues for all the support over the past months.

List of abbreviations

BNEF: Bloomberg New Energy Finance, 24
CAR: Central African Republic, 31
CPI: Corruption Perceptions Index, 22
DRC: Democratic Republic of Congo, 20
EAGI: Electricity Access Governance Index, 23
ECOWAS: Economic Community of West African States, 38
EDL: Economic Distance Limit, 17
ESMAP: Energy Sector Management Assistance Program, 9
EU: European Union, 42
GDP: Gross Domestic Product, 18
GHG: Greenhouse Gas, 16
GIS: Geographic Information System, 12
GOGLA: Global Off-grid Lighting Association, 13
IDA: International Donor Agency, 42
IEA: International Energy Agency, 9
IMAGE: Integrated Model to assess the Global Environment, 12
IRENA: International Renewable Energy Agency, 9
LCOE: Levelised cost of Electricity, 17
MANI: Market Assistance Need Index, 13
NES: National Electrification Scheme, 38
OnSSET: Open-source Spatial Electrification Tool. *See*,
PAYG: Pay as you Go, 13
PBL: Planbureau voor de Leefomgeving, 9
PCA: Principal Component Analysis, 18
PV: Photovoltaic, 13
PWC: Price Waterhouse Coopers, 25
RISE: Regulatory Indicators for Sustainable Energy, 21
SDG7: Sustainable Development Goal 7, 9
SE4ALL: Sustainable Energy for All, 13
SSA: Sub Saharan Africa, 9
SSP2: Shared Socioeconomic Pathway 2, 17
TFEC: Total Final Energy Consumption, 9
TI: Transparency International, 22
TIMER: Targets IMage Energy Regional, 12
UN: United Nations, 13
UN DESA: United Nations Dept. of Economic and Social Affairs, 35
UN OCHA: United Nations Office for the Coordination of Humanitarian Affairs, 36
UNEP: United Nations Environment Programme, 14
USAID: United States Agency for International Development, 42
WB: World Bank, 38
WGI: Worldwide Governance Indicators, 23
WRI: World Resources Institute, 13

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1. Introduction

More than half of the households in Sub-Saharan Africa (SSA) currently do not have access to electricity (ESMAP, 2019), which is essential for modern healthcare, education, communications, and human development. This is unimaginable for those living in societies with 100% access to sufficient, reliable, and affordable electricity: where buildings can be heated and cooled on demand, and productivity continues once the sun has set. There is a pressing need to provide universal access to electricity to enable sustainable development. This is the motivation for Sustainable Development Goal 7 (SDG7) 'Ensure access to affordable, reliable, sustainable, and modern energy for all' which was adopted as part of the SDG agenda in 2015 with the aim to be reached by 2030 (United Nations, 2015).

Not only is there currently a large unserved population without access to electricity in SSA, the demand for electricity in SSA is predicted to increase enormously; quadrupling by 2040 (Castellano, Kendall, Nikomarov, & Swemmer, 2015). This is mainly attributed to a rapidly growing population: in SSA, the population growth rates of countries are some of the highest in the world, with an average of 2.7% annually, compared to the global average of 1.2% (World Bank, 2017b). The most recent data suggests that the proportion of population in SSA with electricity access is growing (World Bank, 2018b), though this growth is unequally distributed in the region. Bazilian et al. (2012a - p10) aptly describe the scale of power generation increase needed to provide universal access to electricity in SSA: "a little more than a Three Gorges Dam (22.5GW) sized project each and every year through 2030", highlighting the colossal capacity and investment requirements in the region.

Currently electricity in SSA is mostly generated in thermal power plants using fossil fuels, or ageing large-scale hydroelectric dams. For SDG7 to be reached, a transition to modern, sustainable, and reliable sources must be made. While developed economies need to shift away from high levels of fossil fuel energy use, SSA, like other developing regions around the world, has the unique and challenging opportunity to bypass this highly energy intense, traditional energy use stage. Off-grid renewable electricity generation has seen tremendous growth over the last decade, with the population in Africa served by these technologies increasing by more than a factor of ten (IRENA, 2018). Continuing this trend has the potential to transform the electricity situation in SSA, and greatly contribute to the achievement of SDG7, industrial and human development, as well as global climate goals such as the Paris Agreement. Unfortunately, the renewable energy share of total final energy consumption (TFEC) is declining in most countries in SSA (World Bank, 2018b) and without an efficient strategy for public and private sector investment, the transition to modern, clean sources will not be made.

To achieve SDG7 in SSA, and for universal electricity access to become a reality, a huge volume of investment of around $30bn per year is needed until 2030 (IEA, 2019) (PBL 2018). Most of this will need to be private sector investment. Dollars alone are not enough; without sound investment strategies, clear pathways, and proven technologies, this investment risks being poorly allocated. The 2019 Tracking SDG7 report states that a key strategy in closing the electricity access gap is the use of data-based decision-making (ESMAP, 2019). Data-intensive computer models are widely used in energy investment planning around the world, and recently in the analysis of providing electricity access in SSA. However, every country in SSA has its own peculiarities regarding access to electricity, and the power sector in general (Morrissey, 2017), meaning that a simple modelling tool cannot provide an optimal solution for every country. To improve the performance of such models in SSA, and guide private sector investment in this sector, more insightful indicators are needed. This research builds on energy planning techniques, by including new factors in an electricity planning model to assess the optimal, and crucially, most suitable options for private sector investment in electricity access in SSA. The aim of this work is to examine the upcoming markets for investment, and to develop a more accurate assessment of the enabling factors for investment. Such assessment will contribute to unlocking the private sector finance for the substantial electricity access investment needed, if SDG7 is to be achieved. This research presents additional social, political, and cost indicators, and implements them in an existing model to help guide investment for electricity access in SSA.

To direct the research methodology and analysis, the following research question and sub-questions were formulated:

'Which regions in Sub-Saharan Africa are suitable for private sector investment in electricity access, and how can this be demonstrated using energy planning models?'

- What factors influence the potential for private sector investment in electricity access in SSA?
- How can quantitative models be improved to more accurately provide pathways for increasing electricity access in SSA?
- Where are the largest and most suitable potential markets for private sector investment in electricity access in SSA, and what are the key regional factors which will determine the investment strategy?

The report is structured as follows: section 2 examines the existing literature and the context of the research, section 3 outlines the methodology used, and section 4 explains the data collection and analysis process. This is followed by the results of the model in section 5, country case studies in section 6, a discussion of the results in section 7, and the conclusion and final remarks in section 8.

2. Background and literature review

The importance of energy for human development has long been examined in academia; Goldemberg, Johansson, Reddy, and Williams (1985) were some of the earliest to show that high-quality and efficient energy is necessary for human development. This seminal work paved the way for research on the energy/development nexus. In 1987, the Brundtland report set out the role of sustainable development in the future of global society (World Commission on Environment and Development, 1987), and since then there has been a proliferation of research on this topic. Academic research on electricity access began to appear in the late 1990s, with Davis (1998) examining the effect of access to electricity on fuel choice in South Africa , and Cecelski (1998) looking at the challenges to scaling up rural electricity access in 4 developing countries. This has been continued in recent years with research on the role of electricity access and energy infrastructure in economic growth development (Khennas, 2012).

More recently, the contribution of renewable energy to electricity access in developing countries - particularly in Africa (e.g. Colombo, Bologna, & Masera, 2013; Kaygusuz, 2012; Oseni, 2012) - was examined. In particular Alstone, Gershenson and Kammen (2015) published a comprehensive perspective in Nature Climate Change on different approaches to increase global energy access, highlighting the importance of decentralised off-grid renewable solutions for the majority of the rural poor. Through this it has emerged that off-grid solutions are beneficial, indeed essential for achieving universal electricity access. The research by van der Zwaan, Kober, Longa, van der Laan, and Kramer (2018) showed that leap-frogging fossil fuels in the African power sector straight to renewable generation is an opportunity to increase access to electricity in a cost optimal way. This has led to research focussing on the optimal solutions, and feasibility studies

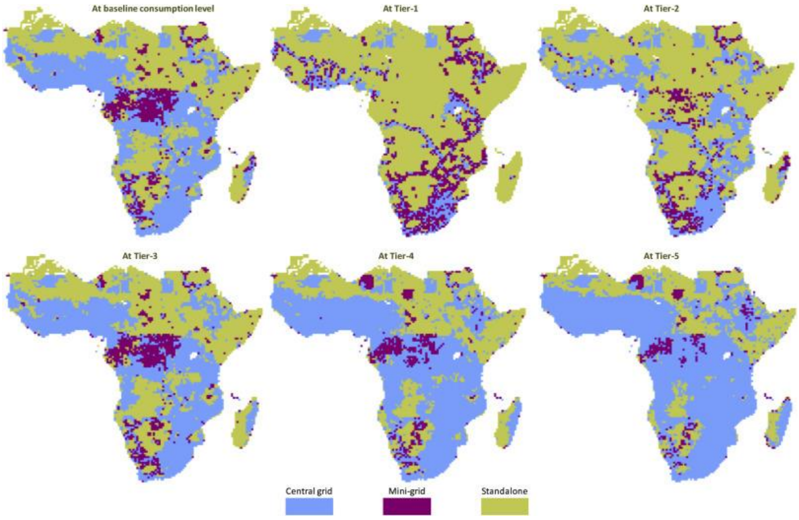

Figure 1 Results of 2017 spatial electrification modelling for universal electricity access in 2030 (Dagnachew et. al. 2017). Tiers of electricity based on ESMAP multi-tier framework (Appendix 4)

for renewable and off-grid technologies in SSA, for instance Aderemi et al. (2018), Okoye & Oranekwu-Okoye (2018), and Eales, Buckland, Frame, Archer, & Galloway (2018). These studies generally investigate either the technical, economic, or techno-economic feasibility of a system in a specific location and at a high-level, scenarios for energy access to 2030 in SSA were investigated by Bazilian et al. in 2012. Due to the magnitude of added electricity generation needed in SSA to reach universal access and the lack of current infrastructure, they conclude that a mix of large-scale and distributed generation is necessary.

In 2017, Dagnachew et al. at the Planbureau voor de Leefomgeving (PBL) used a least-cost optimization model (IMAGE-TIMER see Stehfest, van Vuuren, Kram, & Bouwman (2014)) to assess the optimal solutions for electricity access in SSA (Dagnachew et al., 2017). The model uses levelized cost of electricity (LCOE), population density, and distance-to-grid, where grid extension, mini-grids and standalone systems were considered. Different solutions were given based on different Energy Sector Management Assistance Program (ESMAP) tiers of electricity consumption level achieved. Figure 1 shows the results of this research. Following this work, the link between climate change mitigation and providing universal electricity access in SSA was investigated (Dagnachew, Lucas, Hof, & van Vuuren, 2018) concluding that SSA can benefit from global climate mitigation policy through the lowering of renewable energy technology costs, and efficiency improvements. Another outcome of this research is an estimate that at least $27-33bn of investment is needed annually to achieve universal electricity access in SSA, broadly in line with estimates by the IEA (2019).

Similar research has been done using GIS-based spatial modelling at KTH Stockholm, where the Open-source Spatial Electrification Tool (OnSSET) was developed by Mentis et al. (2017). The OnSSET model is a bottom-up, cost-optimal electrification using more spatial data, and incorporates night-time satellite data to clearly map present electricity access. The OnSSET model has been used for continent-wide as well as national-scale

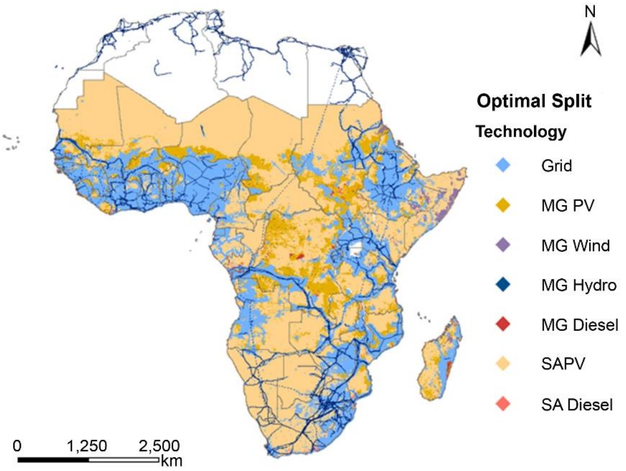

Figure 2 Results of the spatial electrification modelling for universal electricity access in 2030 using the OnSSET model

optimization studies (e.g. Moksnes, Korkovelos, Mentis, & Howells (2017) and Mentis et al. (2015)) and is used by the International Energy Agency (IEA) and the United Nations (UN). Figure 2 shows the results of the continent-wide optimisation completed using the OnSSET model (Mentis et al, 2017).

Both the PBL and KTH models simply provide an optimal solution for the electricity access deficiency, but do not take in to account who can and should invest where. By mapping economic indicators by region, this has been investigated for the cases of Tanzania and India by the World Resources Institute (WRI). The WRI used economic buoyancy and other demographic indicators to assess where the private and public sectors can best invest to improve electricity access (WRI, 2019). The work by the WRI is the first to combine social and economic factors with technical feasibility for electricity access in SSA. On a country scale, this provides good insights for firms already active while on a continent-wide scale, this can indicate where the key upcoming markets are for private sector investment. This has been done at an elementary level using a Market Assistance Need Index (MANI) developed by Mentis et al. in 2017, incorporating country risk and institutional weakness. The international public sector, in this case Lighting Global has also developed an index to measure the market-attractiveness for investments in Pay as You Go (PAYG) systems in Africa (Lighting Global, 2019), though being developed specifically for PAYG solar PV systems, the focus lies beside electricity access alone. These initial indices form the basis for the use of new indicators in electrification planning models in this report.

Bhattacharyya and Timilsina (2009) analysed the effectiveness of energy modelling for developing countries, and concluded that developing countries have “certain specific characteristics which are not adequately captured by models originating from the developed countries”. Data requirements and specific peculiarities of developing countries are cited as the main shortfalls. This is another driver for this research to build on these models to adapt them better to the local characteristics of developing markets and include factors that are typically overlooked.

Besides a large body of academic literature, the international public and private sector also produce regular reports on the current and future needs required to reach universal electricity access in SSA. The most relevant of these are the reports by IRENA, Lighting Africa, GOGLA, and SE4ALL. The nature of these reports is generally to take stock of the current status of renewable penetration, electricity access market development, solar PV development, and SDG7 progress respectively (IRENA, 2019)(Lighting Africa, 2016) (GOGLA, 2018).

2.1 Barriers to electricity access

Despite the literature giving economically optimal solutions, and commentaries on the necessary developments in electricity infrastructure in SSA, significant barriers to investment remain. While cost estimates and technical potentials of energy sources are an attractive way of capturing investor attention for large energy projects, Trotter (2016) argues that democratic performance and institutional strength are key to decreasing electrification inequality in SSA. Without strong performing governments, electricity access in SSA will stay unequal. Poor governance performance is one of the main barriers to electricity access, a view shared by the UN environment programme (UNEP). UNEP examined the barriers to electricity access in SSA, stating that 'public commitment at the local level' is key to unlocking investment for electricity access (Fischer, Lopez, & Suh, 2011). This suggests again that good governance is a prerequisite for electricity access improvement.

Good governance is imperative for obtaining the substantial investments that are required from the private sector for electricity access in SSA (Tagliapietra & Bazilian, 2017). This link between electricity access and governance was first explored in detail in 2012, revealing that government effectiveness is strongly linked to electricity access in SSA, and that the responsibility to provide electricity access on a large scale lie largely with the private sector. (Onyeji, Bazilian, & Nussbaumer, 2012). The link of investment to quality of governance is the lens that this research uses to improve the quantitative model used by the PBL. By taking a closer look at the performance of governments in SSA and selecting additional indicators to include in the model that reflect this, an assessment of the best regions for private sector investment can be given. This is done with the aim of not simply modelling electricity access pathways using cost and distance data, but to also encompass regulatory, social, and governance factors. It can thus provide investors with the necessary guidance on where the most favourable areas are for investment. Private sector investment is characterised by companies investing in projects for market-based returns, meaning a sound regulatory environment is essential, not least to enable a company to enter a market in the first place. Approaching governance in Africa in a quantitative manner presents its own set of challenges, not least the fact that this is essentially an attempt at 'quantifying the unquantifiable'. Despite this, including information on these factors will allow private sector investment in electricity access in SSA to be more efficiently allocated, and to identify promising upcoming markets. Not only will the optimal configurations be calculated in more detail than before, but also recommendations for both the public and private sector can be given to contribute to SDG7.

3. Methodology

The model used by PBL in 2017 and 2018 to explore electrification pathways for SSA was developed to determine the optimal technologies to provide 100% electricity access in SSA. In this study however, this model is used with a different aim in mind: to determine where the private sector can best invest in electricity access. This requires new input variables relating specifically to private sector investment to be included. In this section, the model choice is explained, followed by the selection criteria for the additional input variables and the underlying assumptions in the model. The scenarios used in the model and the steps taken in the analysis of the results are also explained.

3.1 Model

The two main quantitative models that have been used to investigate electrification pathways for SSA in academia are the IMAGE-TIMER model developed at the PBL in The Netherlands, and the OnSSET model developed by the KTH university in Sweden (see section 2 for details). In this research, quantitative modelling of electrification pathways is improved by adding indicators to a model to include the influence of governance on investment in electricity access. One model is used as a basis for this research, to which indicators can be added, and the model re-run. The IMAGE-TIMER least-cost optimization model used by Dagnachew et al (2017) and Dagnachew et al (2018) is chosen. The model has been successfully used for a number of recent publications on electrification pathways in SSA (Dagnachew et al, 2017, 2018, Lucas et al, 2017), and is being developed further. The publications based on the model are an important guidance for the Dutch ministry of foreign affairs for the overseas development agenda. The team behind the model was readily available for contact, and the PBL offices are located near the university where this research was carried out making the model easily useable, and close cooperation with the team at PBL was possible. Section 3.2 gives a concise overview of the model that is used and section 3.3 and 3.4 outline the steps taken to include new indicators in the model, and to run the model. Section 3.5 gives a short explanation of the case study method, which is used to critically review the results of the model.

3.2 IMAGE-TIMER optimization model overview[1]

The IMAGE-TIMER model is part of the IMAGE 3.0 integrated assessment model framework, developed by PBL in 2014. IMAGE 3.0 is used for large-scale and long-term studies, investigating the relations between the environment and human development. The IMAGE framework itself is a very large and data-intensive model. The IMAGE framework uses 26 world regions to take specific local conditions in to account. The 26 different regions are shown in Appendix 2. TIMER is the 'Targets IMage Energy Regional Model', which explores long term trends in energy consumption and energy-related

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[1] Based on Stehfest et al., 2014 and Dagnachew et al. 2017

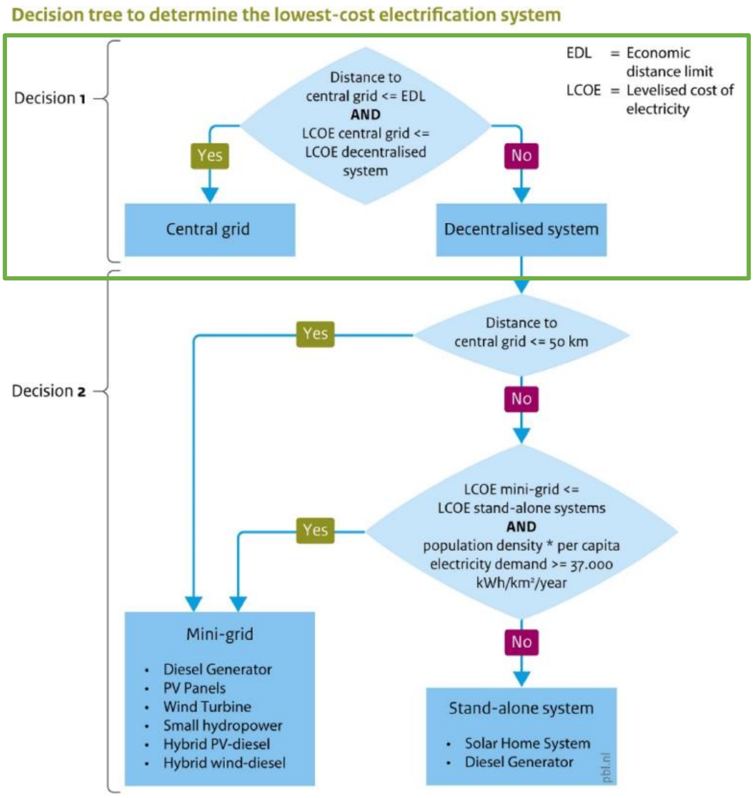

Figure 3 Decision tree for the spatial electrification model used in this research. The green box shows the decision that is focused on in this work. (Source: Dagnachew et al. 2017)

greenhouse gas (GHG) emissions (de Vries et al. 2001). The IMAGE framework is used to explore electrification pathways by using a bottom-up least cost optimization model using the projections from the TIMER model.

The TIMER model was first used for energy access research by van Ruijven et al. in 2011 to investigate household energy use projections for India using a sub-model. This included specific factors related to energy access in a bottom-up style. The research done by Dagnachew et al in 2017 and 2018 used an updated and modified version of this sub-model to investigate electricity access in SSA specifically including off-grid electrification options for 2030. Rather than a global focus, the model used in 2017 looks at SSA in terms of grid cells (0.5° x 0.5°). This allows for results to be disaggregated in to countries, and grid-cells not only the large SSA regions used in the global TIMER model (Appendix 2). The model makes two main decisions for each cell: grid or off-grid, and mini-grid or standalone to find the optimal technology for providing universal electricity access (Dagnachew et al, 2017). These decisions are based on the following main inputs: cost of power generation, population density, household electricity demand, cost of transmission and distribution, technical potentials of renewable energy sources, and distance from existing power line. These inputs are used in calculating the levelized cost of electricity

(LCOE) and the economic distance limit (EDL). The full decision tree for the model is given in Figure 3.

To explore the pathways for universal access in 2030, the model uses demographic data from the Shared Socioeconomic Pathway 2 (SSP2) which was devised by the Integrated Assessment Model community (Riahi et al, 2017). The SSP2 scenario is chosen since it represents moderate population growth and economic growth, along with acceptance for all energy conversion technologies (Dagnachew et al, 2017). Electricity consumption levels in this new, updated use of the model are based on the calculations by Falchetta & Noussan (2019). This new, detailed data was produced using night-time satellite imagery, where the link with income levels was examined. This showed that the night-time data is effective in predicting electricity consumption in low-income countries, suitable for use in analysis of SSA. The high-resolution consumption data gives a good indication of current electricity access and consumption levels in SSA, and is used in the model. The model provides least-cost optimization results for each grid-cell in SSA (see maps in Appendix 8 for example of grid-cells) using the decision tree in Figure 3. The input data maps (population density, electricity consumption, grid extent, solar/wind/hydro potential) are given in Appendix 8. The formulas, and full list of parameters used in the model are given in the supplementary info of Dagnachew et al (2017).

3.2.1 Technologies in the model

The applied model considers different technology options for mini-grid and standalone systems. Table 1 shows the technologies considered in the model. Standalone systems are not interconnected, and provide up to 250 Watt peak (Wp) power. Mini-grid systems are interconnected, and can be connected to the national grid with no limit on peak power.

Table 1 Mini-grid and standalone technologies used in the model

Mini-grid	**Standalone**
Diesel generator	Diesel generator
Solar PV	Solar PV
Wind power	
Small hydropower	
Hybrid PV-diesel generator	
Hybrid wind-diesel generator	

Commented [MD(1]: I would infer that stand-alone is a subset of mini-grid. Correct? Or is there a scale difference? For mini-grid: if I have PV and diesel, what does hybrid PV-diesel add?

Central grid expansion options are classed as high voltage (HV), medium voltage (MV), and low voltage (LV). The specific characteristics of each technology used in the model (Table 1), the grid expansion options, and the cost data used can be found in Dagnachew et. al. (2017) (supplementary information).

3.2 Analytical framework

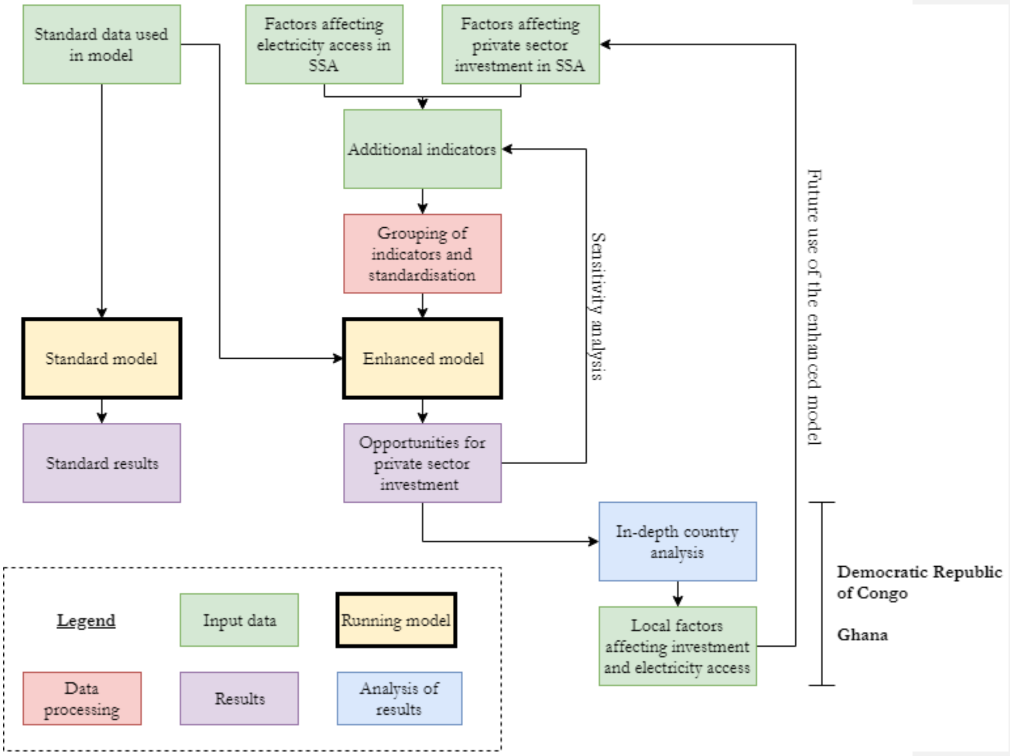

Figure 4 The steps taken in this research, compared with the standard use of the model

Figure 4 shows the methodological steps taken in this research, starting with the gathering of the most important factors that determine private sector investment decisions. First, to broadly examine factors that affect the levels of electricity access in SSA, high level country data is gathered and compared with the most up-to-date electricity access data (World Bank, 2017). These factors include GDP per capita, population, urbanization rate and total installed generation capacity. Following this, factors that are specific to private sector investment decision making are extracted by comparing the factors with literature on private sector investment decision making in SSA, with a focus on renewable energy and off-grid technology. Indicators are also chosen based on data availability and quality; only indicators with recent (post 2010) data available are deemed suitable due to the rapidly developing nature of the electricity sector in SSA (see for instance Figure 7 in (IRENA, 2016)) and the political climate.

In the next stage, indicators are grouped in a composite index, to be included in the model. The indicators are aggregated using a principal component analysis (PCA). PCA is a multivariate statistical method that is used in development research to reduce the number of variables in a dataset, and construct composite indices. This technique was first used by Ram (1982) in the construction of a 'physical quality of life index' and has been used in various fields of development and environmental research since (e.g. (Lai, 2003) (Cahill

& Sanchez, 2001)(Khatun, 2009)). The different variables are weighted according to the variance explained by the first principal component (Booysen, 2002). PCA is only applicable when the variables used are correlated with each other. Rather than a simple mean calculation, PCA gives a more representative score by analyzing correlations between different variables (indicators in this case). The full method for computing the PCA is given in appendix 5.

The index is included in the model input variables along with the standard data, allowing the indicators gathered to influence the model results, and the spatial distribution of optimal technologies for each country.

3.3 Running the model

The model is run after additional indicators have been gathered and included as model inputs. The model produces results for the optimal technology for each grid cell, based on the consumption levels reached in 2030, when universal access is achieved. The model uses 100% access to electricity in SSA as the goal. The 2030 consumption levels are based on the current consumption levels from (Falchetta & Noussan, 2019), where there is a minimum and maximum consumption level given for each grid-cell for current consumption. The results display what the optimal technology is for each grid-cell, and therefore which grid-cells are suitable for private sector investment.

3.3.1 Model assumptions and explanation

The assumptions made in this application of the model inevitably result in simplification. Since this research is aimed at providing broad advice on investment rather than detailed financial appraisal, the simplification that the assumptions result in does not have a big impact on the results. Table 2 shows the main assumptions made in this research, and the justifications.

Table 2 Main assumptions made in this research using the model

Assumption	**Explanation**
Current (2018) electricity consumption data (Appendix 8) used for 2030	Time constraints did not allow for projections to 2030 to be calculated
Demographic projections from SSP2 pathway (Riahi et al., 2017)	SSP2 is a 'middle of the road' scenario, detailing moderate change in demographic indicators
Private sector invests in off-grid systems	Scope of this research is to investigate private sector opportunities for off-grid electricity access investments. In this case the private sector does not invest in grid extension
Public sector invests in grid extension	Electricity grid extension mostly commissioned by the government of a country
Grid electricity is preferred	To best use the existing infrastructure, the current grid and its extension potentials must be utilised
Within 50km of existing grid no standalone systems permitted	Within 50km of the grid it is preferable to have the option of connecting to the grid in future. This is not possible with standalone systems.
All current access is provided by grid	There is no data on the current locations of mini-grids and standalone systems on a continent-wide scale

3.3.2 Sensitivity analysis

Following the model run, a sensitivity analysis is conducted to examine the impacts of different values of the indicators included.

3.4 Country case study

After the initial analysis using the adapted IMAGE-TIMER model, the results for 2 countries are discussed in detail: the Democratic Republic of Congo (DRC) which currently has very low electricity access, and large potential market size, and Ghana which has more purchasing power and a larger population with electricity access. Private sector investment can be used for the step from tier 0 to tier 1 electricity access (Appendix 4), or it can be used to develop present electricity supply to higher, more productive levels (from tier 3 onwards). In the case studies, contact is made with regional stakeholders and experts to investigate the most important factors affecting private sector investment in the country. The case studies are an effective way of validating the results of the model using real time information from stakeholders involved in the sector. New indicators to be tested in future research are determined through the case studies.

4. Data collection and input

The first three steps of the methodology (Figure 4) are focused on the collection of relevant data which can be used to understand electricity access levels and investment climate in SSA. A spreadsheet was constructed with all countries in SSA, and the electricity access levels for each country. At this stage, three countries were omitted since electricity access levels (rural and total) are above 90%, suggesting minimal additional private sector investment is required (Table 3). The 3 omitted countries are not represented further in this report.

Country	Electricity access (2016)	Electricity access (rural) (2016)
Cabo Verde	93%	92%
Mauritius	99%	100%
Seychelles	100%	100%

Table 3 Countries not included in this research using the model. This is due to the limited increases in electricity access needed

4.1 Indicator selection

The initial list of factors includes the key drivers of electricity demand growth and electricity access distribution, these are currently already part of the electrification model. This allowed quick comparison of new factors with the most important drivers. Examining which factors affect private sector investment in electricity access is based on several academic sources (Table 4) where the most common barriers to private sector investment are discussed for general investment, and specific to renewable energy. These sources give an important indication of the most relevant factors which should be included in an assessment of private sector investment opportunities. The most important barriers to private sector investment can be grouped in the following categories: poor governance, corruption, and weak regulatory systems, in line with the findings in section 2.1. Table 5 shows the second and third steps taken in the data-mining process: indicators that directly reflect governance, corruption, and regulatory standards are collected for the countries in the study.

Since this research is focused on off-grid technologies for electricity access, the Regulatory Indicators for Sustainable Energy (RISE) have been selected as a good measure for governance and regulatory strength, specific to the energy sector. These indicators have been developed based on “empirical evidence that shows that policies and regulations matter when countries are seeking to attract investment in sustainable energy” (ESMAP & World Bank, 2018). For this study, with electricity access as the focus, the “Electricity access” category within RISE is used. The methodology used to determine each country’s score is given in World Bank & ESMAP (2018). Unfortunately, data was not available for certain countries, so an average of countries in the same region with similar GDP per capita was taken. The list of unavailable data, and the data used for the averages are given in appendix 3.

Source	Focus	Barriers/ factors that influence private sector investment
(World Economic Forum, 2017)	General investment	1. Access to financing 2. Corruption 3. Inadequate supply of infrastructure 4. Inefficient government bureaucracy 5. Tax rates 6. Inadequately educated workforce 7. Poor work ethic in national labour force 8. Restrictive labour regulations 9. Political instability 10. Inflation
(Anyanwu, 2011)	Foreign Direct Investment (FDI)	• Market size • Openness to trade • Government consumption expenditure
(Engelken, Römer, Drescher, Welpe, & Picot, 2016)	Renewable energy	• Low security of supply • Corruption • Shortcomings in legal framework • Lack of management skills • Lack of entrepreneurship support
(Komendantova, Patt, Barras, & Battaglini, 2012)	Renewable energy	1. Complexity and corruption of bureaucratic process 2. Instability of national regulations 3. Absence of Guarantees 4. Low level of political stability 5. Lack of support from local government
(Schwerhoff & Sy, 2017)	Renewable energy	• Complex bureaucracy • Corruption • Changing regulation • Political stability

Table 4 Most important barriers to private sector investment in SSA, and the sources used. **Numbering is used in some sources to denote importance**

Corruption is widely listed as a major factor influencing private sector investment in Africa (Table 4), so it is essential to reflect this through an indicator. Corruption is not simple to measure, partly due to ambiguity over the definition, and the different aspects of it (Rohwer, 2009). This leads to the measurement of corruption in countries to be based on perception of corruption, which is currently the most frequently used measure. The Transparency International (TI) Corruption Perceptions Index (CPI) is a composite index, which uses corruption-related data from surveys and expert opinions from 13 different data sources (for details see Transparency International, 2014). As an independent member of civil society, TI's CPI gives a neutral indication of the level of corruption in a country and has been widely used to this end since 1995. The CPI scores per country in SSA are used to indicate levels of corruption and reflect the barrier that this imposes on private sector investment for electricity access.

Besides the RISE and corruption indicators, two other indicators have been chosen to represent additional factors influencing private sector investment: “political stability and absence of violence” and “regulatory quality”. Political instability and regulatory issues are stated several times as barriers to private sector investment (Table 4). The World Bank collects data on both factors through its Worldwide Governance Indicators (WGI).

The indicators described above are a measure of the barriers associated with investment given in table 4, and are combined in the electricity access governance index (EAGI) for inclusion in the model. The methods used for this are described in section 4.2.2.

4.1.2 Further indicators

Besides governance indicators, there are other more market-specific indicators that can provide insights into private sector investment opportunities. The cost for a household to get a national grid connection varies greatly between countries in SSA, and can give an indication of a consumer’s willingness to pay for an alternative source of electricity. This can provide the private sector information on where, and how much consumers may be willing to invest in alternatives to the grid. Similarly, the ‘annual household spend on off-grid lighting and mobile phone charging’ (hereafter: annual spend) is another good measure of the willingness and ability of a consumer to pay for off-grid electricity access.

The most recent research into grid connection costs in SSA was published by Blimpo & Cosgrove-Davies (2019) for the World Bank. Connection costs were calculated for 10 different countries in SSA. The original least-cost electrification model used by Dagnachew et al. (2017) uses connection cost data from earlier TIMER model outputs which looked at the costs of power infrastructure per kilometer, but not at the connection and metering fees that Blimpo & Cosgrove-Davies (2019) took in to account. Apart from the World Bank 2019 data on connection costs, in 2013 the World Bank also published data on connection costs for various countries in SSA. Together, these studies cover 19 countries. For countries not covered by the two World Bank studies, the regional averages were used (regions given in Appendix 2). The connection cost data is included in the

Table 5 Indicators reflecting the most important barriers to private sector investment in SSA

Governance indicators			
Indicator	Type	Source	Year
Regulatory Indicators for Sustainable Energy (total and access only)	Score	ESMAP	2017
Corruption perception index	Rank	Transparency International	2018
Political stability and absence of violence	Percentile rank	World Bank	2017
Regulatory quality	Percentile rank	World Bank	2017
Market indicators			
Indicator	Unit	Source	Year
Import tariffs on renewable energy goods	%	Energy Access Practitioner Network (2019)	Country dependent
National grid connection cost	$USD equiv.	Blimpo et al. (2018)	2018
Annual spend on off-grid lighting and mobile phone charging	$USD equiv.	IRENA / BNEF 2016	2016 (2010 data)
Diesel price	$USD equiv.	Worldwide development indicators (World Bank)	2015

model in the grid extension investment cost calculation (Appendix 1). The data replaces the original $Inv_{w\&m,c}$ values (see red highlights in appendix 1).

The estimated annual spend gives an indication of the scale of the potential unreached market for the private sector to invest in. Data at a country level for this was published by Bloomberg New Energy Finance (BNEF) in 2016 (BNEF, 2016). Unfortunately, after further examination, it turns out this data is based on 2010 UN data, reducing the relevance. It can still be used in analysis after the model results to compare the results with the ability to pay for each country.

Detailed diesel prices have been included in this use of the model, since the previous uses of the model assumed a diesel price of 0.9$/liter for all of SSA. Updated, country specific diesel prices from the worldwide development indicators were used to calculate a grid-cell level diesel price for use in the model. The calculations used for the diesel price are given in appendix 1.2, and were devised by Giacomo Falchetta. The new diesel price data improves the accuracy of the results for diesel technologies.

Finally, the ESMAP has published data on import tariffs for renewable energy and off-grid electricity goods in Africa. Since there are currently no domestic production sites for these goods, it can be safely assumed that they are imported. Import tariffs are often levied by governments to stimulate local production of a product. In SSA, import tariffs vary greatly by country and can present a hurdle for private sector investment in electricity access. The import tariff data are used in the discussion of the results of the model to assess the conditions for investment: very high import tariffs are a big barrier to investments in standalone and mini-grid systems. The market-specific indicators, and their sources are given in Table 5.

4.2 Including indicators in the model

The indicators chosen in section 4.1 need to be included in the model inputs. The model uses LCOE and ‘Economic distance limit’ (EDL) as inputs; the formulas used to calculate the LCOE and EDL in the model for the technologies are given in appendix 1. The variables in the LCOE formula that reflect investment are the capital cost (I) and the annuity factor (A) which is calculated from the discount rate (r).

4.2.1 Including governance indicators

Poor governance increases the risk of investment in a given project, which can have negative consequences on the profitability of an investment (Jensen, 2003). In equation 1, the annuity factor reflects the present value of future income from an investment. The calculation of the annuity factor is given below in equation 1 where the discount rate (r) reflects the risk of an investment: the higher the discount rate, the riskier a project.

$$\text{Annuity factor} = \frac{1-(1+r)^{-i}}{r} \qquad \text{Equation 1}$$

Where r = discount rate

i = number of periods

There are no set guidelines for discount rate choice in the private sector (Short, Packey, & Holt, 1995), however, a 2015 survey on valuation methodology in Africa conducted by PWC assessed how the private sector incorporates risk in the valuation of an investment. This showed that most respondents incorporate risk associated with infrastructure projects in Africa in the discount rate (PWC, 2015). In this thesis, the governance indicators are used to determine the discount rate used for each country in the model: the higher the governance score, the lower the discount rate. To achieve this, the governance indicators (Table 5) are grouped in an index.

4.2.2 Electricity Access Governance Index (EAGI) calculation

The indicators (Table 5) that are given as scores or percentile ranks can be easily normalized on a 0-1 scale, using a simple normalization (Eq. 2).

$$Normalised\ value_i = \frac{x_i - \min(x)}{\max(x) - \min(x)} \qquad \text{Equation 2}$$

To accurately aggregate the indicators in the EAGI the principal components of the index are calculated using a PCA (for details see appendix 5). The weights of each indicator as calculated in the PCA are given in Table 6. The final EAGI score for each country is normalized to give a 0-1 range of EAGI scores, which are given in appendix 6.

Table 6 Indicators used in the EAGI and the weighting calculated through PCA. The scores are subsequently standardised

Indicator	Weighting
RISE access	0.776
Corruption perception index	0.935
Political stability & absence of violence	0.779
Regulatory quality	0.899

In previous research using this model, the discount rate was fixed at 10% for all countries in SSA. The EAGI score determines the new discount rate. Boundaries are set for a minimum and maximum discount rate to keep a reasonable range. The range of discount rates chosen is 2-18%, with the highest EAGI giving a 2% discount rate, and the lowest an 18% discount rate. The discount rates for each country are calculated using a min/max standardization (Eq. 3). The choice of the range of discount rates is further explored in a sensitivity analysis, conducted after the initial model run, using 4-12% and 2-25%. The ranges taken in the sensitivity analysis are elaborated on in section 5.2. The different discount rate for each country modifies the results of the model for each grid cell, changing the optimal split of grid-extension, mini-grid and standalone systems, as each system has a different initial investment cost (Appendix 1).

$$x_{normalized} = (0.02 - 0.18)\frac{x - \min(x)}{\max(x) - \min(x)} + 0.18 \qquad \text{Equation 3}$$

4.2.3 Including market-specific indicators

Grid connection cost data gives an indication of the barrier that households in SSA face for gaining access to electricity. In countries where the connection cost is very high relative to GDP per capita, households may be more likely to be willing to invest in an alternative to the grid. The connection cost data can be used in the first decision that the model takes: grid or off-grid. Connection charges were previously not included in the calculation of the cost of grid electricity. The connection charges per country are added in the calculation of the cost of grid-expansion (see Appendix 1 for calculation). The connection cost data per country are given in Appendix 9.

The data on import tariffs and annual spend on electricity is not included in the model, but is rather used to analyze and explain the results (see section 7.1), since data is not available for many countries and technologies.

5. Results

In this section, the results of the model are presented along with a brief analysis. A more comprehensive analysis is given in the discussion section. Additionally, the results of the sensitivity analysis are given.

5.1 Discount rate

Discount rates per country calculated as described in section 4 are listed below:

Country	**Discount rate EAGI**	**Country**	**Discount rate EAGI**
Botswana	2.0%	Niger	11.6%
Namibia	4.9%	Sierra Leone	11.6%
Rwanda	5.0%	Cameroon	11.8%
South Africa	6.3%	Guinea	11.9%
Ghana	6.8%	Angola	12.4%
Sao Tome and Principe	8.1%	Madagascar	12.7%
Senegal	8.2%	Equatorial Guinea	12.9%
Benin	8.4%	Mali	12.9%
Lesotho	8.6%	Zimbabwe	13.0%
Zambia	8.6%	Mauritania	13.2%
Swaziland	8.7%	Liberia	13.4%
Uganda	9.0%	Nigeria	13.8%
Tanzania	9.4%	Guinea Bissau	14.0%
Kenya	9.7%	Mozambique	14.0%
Burkina Faso	10.0%	Burundi	14.5%
Cote d'Ivoire	10.2%	Congo	14.5%
Gambia	10.5%	Sudan	14.6%
Gabon	10.8%	Eritrea	14.8%
Malawi	11.1%	Democratic Republic of the Congo	15.3%
Togo	11.1%	Central African Republic	15.8%
Comoros	11.3%	Chad	15.9%
Ethiopia	11.3%	South Sudan	17.0%
Djibouti	11.4%	Somalia	18.0%

Table 7 Discount rates by country calculated using EAGI scores and min/max standardisation between 2% and 18%

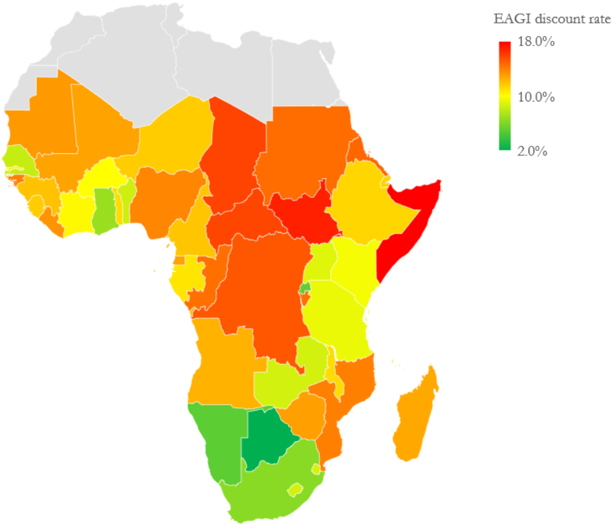

Figure 5 Map showing the EAGI calculated discount rates for countries in SSA

Discount rates are most favourable in Southern Africa with Namibia, Botswana and South Africa under 10%. This is lower than the average taken in the previous use of the model. There are several other countries with discount rates below 10%, suggesting investments by the private sector in these regions are relatively low risk. Central Africa displays the highest discount rates, and therefore the highest risk on investment. The EAGI scores for CA are very low, with most countries scoring poorly in all 4 categories (Appendix 6.2). In West Africa there is a big variation in discount rates, explained partly by big differences in political stability and RISE (access) score. East Africa generally performs well in the EAGI, with the exception of Sudan, South Sudan, Somalia and Eritrea. In these countries political stability is very poor, along with regulatory quality.

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5.1 Model results

Following the calculation of the discount rates, the model is run to find the optimal technologies for each grid cell. The model displays results on a map of SSA made up of 0.5°x0.5°grid-cells, with each different technology displayed as a different colour. Figure 6 shows the optimal technology distribution for SSA, with grid extension options left white as they are not relevant for private sector investment. Furthermore, Gabon and Somalia are not covered. Due to an error in the grid data (Appendix 8), Gabon (electricity access 92%) was only given mini-grid and standalone options. Considering the high current grid-provided access rate, this clearly was incorrect. Somalia is not covered since it currently has no functioning government. Even though it is assigned an EAGI score, it is considered 'un-investable' by the private sector. The north western part of Somalia (Somaliland) has a de-facto government and has attracted private sector investment. In future model runs, the country could be separated and Somaliland be treated separately. The model also treats Sudan as one country, rather than including South Sudan, since the underlying country borders were created before the split. Data for Sudan only is used.

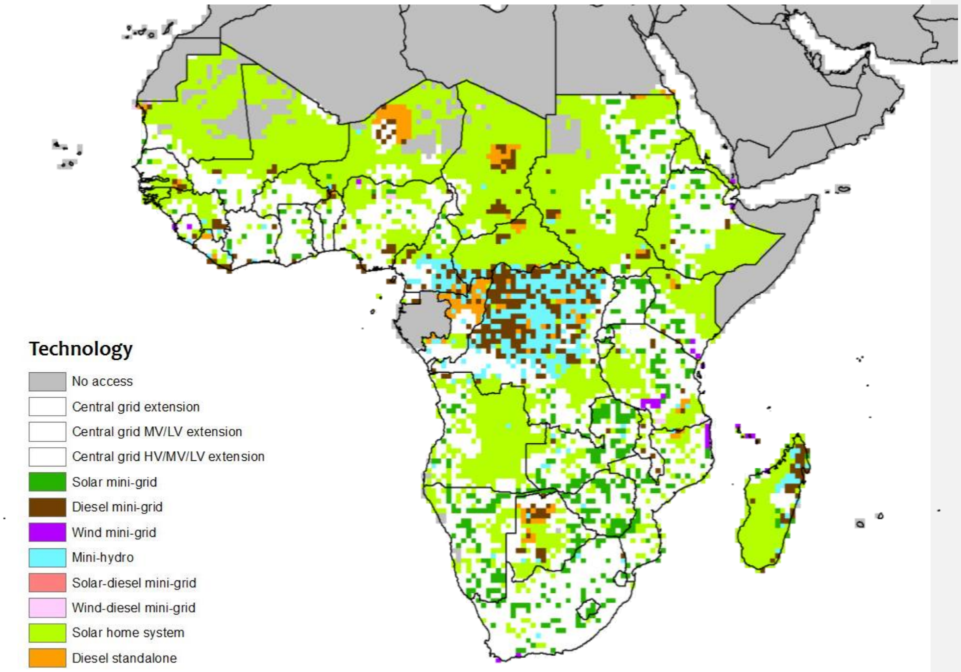


Figure 6 Map showing results of the model showing the optimal technologies for 100% electricity access in SSA in 2030

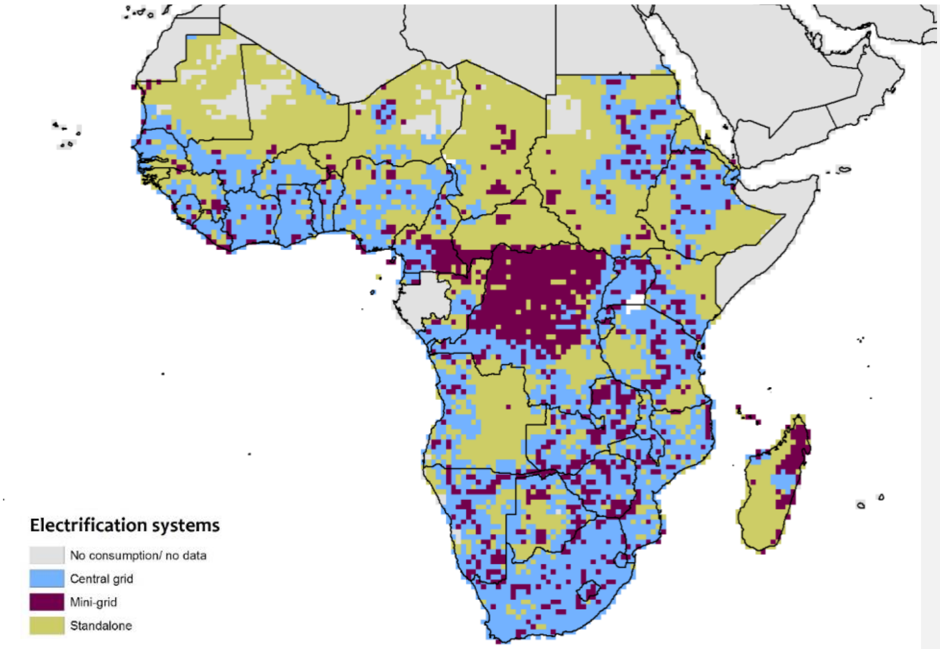


Figure 7 Map showing results of the model for optimal electrification systems aggregated in grid, mini-grid, standalone

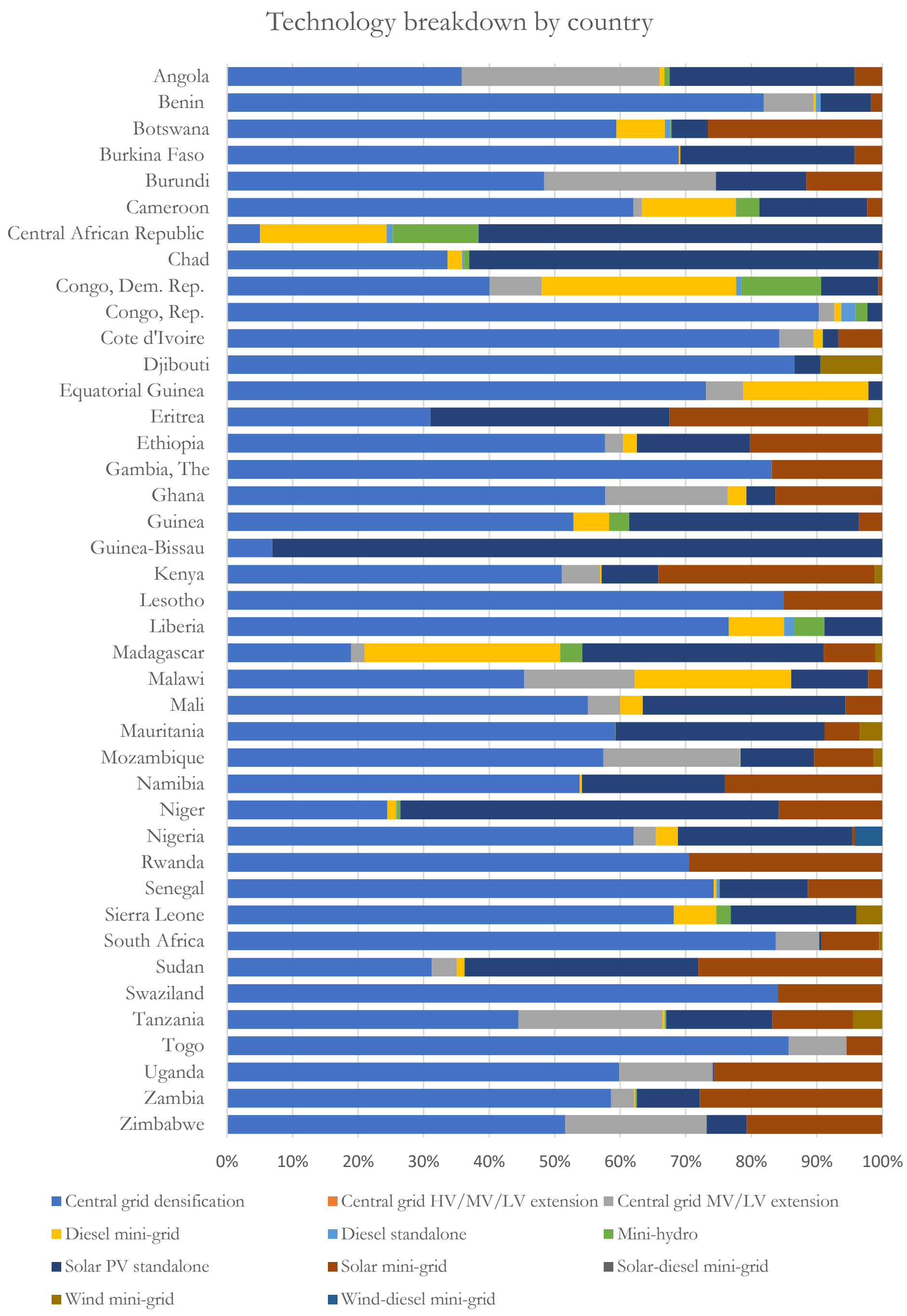


Figure 8 Optimal technology for each country to provide 100% electricity access in 2030. Grid densification refers to the population currently living right under the grid, where no added transmission and distribution lines are needed, only connection costs

Figure 7 groups the separate technologies under grid-extension, mini-grid, and standalone systems. The population density, electricity consumption, and national grid maps are given in appendix 8 for reference. The technology maps show a large variation in optimal technologies across SSA. The high population density regions of west and east Africa are dominated by grid extension, as the distance to the national grid is generally low and consumption is relatively high (Appendix 8). A large part of central Africa displays mini-grid technologies as the optimal solution. This is due to the low solar PV potential, and the lack of a central grid. SA is served with a mix of grid, and off-grid technologies due to the current extent of the grid. Northern SSA is dominated by stand-alone systems, explained by the sparse population density, low consumption, large distances to the grid, and high solar PV potential (Appendix 8). This renders grid extension unfeasible, and mini-grids are only feasible in large population centers. For each country, the technology breakdown of the total is given in Figure 8.

Despite scoring very low on the EAGI, South Sudan, Chad and the CAR are largely dominated by standalone and mini-grid systems, suggesting a large amount of private sector investment is required to achieve SDG7. This brings in to question the effect the discount rate has on the cost and choice of off-grid technologies. Certainly, the extent of the current grid in those countries makes grid-extension a very costly option, however, these are also countries where there is little to no enabling environment for the private sector, reflected by the low EAGI scores (Appendix 6). This highlights one limitation of this approach: although the optimal technologies can be determined, barriers to investment remain substantial and thus the likelihood of investments happening without further stimulus may be low.

Most of the countries in SSA display similar technology breakdowns in Figure 8 while Lesotho, The Gambia, Swaziland, Uganda and South Africa do not have any standalone systems in the optimal mix. This is due to the small size of these countries, making grid extension quite favourable. For South Africa, this is due to the wide extent of the current grid (Appendix 8). Of note is also the lack of hydropower generation in countries with high potentials like Ethiopia (Bekele & Tadesse, 2012) and Zambia, while the DRC does contain hydropower mini-grids in the optimal mix. This is explained by the input data for hydropower potentials: in regions without central grid access in Ethiopia, there is also no hydropower potential.

The results of the model show that there is high potential for private sector investment in off-grid-electricity in SSA. Despite high discount rates reflecting poor governance in many countries, the cost of off-grid technologies is so low in many areas that they are still favourable. This encourages the private sector to look beyond countries with good governance performance, and consider investments in other countries, based on the maps showing the optimal technology.

5.2 Sensitivity analysis

Since the results of the model are inherently linked to the choice of EAGI-discount rate relationship, it is worth conducting a sensitivity analysis. Indeed, in the comprehensive work on energy efficiency and renewable energy valuation by Short, Packey, and Holt

(1995), it is recommended to conduct a sensitivity analysis with respect to the discount rate for private sector valuation because of the somewhat arbitrary nature of discount rate choice. To do this, the effect of significant changes in governance were examined.RISE (access) scores for the period 2010-2016 are available for SSA. These can be used as a proxy for a reasonable change in governance performance, since progressive data for all the indicators is not available. The average change in RISE (access) scores for countries in SSA between 2010 and 2016 is a 100% increase. This change is used to modify the EAGI scores for the sensitivity analysis. Besides improvement, deterioration of governance is also possible. The RISE (access) score for Guinea decreased by 8% between 2010 and 2016. This change is used as a proxy for the decrease in governance in the sensitivity analysis.

It appears that the effect of the EAGI adjusted discount rate on the results is somewhat inconsistent. The choice of standalone systems by the model seems to be largely unaffected by the discount rate, apart from a small change in Cameroon, Madagascar, Nigeria, and Tanzania. The effect of the discount rate on the technology mix appears inconsistent. For mini-grids the effect of the discount rate is more pronounced, but still inconsistent. Several countries exhibit a far higher proportion of mini-grids with a low discount rate range. The reason for these inconsistent effects is not immediately clear, and due to time constraints, it could not be fully investigated. One explanation is that in many countries the cost of extending the central grid is so prohibitively high, that even with a very high discount rate, the standalone technologies are still necessary. The same goes for mini-grids. It appears that the results change most significantly for mini-grids in countries with relatively high EAGI scores, and low associated discount rates, suggesting that in these countries governance improvement has a big effect on private sector investment potential.

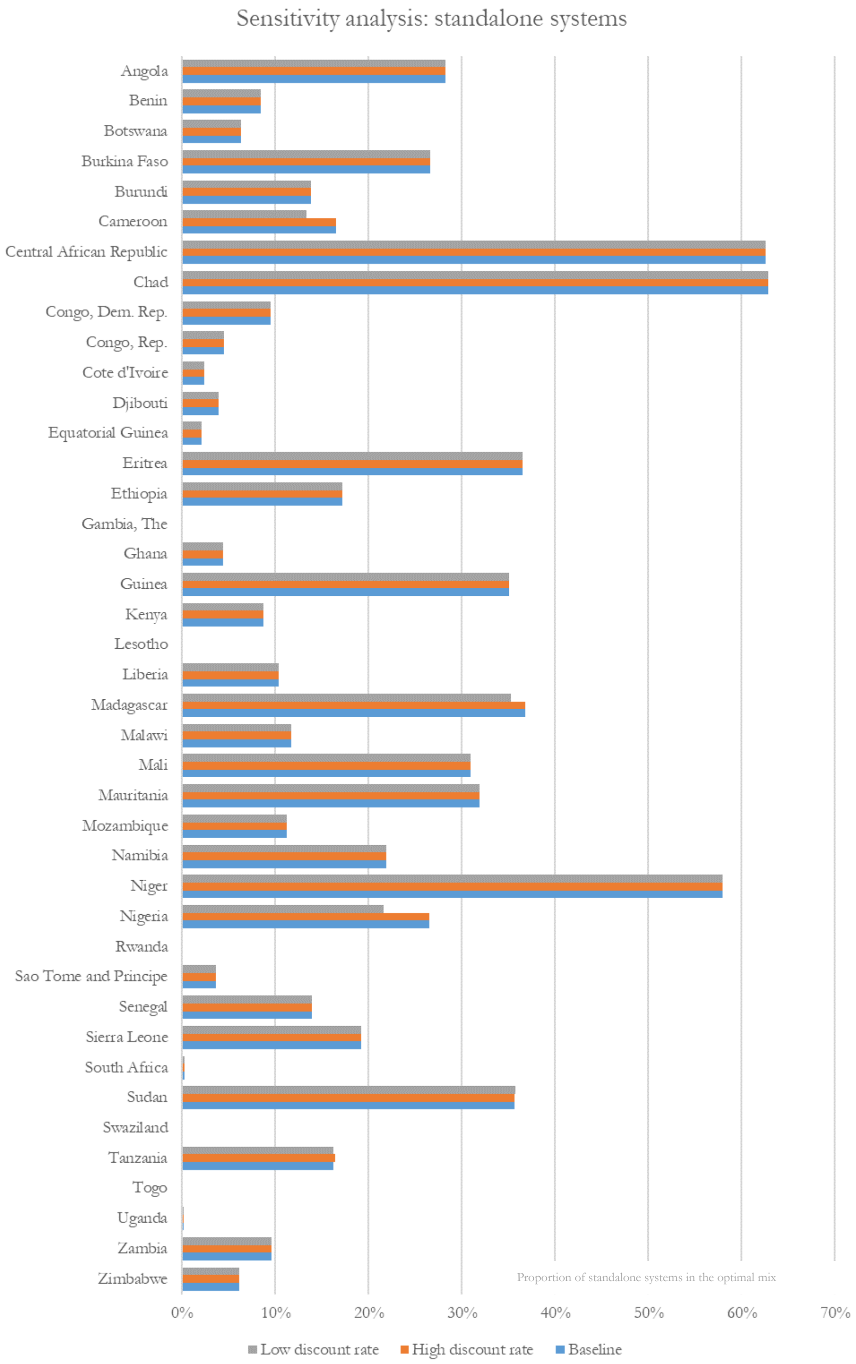


Figure 9 Standalone system proportions for the two discount rate scenarios (low and high)

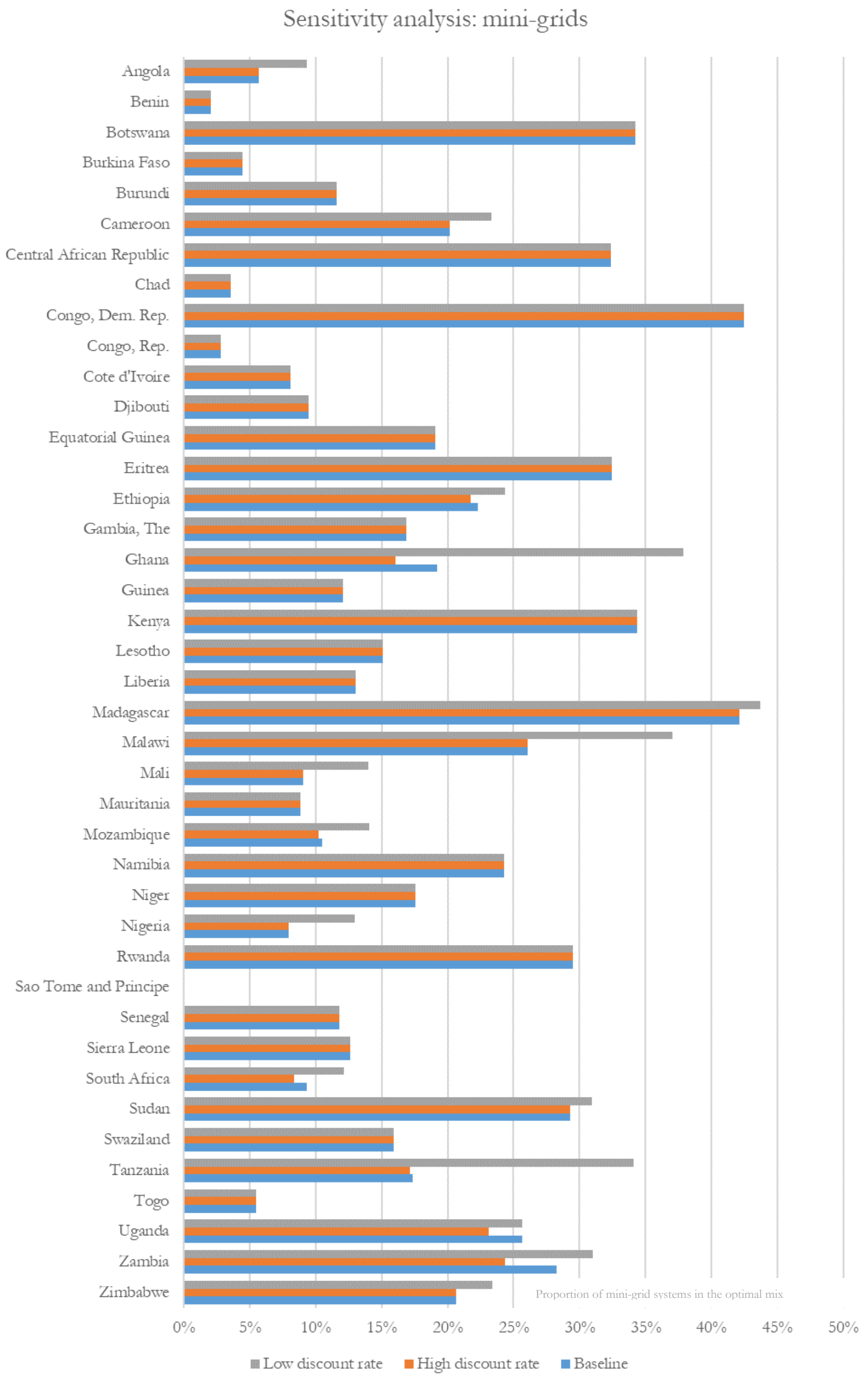


Figure 10 Mini-grid system proportions for the two discount rate scenarios (low and high)

6. Country focus

6.1 Democratic Republic of Congo

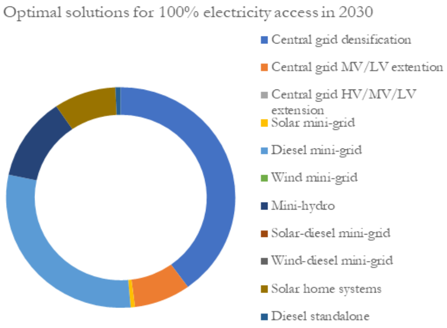


Figure 11 Optimal solutions for 100% electricity access in the DRC in 2030

Indicator	Score
Electricity access (2017)	19%
RISE access (2017)	35
CPI	20
Political stability & absence of violence	4
Regulatory quality	5
EAGI	0.17
Discount rate	15.3%

Table 8 Key statistics for the DRC

As can be seen in the model results (Figure 6, Figure 7, Figure 11), there is a considerable amount of off-grid electricity generation needed to reach 100% electricity access by 2030 in the DRC, mostly through mini-hydroelectric and diesel generation.

The DRC is one of the largest countries in SSA, with a hugely diverse terrain. The population is growing steadily at over 3% per year and is predicted to reach over 120 million by 2030 (UN DESA). The total electricity access level is only 19%, well below the SSA average of 45%. This presents a huge potential opportunity for investment in electricity access: DRC is one of the most populous countries in SSA, with one of the largest unreached populations. Considering this, and the recent increase in GDP growth rates, the market for investment in electricity access investments in DRC appears attractive.

The EAGI score for the DRC is 0.167, resulting in a high discount rate of 15.3%. This reflects the especially poor performance in the 'political stability & absence of violence' and 'regulatory quality' categories (Appendix 6.2). Indeed, the DRC has been marred by

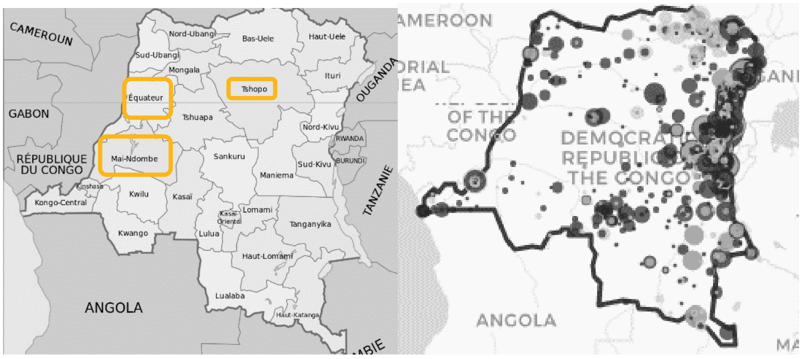


Figure 12 Left: map showing provinces of the DRC | Right: map showing conflicts in DRC (REF)
Sources: (l) map.comersis.com, (r) ACLED.com

persistent conflict over the last decades, and is currently embroiled in a resource driven conflict (UNGoE, 2016). Nevertheless, there are several provinces such as Tshopo, Equateur, and Mai-Ndombe that enjoy relative stability (Figure 12) and are being earmarked for investment (UN OCHA, 2019).

In the 2013 Rapid Assessment Gap Analysis by SEforALL, the funding requirements for DRC to reach universal access by 2030 were estimated at $44bn (SEforALL, 2013), and based on the results of the model, in many areas this can be optimally used for small-scale hydroelectric systems.

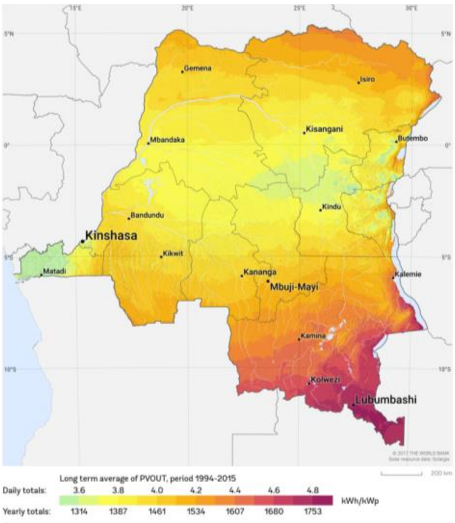


Figure 13 Map showing photovoltaic power potential for the DRC (Source: World Bank (2017c))

An examination of (the limited) academic literature on electricity access in the DRC reveals that there is a positive causality between electricity consumption and economic growth, suggesting a strong motive for investment in electricity access to foster growth (Wolde-Rufael, 2006). Academic sources also discuss the lack of development in wind power (~77GW potential) and geothermal power. The southern states of Haut-Katanga, Haut-Lomami, and Lualaba along with the far north of the country exhibit high solar-PV potential (Figure 13), which is unlikely to be developed at a large scale (Selvakkumaran & Silveira, 2019).

Since 2018, the first PAYG solar PV investments in the DRC have been made by BBOXX, pioneers of the PAYG electricity movement. Despite the difficulty of operating in the DRC, BBOXX aims to provide 2.5 million people with electricity, and expand across the eastern provinces and Kinshasa (BBOXX, 2018). This demonstrates that the large market-size of the DRC makes it sufficiently attractive for private sector investment, despite challenges with security. Even with the large number of conflicts in the east of the country, BBOXX commenced their operations in the region. The large number of international organizations active in conflict areas makes access for off-grid companies like BBOXX somewhat lower risk.

The fact that BBOXX has invested in the DRC despite the challenges suggests that market-size is an indicator that should be included in the modelling of private-sector investment opportunities. This can be supplemented with local survey data on the ability and willingness to pay for electricity access to get localized estimates for market size. Since logistical challenges are a major barrier to doing business in the DRC, including this in the model in the form of an accessibility indicator could indicate the most suitable areas for investment.

Figure 14 Photo showing the use of micro-hydro turbines at a pilot project in the DRC (Source: Energies de la Mer)

Notwithstanding the potential for a huge hydropower project (e.g. the Grand Inga III) to disrupt the power market in the DRC, the transmission and distribution infrastructure is not capable of reaching all households. Besides, large-scale hydropower projects in Southern Africa have repeatedly been plagued by droughts, with serious consequences for the power output. Climate change could increase this risk in the coming decades. This suggests that the future of electricity in the DRC may be best approached in a bottom-up, locally tailored manner, taking in to account the suitability of specific local energy resources. Grid improvement in the DRC is receiving investment from the World Bank, while off-grid electricity can benefit from private sector investment. The PAYG solar-PV model may be suitable in certain regions, whereas a small-scale hydropower approach can be adopted along many watercourses in the interior. Small scale-hydro generation has been piloted in the DRC by Eco-Cinetic (Energies de la Mer, 2015), using standalone hydroelectric turbines (Figure 14) the flexibility of these systems and their suitability for the terrain could prove instrumental in the widespread provision of electricity access in the DRC. To assess the potential of these systems, in future research standalone hydro could be included as a technology in the model.

The key factors determining investments in off-grid electricity in the DRC from the country focus are as follows:

- Accessibility
- Market-size
- Hydropower

6.2 Ghana

Indicator	Score
Electricity access (2017) (WB)	79%
RISE access (2017)	68
CPI	41
Political stability & absence of violence	50
Regulatory quality	50
EAGI	0.7
Discount rate	6.8%

Table 9 Key statistics for Ghana

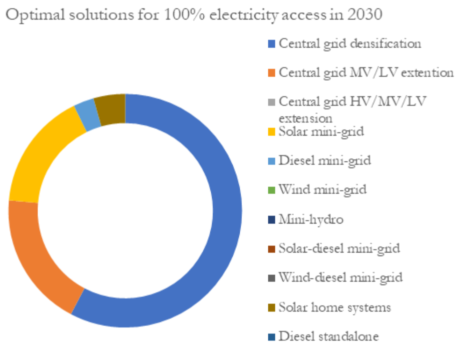


Figure 15 Optimal solutions for 100% electricity access in Ghana in 2030

The model results in Figure 15, show that to reach 100% electricity access by 2030 in Ghana, mostly grid densification and extension will be needed, along with small patches of solar home systems and solar mini-grids. Since Ghana has a far-reaching electricity grid, and the country is relatively small, grid extension is a low-cost option.

Ghana is characterized by high population density, distributed fairly evenly throughout the country (Appendix 8). The electricity access rate is almost 80%, a very high value for SSA (Appendix 7), with most of the currently connect population consuming grid electricity. One of the main challenges that remains in Ghana is access to reliable electricity. Electricity is generated largely by large-scale hydroelectric dams, and thermal power plants, and transmitted and distributed through ageing and unreliable infrastructure (Mensah, 2016), resulting in frequent, persistent power outages. This, along with the low distribution of standalone and mini-grid systems in the results, suggests that the private sector may be most needed in improving the existing access to electricity rather than providing new access. This is very different to the needs in the DRC, where investment in providing access to electricity is most vital.

The regulatory environment in Ghana is strong, and commitment to SDG7 is demonstrated in the SEforALL action plan submitted in 2015. The plan was developed in line with Economic Community of West African States (ECOWAS) regional objectives, and builds on the National Electrification Scheme (NES). As part of the scheme, communities are stimulated to invest in connections to the grid, however there are various areas where this is prohibitively expensive (SEforALL, 2015). For these communities, the option of investing in mini-grids and standalone systems is more attractive. With a GDP per capita of over $2000 (World Bank, 2018a) Ghana is one of the more prosperous nations in the region, and the ability to pay for such systems is relatively high, indicating that private sector investment is likely to be successful.

The ESMAP tiers of energy access (Appendix 4) is a useful framework for assessing the needs for investment in electricity access. In Ghana the annual per capita consumption of electricity is 351kWh. This suggests that investments are needed to increase access levels from tier 2 onwards. Rather than an alternative to the grid, standalone PV systems could be used in Ghana to supplement the grid, and mitigate its poor reliability and the associated challenges. Standalone PV systems use batteries as storage allowing electricity to be consumed during low generation, or when the national grid is not functioning.

A big reason for the reliability issues in Ghana is the discrepancy between electricity demand and supply. There is currently a major supply shortage, mostly due to transmission and distribution losses (Kumi, 2017). Given SDG7s focus on 'modern' and 'sustainable' energy, the high and increasing proportion of thermal electricity generation in Ghana, and the far-reaching power grid, there is also good potential for private sector investment in larger IPP-scale renewable projects such as solar PV parks.

Given the reach of the national grid in Ghana, it is important to consider it in private sector investment decisions. Compared to the investments needed in the DRC, investment in Ghana would better be focused at strengthening the national grid through IPPs to increase generation capacity, or to supplement it with standalone systems to increase the reliability of supply.

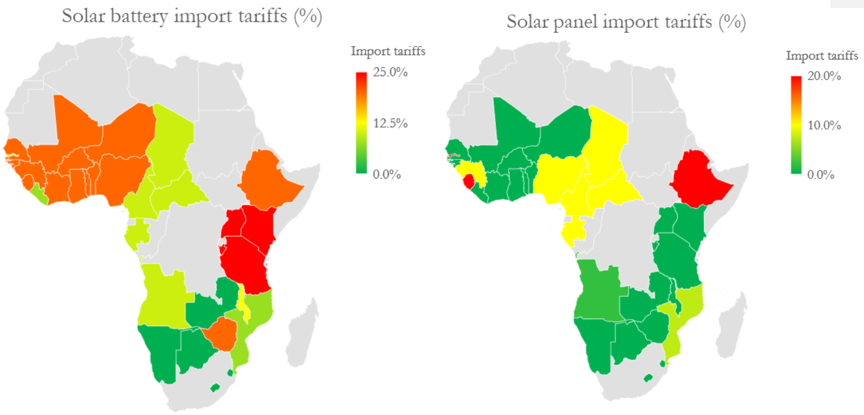
The key factors determining investments in off-grid electricity in the Ghana from the country focus are as follows:

- Grid reliability
- Ability to pay
- Grid extension prospects

7. Discussion and analysis

The grid-cell maps of the results display some interesting findings: the optimal mix of electricity generation technologies varies considerably between countries. By including the EAGI in the electrification tool, this research provides balanced advice for private-sector investors and policy makers to improve electricity access in SSA in support of SDG7. This, together with the EAGI scores, gives an indication on where and in what the private sector can best invest in electricity access in SSA. A deeper analysis of the DRC and Ghana model results gave further insights for these two countries.

7.1 Explanation of results


Solar battery import tariffs (%)

Solar panel import tariffs (%)

Figure 17 Examples of import tariffs levied by countries on off-grid technologies (source data: Energy Access Practicioner Network (2019)) No data available in grey areas

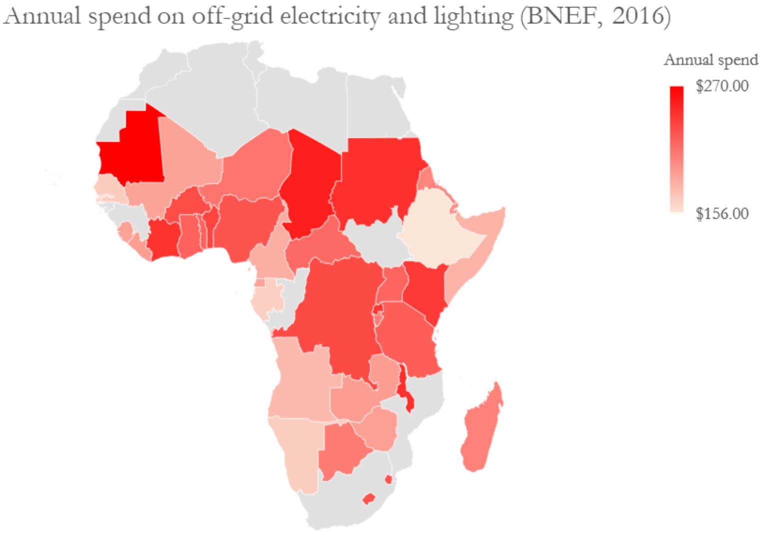

Annual spend on off-grid electricity and lighting (BNEF, 2016)

Figure 16 Annual spend data per country (source data: BNEF (2016)) No data available in grey areas

While the EAGI and the associated discount rates give an indication on the investment climate of a given country with respect to electricity access thereby improving the model, there are further factors that if they could be included would further improve the model. They were not able to be included in the model either due to lack of data, or poor data quality. Data on import tariffs of solar PV and battery systems give an indication of the variability in capital investment costs ('I_i' in the LCOE formula in appendix 1) of solar PV mini-grids and standalone systems. Figure 17 shows the large range of import tariffs levied in SSA: batteries for the balance of service (BOS) of solar PV systems are subject to high import tariffs across most of West Africa, and PV panels are subject to high tariffs in Ethiopia and parts of Central Africa. It is likely that in countries with very high import tariffs, the optimal technologies for off-grid electricity generation may differ from those observed in the results of the current model due to the added costs. Import tariffs could be included in a subsequent run of the model to gain more insights in to the real cost of investing in off-grid technologies. On the other hand, high import tariffs can be seen as a message to policy makers. With respect to the SDG7 goal, high import tariffs for off-grid technologies may deter investments, and progress towards SDG7 despite the attempt to stimulate local production.

Another important factor that was not included in the model inputs is an indicator of the ability and willingness to pay for off-grid technologies. This can indicate which regions of SSA would have higher margins on investment, and where investments are not bankable. As mentioned in section 4.1.2 the data on the annual spend originates from 2010, meaning the data may not be representative of the current situation. Figure 16 shows this data (BNEF, 2016). Interestingly, households in countries with very low electricity access rates and governance performance are spending a large amount on electricity per year (e.g. Chad, Sudan, DRC). This shows that there is a considerable electricity access market for the private sector to invest in in these countries, as the results of the model suggest that standalone and mini-grid solutions are optimal for these countries, though operational challenges due to poor governance remain.

These extra factors could, with some further research be incorporated in this model through a market index, indicating the quality of the market, in addition to the quality of governance. Where there is a high annual spend on electricity, and a large unreached population, a factor could be introduced in the model that preferentially chooses off-grid solutions over grid-extension to stimulate private sector investment. Up-to-date, audited data would need to be collected for annual spend for it to be included in the model. By including data on import tariffs for each off-grid technology, a more accurate and realistic determination of the optimal technologies and their costs would be given.

7.2 Data

The model used in this research is data-heavy, with many parameters being used in the calculation of the optimal technology for each grid cell in SSA (see appendix 1). Therefore, the results can only be as good as the data that is used. Unfortunately, good-quality, regularly gathered data is hard to find for SSA, demonstrated by the BNEF annual spend data, and the many gaps in the data for the other indicators. It is for this reason that the results of this report should not be taken as conclusive indications, due to the high-level nature of most of the data used. Nevertheless, the results provide a useful tool to guide private sector investment strategies at an early stage. A key improvement to this study, and indeed for other studies on electricity access challenges in SSA, would be the comparison of high-level data with locally-sourced, independently audited data on indicators such as diesel prices, connection fees, and technology costs. This would provide a more accurate indication of the real costs and challenges of investing in electricity access in a country.

The consumption data used in this model is taken from a recent study using night-time satellite imagery. Coupled with demographic indicators, this gives a more accurate representation of the current levels of electricity consumption in SSA. In previous model uses, IMAGE-TIMER projections (2030) of consumption levels were used, while here the consumption levels are treated as static data; 2030 consumption is the same as 2018 consumption, as a preliminary use of the updated data. To include accurate electricity consumption levels for 2030, projections can be made using the SSP2 demographic indicators in future uses of the model.

7.3 Model assumptions

The assumption that only the private sector invests in standalone and mini-grid systems limits the results of the model. In reality, the lines are not so clear cut. It is true that most of the standalone systems in use in SSA currently are marketed by private sector companies, but there are numerous international donor agencies (IDA) that are also distributing and investing in the same systems, most notably United States Agency for International Development (USAID) and the European Union (EU). The aim of this assumption was to keep the focus of this research on the private sector, however the results explained in section are not limited to the private sector. The optimal technology maps described can serve also to advise the international donor agency (IDA) sector, and indeed governments on which technologies are most suitable in the different regions.

By applying a high discount rate to countries with poor governance performance, private sector investment is deterred, and therefore the responsibility of providing electricity access lies with the government. If a country performs poorly in electricity access governance, it is unlikely to be able to provide electricity to its citizens by 2030 through grid-extension. Also, certain low-scoring countries are simply not investment-grade for the private sector, but still require off-grid electricity generation to reach SDG7. Thus, rather than suggesting only 2 options, central grid (public) and private sector investment, IDA could be included as another option. IDAs are capable of providing services in regions where the private sector is deterred by poor governance performance, as the IDA investments do not require market-based returns. Including IDAs in the model used in this research could provide more widely usable results, also advising the IDA sector.

An inherent issue with the EAGI is the attempt to quantify governance, and the effect this has on investment attractiveness. Governance cannot be measured directly in the way that GDP, life-expectancy and other development indicators can. Therefore the scores that this research attaches to the electricity access governance performance are inherently the same as that of the governance performance as a whole in a given country. However, as the aim of this work is to give broad recommendations of where the private sector should invest, not to give project-specific investment appraisals, this limitation is likely to be of modest impact. Combining quantitative data analysis and qualitative evaluations in research on the SDGs in SSA is crucial (Mandelli, Barbieri, Mattarolo, & Colombo, 2014). The two examples of qualitative studies given here on the DRC and Ghana illustrate how the quantitative results of the continent-wide model can inform a qualitative country-specific analysis. Interviews and stakeholder consultations can provide meaningful insights in to the current state of affairs in SSA, and reveal important points that are not reflected in literature. Qualitative research in this field has revealed that radical changes in the institutional environment are needed for widespread adoption of off-grid renewables in SSA, mainly in finance and regulations (Dagnachew, Hof, Roelfsema, & Vuuren, 2019) suggesting that despite the relatively good governance observed in some countries based on EAGI scores, there are still big improvements to be made.

In the model used in this report, grid connections are assumed to provide electricity access, and no improvement is needed to current grid connections. In reality, many grid connections in SSA are far from reliable, with firms in SSA connected to the grid experiencing 56 days without power per year on average (Africa Infrastructure Country Diagnostic, 2008). Hence, grid electricity does not actually represent stable access to electricity – these connections are known as 'under-the-grid'. Appendix 10 shows the number of power outages experienced per month by firms for countries in SSA. It shows that in many countries grid connections are not so useful after all, with up to 33 outages per month in Nigeria. This suggests that rather than just providing solutions for households without any grid connection at all, investment should also tackle the issue of an unreliable grid. This is further highlighted in the case study of Ghana, where electricity access is very high (79% - appendix 7), though there is still considerable scope for private sector investment in improving this access with standalone or mini-grid systems.

The results of the model are also based on the assumption that current governance performance stays constant till 2030, with the discount rate staying constant. Since the time horizon is relatively short, this is a reasonable assumption to make. Data on the change in governance performance over time can be plotted against electricity access change to give an indication of which countries have the most successful link between improved regulation and improved electricity access. Figure 18 shows the change in RISE (access) scores and electricity access for SSA from 2010 to 2016. East Africa arguably has the best performers, with RISE improvement being paired with a significant increase in electricity access in Uganda, Kenya, Tanzania, and Rwanda. This contrasts with several countries where regulations for electricity access have not improved much, and access to electricity has only improved marginally (e.g. Madagascar, Burundi, Malawi, Eritrea, Mauritania). Examining the change in governance over time, and its effect on electricity access validates the choice of RISE as an indicator for governance, and also its incorporation in the EAGI in the model. Additionally, this demonstrates which countries have made good progress with regulations but have not yet seen an increase in electricity access (e.g. Niger, Sierra Leone, Burkina Faso, Liberia). These are areas where private sector investment is less risky and can have a big positive impact in reaching SDG7.

The discount rate range used in this research was arbitrarily chosen, based on values often used in literature. As the sensitivity analysis showed, the effect of the EAGI-adjusted discount rate on the model results is somewhat inconsistent, and needs further research to be explained fully. Due to time constraints with this research, a second sensitivity analysis modifying the range of discount rates could not be run. Using a wider and narrower range (2-25% and 4-15%) of discount rates could shed light on the reasons for the inconsistent effects observed in section 5.2. Additionally a sensitivity analysis on the other included parameters (diesel price and connection fees) is necessary to fully understand the impact of these parameters.

A key difficulty in researching private sector activities in SSA is the limited research trail that is left behind. Academic literature often states the private sector as a key implementing actor for SDG7, while accurately documented results and experiences from the private sector (aside from informal interviews with people involved) are hard to come by. This is compounded by the lack of rigorous, up-to-date data from the region related to electricity access, and current projects. This is shown particularly clearly with the annual spend data from BNEF. These figures published in 2016, were in fact based on 2010 data collected by the UN. Due to the rapidly changing nature of the energy situation in SSA (explained in section 2), this renders advice based on such data rather spurious, and is the reason why only recent data was used in this report.

In this report, for 100% electricity access, much of SSA requires power from standalone PV systems. Indeed, there is incredible interest and investment devoted to the development of standalone PV in Africa, and many companies are active in this sector. However, caution must be taken to not treat solar PV as a silver bullet. For example, while the case has been made by BBOXX to start investing in PAYG solar in the DRC, from the model results it should be noted that for much of the country, hydropower (mini-grid scale) is more suitable. Where possible, the private sector should take in to account geographical and technical potentials in the appraisal of a new market to invest in.

7.4 Further research

This report presented the first findings of the updated use of the least-cost optimization model, laying the foundations for more detailed investigations in to the optimal technologies for electricity access in SSA.

With (inter)national climate policies taken in to account, the large number of diesel standalone and mini-grid systems shown in Figure 6 would not be optimal. This was shown by Dagnachew et al. (2018) where the same model was used to explore the tradeoffs and synergies between electricity access goals and climate change mitigation. In this research, the climate policy scenarios were not included, as it would detract from the focus on achieving SDG7 in this work. In future research, the link between governance and climate policy implementation could be studied to gain further insights in to the optimal investments. This could be complemented by studying the development of climate policies over recent years compared to the changes in governance observed in Figure 18, exploring the causality between the two.

The technologies included in this research are fairly limited with respect to climate change mitigation goals. Solar PV, hydropower, and wind are good examples of sustainable electricity generation, however there are several other technologies also available. In particular, biofuels and geothermal energy are proven technologies which have been implemented in SSA. Even though the scope of this study was limited to electricity generation, if energy access (rather than electricity access) is considered as a whole, it would be of great value to include other technologies. The interaction between electricity access and access to clean cooking could also be explored, to see where the private sector can contribute to clean cooking access in SSA.

Finally, in this use of the model, the volume of investment needed per country per technology has not been calculated. This was unfortunately due to a bug in the model, that time constraints did not allow to be smoothed out. In future research, the calculation of the investment needs could provide valuable information to both the private sector investors, and local policy makers to tailor strategies and policies.

7.5 Recommendations

The assessment of countries based on governance has revealed that while governance has an effect on the optimal systems for 100% electricity access in SSA, there is considerable potential for the private sector to invest. The following points are final remarks by the author aimed as recommendations for the private sector, and local energy policy makers to stimulate the necessary investment.

- Partnership with locally based enterprises can mitigate some of the risks involved with investment in poorly governed countries
- To most effectively use funds for investment, the optimal technologies should be taken in to account when proposing investment strategies
- Local data is crucial to an accurate assessment of the opportunities for electricity access, even though it is challenging to procure
- Local policy makers can take in to account the calculated optimal technologies in their regions to tailor policies more effectively
- Not only can investment in standalone and mini-grid systems be used to provide electricity access, it can also be crucial to mitigating the unreliability of the grid in many countries

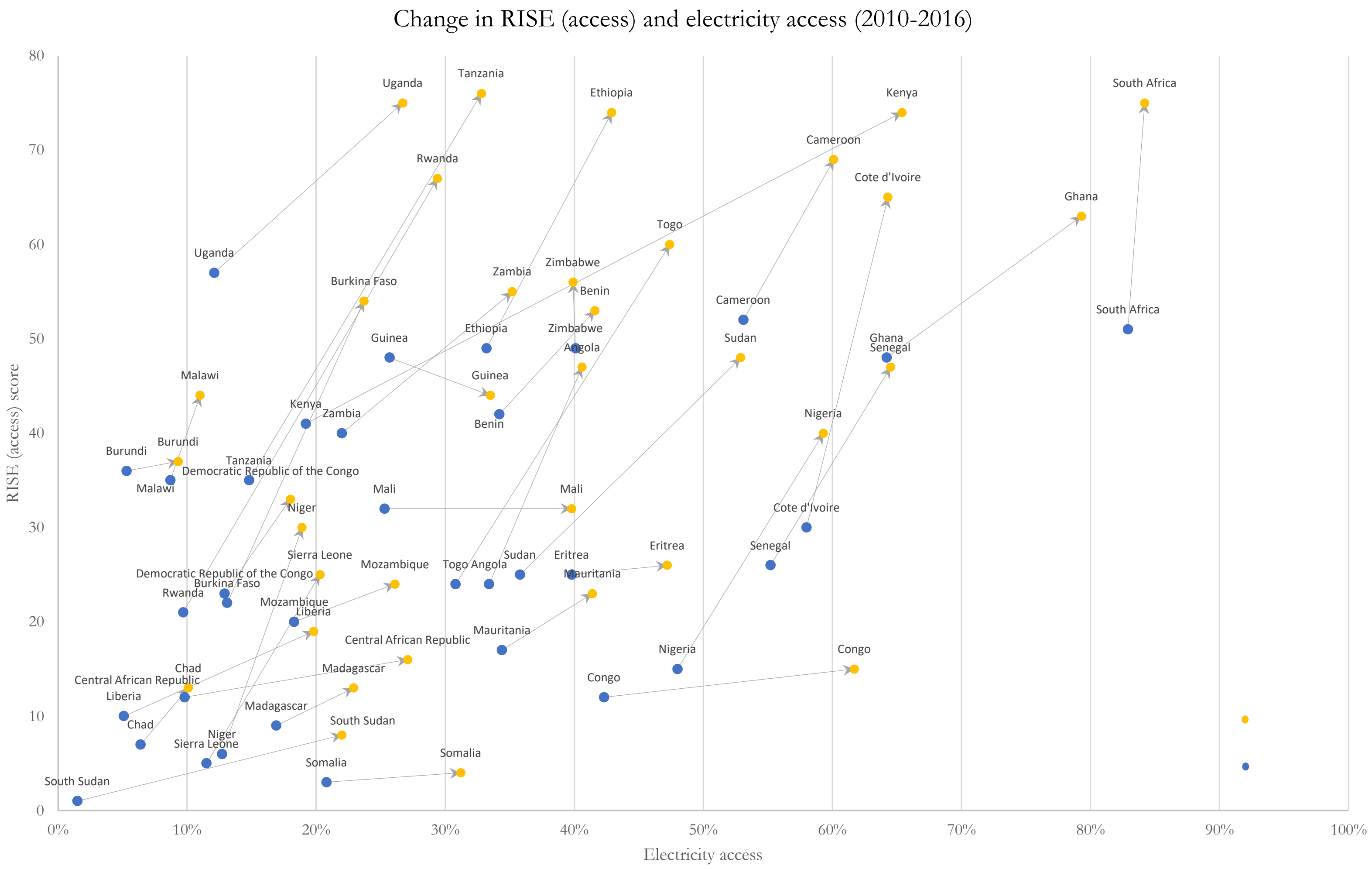


Figure 18 Graph showing the change in RISE (access) scores for countries in SSA between 2010 (blue) and 2016 (yellow)

8. Conclusion and final remarks

By using a new governance-based approach in spatial electrification modelling for SSA, this research demonstrated both the challenges and opportunities for private sector investments in electricity access in the region. Despite data availability in this field in SSA being a major issue, an attempt was made to quantify the effect that governance performance has on private sector investments. From literature, it was clear that there are several key governance-related barriers to private sector investment in electricity access in SSA. Four different categories were used to measure governance performance related to electricity access: RISE (access), Corruption Perception, Political Stability and Absence of Violence, and Regulatory Quality. These were aggregated in the Electricity Access Governance Index (EAGI), which in turn was used to modify the discount rate used in the spatial electrification model for each country. Besides the EAGI, data was also included for connection charges per country, and diesel prices per country to further improve the results of the model.

The model revealed that there is considerable potential for private sector investment in electricity access in SSA, despite the challenges related to poor governance in certain areas. Central and northern SSA have the most scope for private sector investments in standalone and mini-grid systems, where in central SSA this is mostly small-scale hydropower, and in the north mainly standalone PV. The in-depth qualitative analysis of the results for the DRC showed that micro-scale hydropower is optimal for most of the country, and that foundations for market entry by the private sector exist. The DRC is one of the largest unexplored markets for investment in electricity access, and will continue to grow in the coming years. For Ghana, the qualitative analysis revealed that the private sector can contribute to SDG7 by investing in the mitigation of power outages and unreliable grid power, for instance in the form of standalone PV systems with battery storage.

Data quality and availability are the major limiting factors to this research. Even though the EAGI developed here gives an indication of the level of risk investments are exposed to due to poor governance, it is unfortunately no more than exactly that: an indication. The country case studies aimed to give a more detailed explanation of the factors affecting investment by the private sector, and in future research consultations with stakeholders involved could provide the extra clarity needed for a proper investment strategy assessment.

Private sector investment is key to reaching SDG7, and providing the population of SSA the opportunities associated with electricity access that the developed world takes for granted. In several regions governments must improve the enabling environment to attract this investment: improving regulations will be paired with interest from the private sector. It is crucial that the private sector invests in the optimal and most suitable technologies in SSA to ensure long term sustainability and avoid stranded assets, rather than simply following the market. To mitigate some of the risks involved with investment in poorly governed countries, partnership with locally owned and operated enterprises could be instrumental.

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10. Appendices

Appendix 1: Key formulas and parameters used in the model

Adapted from (Dagnachew et al., (2017) supplementary data)

Underlying formulas in the household electrification model. Terms that have been updated/modified in this research are given in red

$$LCOE \quad = \frac{\sum_{i=1}^{m}[A_i * I_i + C_{FC,i} + \beta_i I_i]}{\sum_{i=1}^{m} E_i}$$

Annuity factor $= \frac{1-(1+r)^{-i}}{r}$

Where $i =$ the power generating technology (1, 2,…., m),
$m=$ the total number of power generating plants
$E_i =$ the annual electricity output (kWh)
$A_i=$ Present value annuity factor
$I_i=$ the capital cost of plant i (USD),
$C_{FC,i}=$ the fuel cost (USD/MJ) $= E_i * \emptyset_{HR,i} * P_{fuel}$,
$\emptyset_{HR,i}=$ the heat rate of the plant measured in (MJ per kwh),
$P_{fuel}=$ the price of fuel (USD per MJ),
$r=$ discount rate
$\beta_i=$ OPEX (fraction of the capital cost for annual operation and maintenance of plant) i.

The EDL (based on Kemausuor et al., 2014) calculates whether it is more economic to extend the central grid (cg) or to install an alternative technology (alt).

$$EDL_c = \frac{(LCOE_{alt} - LCOE_{cg}) * \sum_{t=Baseyear}^{Baseyear+Lifetime} E_{t,c(t)}}{C_{HV\&MV}} km$$

Where $LCOE_{cg}$ = LCOE per grid cell of central power plants (USD per kWh)
$LCOE_{alt,c}$= LCOE per grid cell of off-grid electrification (USD per kWh)
$E_{t,(t)}$ = total electricity consumption per grid cell (kWh per year)
$C_{HV\&MV}$ = transmission network cost (high and medium voltage lines) required to link households in a grid cell to the central grid (USD per km)

The investment cost for central grid extension is calculated as follows:

$$Inv_{tot,c} = Inv_{w\&m,c} + Inv_{int,c} + Inv_{Ext,c}$$

Where;

$Inv_{w\&m,c}$ is the cost connecting a household to the grid

$Inv_{int,c}$ is the cost of the internal component of electrification for a grid-cell which includes the costs of low-voltage line network for a grid-cell (USD)

$Inv_{Ext,c}$ is the cost of the external component of grid extension for a grid-cell which includes the costs of high-voltage and medium-voltage lines and transformers (USD).

The LCOE of central grid extension is therefore:

$$LCOE_{dis,c} = \frac{\sum_{i=1}^{m}[Annuity_i \ * \ Inv_{i,tot,c}]}{\sum_{i=1}^{m} E_i}$$

The capacity of mini-grid systems is calculated using the following equation:

$$MG_{i,cap,c} = \frac{E_{t,c}}{(CF_i \ * \ Annual\ load\ hours\ ) * (1 - \ Loss_{dis})}$$

$E_{t,c} = annual\ electricity\ consumption\ of\ the\ grid\ cell$

$CF_i = capacity\ factor\ of\ the\ system$

$Loss_{dis} = distribution\ losses$

And for standalone systems using the following equation:

$$StAl_{i,cap,c} = \frac{E_{t,hh}}{(CF_i \ * \ Annual\ load\ hours\ )}$$

$E_{t,hh} = annual\ electricity\ consumption\ of\ the\ household$

For key parameter assumptions and details of the model technologies, please refer to the supplementary information of Dagnachew et. al. (2017).

Appendix 1.2: Diesel price calculation

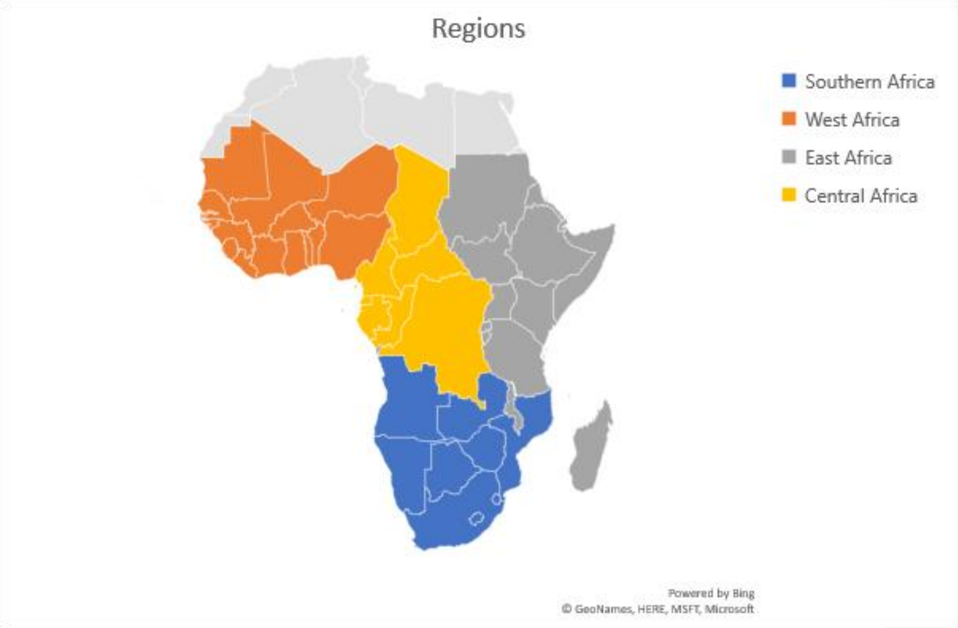
Diesel price:

- Diesel price = from World Bank (2015)
- Truck consumption liter per hour = 20 liter
- Truck capacity liters = 7500
- Travel time to large city: Weiss et al. (2018)

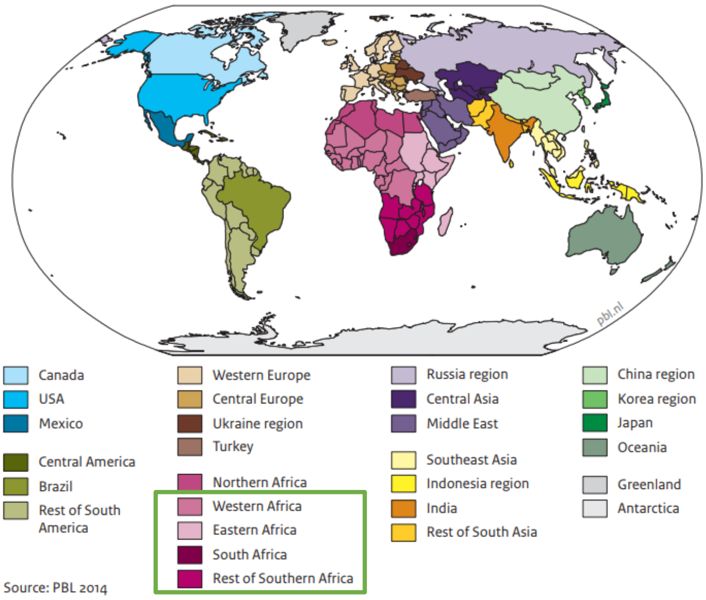
$$Diesel\ price_{for\ grid\ cell\ i} = Diesel\ price + \left(\frac{Travel\ time\ to\ large\ city * truck\ consumption\ liter\ per\ hour}{truck\ capacity}\right)$$

Appendix 2: Regions

The regions used in the description of the results, and the calculation of regional averages are shown below.



The regions used in the IMAGE-TIMER model for projections for 2030 are as follows:



Source: PBL 2014

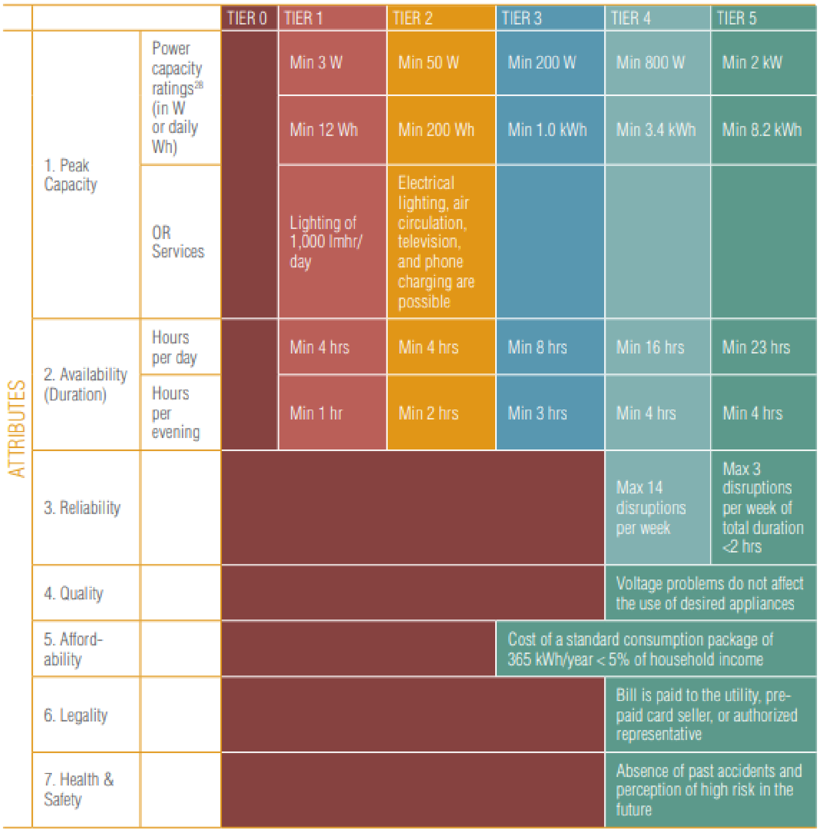
Appendix 3: RISE (access) scores, averages taken

RISE scores

Country	**Average taken**
Comoros	Tanzania, Madagascar
Djibouti	Eritrea, Ethiopia
Equatorial Guinea	Congo, Cameroon
Gabon	Congo, Cameroon
Guinea-Bissau	Guinea, Sierra Leone
The Gambia	Guinea, Sierra Leone
Lesotho	Zimbabwe
Sao Tome & Principe	Cameroon
Namibia	South Africa
Botswana	South Africa
Swaziland	South Africa

Appendix 4: tiers of electricity supply

Multi-tier framework for measuring access to household electricity supply (ESMAP, 2015)



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

Appendix 5: PCA method

First the correlation of the indicators must be checked, to ensure that a PCA will give meaningful results. This is done by calculating the correlation matrix:

	RISE	CPI	PS	RQ
RISE	1	0.626522	0.406562	0.630549
CPI	0.626522	1	0.695885	0.825136
PS	0.406562	0.695885	1	0.566284
RQ	0.630549	0.825136	0.566284	1

Following this, the principal components can be calculated.

$$PC1 = (W * RISE) + (X * CPI) + (Y * PS) + (Z * RQ)$$

The 1st principle component (PC1) explains 72.3% of the variance, and with an eigenvalue of 2.893, it is sufficient to use only PC1 when calculating the weighting for each indicator in the index. The weighting of the each indicator in the EAGI is therefore:

Indicator	Weighting
RISE	0.776
CPI	0.935
PS	0.779
RQ	0.899

Appendix 6: EAGI scores

Country	EAGI score	Country	EAGI score
Angola	0.35	Liberia	0.29
Benin	0.60	Madagascar	0.33
Botswana	1.00	Malawi	0.43
Burkina Faso	0.50	Mali	0.32
Burundi	0.22	Mauritania	0.30
Cameroon	0.39	Mozambique	0.25
Central African Republic	0.14	Namibia	0.82
Chad	0.13	Niger	0.40
Comoros	0.42	Nigeria	0.26
Congo	0.22	Rwanda	0.81
Cote d'Ivoire	0.49	Sao Tome and Principe	0.62
Democratic Republic of the Congo	0.17	Senegal	0.61
Djibouti	0.41	Sierra Leone	0.40
Equatorial Guinea	0.32	Somalia	0.00
Eritrea	0.20	South Africa	0.73
Ethiopia	0.42	South Sudan	0.04
Gabon	0.45	Sudan	0.21
Gambia	0.47	Swaziland	0.58
Ghana	0.70	Tanzania	0.54
Guinea	0.38	Togo	0.43
Guinea Bissau	0.25	Uganda	0.56
Kenya	0.52	Zambia	0.59
Lesotho	0.59	Zimbabwe	0.31

Appendix 6.2: Breakdown of EAGI scores

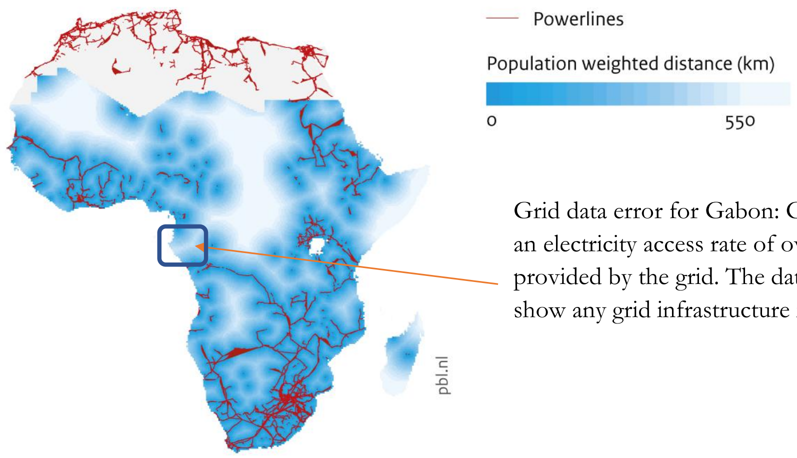
Country	RISE (access)	Corruption Perceptions Index	Political Stability	Regulatory Quality
Angola	51	19	34	13
Benin	63	40	48	33
Botswana	75	61	86	70
Burkina Faso	62	41	16	35
Burundi	38	17	5	18
Cameroon	69	25	12	20
Central African Republic	16	26	6	5
Chad	13	19	10	9
Comoros	50	27	47	13
Congo	25	19	29	7
Cote d'Ivoire	67	35	12	38
Democratic Republic of the Congo	35	20	4	5
Djibouti	52	31	20	28
Equatorial Guinea	47	16	40	6
Eritrea	26	24	23	1
Ethiopia	78	34	8	14
Gabon	47	31	42	23
Gambia	36	37	39	34
Ghana	68	41	50	50
Guinea	52	28	25	18
Guinea Bissau	36	16	25	11
Kenya	76	27	13	44
Lesotho	61	41	38	40
Liberia	19	32	30	15
Madagascar	25	25	33	26
Malawi	45	32	35	24
Mali	34	32	6	30
Mauritania	24	27	24	23
Mozambique	24	23	14	25
Namibia	75	53	69	47
Niger	56	34	10	27
Nigeria	40	27	5	17
Rwanda	73	56	48	61
Sao Tome and Principe	69	46	55	19
Senegal	47	45	43	49
Sierra Leone	36	30	47	16
Somalia	4	10	3	0
South Africa	75	43	36	63
South Sudan	12	13	1	3
Sudan	53	16	4	4
Swaziland	75	38	34	31
Tanzania	76	36	26	30
Togo	66	30	20	22
Uganda	75	26	27	46
Zambia	61	35	50	34
Zimbabwe	61	22	18	4

Appendix 7: Electricity access rates (World Bank, 2017a)

Country Name	Electricity access (2017)	Country Name	Electricity access (2017)
Angola	42%	Liberia	21%
Benin	43%	Madagascar	24%
Botswana	63%	Malawi	13%
Burkina Faso	25%	Mali	43%
Burundi	9%	Mauritania	43%
Cabo Verde	93%	Mauritius	98%
Cameroon	61%	Mozambique	27%
Central African Republic	30%	Namibia	53%
Chad	11%	Niger	20%
Comoros	80%	Nigeria	54%
Congo, Rep.	66%	Rwanda	34%
Cote d'Ivoire	66%	Sao Tome and Principe	73%
Democratic Republic of Congo	19%	Senegal	62%
Djibouti	60%	Sierra Leone	23%
Equatorial Guinea	67%	Somalia	33%
Eritrea	48%	South Africa	84%
Ethiopia	44%	South Sudan	25%
Gabon	92%	Sudan	56%
Gambia, The	56%	Swaziland	74%
Ghana	79%	Tanzania	33%
Guinea	35%	Togo	48%
Guinea-Bissau	26%	Uganda	22%
Kenya	64%	Zambia	40%
Lesotho	34%	Zimbabwe	40%

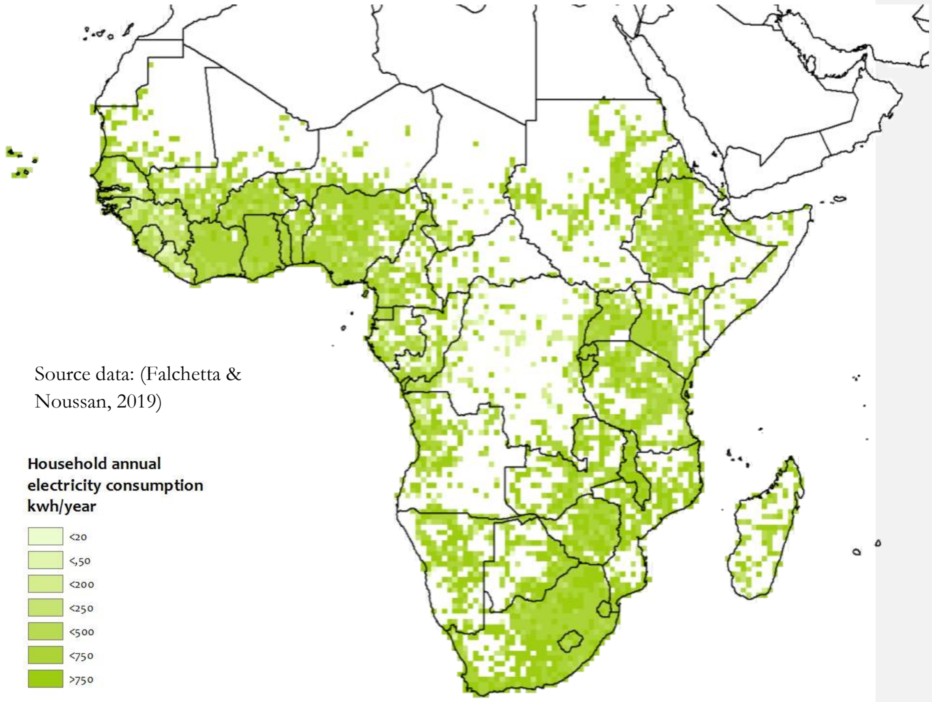
Appendix 8: Input data for model maps

Distance from central grid, 2010

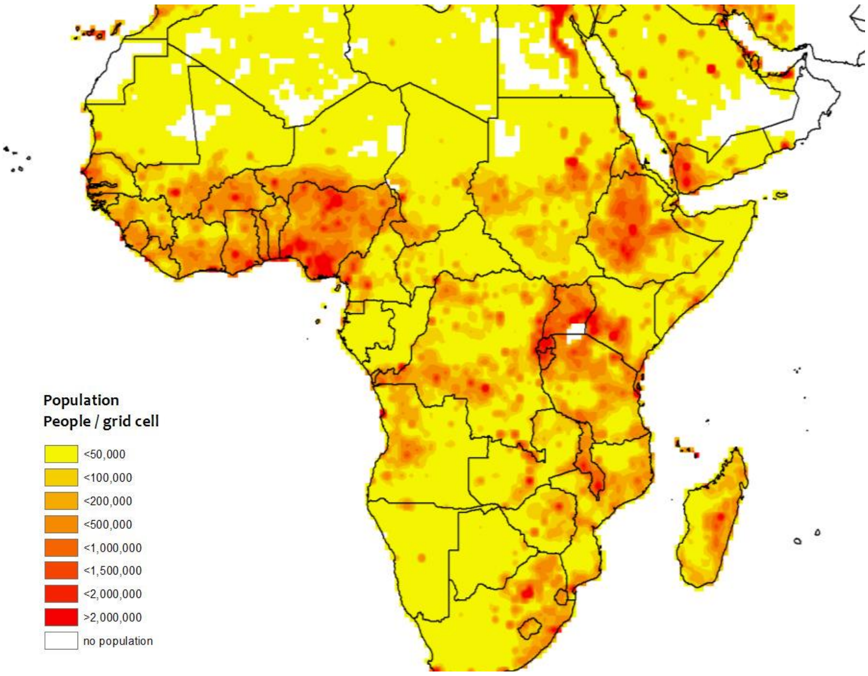


Grid data error for Gabon: Gabon has an electricity access rate of over 90%, provided by the grid. The data does not show any grid infrastructure in Gabon

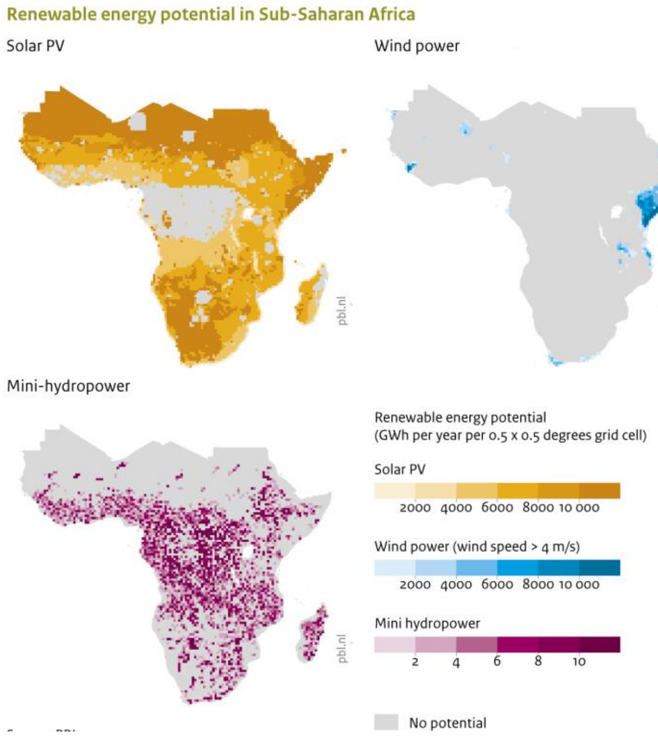
Source: PBL; OpenStreetMap 2015



Source data: (Falchetta & Noussan, 2019)

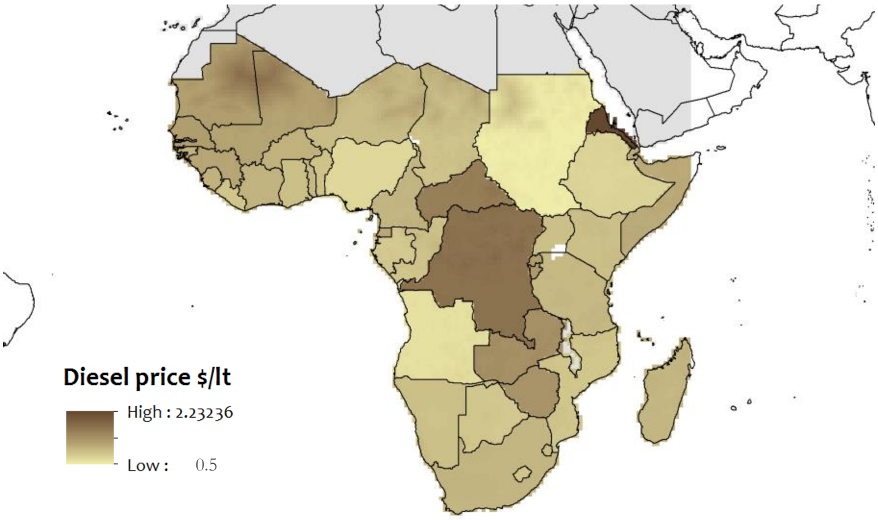


Source data: Landscan 2010 and van Vuuren et. al. (2007)



Source data: PBL (2017), based on Hoogwijk (2004)

Adjusted diesel price



Appendix 9: Connection fees per country

Commented [MD(3]: SOURCES

Country	Connection charge ($USD)	Country	Connection charge ($USD)
Angola	512	Liberia	369
Benin	150	Madagascar	181
Botswana	512	Malawi	181
Burkina Faso	264	Mali	369
Burundi	181	Mauritania	106
Cameroon	204	Mozambique	181
Central African Republic	283	Namibia	512
Chad	597	Niger	504
Comoros	181	Nigeria	406
Congo	597	Rwanda	78
Cote d'Ivoire	388	Sao Tome and Principe	369
Democratic Republic of the Congo	597	Senegal	369
Djibouti	181	Sierra Leone	369
Equatorial Guinea	597	Somalia	181
Eritrea	181	South Africa	512
Ethiopia	148	South Sudan	181
Gabon	1303	Sudan	38
Gambia	369	Swaziland	512
Ghana	799	Tanzania	297
Guinea	369	Togo	336
Guinea Bissau	369	Uganda	125
Kenya	400	Zambia	200
Lesotho	512	Zimbabwe	824

Appendix 10: Grid reliability

Country Name	Power outages in firms in a typical month
Equatorial Guinea	-
Sao Tome and Principe	-
Somalia	-
Comoros	-
Nigeria	32.8
Central African Republic	29
Benin	28
Niger	22
Congo, Rep.	21.5
Gambia, The	21.1
Burundi	16.6
Democratic Republic of Congo	12.3
Burkina Faso	9.8
Sierra Leone	9.1
Tanzania	8.9
Ghana	8.4
Ethiopia	8.2
Cameroon	7.6
Madagascar	6.7
Malawi	6.7
Uganda	6.3
Senegal	6
Togo	5.5
Mauritania	5.3
Guinea-Bissau	5.2
Zambia	5.2
Angola	4.7
Gabon	4.6
Chad	4.5
Guinea	4.5
Liberia	4.5
Zimbabwe	4.5
Mali	4.2
Botswana	4.1
Rwanda	4
Kenya	3.8
Eswatini	3.7
Cote d'Ivoire	3.5
Sudan	3.4
Lesotho	2.2
Djibouti	1.6
Mozambique	1.6
South Sudan	1.5
South Africa	0.9
Namibia	0.6
Eritrea	0.5