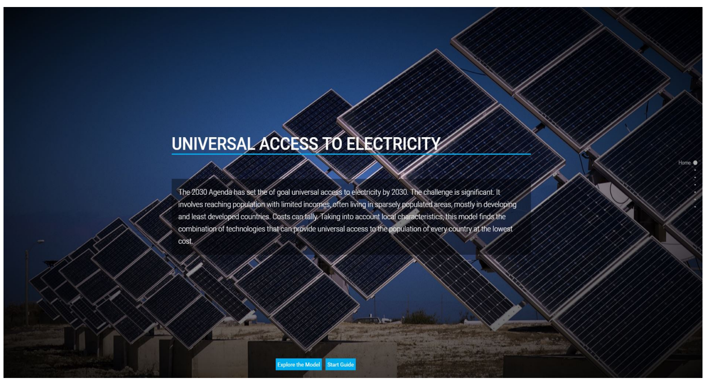


Understanding Modelling Tools for Sustainable Development

MODULE

MODELLING UNIVERSAL ACCESS TO ELECTRICITY: A READER

The Open Source Spatial Electrification Toolkit

TABLE OF CONTENTS

PRESENTATION

SUMMARY

Access to modern energy is key for improving the well-being of 2.7 billion people around the world who lack access. Use of less polluting fuels is a critical step in building a sustainable development path.

Providing access to electricity has been mainly constrained by dependence on extending national centralized grids. Technological progress has opened a wide range of options to accelerate electrification, but taking full advantage of new opportunities requires complementing traditional national energy planning exercises with planning tools that use detailed geospatial data on different options in specific localities. The Open-Source Spatial Electrification Tool (ONSSET) identifies the lowest-cost options for geographically defined areas of 10 by 10 kilometres in any country in the world. The ONSSET Module provides an overview of this tool, and its capabilities and limitations, using predefined modelling results for more than 60 countries in Africa and Latin America. It further provides hands-on experience in the use of the tool to plan electrification in any country using the variables and parameters defined by users.

LEARNING OBJECTIVES

- Review evidence underscoring the importance of access to electricity.
- Understand how geographic information systems (GIS) can help assess relevant energy resources for specific locations, particularly in remote areas.
- Understand the steps involved in estimating comparable investment costs of alternative technologies to provide access to electricity.
- Understand how to aggregate estimated local costs to obtain subregional, country and regional estimates.
- Perform an electrification analysis and identify the lowest overall cost option for a given region using the ONSSET standalone interface.

OUTLINE

1. Introduction to electrification
2. Energy resources assessment using GIS
3. Electrification analysis using GIS
4. ONSSET – Open-Source Spatial Electrification Tool
5. Results from ONSSET

QUESTIONS TO ACTIVATE RELATED KNOWLEDGE

- How are electricity and development interrelated?
- What is the development impact of providing broader access to modern and affordable energy?
- What are the main energy sources used to generate electricity (list three)?
- What is likely to be the lowest-cost option to expand electrification to low-income populations?
- What is likely to be the lowest-cost option to expand electrification in remote areas?
- What is likely to be the lowest-cost option to expand electrification for low-income population groups in urban areas?

1. UNIVERSAL ACCESS TO ELECTRICITY

MODELLING ACCESS TO ELECTRICITY

Electrification has long been considered an important achievement and a catalyser of development. The world map of access to electricity mirrors global inequalities. While a number of countries have achieved universal access, 1.1 billion people still go without electricity. In about 50 developing countries, more than one-third of the population does not have access. Many of these people live in rural areas, mainly in Asia and Africa.

Access to electricity can improve education, food preservation, communication, home-based income generation, employment and agricultural productivity.

Universal access to electricity is part of the goal of providing universal access to modern energy services under the seventh Sustainable Development Goal (SDG). In parallel to the 1.1 billion people without access to electricity, 2.7 billion people around the world rely on the traditional use of biomass, predominantly for cooking on inefficient stoves in poorly ventilated indoor spaces. Access to modern, less-polluting and affordable energy services, i.e., electricity and clean fuels, is key for poverty alleviation and well-being. The benefits for education, food preservation, communication, home-based income generation, employment and agricultural productivity have long been documented Access to electricity and mechanical power fosters small and microenterprises, and helps establish nonfarm income in rural areas.[1]

[1] See International Energy Agency 2015, World Bank 2016, Pachauri et al. 2012 and UN-Energy 2014.

The focus of this module is on access to electricity. The module concentrates on the use of a tool providing insights for strategies seeking universal access to electricity. The emphasis on electricity should not be taken, under any circumstance, as implying that access to cleaner cooking fuels or other energy services is of secondary importance. While electric cooking stoves provide the cleanest form of meal preparation, for example, they might not be the most affordable option. But this module will not explore this level of detail.

The approach of traditional grid expansion was largely based on economies of scale and the absence of economically feasible alternative technologies.

Historically, electrification around the world resulted from government programmes. The adoption of traditional large power plants has been largely based on economies of scale arguments (the larger the plant and the larger the upfront investment, the lower the specific per kW installed costs[2]). Economic viability led to centralized electricity generation by large plants accompanied by investments in transmission and distribution to reach consumers. A rule of thumb suggests that electricity sector investments are split about half each between generation and connecting end-users. In this context, electrification is an arduous, slow and, above all, capital-intensive endeavour. Grid expansion has been guided by (a) proximity of villages and settlements to the existing grid, (b) projected demand density (using population density as a proxy) and (c) areas with high economic potential.

[2] Economies of scale also result from increasing the scale of manufacture of a specific product (technology learning).

The possibility of connecting the urban poor to the electricity grid does not imply affordability or reliable access.

Technology advances and lower prices in standalone systems and mini-grid systems can provide access to electricity without having to connect to the grid.

Today, the economics of grid expansion have not changed. What has changed is the scale of power plant economics and the reduction in the cost of off-grid alternative energy sources. Technological advances in the production of wind turbines and solar photovoltaic (PV) have lowered their cost to make them economically attractive for deployment in remote rural areas. Whether as standalone systems (with battery storage) or mini-grid arrangements (with diesel-fuelled back-up), these systems can provide access to electricity without grid connections. Higher technology costs due to geographical circumstances are compensated for by the fact they do not require costly expansion of the grid.

QUESTIONS

- Why was access to electricity determined by the expansion of centralized grid infrastructure?
- What are the main differences between access to electricity, and the affordability and reliability of electricity services?
- Electricity is a key enabler of socioeconomic development. List three other aspects of the 2030 Agenda that would benefit from the achievement of SDG 7.

2. ENERGY RESOURCES ASSESSMENT USING GIS

Models addressing electrification and access need reliable energy-related data and information on a geographical basis, such a settlement sizes and locations, distances from existing grids, the electric grid network, economic activity and local renewable energy flows. In most developing countries, this information is not readily available or is outdated. Among other consequences, information gaps have hampered energy planning in Africa, particularly in remote rural areas.

The situation has fundamentally changed with the increasing availability and application of GIS,[3] which can provide location-specific energy-related information that has not been previously accessible. Integrating GIS and energy system modelling helps identify the most effective electrification strategy on a geospatial basis.

GIS can support energy planners in assessing resources availability and energy potentials, as can be shown in the example below taken from Africa. The fundamental questions an energy planner should answer are:

- What is the energy resource situation at each location?
- Which technologies are best suited to tap into these resources?
- What are the costs of electricity generation by technology and resource input?

GIS helps to provide answers to these questions by identifying and quantifying available resources and energy potentials per location.

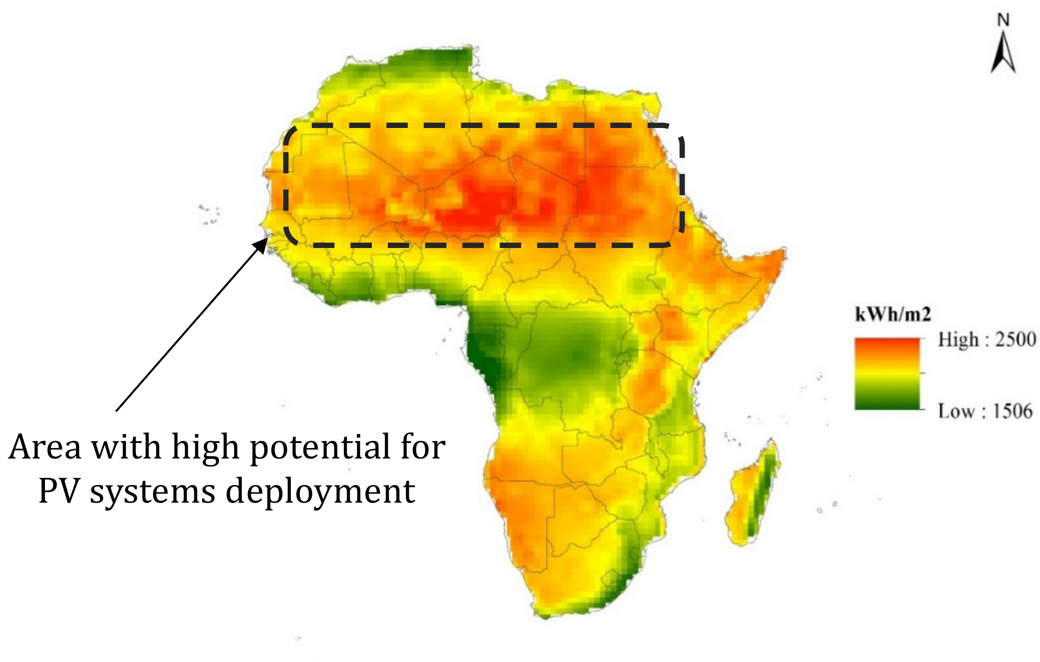
SOLAR AVAILABILITY

Solar radiation is the amount of energy received from the sun in an area over a specified time interval, such as a day or a year. In solar engineering, solar radiation is often expressed in units of kWh/m².

Figure 1 shows solar availability in Africa. The layer was developed based on global horizontal radiation (kWh/m²/day) data obtained from the **Atmospheric Science Data Center at the National Aeronautics and Space Administration (NASA) Langley Research Center**. The data provide 22-year (July 1983 to June 2005) monthly and annual average radiation values, with spatial resolution of 1x1 degree and global spatial coverage defined by the Conventional Terrestrial Coordinate System. The data were inserted into ArcGIS and processed to obtain the radiation on an annual basis (kWh/m²/year) in the desired database format (e.g., raster formats in ArcGIS).

[3] GIS software captures, stores and displays data relate to positions on the earth's surface. Data in many different forms can be entered, i.e., data already in map form (e.g., rivers, roads, power lines, renewable energy flows) or data collected by satellites (e.g., land use, location of settlements, agricultural/non-agricultural areas). GIS software allows the overlay of different types of information on a single map.

FIGURE 1: GLOBAL HORIZONTAL RADIATION MAP OF THE AFRICAN CONTINENT



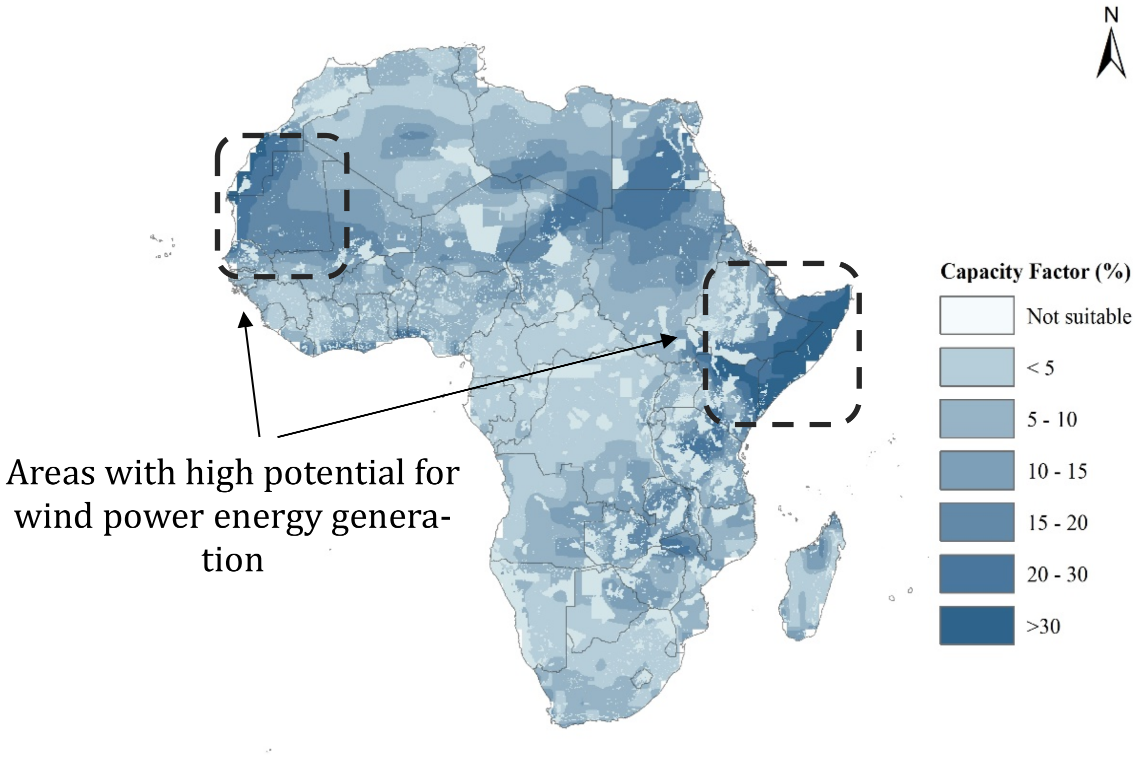
Source: Langley Atmospheric Science Research Center.

The results show high potential for PV systems deployment in Eastern and Southern Africa.

WIND AVAILABILITY

To assess wind availability in Africa, GIS modelling uses raw GIS data from NASA for 1995 to 2014, consigning average wind speed at a height of 10 metres with a spatial resolution of 0.5°x0.5° (approximately 55 km^2). Results are shown in figure 2.

FIGURE 2. WIND POWER CAPACITY FACTOR MAP OF THE AFRICAN CONTINENT



Source: NASA, GES DISC.

The wind speed changes with altitude because of frictional effects at the surface of the earth. Since the wind speed data are given at 10 metres in height, a proper extrapolation should be applied to obtain wind speed reading at the hub height (55 metres) of the chosen wind turbine (Vestas-44 (V-44) having 600kW rated power).

Moreover, to estimate the wind energy potential available in each grid cell, it is necessary to obtain the wind speed probability distribution. It provides the repetition frequency of a specific wind speed reading (1 to 25 m/s) at a given site. The power produced by a wind turbine is estimated by combining the probability distribution and the manufacturer's power curve of the selected wind turbine. The yearly expected wind energy yield of each

The capacity factor reflects the potential wind power at a given site; it can be used for comparing different sites before the installation of wind power plants. The capacity factor of a wind turbine is defined as the ratio of the yearly expected wind energy production to energy production if the wind turbine were to operate at its rated power throughout the year.

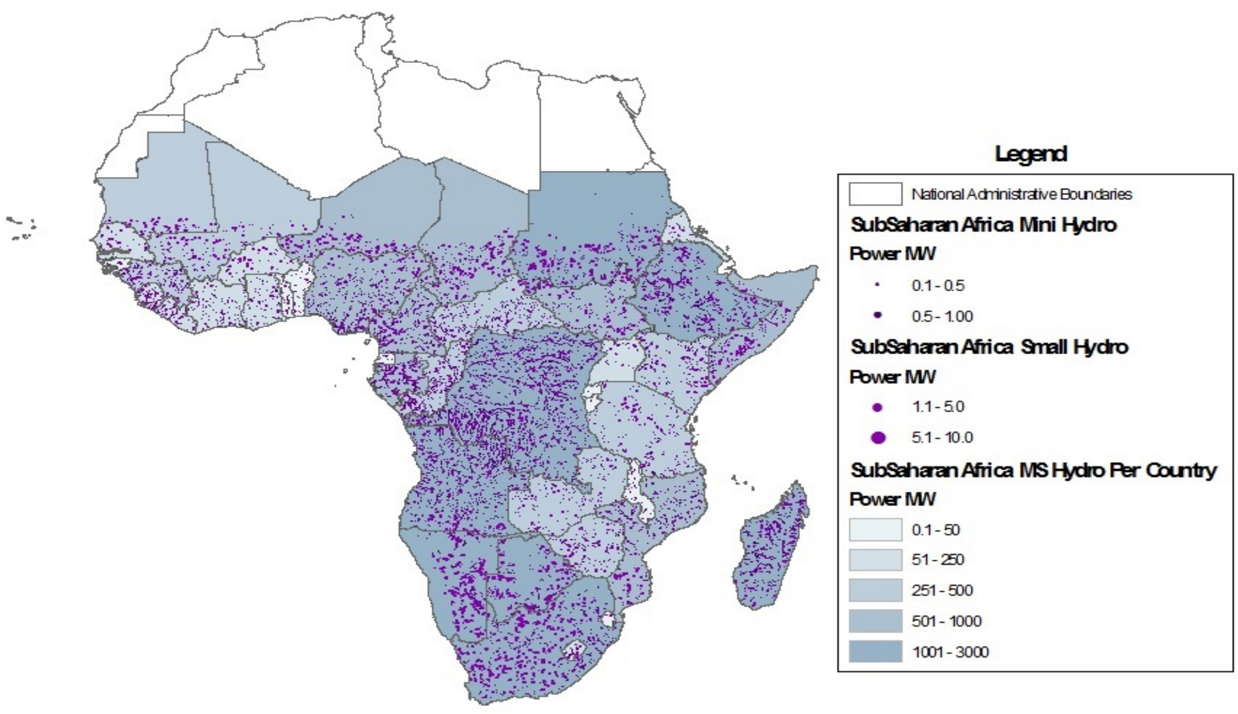
grid cell is estimated after considering the availability factor of a wind turbine as well as electrical and mechanical losses, and several criteria regarding the localization of wind farms, such as protected areas, water bodies and others. The next step is the calculation and the visualization of the capacity factor. The analysis shows high wind power potential in the eastern and north-western parts of the continent.

HYDROPOWER AVAILABILITY

Africa is rich in hydro resources, with a significant portion of current electricity generation (16 per cent) coming from hydropower. Yet an estimated 90 per cent of the potential remains untapped. GIS software can help identify sites with hydropower potential using several datasets.

Figure 3 identifies the potential sites for mini and small hydropower deployment in sub-Saharan Africa. Approximately 10,000 sites with the highest potential were identified in the southern part of the subcontinent.

FIGURE 3. SPATIAL MINI/SMALL HYDROPOWER AVAILABILITY OF THE AFRICAN CONTINENT

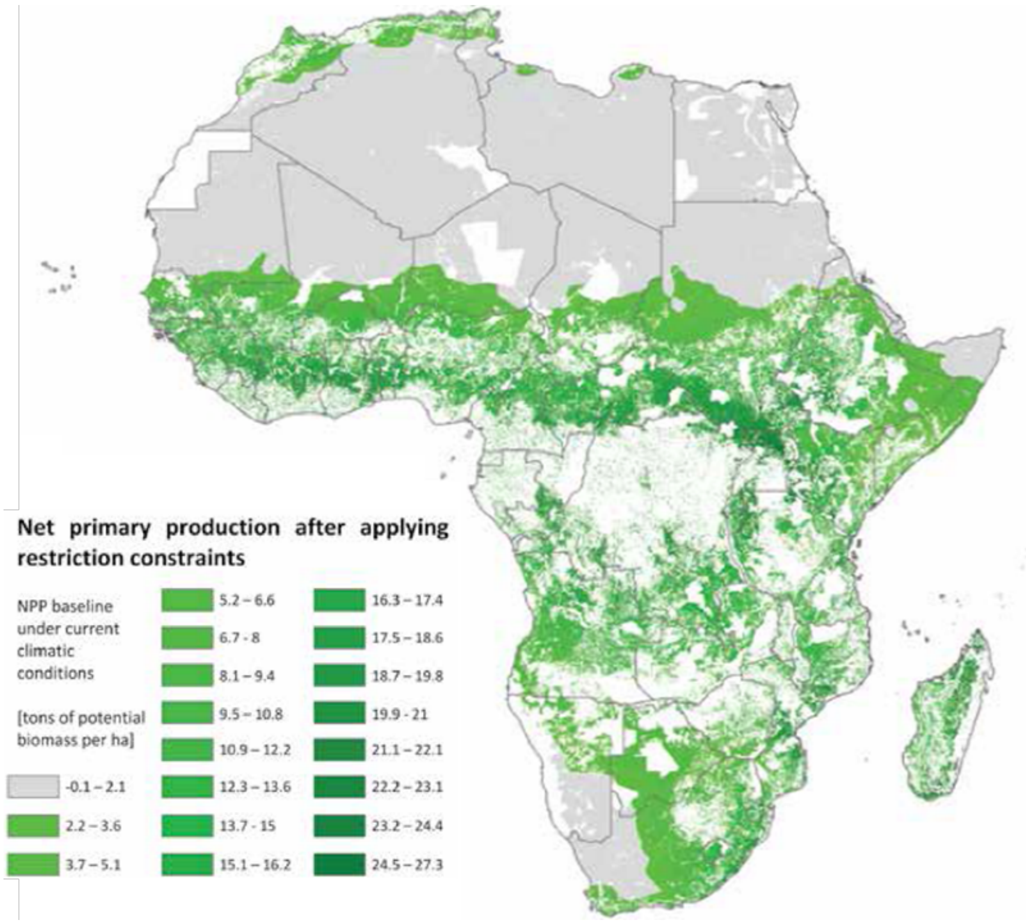


Sources: USGS/NASA SRTM, CGIAR-CSI, EU JRC, WWF.

SPATIAL BIOENERGY AVAILABILITY

Bioenergy data have been extracted from an open data platform developed by the International Institute for Applied Systems Analysis (IIASA), the Global Agro-ecological Zoning. This is a vast database of downloadable land data in GIS format.

FIGURE 4. NET PRIMARY BIOMASS PRODUCTION ON THE AFRICAN CONTINENT



Source: IIASA, Global Agro-ecological Zoning.

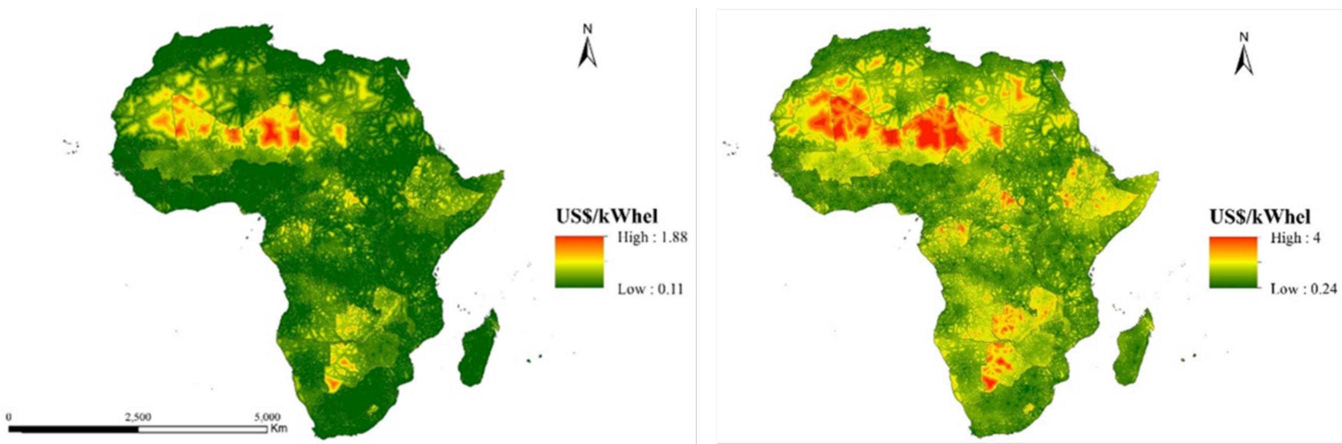
Figure 4 presents the net primary production of biomass under current climatic conditions; expressed in tons of potential biomass per hectare after applying plausible constraints.

SPATIALLY EXPLICIT COST OF GENERATING ELECTRCITY USING DIESEL GENERATORS

The suitability of diesel generators is basically represented by the levelized cost of energy (LCOE) they can achieve. In order to estimate this cost, a number of factors are taken into consideration. Initially, using global coastlines and administrative boundaries layers in GIS, we characterize the countries as landlocked or coastal. Landlocked countries tend to have higher fuel costs. Then, the travel time to major cities is considered and combined with the international diesel price to yield a current and projected map of LCOE for diesel generation.

The LCOE measure allows analysis of the lowest cost possible, by comparing, for example, high investment and low operating cost vis-à-vis low investment and high operating cost over the lifetime of the technology.

FIGURE 5. SPATIAL LCOE FOR DIESEL GENERATORS



Sources: EU JRC, IEA, BLOOMBERG.

Figure 5 shows the spatial LCOE using diesel generators. The map on the left-hand side shows the LCOE for the current fuel price, while the map on the right-hand side shows the projected fuel price based on the International Energy Agency's New Policies Scenario.

QUESTIONS

- How can the increased availability of GIS contribute to energy planning and analysis?
- Can we say that Africa should primarily use one or another source of energy?
- Which sources of energy can you name as the most advantageous for African countries? Name three and explain.

3. ELECTRIFICATION ANALYSIS USING GIS

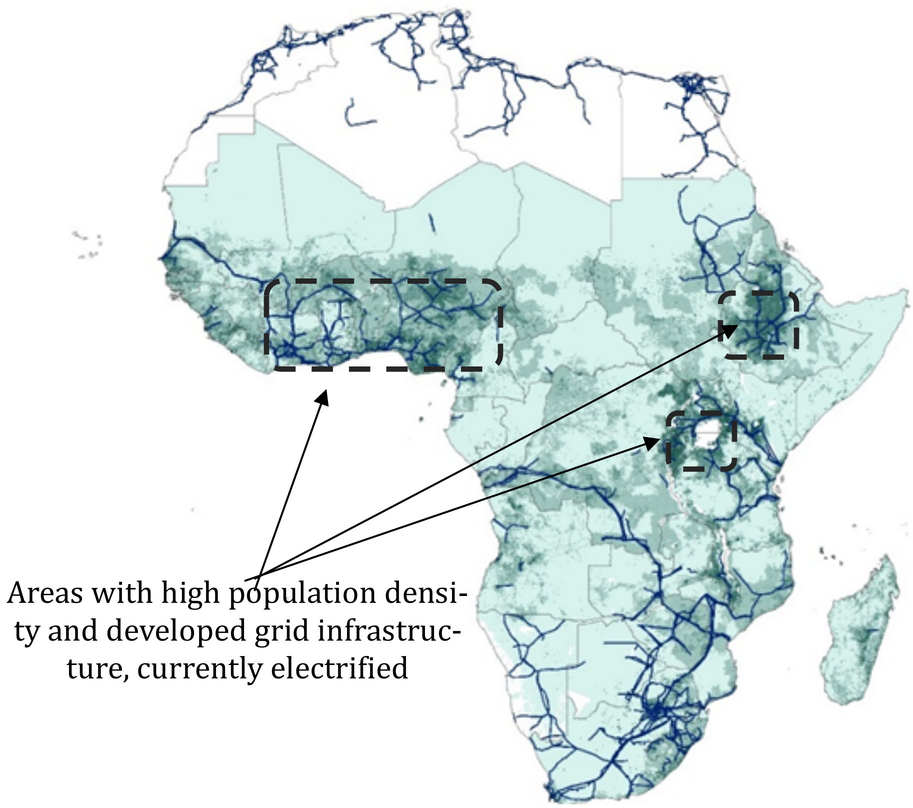
The electrification analysis using GIS can be performed in three steps: defining the current electrification status, identifying future electricity demand and analysing electrification options.

CURRENT ELECTRIFICATION STATUS

In the first step of the analysis, we use several datasets to retrieve information about the existing infrastructure as well as identify where the population lives. This will give us an indication of where people without electricity are located and where the electricity demand might be, as illustrated in figure 6. These datasets include:

- Administrative boundaries,
- Existing and planned transmission networks,
- Existing and planned power plants,
- Road networks,
- Population density and
- Nighttime lights (help to identify underserved areas).

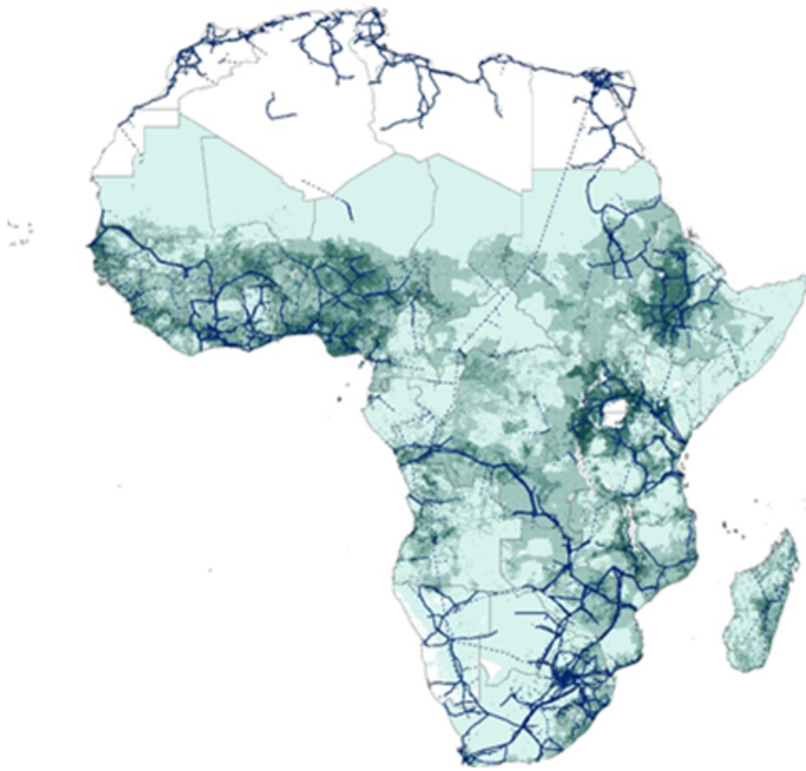
FIGURE 6. CURRENT POPULATION AND TRANSMISSION NETWORK IN THE AFRICAN CONTINENT



IDENTIFYING THE FUTURE ELECTRICITY DEMAND

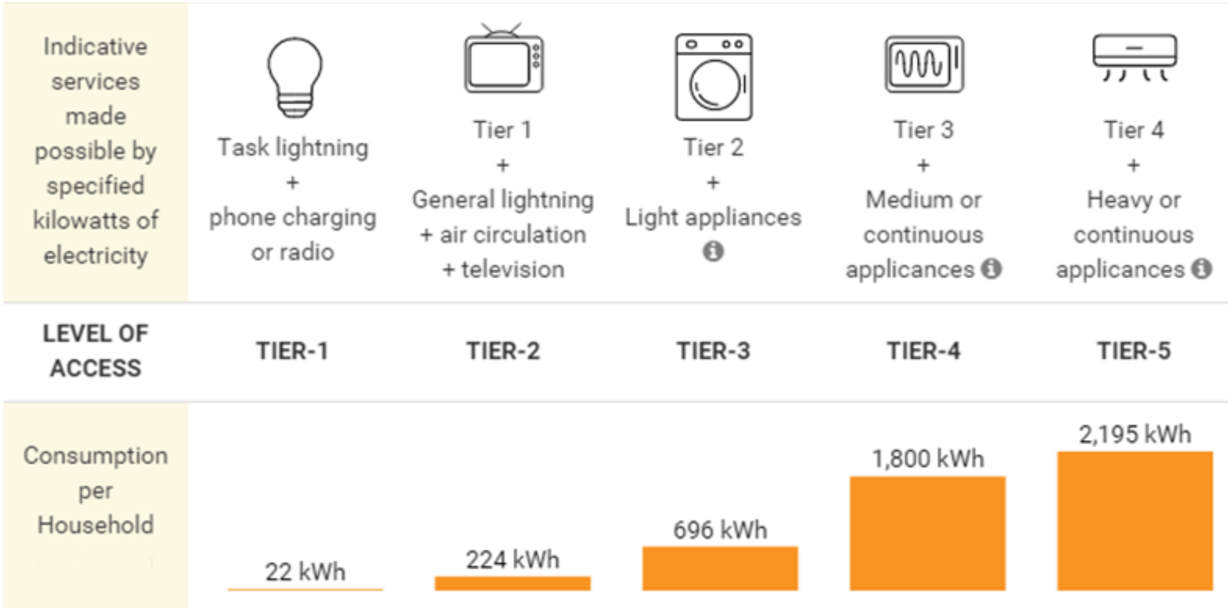
Once populations with and without electricity have been spatially identified, we need to incorporate expected population growth rates per region to estimate the total population in 2030 (presented in figure 7). This is one of the two parameters we need to know in order to quantify and locate future demand for electricity.

FIGURE 7. PROJECTED POPULATION AND TRANSMISSION NETWORK IN THE AFRICAN CONTINENT, 2030



The second parameter is electricity consumption; the modelling adopts the consumption levels defined by the Global Tracking Framework (2015). Five electricity consumption levels are defined, as indicated in figure 8. The lowest consumption level is 22 kWh/hh/year, enough for single tasks such as charging a phone or powering a radio. At the other extreme, the highest consumption is 2,195 kWh/hh/year, allowing for enough electricity to run several heavy or continuous appliances such as refrigerators, washing machines, ovens, etc. The five indicative consumption levels are identified as consumption tiers.

FIGURE 8. ELECTRICITY CONSUMPTION TIERS FOR ACCESS ANALYSIS



The combination of population growth and desired electrification consumption levels yields estimates of future electricity demand per location. These estimates assume uniform consumption of energy for all households, which is obviously a simplifying assumption. In reality, electricity consumption levels vary across income levels and across geographical locations. National planning exercises can relax this assumption or combine different scenarios to identify which technology option should be chosen for a given location under different consumption levels.

QUESTIONS

- What data are needed to identify future spatial electricity demand?
- Why does the modelling exercise need to define different levels of electricity consumption?
- How can the definition of levels of electricity consumption be made more useful for national planning?

OPTIONS FOR THE PROVISION OF ACCESS TO ELECTRICITY

Over decades, access to electricity has been established by connecting households and businesses to the national central electrical grid. Technological innovation in renewable energy sources and concerns about social inclusion, however, have encouraged use of a handful of technologies to generate electricity in a decentralized manner through mini-grids or standalone alternatives.

GRID EXTENSION

Electricity is usually generated from big power plants connected by a national grid. Due to economies of scale, central grids can offer low generating costs, from 0.03 to 0.15 US$/kWh, depending on the type of plant and the source of energy. Hydro plants are among the lowest-cost options. Electricity then reaches households through the transmission and distribution network at relatively low costs.

This is the way access to electricity has been established over decades. Expansion of electrical grid infrastructure is a capital-intensive, time-demanding process, requiring the front-loading of large investments and long-term planning. Such investments need a reasonable investment recovery time horizon, which in turn requires a population with high purchasing power and sophisticated consumption patterns, and/or a solid social return, depending on the funding source.

Central grids can offer low generating costs. Grid extension might not be economically feasible, however, if the purpose is to meet relatively small electricity demand.

It might not be economically feasible to extend the central grid if the population to be served will only demand and/or can only afford a relatively small quantity of electricity. If the target population is far from existing transmission lines, it might not be advisable to connect to the grid if demand is not large enough. In these and similar cases, grid extension might not be the lowest-cost electrification option. This is typically the situation for low-income, low-consumption population groups in rural areas, particularly remote areas.

MINI-GRIDS

Mini-grids are an important decentralized alternative to grid extension. Mini-grids usually provide electricity from small power plants with a generating capacity of a few MWs.

Mini-grids can provide affordable electricity to rural and remote areas with low to medium electricity consumption levels

Mini-grids tap locally available energy resources such as solar, hydro or wind, or can use commonly available fuels such as diesel. Mini-grids require simple transmission infrastructure and carry modest distribution costs; they are an affordable alternative to providing electricity to rural and remote areas with low to medium electricity consumption levels.

Mini-grids based on renewable sources usually have moderate to high upfront investment costs, but small operational costs and no fuel costs. On the other hand, diesel generator sets (gensets) are a mature technology with a low upfront investment cost, but are subject to operational costs depending on fluctuations in the price of diesel and transport costs.

STANDALONE SYSTEMS

Standalone systems are a good electrification option for remote, low-population areas with limited electricity consumption levels.

The third option available for electrification involves standalone systems. As mini-grids, these systems are usually based on local energy resources, but the difference is that they can produce only a few kWhs per day, suitable to cover the electricity demand of a single household or a small business, but no more.

Standalone systems do not require a transmission and distribution network nor construction investments. The capital cost of these systems is not high and depends mainly on size. Batteries, allowing for electricity when dark, may increase the upfront cost for PV systems. On the other hand, storing diesel to run gensets is not particularly expensive, but, again, the cost of this technology is subject to operational costs depending on fluctuations in the price of diesel and transport costs.

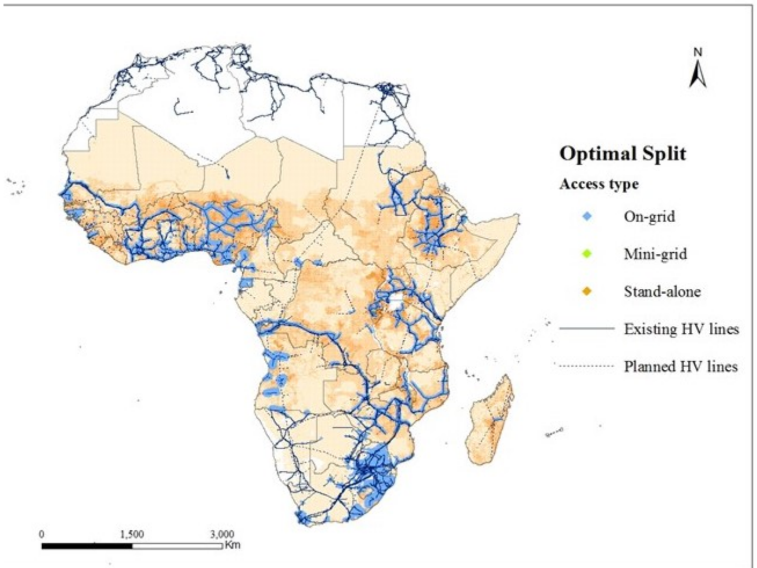
EXAMPLE: AN ELECTRIFICATION ANALYSIS FOR THE AFRICAN CONTINENT

An electrification analysis using GIS has been performed for the African continent. The objective is to reach full access to electricity in 44 countries. Seven electrification technologies were considered, arranged into three main electrification options or categories, as follows:

- Grid: higher electricity consumption levels and close to the planned transmission network
- Mini-grid: such as with wind turbines, solar PVs, mini/small hydro and diesel gensets, which can provide affordable electricity to remote populations with low to medium electricity consumption
- Standalone: such as solar PVs and diesel gensets for remote, low-population areas with limited electricity consumption

Five demand tiers were considered, as described in figure 8. The electrification results for a level of consumption equivalent to 22 kWh/HH/year, Tier 1, indicate that standalone technologies often represent the lowest-cost option (figure 9).

FIGURE 9. ELECTRIFICATION RESULTS: 22 KWh/hh/year, LIGHTING



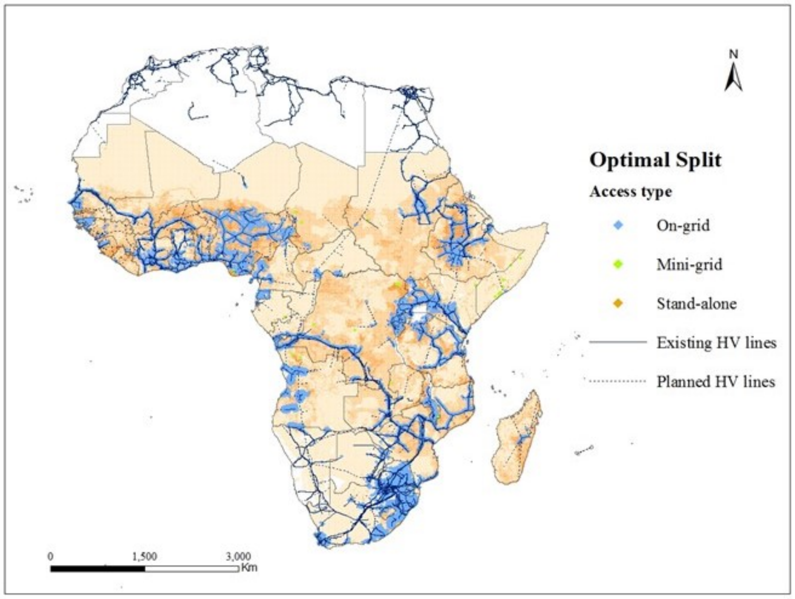
Technology split

Grid extension:	**16%**
Mini-grid:	**0%**
PV	
Diesel	
Wind	
Hydro	
Stand-alone:	**84%**
PV	50%
Diesel	50%

The diesel price was set at 0.82 $/litre following the projections suggested by the New Policy Scenario (International Energy Agency) for 2030. As shown, 16 per cent of electrification is accomplished by grid-based electricity for settlements located close to previously electrified villages and transmission lines, and 84 per cent by standalone systems elsewhere. Mini-grids play a minor role.

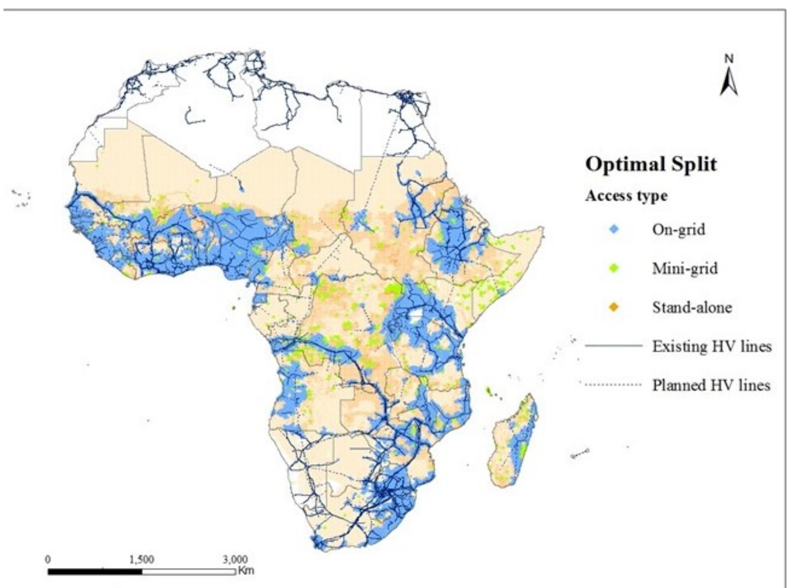
If the electricity consumption level increases to 224 kWh/hh/year, Tier 2, allowing for lighting, perhaps a fan and a TV, the standalone systems are still the predominant electrification solution with PV systems gaining a slightly higher share over diesel gensets (figure 10). Grid-based electricity is increased from 16 per cent to 33 per cent, but is still a least-cost option for settlements located close to previously electrified villages and transmission lines. Mini-grids play a minor role, with small hydro and wind power plans playing the biggest role.

FIGURE 10. ELECTRIFICATION RESULTS: 224 KWh/hh/year, LIGHTING, FAN TV



Technology split	
Grid extension:	**33%**
Mini-grid:	**1%**
PV	0%
Diesel	4%
Wind	45%
Hydro	52%
Stand-alone:	**66%**
PV	54%
Diesel	46%

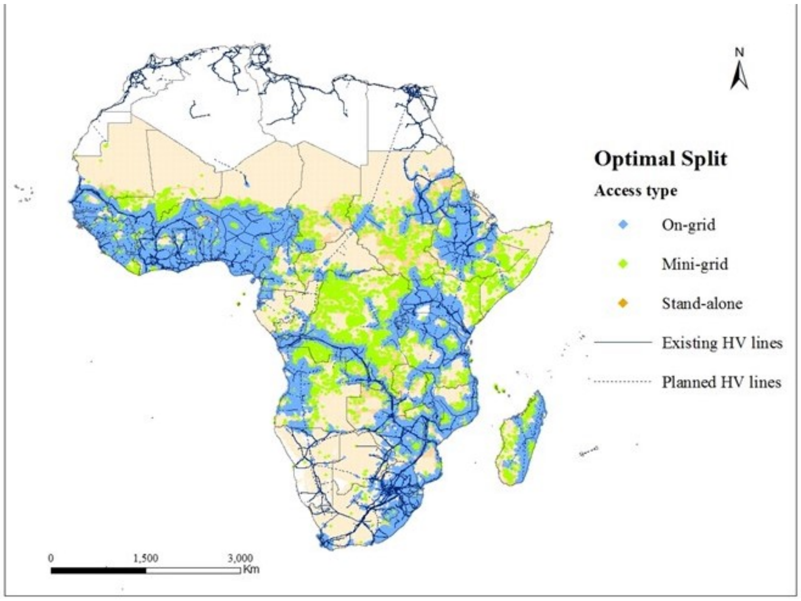
FIGURE 11. ELECTRIFICATION RESULTS: 696 KWh/hh/year, LIGHT APPLIANCES



Technology split	
Grid extension:	**67%**
Mini-grid:	**3%**
PV	43%
Diesel	16%
Wind	17%
Hydro	25%
Stand-alone:	**30%**
PV	62%
Diesel	38%

Results considering an expansion of the electricity consumption to 696 kWh/hh/year to allow for the use of light appliances, Tier 3, show that grid extension is the most economic electrification option for 67 per cent of the population needing electricity by 2030. Figure 11 shows that standalone systems still play an important role especially in sparsely populated remote areas. As electricity consumption increases, however, mini-grid solutions start playing a larger role, including in remote areas.

FIGURE 12. ELECTRIFICATION: 1,800 KWh/hh/year, MEDIUM APPLIANCES



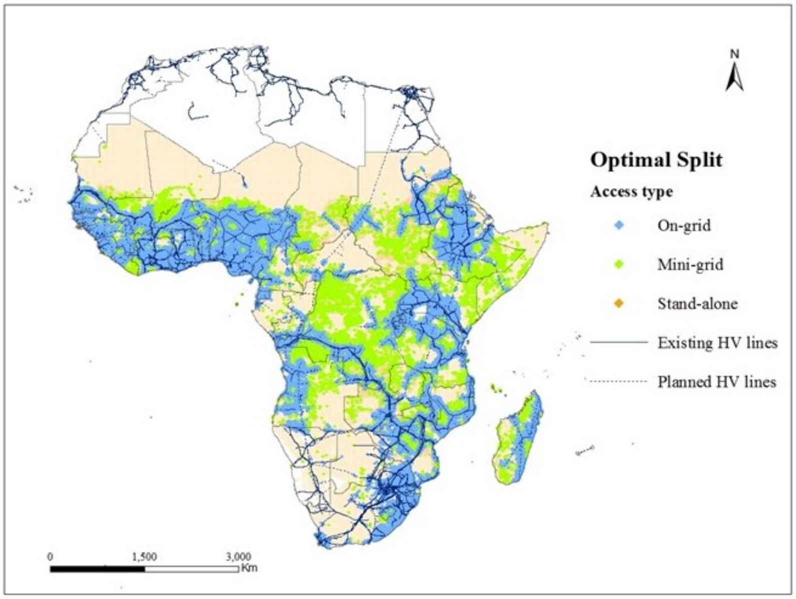
Technology split

Grid extension:	**77%**
Mini-grid:	**8%**
PV	50%
Diesel	26%
Wind	11%
Hydro	14%
Stand-alone:	**15%**
PV	66%
Diesel	34%

As illustrated in figure 12, pondering an electricity consumption level of 1,800 kWh/hh/year, Tier 4, the results favour grid extension, which in this scenario accounts for 78 per cent of new access to electricity, and mini-grids (predominantly PV systems and diesel gensets).

Finally, for the most demanding electrification alternative, providing 2,195 kWh/hh/year, Tier 5, the importance of grid extension increases slightly in comparison with the previous scenario; it accounts for the biggest portion of new access. In this case, mini-grid technologies will still be the least-cost option for 10 per cent of the population needing electricity by 2030. Standalone systems will provide electricity to the remaining 12 per cent of the population needing access.

FIGURE 13. ELECTRIFICATION: 2,195 KWh/hh/year, HEAVY APPLIANCES



Technology split

Grid extension:	**78%**
Mini-grid:	**10%**
PV	52%
Diesel	27%
Wind	11%
Hydro	10%
Stand-alone:	**12%**
PV	65%
Diesel	35%

Summarizing:

- Grid extension is the least-cost solution in densely populated areas close to the grid network.
- Diesel prices influence the electrification mix. Lower prices favour diesel gensets, while higher prices will prompt higher penetration of mainly PV systems.
- Other renewables (wind, hydro) penetrate in areas where these resources are available and have development potential.
- Higher electricity demand levels move the favourable electrification option from standalone to mini-grids and finally to central grids.
- The share of renewable energy sources in total electricity generation almost doubles from 34 per cent in 2012 to 66 per cent in 2030 (this includes the electricity generated by the national power network and is a result of a cost minimization analysis).

The analysis presented in this example has some limitations that can be overcome.

The levelized cost measure allows analysis of the lowest cost possible, by comparing, for example, a high investment and low operating cost scenario with a low investment and high operating cost scenario over the lifetime of the technology.

- The electrification mix is shown only for 2030. Thus, the electrification mix and status in the meantime (between today and 2030) is not considered. To include the whole period, it will be necessary to decide which areas need to be electrified first.
- A detailed breakdown of the generation mix of each country, which would provide different grid electrification costs, is not considered in detail. To do so, it will be necessary to link GIS data with OSeMOSYS (the Open-Source Energy Modelling System) to obtain the optimal generation mix based on the country's resources, demand for electricity and trade with other countries.
- Another critical issue is the various resolution of different datasets. To illustrate, population density data are given at 1 square kilometre while the wind speed is provided for areas of 50 square kilometres. This means that we need to harmonize datasets, which sometimes leads to misleading representation of information.
- The analysis considers only household electrification. Other productive uses of electricity (such as health, education, rural enterprises, agriculture, etc.) should also be considered. These would increase demand levels and will therefore change the electrification mix.
- Lastly, it is important to keep in mind that this analysis assumes five homogeneous consumption tiers across all 10x10 kilometre locations in Africa. Significant income differences across the continent, however, would imply different electricity demand levels. This issue shall be approached using statistical correlations, existing in the literature, that relate nighttime light with income and electricity consumption levels.

QUESTIONS

- How does the mix of off-grid electrification technologies vary as electricity consumption levels increase when achieving universal access to electricity in Africa (compare, for example, Tier 2 and Tier 4 electricity consumption levels)?

List three limitations of the electrification planning exercise for Africa and provide possible ways to approach them.

DECIDING WHICH ELECTRIFICATION OPTION BEARS THE LOWEST COST

Levelized cost is the net present value of the unit cost of electricity.

Covering future electricity demand requires consideration of investments needed to increase generation capacity as well as the operational costs. Deciding which of the available technologies is the most economical depends on looking at these two factors. A given technology with high initial investment costs might have low operating costs, and, vice-versa, a technology requiring low initial investment might have high operating costs. One needs to look at both and find a way to compare, for example, a high investment and low operating cost option versus a low investment and high operating cost one. To make such assessments and come up with a single number to compare alternative technologies, engineers use the levelized cost measure.

The levelized cost is the net present value of the unit cost of electricity, a comprehensive measure that considers:

- Investments needed to provide access to electricity. To illustrate, the levelized cost accounts for the investment needed to connect to or extend the existing grid, and the upfront investments needed to build a mini-grid or acquire rooftop solar panels or small diesel generator sets. In all cases, the levelized cost considers the cost of funding investment as well as the useful life of the acquired technology (see figure 14).
- Fixed and variable operating and maintenance costs as well as the cost of fuel, where applicable, e.g., the cost of diesel used by generators for mini-grids or household sets. In the case of grid connections, the levelized cost is calculated by adding

the average cost of generating electricity from the national grid to the marginal cost of transmitting and distributing this electricity to the demand location.

In addition, the levelized cost also includes the capacity factor, a number that gives a ratio between the effective capacity of the technology in the site of installation and the nameplate capacity specified by the manufacturer. (See the online levelized cost calculator of the National Renewable Energy Laboratory of the United States Department of Energy at www.nrel.gov/analysis/tech_lcoe.html.)

FIGURE 14. THE NATIONAL RENEWABLE ENERGY LABORATORY LEVELIZED COST CALCULATOR

To estimate simple cost of energy, use the slider controls or enter values directly to adjust the values. The calculator will return the LCOE expressed in cents per kilowatt-hour (kWh).

The U.S. Department of Energy (DOE) Federal Energy Management Program (FEMP) sponsored the distributed generation data used within this calculator.

If you are seeking utility-scale technology cost and performance estimates, please visit the Transparent Cost Database website for NREL's information regarding vehicles, biofuels, and electricity generation.

Capital Cost (February 2016 Update)	Operations & Maintenance (February 2016 Update)	Utility-Scale Capacity Factors	Useful Life	Land Use by System Technology	LCOE Calculator

Simple Levelized Cost of Energy Calculator

Financial

Periods (Years): 20 ?

Discount Rate (%): 3.0 ?

Renewable Energy System Cost and Performance

Capital Cost ($/kW): 1050 ?

Capacity Factor (%): 43.6 ?

Fixed O&M Cost ($/kW-yr): 25 ?

Variable O&M Cost ($/kWh): 0.002 ?

Heat Rate (Btu/kWh): 10000 ?

Fuel Cost ($/MMBtu): 8 ?

Today's Utility Electricity Cost

Electricity Price (cents/kWh): 12 ?

Cost Escalation Rate (%): 3.0 ?

Results

Levelized Cost of Utility Electricity (cents/kWh): ?

QUESTIONS

- What costs are considered in the levelized cost of generating electricity?
- Besides various cost components, what else is accounted for when estimating the levelized cost of generating electricity?

4. ONSSET – OPEN SOURCE SPATIAL ELECTRIFICATION TOOL

KTH Division of Energy Systems Analysis in collaboration with the United Nations Department of Economic and Social Affairs and other partners has developed a Transferable Electrification Tool, ONSSET, which stands for Open-Source Spatial Electrification Tool.

ONSSET uses the levelized cost of generating electricity to identify which technology provides access to electricity at the lowest cost.

The ONSSET tool uses the levelized cost of electricity calculated for each of the geospatial units. It identifies which technology provides access to electricity at the lowest cost. Geospatial units close to an existing electricity grid will likely find that this is the lowest-cost option, since distance to the grid is a very important variable determining the cost of connection. This is likely to be the case especially at high levels of demand per household. This rule of thumb might not apply, however, in countries where electricity fares are high. Here ONSSET might find that the lowest-cost option is something other than connecting to the grid. If the assumed electricity demand of households is low, other standalone options might be found to be lowest cost: a rooftop PV panel in locations where solar radiation is strong and diesels prices are high; or diesel generator sets where solar radiation is not strong and diesel prices are low. ONSSET does all these calculations and finds the lowest-cost option using data relevant to the location of the settlement for all the scenarios considered in the exercise, as defined by the user. Results are graphically represented on maps and in tabular form.

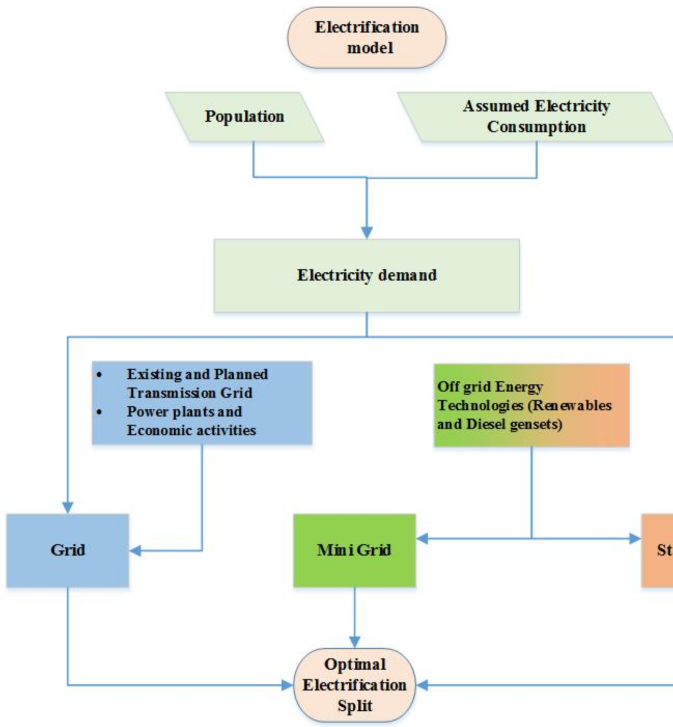
Like any other quantitative energy modelling, the first step in setting up an ONSSET model is data acquisition.

GIS data collection occurs layer by layer. One layer includes the definition of administrative boundaries; a second layer refers to the geospatial coordinates of population settlements; and a third layer is represented by the number of people in the settlement. Other sources of information include, among others: the distance of settlements to the grid, to power plants and to a transmission network; the status of transportation infrastructure; the values for solar irradiation and wind speed; and the potential for mini-hydro systems. The final map then is overlaid with a layer containing the grid structure. The size of grids depends on the total area to be analysed and the desired resolution. Typical grid cells are 1 kilometre by 1 kilometre to 10 kilometres by 10 kilometres. The training course will address the data acquisition challenges, demonstrate representative data preparation steps and point to readily available open source GIS layers.

ONSSET, as with any other quantitative energy modelling, requires data that should be adequately adjusted and updated.

GIS data are not always up-to-date, or do not always contain the data in the required form. Some data adjustment and updating may be necessary. For example, population data statistics and the spatial population density and distribution layer usually originate from different sources and thus need harmonization. Population statistics do not include the level of detail down to settlements. In short, the sum of inhabitants per settlement over all settlements must add to the aggregate population distribution of the country.

FIGURE 15. PRINCIPAL COMPONENTS AND STRUCTURE OF ONSSET



Demographic data (population estimates) are crucial for modelling future demand for electrification.

Estimating future population and its purchasing power is central to any electrification analysis. The number of people and their income are key drivers of future electricity demand. Estimating future population growth is not straightforward, however. Changes over time in the socioeconomic conditions of people in particular locations make the estimation of future fertility and mortality rates as well as people's migratory practices a complex task. Ideally, one would want to have an estimate of the future population by geospatial location, but anything approaching this is very useful. Even a binary population estimate by rural and urban areas helps. The modelling of the dynamics of electrification over time benefits from population estimates with as much detail as possible.

In the model, future electricity demand is a function of the projected population growth per geospatial unit and the amount of electricity consumption selected for the construction of each scenario. Modelling uses five benchmarks of electricity consumption, starting from very low consumption to the high consumption standard of a household with many amenities. The lowest assumed consumption only allows for task lighting and charging a cell or radio battery while the highest consumption allows enjoying comfort services such as continuous lightning, running a refrigerator, air conditioning, and many others. In this exercise, the model is built assuming everybody will have access to electricity between now and 2030 at the same level of consumption assumed by the various benchmarks or tiers as defined by the Sustainable Energy for All Global Tracking Framework (see table 1).

TABLE 1. INDICATIVE SERVICES THAT MIGHT BE ACCESIBLE TO HOUSEHOLDS BY ELECTRICITY ANNUAL CONSUMPTION TIER

Access tier	Tier 1	Tier 2	Tier 3	Tier 4	Tier 5
Indicative appliances powered	Task lighting + phone charging or radio	General lighting + fan + television	Tier 2 + medium power appliances (i.e., general food processing, refrigeration)	Tier 3 + medium or continuous appliances (i.e., water heating, ironing, water pumping, rice cooking, microwave)	Tier 4 + high power and continuous appliances (i.e., air conditioning)
Consumption per household and year (kWh)	22	224	695	1,800	2,195

Source: Adapted from the Global Tracking Framework, 2015. Available at [www.se4all.org/tracking-progress/sites/default/files/l/2013/09/GTF-2105-Full-Report.pdf.](www.se4all.org/tracking-progress/sites/default/files/l/2013/09/GTF-2105-Full-Report.pdf)

QUESTIONS

- What is the objective of ONSSET?
- What is the indicator used by ONSSET to select the lowest-cost electrification technology?

- How is future electricity consumption considered in ONSSET?
- Why is it important to harmonize GIS data and national statistics?

5. RESULTS FROM THE ONSSET ELECTRIFICATION TOOL

ONSSET results clearly show that the assumed level of electricity demand per household in each of the GIS cells is the main factor determining which technology offers the lowest cost. At the lowest consumption level – 22 kWh – most population settlements close to previously electrified villages and transmission lines will find connecting to the central electricity grid is the lowest-cost option (see figures 16 to 19). Elsewhere, however, most settlements will find standalone systems are the most economical option (with PV panels dominating when diesel prices are high). At this low level of consumption, mini-grids only play a minor role.

When assuming a midrange electricity consumption per household, 695 kWh, grid connection becomes a viable proposition (instead of standalone technologies). Assuming high consumption levels, 2,195 kWh, further expands the presence of connection to the central grid, but interestingly, high consumption levels imply that mini-grids become an economically attractive option and replace standalone technologies in many settlements. High diesel prices[4] boost grid-based electricity and mini-grids (see figure 19).

FIGURE 16. LEAST-COST ELECTRIFICATION STRUCTURE (TIER 1 AND LOW DIESEL PRICES

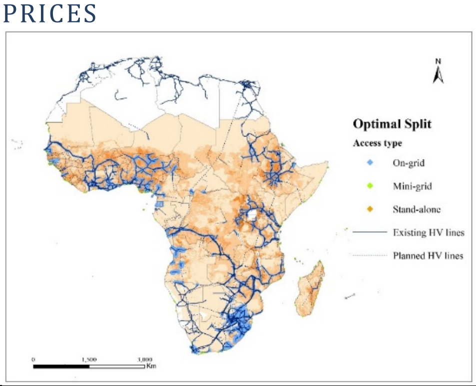
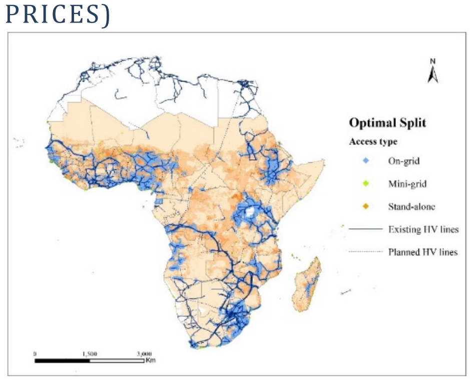


FIGURE 17. LEAST-COST ELECTRIFICATION STRUCTURE (TIER 3 AND LOW DIESEL PRICES)



[4] Diesel prices vary from location to location depending on transportation distances, truck travel times, taxes, etc. In this examples, low diesel prices are based on refinery acquisition costs of about $45 per barrel of crude oil; high diesel prices are based on a cost of almost $100 per barrel.

FIGURE 18. LEAST-COST ELECTRIFICATION STRUCTURE (TIER 5 AND LOW DIESEL PRICES

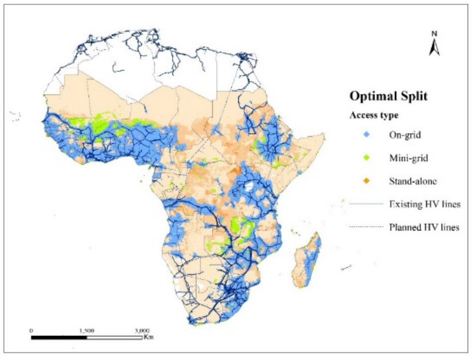
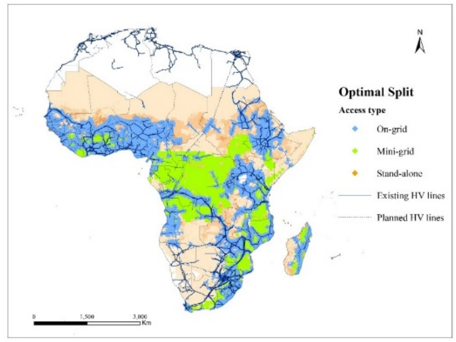


FIGURE 19. LEAST-COST ELECTRIFICATION STRUCTURE (TIER 5 AND HIGH DIESEL PRICES



Standalone technologies are the lowest-cost solution to achieve universal access to electricity by 2030 for most of the 10 by 10 kilometre locations in the 44 African countries considered, when a low electricity consumption level (22 kWh or 223 kWh) is assumed (see tables 2A and 2B). Connecting or extending the existing central grid is the predominant lowest-cost technology when modelling assumes a relatively high level of electricity consumption per household (1,800 kWh or 2,195 kWh). The model finds that between 67 per cent and 84 per cent of the population might access electricity via off-grid technologies. When the assumed electricity consumption is relatively high, however, off-grid technologies might account for between 22 per cent and 30 per cent of the people gaining access to electricity.

Shifting between low and high diesel prices not only has the expected result of reducing the importance of diesel generators for mini-grids or standalone systems, but also increases the overall contribution of mini-grids to universal access to electricity.

TABLE 2A. ELECTRIFICATION IN SUB-SAHARAN AFRICA BY 2030: NUMBER OF PEOPLE WHO WOULD GAIN ACCESS TO ELECTRICITY BY TECHNOLOGY AND TIER (LOW DIESEL PRICES)

Consumption per household	Mini-grids				Standalone		Grid-based
	Gensets	PV	Wind	Mini-hydro	Gensets	PV	
22	-	-	-	-	887,274,744	54,033,249	173,370,633
224	1,208,096	-	-	477,027	886,350,261	53,272,608	173,370,633
695	29,473,716	-	666,667	5,834,631	541,849,284	30,943,613	505,910,715
1,800	71,204,104	-	4,095,286	7,635,960	237,856,992	10,007,327	783,878,957
2,195	59,679,051	-	7,074,707	7,131,456	217,954,164	10,364,514	812,474,733

TABLE 2B. ELECTRIFICATION IN SUB-SAHARA BY 2030: PERCENTAGE OF POPULATION WHO WOULD GAIN ACCESS TO ELECTRICITY BY TECHNOLOGY AND TIER (LOW DIESEL PRICES)

Consumption per household	Mini-grids				Standalone		Grid-based
	Gen-sets	PV	Wind	Mini hydro	Gen-sets	PV	
22	-	-	-	-	79.6%	4.8%	15.6%
224	0.1%	-	-	0.0%	79.5%	4.8%	15.6%
695	2.6%	-	0.1%	0.5%	48.6%	2.8%	45.4%
1,800	6.4%	-	0.4%	0.7%	21.3%	0.9%	70.3%
2,195	5.4%	-	0.6%	0.6%	19.6%	0.9%	72.9%

In 2012, some 325 million people out of a total sub-Saharan African population of 922 million had access to electricity. By 2030, the sub-Saharan African population is expected to grow to 1,448 million. Achieving universal access to electricity, as part of SDG 7, means that some 1.114 billion people would have to be provided with electricity between now and 2030. This is as daunting task. The number of people with access to electricity in the world increased by 1.7 billion between 1990 and 2010, however (United Nations Development Programme, 2016), without a globally identified target on universal electrification. Indeed, some global energy models estimate that almost universal access to electricity will be achieved in all regions of the word by 2030, except in sub-Saharan Africa. This result would be produced by simple continuation of GDP growth at historical rates (Global Energy Assessment, 2012).

The share of renewables in total sub-Saharan electricity generation is unlikely to contribute to the global renewable energy goal of SDG 7, especially under a regime of low diesel prices. A large penetration of higher tier households quickly erodes the competitive edge of electrification based on mini-grids and standalone systems (both PV and diesel-fuelled gensets) in favour of grid-based electricity. But Tier 5 for all is not a realistic target by 2030. Tiers 1 to 3 are more likely as electrification at these levels is more consistent with expected rural income levels (and more feasible to finance). In fact, here is a classical trade-off situation for rural electrification.

TABLE 3A. ELECTRIFICATION IN SUB-SAHARAN AFRICA BY 2030: NUMBER OF PEOPLE WHO WOULD GAIN ACCESS TO ELECTRICITY BY TECHNOLOGY AND TIER (HIGH DIESEL PRICES)

Consumption per household	Mini-grids				Standalone		Grid-based
	Gensets	PV	Wind	Mini-hydro	Gensets	PV	
22	-	-	-	-	469,744,381	471,563,612	173,370,633
224	281,679	-	3,417,742	3,977,705	339,309,329	404,547,484	363,144,687
695	5,775,899	15,415,490	6,031,430	8,964,789	127,754,296	207,021,815	743,714,906
1,800	22,053,202	42,135,239	9,032,829	11,763,165	55,143,529	107,639,707	866,910,954
2,195	28,460,670	55,345,043	11,303,873	10,558,048	47,710,052	88,670,840	872,630,099

TABLE 3B. ELECTRIFICATION IN SUB-SAHARAN AFRICA BY 2030: PERCENTAGE OF POPULATION WHO WOULD GAIN ACCESS TO ELECTRICITY BY TECHNOLOGY AND TIER (HIGH DIESEL PRICES)

Household consumption kWh	Mini-grids				Standalone		Grid-based
	Gensets	PV	Wind	Mini-hydro	Gensets	PV	
22	-	-	-	-	42.1%	42.3%	15.6%
224	0.0%	-	0.3%	0.4%	30.4%	36.3%	32.6%
695	0.5%	1.4%	0.5%	0.8%	11.5%	18.6%	66.7%
1,800	2.0%	3.8%	0.8%	1.1%	4.9%	9.7%	77.8%
2,195	2.6%	5.0%	1.0%	0.9%	4.3%	8.0%	78.3%

What is the cost of ensuring everybody has access to electricity access by 2030? The total investment required ranges between $70 billion and $1.6 trillion over the entire 15-plus year period and the 44 countries considered. Included in these figures are the upfront capital investments for extending the transmission and distribution grid lines, building the mini-grid systems, and installing standalone solar and diesel technologies. Figures are lower with lower household electricity consumption and diesel prices. The lowest investment ticket of providing universal access corresponds to the case when consumption is assumed to be lowest, 22 kWh, and the diesel price is low; and the highest ticket corresponds to the highest household consumption of 2,195 kWh at the high price for diesel.

The model allows for identification of the role of renewable sources of energy in off-grid technologies. The role of renewables critically depends on the price of diesel. Under conditions of low diesel prices, renewable sources will be used to provide electricity to an average of 6 per cent of the population. Doubling the price of diesel multiplies by 10 the average contribution of renewable sources, as they rise to cover 60 per cent of the population. Interestingly, the proportion of people obtaining access to electricity from renewable sources of energy tends to increase as household electricity consumption is assumed to increase.

QUESTIONS

- Provide two important factors considered in ONSSET for determining the choice of technology. Why are these factors essential for electricity planning?

- What is the role of renewable energy sources in off-grid electrification? How does an increased price for diesel affect the optimal electrification technology?
- Explain the reason why increasing electricity demand (Tier 1 → Tier 5) gradually moves the least-cost option from standalone to mini-grid and then to central grid.

CLOSING REMARKS

ONSSET provides useful insights to assess electrification for population settlements in well-identified locations, and to aggregate results at the subregional, national or regional levels.

The prime focus is on the full electrification of households in fulfilment of SDG 7 as well as other electrification demands that will be addressed in due course. In its current state, ONSSET can already provide invaluable support to policy and decision makers on least-cost electrification strategies. Most importantly, the tool specifically addresses the needs of the energy poor and offers feasible solutions.

Its open source feature allows interested energy experts from African countries (and elsewhere) to refine the model's resolution or explore additional scenarios. Most importantly, the analysis can be carried out at national and subnational levels, including the full presentation of a country's centralized and grid-delivered electricity system. ONSSET in combination with the OSeMOSYS approach offers an extremely powerful analytical and planning tool.

Finally, a word of caution: Numerically, the model accomplishes the SDG 7 electrification target for sub-Saharan Africa by 2030. It provides insights on the least-cost mix and aggregate investment requirements, and highlights the challenges before policy and decision makers charged with implementation of SDG 7. It allows the analysis of trade-offs between competing demands on financial resources and thus prudent prioritization of available resources. Additional management tools will be needed for implementation of identified strategies and for detailed estimation of finance requirements.

Like most models, ONSSET is a work in progress, especially as new satellite data and GIS information become available.

Note: While this document refers to aggregate results for sub-Saharan Africa, analysis can be carried out for each country individually.

REFERENCES

International Energy Agency (2015). *World Energy Outlook 2015.* Paris.

Pachauri, S., N. D. Rao, Y. Nagai and K. Riahi, 2012. "Access to Modern Energy: Assessment and Outlook for Developing and Emerging Regions." Luxemburg, Austria: International Institute for Applied Systems Analysis.

UN-Energy (2014). *Electricity and education: The benefits, barriers, and recommendations for achieving the electrification of primary and secondary schools.*

United Nations Development Programme (2016). "Goal 7: Affordable and clean energy." Available at www.undp.org/content/undp/en/home/sdgoverview/post-2015-development-agenda/goal-7.html.

United Nations Industrial Development Organization (2011). *Access to Modern Energy: Assessment and Outlook for Developing and Emerging Regions.*

World Bank (2015). *Beyond Connections: Energy Access Redefined.* Washington, DC: Energy Sector Management Assistance Program.

——— (2016). World Development Indicators: Electricity production, sources, and access. Available at http://wdi.worldbank.org/table/3.7 and http://data.worldbank.org/indicator/EG.ELC.ACCS.ZS.