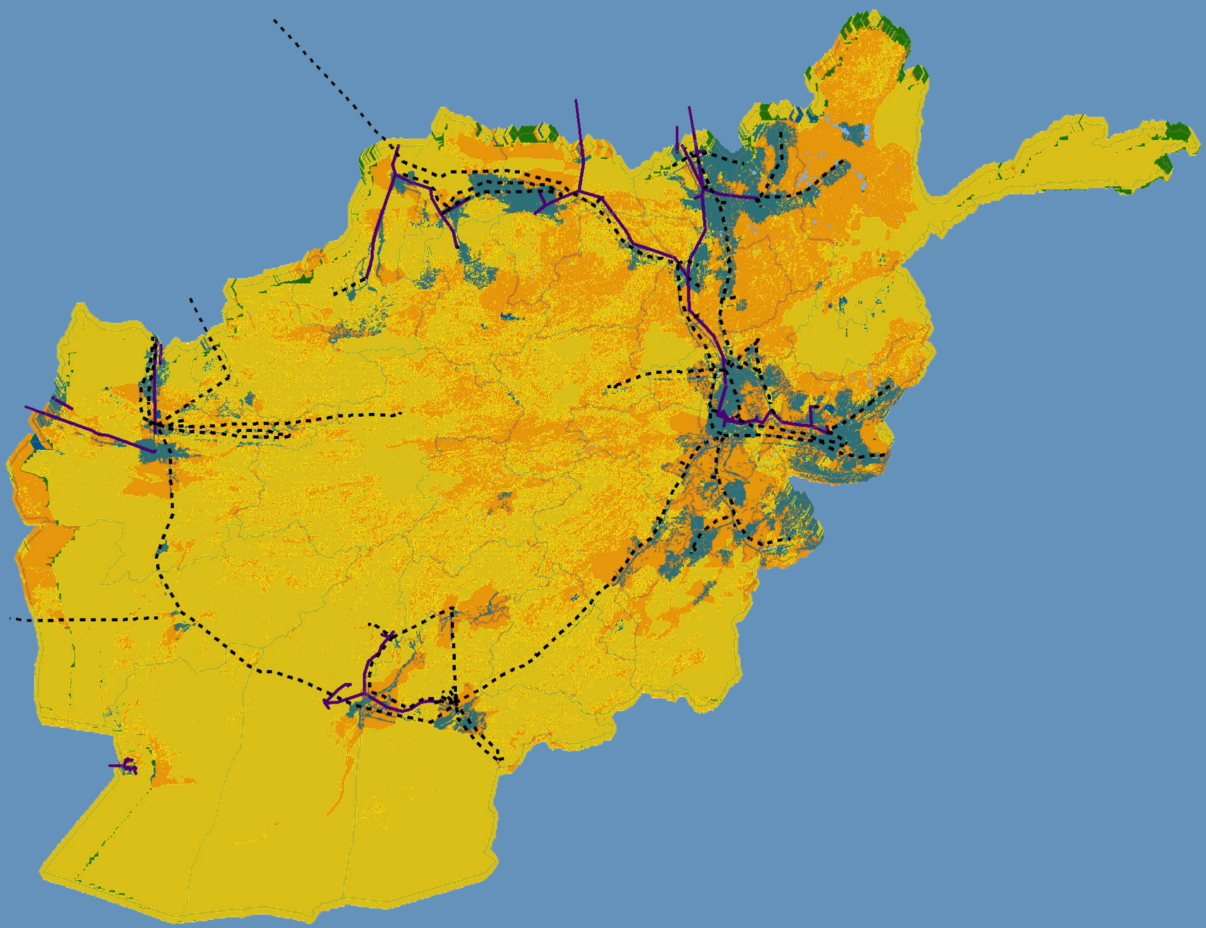
AFGHANISTAN ENERGY STUDY



A GIS APPROACH TO PLANNING ELECTRIFICATION IN AFGHANISTAN

Alexandros Korkovelos, Morgan Bazilian, Dimitrios Mentis, and Mark Howells

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Cover map: KTH dESA.

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Foreword

Access to affordable and reliable electricity is essential to the success of any economic growth strategy. Yet the percentage of the population with access to grid electricity in Afghanistan is among the lowest in the world. Annual per capita consumption averages 186 kilowatt-hours (kWh), far below the global average of 3,126 kWh. In rural areas, where three-quarters of Afghans live, only 11 percent are connected to the grid.

Using an original tool and a new database of geospatial data, this study offers an initial analysis of the technological options and investment requirements needed to expand electricity access across Afghanistan. As part of a larger effort—the Afghanistan Energy Study—it will enable the government to "ensure access to affordable, reliable, sustainable and modern energy for all" (Sustainable Development Goal 7).

Afghanistan's diversity in terms of demographic attributes, terrain types, wealth levels, access to infrastructure, resource availability, and other factors complicates the planning of electrification. To plan in a way that will be persuasive to investors, these diverse factors need to be captured quantitatively and with local specificity using a modeling platform that will allow users to view, share, and modify underlying data and assumptions. But acquiring energy-related data at the local level can be a challenging task, particularly in a country like Afghanistan.

Fortunately, new geospatial tools have greatly reduced the costs of mapping resources and compiling geospatial datasets, thereby facilitating the creation of electrification plans with "investment grade" specificity and accuracy.

In 2017, the Division of Energy Systems Analysis of the KTH Royal Institute of Technology in Sweden (KTH dESA), with assistance from the World Bank, moved the electrification-planning process in Afghanistan a big step forward by building a database of geospatial information and helping Afghan planners create a modifiable least-cost electrification model, complete with targets and timetables. This model, known as the Open Source Spatial Electrification Tool (OnSSET), estimates and analyzes the most cost-effective electrification options for the achievement of electricity access goals.

In Afghanistan, a plan that relies solely on grid expansion can be expected to increase the rate of electrification only slowly, particularly if donor financing for large infrastructure investment dwindles. A systematic off-grid plan that is implemented concurrently with the grid-expansion plan can help ensure that affordable, basic electricity services are made available to a wider segment of the population.

I am happy to say that this study has brought such a plan within reach.

H.E. Eng. Ali Ahmad Osmani
Minister of Energy and Water

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Abbreviations

BoS	balance of system
GDP	gross domestic product
GIS	geographic information systems
GW	gigawatt
GWh	gigawatt hour
HH	household
HV	high voltage
km	kilometer
kW	kilowatt
kWh	kilowatt-hour
LCoE	levelized cost of electricity
LV	low voltage
MV	medium voltage
MW	megawatt
OnSSET	Open Source Spatial Electrification Tool
OSeMOSYS	Open Source Energy Modelling System
PV	photovoltaic

Key Terminology

Centralized electricity generation: Refers to the large-scale generation of electricity at centralized facilities, located usually away from end-users and connected to a network of high-voltage transmission lines (US EPA 2017).

Distributed electricity generation: Refers to a variety of technologies that generate and distribute electricity at or near where it will be used. It may serve selected loads in the vicinity or it may be part of a greater system (regional and/or national grid) (US EPA 2017) (Pepermans 2005).

Under this perspective and for the purposes of this report we define the following:

National grid (or grid): A system of centralized and distributed electricity generation facilities that are inter-connected through an extensive transmission network spreading throughout the country.

Mini-grids: Isolated power generation-distribution systems that are used to provide electricity to local communities (power output ranging from kilowatts to multiple megawatts) covering domestic, commercial and/or industrial demand.

Stand-alone systems: Small power systems that are not tied to the national grid, operate autonomously on island mode, and can satisfy on site, low electricity demand for a limited time.

Executive Summary

This study explores the technological options and investment requirements needed to boost electricity access levels in Afghanistan and presents a method for performing a spatial based electrification analysis. As part of the World Bank's wider effort to inform investments focused on increasing Afghans' access to affordable and sustainable energy, the study offers an initial, "quick pass" at selected data to provide a sense of scale and to inform a more detailed analysis to be performed at a later date.

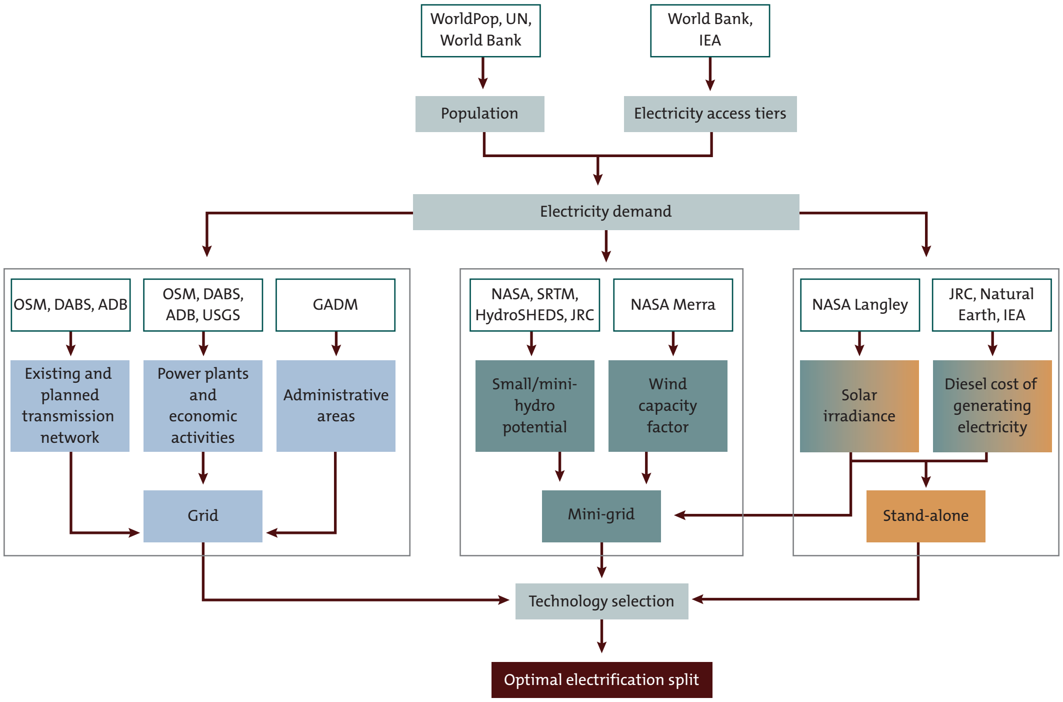
The recent experience of electricity utilities in many developing countries has shown that spatial diversity—of demographic attributes, terrain types, wealth levels, access to infrastructure, and resource availability, among other factors—affects the planning of electrification. These factors need to be captured quantitatively and with local specificity, using a data-modeling platform that allows users to view, share, and modify underlying data and assumptions. The widespread availability of new and openly accessible geospatial information and tools reduces the costs of mapping resources and greatly assists in establishing and maintaining geospatial datasets that enable the rapid creation of electrification plans with quantitative and spatial specificity and accuracy.

Recent global experience shows that the most effective and efficient way of achieving a rapid increase in electrification is through a sector-wide approach in which on- and off-grid electrification is pursued in a complementary manner, while also taking exogenous variables like security issues and climate change into account. Such an approach suggests solutions in line with a national-level, least-cost electrification plan.

In the case of Afghanistan, a plan that relies solely on grid expansion can be expected to increase the rate of electrification only slowly, especially if available donor financing for large infrastructure investment becomes increasingly scarce. A systematic off-grid plan to be implemented concurrent with grid expansion would help ensure that affordable, basic electricity services are made available to a wider segment of the population.

In 2017, the Division of Energy Systems Analysis at the KTH Royal Institute of Technology in Sweden (KTH dESA) took the electrification planning process in Afghanistan one step further by building a database of geospatial information, and helping planners create a modifiable least-cost electrification model. This model, known as the Open Source Spatial Electrification Tool (OnSSET), estimates, analyzes, and visualizes the most cost-effective electrification option for the achievement of electricity access goals. The geodatabase is available at https://energydata.info. Data were gathered from different years (2011–2016).

Figure ES.1. Principal components and structure of OnSSET



Source: KTH dESA.
Note: ADB = Asian Development Bank; DABS = Da Afghanistan Breshna Sherkat; GADM = Global Administrative Areas; HydroSHEDS = Hydrological data and maps based on SHuttle Elevation Derivatives at multiple Scales; IEA = International Energy Agency; JRC = Joint Research Centre; OSM = Open Street Maps; Merra = Modern-era Retrospective Analysis; NASA SRTM = National Aeronautics and Space Administration Shuttle Radar Topography Mission; UN = United Nations; USGS = United States Geological Survey.

The objective of the electrification analysis is to identify the most economic electricity supply mix that will allow full electrification of Afghanistan by 2030. It is unlikely that the employment of only one technology can achieve this goal. Every location (or geospatial unit) in the country has different characteristics, some of which may favor one technology over another. OnSSET considers seven technological options; these are arranged into three main electrification categories: grid, mini-grid, and stand-alone systems. (Stand-alone systems are usually a good option for remote, sparsely populated areas with limited electricity consumption needs.)

OnSSET uses the levelized cost of electricity (LCoE) calculated for each geospatial unit and then finds the lowest-cost option for a particular location under all scenarios considered in the exercise or defined by the modeler. To date 32 scenarios have been developed for Afghanistan, considering variations of diesel price, grid cost[1] and electricity

1. The cost of electricity production (US$/$kWh_{el}$) by the centralized national grid.

consumption level. A few of them are presented in this study as a showcase of OnSSET's capabilities. The results are graphically represented using maps, and are also available in tabular format so as to facilitate further analysis. Figure ES1 schematically represents the model's main methodological processes.

What is the cost of ensuring access to electricity for all Afghans by 2030? The total investment required ranges between $7.82 billion and $26.04 billion over the period 2015–30. The assumed level of electricity demand per household in each settlement, is an important factor determining which technology offers the lowest cost. At the lowest consumption levels, most population settlements close to already-electrified villages and transmission lines will find that connecting to the central electricity grid is the lowest-cost option. Elsewhere, most settlements will find that stand-alone systems are the most economical option (with PV panels a better option than diesel gensets, especially when diesel prices are high). At this low level of consumption, mini-grids play only a minor role.

Assuming a midrange electricity consumption per household, makes grid connection a more viable option (to the detriment of stand-alone options). Assuming high consumption levels furthers the viability of increasing connections to the central grid; but, interestingly, higher consumption levels imply that mini-grids become an economically attractive option and replace stand-alone technologies in many settlements.

* * *

OnSSET's open-source features allow energy experts to refine results resolution and explore additional scenarios. KTH dESA has been developing an online open interface to support the use of OnSSET by professionals without knowledge or experience using geospatial software. The interface allows the user to conduct an electrification analysis of a selected country based on few key input parameters (energy access targets, population characteristics, technology costs). The results can be visualized quickly in an embedded map that shows at a glance the most cost-effective electrification pathways. This interface is accessible at OnSSET.org. OnSSET is a work in progress, especially as new satellite imagery and GIS data become available. The current analysis has limitations, of course; these, along with possible solutions, are described in the report.

1. Background, Context, and Scope

With a gross national income per capita of $580,[1] Afghanistan is the lowest-income country in the South Asia region. Wracked by more than three decades of conflict, it remains an extremely fragile state and faces enormous development challenges, including high levels of poverty (39.1 percent) and unemployment (22.6 percent) (CSO 2016). Despite significant institutional advances and rapid economic growth until 2012, the trend was significantly reversed in 2013, due to declining international spending, worsening conflict and growing overall uncertainty. Following annual GDP growth averaging more than 9 percent between 2003 and 2012, growth dropped to 1.7 percent between 2013 and 2016 (World Bank 2017b).

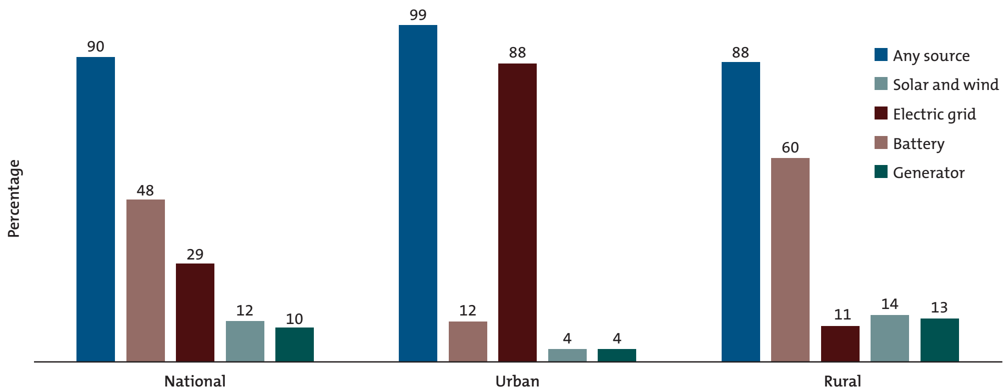
With foreign aid declining and the labor force expanding by about 300,000 a year, Afghanistan urgently needs to find ways to sustainably accelerate broad-based growth in the medium term—implying, among other things, an adequate and stable electricity supply to meet growing demand. But even under reasonably optimistic scenarios, GDP growth in Afghanistan is projected to fall from a 10-year average of more than 9 percent to between 5 and 6 percent over 2011–18. Unemployment is projected to rise further, with potentially destabilizing effects. In this context, Afghanistan is seeking ways to accelerate growth through increased private and public investment, with a particular focus on addressing the country's severe infrastructure bottlenecks.

Access to affordable and reliable electricity is essential to the success of any economic growth strategy. Afghanistan has made impressive progress in improving electricity access. In 2013–14, 90 percent of Afghan households had access to some source of electricity, as compared with only 42 percent in 2007–8 (CSO 2016). This huge gain was mainly driven by improved access to electricity in urban areas, where 99 percent of the population had access to electricity, and, more recently, through the promotion of community-level micro-hydropower and solar systems in rural areas, where the overall electricity access rate reached 88 percent.

Nonetheless, rates of access to the electric grid are somewhat different. Although grid electricity is available to 88 percent of the urban population, it remains a serious challenge in rural areas, where more than 73 percent of Afghans live and only 11 percent are connected to the grid (figure 1.1). Low access to grid electricity is also reflected in consumption levels. At the national level, per capita consumption is estimated at 186 kilowatt-hours (kWh) per year,[2] which is significantly lower than the South Asia average

1. 2016 data (World Bank 2017a).
2. Based on authors' calculations.

Figure 1.1. Percentage of households with access to electricity, by source and residence type



Source: CSO 2016.

of 707 kWh per year and far below the global average of 3,126[3] kWh. Thus, access rates alone do not provide sufficient indication of the quantity and quality of the electricity supplied.

Even households with access to the electricity grid suffered prolonged power outages in the past, but the situation has improved significantly in the major cities and towns along the critical northeast corridor between Mazar-e-Sharif and Kabul, following the import of power from Uzbekistan and the rehabilitation of three hydropower plants (work on Mahipar and Sarobi is complete; Naghlu is in progress). Parts of some cities, for example, Kabul, Herat, Mazar-e-Sharif, and Pul-e-Khumri, now have a 24-hour power supply for the first time in decades.

In light of budget restrictions and overall insecurity, several least-cost electricity plans have been developed over the past few years. These include a 2013 Power Sector Master Plan supported by the Asian Development Bank (ADB 2013), and the recommendations of a World Bank study on uncertainty in Afghanistan's power sector (World Bank forthcoming). The present study will build on the lessons of these previous efforts and add relevant information on sector capacity, with the aim of supporting the sustainable development of Afghanistan's power sector.

On a national level, one significant barrier to Afghanistan's electrification is the lack of a "bankable" investment plan. While a least-cost expansion plan exists, it has not yet been translated into actionable targets and timetables. On a local level, most efforts to improve rural access to electricity were driven by support from the National Solidarity Program launched in 2003. The program promoted local—community based—governance over

3. 2014 data (World Bank 2017c).

infrastructure development (Yemak, Gan, and Cheng 2013). Efforts focused mainly on the provision of electricity access through off-grid solution (e.g. solar power). As a result, 88 percent of the rural population in Afghanistan had access to electricity in 2013–14, amid which 60 percent obtained access through solar power and only 11 percent through the electric grid (figure 1.1).

This study aims to develop a framework that allows for a "quick" electrification analysis and provides, useful insights into the technological options and investment requirements necessary to boost electricity access levels in Afghanistan. It is part of the World Bank's wider effort to provide an updated assessment of the energy sector to the government so as to inform investments focused on increasing access to affordable and sustainable energy. This effort—called the Afghanistan Energy Study—is a five-part series of complementary assessments and surveys being conducted over a period of four years (from June 2015 to June 2019). Its five parts are as follows:

1. Transactional advice and knowledge sharing
2. Financial, economic, and community assessment
3. Collection of household and enterprise energy diaries
4. Development of a least-cost electrification plan and investment prospectus
5. Institutional assessment

This assignment corresponds to the fourth of these five parts. The recent experience of electricity utilities in many developing countries has shown that spatial diversity—of demographic attributes, terrain types, wealth levels, access to infrastructure, and resource availability, to name a few factors—affects the planning of electrification. These factors need to be captured quantitatively and with local specificity, using a data-modeling platform that allows users to view, share, and modify underlying data and assumptions.

The widespread availability of new and low-cost geospatial information and tools greatly reduces the costs of mapping resources and establishing and maintaining geospatial datasets. This allows the rapid creation of electrification plans with quantitative and spatial specificity and accuracy. These relatively low-cost and improved tools also make it easier for otherwise underfunded institutions to establish and maintain datasets on infrastructure, social services (education, health), and other key resources essential for development.

While the quantity and quality of efforts to gather geospatial data have improved in many developing countries around the world, much of these data have been captured in "one-off" events, creating datasets that become quickly out of date as populations grow and infrastructure is built. Going forward, a key challenge is how to provide flexible, updateable systems that will allow local practitioners to correct errors as well as to add and update data incrementally as local conditions change. Maintaining and storing such a database at a national level requires a Web-based energy access platform.

Recent global experience shows that the most effective and efficient way of achieving a rapid increase in electrification is through a sector-wide approach in which both on- and off-grid-based electrification strategies are pursued in a complementary manner, while taking exogenous variables like security issues and climate change into account (World Bank 2017d). Under such an approach, implementation will be channeled toward the deployment of solutions in line with a national-level, least-cost electrification plan, as well as financial and physical resources mobilized in a predictable and structured fashion, while allowing for uncertainty in security conditions. This study offers an initial, "quick pass" analysis of selected data to provide a sense of scale and to inform a more detailed analysis.

In the case of Afghanistan, a plan that relies solely on grid expansion alongside coordinated investments in generation and transmission can be expected to increase the rate of electrification only slowly, especially if available donor financing for large infrastructure investment becomes increasingly scarce. A systematic off-grid plan that is implemented concurrent with the grid expansion plan would help ensure that affordable, basic electricity services are made available to a wider segment of the population.

Experience has shown that effective electrification plans build local capacity to undertake requisite energy planning exercises and tasks. This study, therefore, recommends the provision of a training package to equip the staff of relevant Afghan agencies with the necessary knowledge and tools to continue the work of sector planning in the future. Such a training package would feature easy-to-understand documents that minimize jargon.

The least-cost electrification plan suggested here would serve as a fundamental part of any high-level investment prospectus for Afghanistan. To set short-term, actionable milestones, more detailed, province-level analysis is needed. This will be conducted in a later stage of this project.

2. Geospatial Energy Planning

To take on the challenge of developing energy infrastructure, plan its long-term development, and make it climate resilient, national governments must answer several policy and investment questions. Will available resources be enough to meet growing demands and development needs? What will the environmental and economic costs of energy transitions be? Can a trade-off between them be found?

A quantitative approach is necessary because energy system planning is essential in order to match supply with growing demand, and in the most cost-effective way. In addition, moving from planned, centralized, and expensive energy carriers toward fluctuating, decentralized, and cost-effective renewable energy production necessitates considerable modifications in energy infrastructure that must be carefully planned for optimal results. These modifications are most often motivated by geospatial concerns. Therefore, ground-level geospatial data are of key importance to help identify the most effective electrification strategy. Unfortunately, the acquisition of energy-related data at the local level is a challenging task, especially in countries where universal access to electricity has not yet been achieved.

This is where a Geographic Information System (GIS) can be an asset. The integration of GIS into energy planning can have several advantages; for example, spatial data can be used to analyze demand at a particular location, while making projections that consider the location's unique characteristics (for example, position in an urban or rural area) and corresponding energy access targets. Furthermore, GIS takes into account resource availability and energy potentials. Renewable energy maps, for example, are overlaid with several socioeconomic and geographic restrictions yielding technical energy potentials at the local level in areas where such data would otherwise not be available. Moreover, GIS can be used to illustrate results in interactive maps. These graphics communicate the key indicators for electrification planning "at a glance," and can be easily understood by policy makers with time constraints.

In 2017, the Division of Energy Systems Analysis within the KTH Royal Institute of Technology in Sweden (KTH dESA)[4] took the electrification planning process in Afghanistan one step further by building a database of geospatial information, and helping planners create a modifiable least-cost electrification model. This model is known as the Open Source, Spatial Electrification Tool (OnSSET), and it estimates, analyzes, and visualizes the most cost-effective electrification option for the achievement of electricity access goals. The tool is focused on the assessment and deployment of primarily renewable

4. https://www.kth.se/en/itm/om/organisation/institutioner/energiteknik/forskningsavdelningar/desa.

technologies to "ensure access to affordable, reliable, sustainable and modern energy for all" (Sustainable Development Goal 7).[5]

This section will outline the methodology behind OnSSET; its application to geospatial electrification analysis; and the key, discernible steps—data mining, GIS processing, model structuring and calibration, scenario building, result aggregation, and visualization—of the analysis process, with a focus on the particular case of Afghanistan.

2.1. GIS data collection and processing

OnSSET is a GIS-based tool and therefore requires data in a geographical format. In the context of the power sector, necessary data include those on current and planned infrastructure (electric grid networks, road networks, power plants, public facilities), population characteristics (distribution, location), economic and industrial activity, and local renewable energy flows.

OnSSET, as any other quantitative energy modelling, requires data acquisition and a constant data adjustment and updating.

Before a model can be built, one must acquire the "layers" of data outlined above. More often than not, each layer must be acquired on its own. For example, one layer may be administrative boundaries, another the coordinates of population settlements, and another the number of people in these settlements. Other useful data include the location of existing power plants and transmission networks; the transportation infrastructure; solar irradiation levels; wind speeds; hydrological potential; and other relevant geospatial information. The final outcome is a multilayer map conveying all the information necessary to initiate an OnSSET electrification analysis.

The spatial resolution of the final map depends on the availability of input data and on the targeted level of accuracy. OnSSET can handle various levels of input data, with typical resolutions ranging from 1x1 kilometers (km) to 10x10 km.

The selection of inputs usually involves a trade-off between the time needed for computation and the desired level of detail. The modeler has to decide which resolution best fits the purpose of the analysis. All analyses using OnSSET require that the following layers be obtained and processed:

1. Administrative boundaries
2. Population distribution and density
3. Nighttime light maps
4. Land cover
5. Digital elevation model

5. UN Sustainable Development Goals: http://www.un.org/sustainabledevelopment/energy. A preview of this work can be found in (Mentis et al. 2015) and (Fuso Nerini et al. 2016).

6. Mini/small hydropower potential (with restrictions)
7. Solar irradiation (with restrictions)
8. Wind power capacity factor (with restrictions)
9. Travel time to nearest town
10. Road network (existing and planned)
11. Transmission network (existing and planned)
12. Power plants (existing and planned)
13. Substations (existing and planned)
14. Quarries and mines

KTH dESA and the World Bank have collaboratively collected and processed the data needed for these layers for Afghanistan, with the aim of representing the status of the country's energy sector today as accurately as possible, given data constraints. The layers populate a geodatabase available at https://energydata.info. Please note that data were gathered from different years (2011–2016) and are considered the "best available" as of December 2016.

Note that the results presented hereafter are based on the developed geodatabase. The combination of datasets with varying spatial-temporal resolutions and geographic projections may have led to compounding inaccuracies and imprecisions, fact that should be taken into account when interpreting the results. Despite this, the use of the geodatabase by a wider audience is highly recommended.

That said, the modeler may choose to calibrate and/or reconstruct the map. Two workshops organized in February and July 2017 as part of the Afghanistan electrification project, aimed to address data acquisition challenges, demonstrate representative data preparation steps, and point to readily available open-source GIS layers.[6]

Demographic data are crucial for modelling future demand for electrification of households.

2.2. Identifying demand

An important parameter for identifying least-cost electrification technologies is electricity demand. Future residential electricity demand is a function of projected population growth and specific assumptions regarding demand (based on, for example, the appliances that households might use). In the residential sector, universal access to electricity does not imply that living and income standards will be uniform across all settlements.

Forecasting a population's size and purchasing power is central to any electrification analysis. Modeling the dynamics of electrification over time benefits from the best possible population estimates. The number of people in a given area, and their income,

6. The workshops were held in New Delhi on February 1–2, 2017 and Dubai on July 11–13, 2017 (training and educational material are available upon request).

Table 2.1. Population characteristics for urban and rural settings in Afghanistan

Parameter	Metric	Value 2015	Value 2030
Population, total	Million persons	32.527[a]	44.310 (estimated based on growth rates below)
Urban population	Percent of total population	26.3%[b]	35.8% (estimated based on growth rates below)
Rural population	Percent of total population	73.7%[b]	64.2% (estimated based on growth rates below)
Urban growth	Percent growth per year	3.96%[b]	3.49% (average value used in the model as 3.65% per year)[b]
Rural growth	Percent growth per year	1.85%[b]	1.12% (average value used in the model as 1.35% per year)[b]
Electricity access	Percent of total population	29%,[c, d] (access to the national grid)	100%
Electricity access, urban	Percent of urban population	88%[d] (access to the national grid)	100%
Electricity access, rural	Percent of rural population	11%[d] (access to the national grid)	100%
People per household, urban	People per household	7.4[d,e]	7 (assuming 5% decrease over the 15-year period)[f]
People per household, rural	People per household	8.5[d,e]	8.1 (assuming 5% decrease over the 15-year period)[f]

Sources: a. World Bank 2017e; b. UN DESA 2014, 2015; c. Infrastructure Development Cluster 2012; d. CSO 2016; e. The Asia Foundation 2015; f. Ellis and Roberts 2016.

are key drivers of future demand for electricity and thus the pay-back period for capital investments. But estimating population growth is not a straightforward task. Changes in socioeconomic conditions make the estimation of future fertility and mortality rates—as well migratory patterns—a complex task.

Ideally, one would estimate the future population by geospatial location. In OnSSET, urban population growth estimates are separated from rural, since these two groups usually follow slightly different growth profiles. Table 2.1 shows the population characteristics considered in the case of Afghanistan.

Following population estimates, the next step entails the estimation of electricity consumption in urban and rural settings. OnSSET uses five tiers for household electricity consumption, starting from very low to high consumption standards.

Following the "Sustainable Energy for All" Global Tracking Framework (IEA and World Bank 2015), the model groups the assumed consumption benchmarks into tiers (see table 2.2). The lowest assumed consumption allows for no more than low-consumption tasks, such as turning on a light for a few hours or charging a mobile-phone or radio battery. The highest consumption tier allows for energy services such as continuous lightning and the running of a refrigerator, air conditioner, and so on. The model assumes that at the end year (here 2030) all persons gaining access to electricity will reach the same assumed consumption benchmark.

Table 2.2. Indicative services that might be accessible to people, by annual electricity consumption tier

Access level	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 capita and year (kWh)	7.7	43.8	160.6	423.4	598.6
Consumption per urban household and year in Afghanistan (based on average household size: 7)	54	307	1,124	2,964	4,190
Consumption per rural household and year in Afghanistan (based on average household size: 8.1)	62	355	1,301	3,430	4,849

Source: Adapted from the Global Tracking Framework (SE4ALL, 2015).

2.3. Electricity access targets in Afghanistan

It is estimated that approximately 29 percent of the Afghan population has access to the national electric grid (ANPDF 2016; Infrastructure Development Cluster 2012; CSO 2016). The access rate is higher for urban households (approximately 88 percent) than for rural households (approximately 11 percent) (Infrastructure Development Cluster 2012; CSO 2016). The electricity consumption of connected households varies significantly across provinces. For example, annual electricity consumption can range from as low as 178 kWh per household in Ghor, and 551 kWh/household in Laghman, to comparatively higher levels in urban centres such as Kabul (3,000 kWh per household) and Herat (2,600 kWh per household) (ADB 2013).

Interestingly, households not connected to grid electricity seem to have access to some source of electricity, mostly solar and wind power, as well as batteries. About 60 percent of Afghan households have access to electricity through such sources (see figure 1.1). This electricity is primarily used for lighting or occasionally to power low-consumption household devices (a mobile phone, fan, or radio). The use of these devices does not exceed 300 kWh per year for the average household not connected to a grid (Infrastructure Development Cluster 2012).

Based on the Power Sector Master Plan estimates (ADB 2013), the average electricity consumption in Afghanistan by 2030 will be approximately 1,500 kWh/household/year (Infrastructure Development Cluster 2012). Using this estimate, tier 5 (4,190 kWh/household/year) and tier 3 (1,301 kWh/household/year) were selected as base electricity access targets for urban and rural households, respectively. (See table 2.2 for tier definitions.)

2.4. Identifying supply

The objective of the electrification analysis is to identify the most economic electricity supply mix that will allow full electrification of Afghanistan by the end year. It is unlikely that the employment of only one technology would achieve this goal. Every location has different characteristics, some of which might favor one technology over another. OnSSET considers seven technological options; these are arranged into three main electrification categories: grid, mini-grid, and stand-alone systems.

2.4.1. Grid

This option entails the extension of the national electricity grid to settlements not yet connected. Grid extension is a capital-intensive option; however, due to economies of scale in power generation, it can provide low generating costs. Previous electrification efforts have shown that extending the electricity grid is a good option where electricity consumption levels are relatively high (for example, in urban and highly populated areas) or populations live relatively close to current grid lines (for example, within 10 km). Table 2.3 provides indicative values of the parameters that OnSSET considers when estimating the cost of grid extension to unelectrified areas.

Table 2.3. Parameters related to the extension of the national electricity grid

Parameter	Cost unit
HV lines (>110kV)	120,000 $/km
MV lines (20 kV)	9,000 $/km
LV lines (220 V)	5,000 $/km
MV/LV transformer	3,500 $/unit (50 kVA)
Transmission losses	18.3%
Connection cost per HH	$122
Cost of producing electricity	0.062–0.077 $/kWh[a]

Source: ADB (2013);
a. This value was estimated based on author's calculations available at: https://energydata.info.
Note: HH = household; HV = high voltage; kV = kilovolts; LV = low voltage; MV = medium voltage.

2.4.2. Mini-grid

This option entails small-scale, isolated grids, able to cover the demand of a cluster of households. The model named four types of resources—namely, wind, solar photovoltaic (PV), hydropower, and diesel generators (also called gensets)—for these small-scale grids. Future iterations of the model might include biomass options as well as hybrid solutions combining two or more available resources. Mini-grids are a good option where electricity consumption is moderate and the renewable resources in question are abundant.

2.4.3. Stand-alone

Stand-alone systems refer to low-capacity off-grid options used to cover the demand of single households. Mini PV installations and small diesel gensets are currently included in the model. Stand-alone systems are usually a good option for remote, sparsely populated areas with limited electricity consumption needs. Table 2.4

Table 2.4. Electricity generation technology parameters used in the model

Plant type	Plant capacity (kW)	Investment cost ($/kW)	O&M costs (% of investment cost/year)	Fuel cost $/liter (future)	Efficiency %	Capacity factor[a]	Life (years)[b]
Diesel genset Mini grid	100	1,200 (ADB 2013)	10.0	0.69 (1.00)	37 (ADB 2013)	0.7	15
Small hydro Mini grid	1,000	2,500 (IRENA 2015)	2.0	-	-	0.5	30
Solar PV Mini grid	100	2,600 (ADB 2013; IRENA 2015)	1.8	-	-	Obtained for each grid point depending on solar availability	20
Wind turbines Mini grid	100	2,300 (ADB 2013; IRENA 2015)	3.5	-	-	Obtained for each grid point depending on wind availability	20
Diesel genset Stand-alone	1	2,000 (ADB 2013)	10.0	0.69 (1.00)	28 (ADB 2013)	0.5	10
Solar PV Stand-alone	0.4	5,500 (ADB 2013) Including BoS costs.	1.8	-	-	Obtained for each grid point depending on solar availability	15

Sources: a Adopted from IRENA (2015); b Adopted from ESMAP (2017).
Note: BoS = Balance of System; kW = kilowatts; PV = photovoltaic.

lists the technical and economic characteristics of the technologies considered in the electrification analysis of Afghanistan.

The *plant capacity* presented in table 2.4 is an indicative value to illustrate the capacity range for each type of technology used in this analysis. *Efficiency* (or thermal efficiency) is a dimensionless factor showing the amount of input energy required by an electrical generator or power plant (usually thermal) in order to produce one unit of useful output (in this case 1 kilowatt-hour of electricity). The *capacity factor* is the ratio of the net electricity generated, for the time considered, to the energy that could have been generated at continuous full-power operation during the same period. The *technical life* of a power plant refers to the estimated years of operation. These factors affect the performance of a power generator directly or indirectly, which in OnSSET's methodology is expressed through the calculation of the levelized cost of electricity, explained below.

OnSSET uses the levelized cost of electricity calculated for each of the geospatial units and identifies which technology provides access to electricity at the lowest cost. The levelized cost from a specific source represents the final cost of the electricity required for the overall system to break even over the project lifetime. It is calculated through the following formula:

$$LCoE = \frac{\sum_{t=1}^{n} \frac{I_t + O\&M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \qquad (2.1)$$

Where I_t is the investment expenditure for a specific system in year *t*; $O\&M_t$ is the operation and maintenance cost; F_t is the fuel expenditure; E_t is the generated electricity; *r* is the discount rate; and *n* is the lifetime of the system.

Geospatial units close to an existing electricity grid might find that grid expansion is the least-cost option, since distance to the grid is a very important variable determining the cost of connection. This is especially the case where household consumption levels are potentially high.

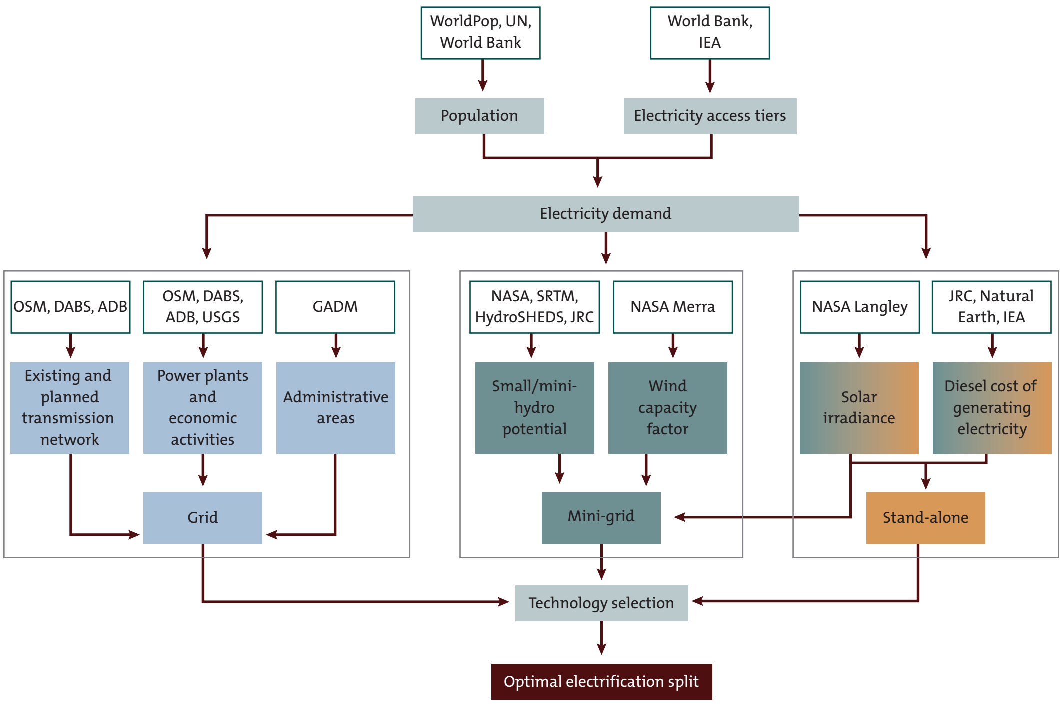
But this logic does not always hold; for example, in countries where electricity prices are very high, a grid connection may not be the lowest-cost option. If the assumed electricity demand of households is very low, other, stand-alone options might incur the lowest cost: for example, a rooftop PV panel, in locations where solar radiation is strong and diesel prices are high, or a diesel generator set where solar radiation is not strong and diesel prices are low.

OnSSET makes all these calculations and finds the lowest-cost option using data relevant to a particular location for all the scenarios considered in the exercise or defined by the modeler. The results can be graphically represented using interactive maps, and they are also available in tabular format so as to facilitate further analysis. Figure 2.1 schematically represents OnSSET's main methodological processes.

2.5. Scenario formation

OnSSET provides the possibility of generating various scenarios, thus investigating alternative pathways for electrification. Thirty-two scenarios have been developed for Afghanistan that consider variations of diesel price, grid cost and electricity consumption level. The following paragraphs present in brief the main input parameters considered in the construction of these scenarios.

Figure 2.1. Principal components and structure of OnSSET



Source: KTH dESA.
Note: ADB = Asian Development Bank; DABS = Da Afghanistan Breshna Sherkat; GADM = Global Administrative Areas; HydroSHEDS = Hydrological data and maps based on SHuttle Elevation Derivatives at multiple Scales; IEA = International Energy Agency; JRC = Joint Research Centre; OSM = Open Street Maps; Merra = Modern-era Retrospective Analysis; NASA SRTM = National Aeronautics and Space Administration Shuttle Radar Topography Mission; UN = United Nations; USGS = United States Geological Survey.

2.5.1. First parameter—Energy access target

As described in the previous paragraphs, the level of electricity to be provided can vary significantly from area to area. In this study, we consider two population groups: urban and rural. Since, in Afghanistan, these populations have different electricity needs, the level of effort needed for full electrification also varies. To illustrate this, two sets of scenarios were constructed. The first assumes different access targets for urban and rural areas (several combinations of tiers), while the second assumes the same access target for all settlements by 2030 (either tier 3 or tier 4) (see table 2.2 for tier definitions).

2.5.2. Second parameter—Diesel price

Diesel generators are an established and reliable technology used for electrification especially in remote areas and also as backup alternatives throughout Afghanistan. Despite the low capital investment required up front, diesel generators can induce high operating costs, depending on fuel price. To account for price fluctuation, two additional scenarios were constructed in OnSSET, one with a low and another one with a high fuel price. The first assumes that the price of diesel will remain close to the current low levels,

Table 2.5. Characteristics of the national power grid in Afghanistan, 2015

	Base year 2015				
Power System in Afghanistan	MW	GWh	(%)	USD/kWh	Investment (USD/kW)
Imports		**3500**	**76.2**	**0.049**	-
Turkmenistan	up to 90	595.0	17.0	0.028	-
Uzbekistan	up to 300	1,995.0	57.0	0.060	-
Tajikistan	up to 300	140.0	4.0	0.035	-
Iran	up to 150	770.0	22.0	0.040	-
Indigenous generation		**1,093**	**23.8**	**0.104**	
Hydro	254.0	711.9	65.1	0.091	2,200
Oil	199.6	131.1	12.0	0.300	500
Gas	67.0	249.4	22.8	0.037	1,000
Coal	0.0	0.0	0.0	0.055	1,500
Solar	0.1	0.3	0.0	0.000	1,953
Wind	**0.0**	**0.0**	**0.0**	**0.065**	**1,750**
	520.7	**4,592.8**	**100.0**	**0.062**	**1,722.01**

Source: ADB (2013), Infrastructure Development Cluster (2012), ANPDF (2016), Shift Project Data Portal (2015).
Note: GWh = gigawatt-hours; kWh = kilowatt-hours; MW = megawatts.

at about $0.69/liter (45.9 afghanis (Af)/liter[7]), while the second assumes an increase to $1/liter (66.5 Af/liter) based on the estimated crude oil price level over the next years (IEA 2015).

2.5.3. Third parameter—Electricity price of national grid

Previous electrification efforts have shown that the expansion of an electricity grid (new capacity—transmission and distribution) is a capital-intensive process. But because of economies of scale in power generation, grid extension can provide low electricity prices to the end-user. The price at which the electricity is produced is a critical consideration. OnSSET, meanwhile, does not distinguish between the different technologies in the grid's generation mix; it rather sees the grid as a "black box." Other grid-optimization tools can be developed and interlinked with OnSSET to distinguish elements of the generation mix (for example, OSeMOSYS); however, they are not within the scope of this study. In this case, the national grid's cost of generated electricity has been estimated based on a review of relevant literature and the development plans elaborated by the Afghan government.

7. Based on the exchange rate $1 = Af 66.5. (at the base year—2015).

In 2015 the installed capacity in operation in Afghanistan was 520.7 megawatts (MW), generating approximately 1,093 gigawatt-hours (GWh). Domestic electricity production relied mainly on hydropower, oil, and natural gas and accounted for 23.8 percent of the total consumption, while the rest of the demand was covered by imports. The country imports approximately 3,500 GWh from Uzbekistan (57 percent), Iran (22 percent), Turkmenistan (17 percent), and Tajikistan (4 percent) (ADB 2013; Infrastructure Development Cluster 2012; The Shift Project Data Portal 2015). Based on this specific mix, the cost of generation was estimated at approximately $0.062/kWh.[8] Table 2.5 presents the basic parameters describing Afghanistan's power sector as of 2015.

Restructuring the power sector in Afghanistan would require significant investments in additional capacity and expansion of the transmission and distribution network. According to the National Energy Supply Plan (Infrastructure Development Cluster 2012) and the Power Sector Master Plan study conducted by Fichtner and others, approximately 3,000 MW are planned to be added to the national system by 2025 (Infrastructure Development Cluster 2012; ADB 2013). This entails 2,500 MW from 13 hydropower projects, 400 MW from coal power plants in the Aynak and Hajigak mine sites, and 200 MW from Sheberghan. The end goal is a robust and flexible power system able to effectively utilize the country's abundant natural resources while also enhancing interconnectivity with neighboring countries (TUTAP–TAPI–CASA 1000).[9] Solar and wind are additional sources with high estimated potential (wind power is estimated at 158 GW) (ADB 2013). To incorporate these plans in OnSSET, we mapped out three paths to achieving the government's goal by 2030.

The first path assumes that electricity imports will remain stable while the additional capacity will come primarily from hydropower, coal, and natural-gas-fired power plants (table 2.6). Reduction in the use of diesel generators is also included. This would force the generating cost to increase to $0.077/kWh while the capital investment requirement (that is, the value used in OnSSET to assess the investment required) is estimated at $1,970/kW.

The second path was developed to assess how the increased penetration of renewable-energy projects could affect the generating cost and therefore the output of the model. It was assumed that imports will remain the same, while 40 MW of solar[10] and 26 MW of wind[11] will replace the oil-based generators. This would result in a lower generation cost of approximately $0.075/kWh but higher capital investment requirements at $1,989/kW. Table 2.7 presents the basic parameters of this path.

8. Based on the author's estimations.
9. TUTAP: Turkmenistan-Uzbekistan-Tajikistan-Afghanistan-Pakistan electricity project, TAPI: Turkmenistan-Afghanistan-Pakistan India gas pipeline, CASA: Central Asia South Asia Electricity Transmission and Trade Project
10. AEIC: http://aeic.af/en/gismap/60.
11. Projects: Herat Wind Park (14 MW), Herat Solar + Wind (2 MW), Mazar Wind Project (10 MW) in Balkh.

Table 2.6. Forecast of national power grid based on current government plans, 2030

	End year 2030—Path to government goal as presently planned				
Power System in Afghanistan	MW	GWh	(%)	USD/kWh	Investment (USD/kW)
Imports		**3,500.0**	**24.3**	**0.066**	**-**
Turkmenistan	up to 90	595.0	17.0	0.038	-
Uzbekistan	up to 300	1,995.0	57.0	0.081	-
Tajikistan	up to 300	140.0	4.0	0.047	-
Iran	up to 150	770.0	22.0	0.054	-
Indigenous generation		**10,897.8**	**75.7**	**0.080**	
Hydro	2,767.5	7,757.8	71.2	0.091	2,230.0
Oil	66.0	43.4	0.4	0.300	500.0
Gas	267.0	994.0	9.1	0.037	1,000.0
Coal	400.0	2,102.4	19.3	0.055	1,500.0
Solar	0.1	0.3	0.0	0.060	1,130.0
Wind	0.0	0.0	0.0	0.065	1,600.0
	3,500.6	14,397.8	100.0	0.077	1,970.1

Source: ADB (2013), Infrastructure Development Cluster (2012), ANPDF (2016), Shift Project Data Portal (2015).
Note: GWh = gigawatt-hours; kWh = kilowatt-hours; MW = megawatts.

Table 2.7. Forecast of national power grid with greater renewable energy penetration, 2030

	End year 2030—Alternative path to government goal making greater use of renewables				
Power System in Afghanistan	MW	GWh	(%)	USD/kWh	Investment (USD/kW)
Imports		**3,500.0**	**24.1**	**0.066**	**-**
Turkmenistan	up to 90	595.0	17.0	0.038	-
Uzbekistan	up to 300	1,995.0	57.0	0.081	-
Tajikistan	up to 300	140.0	4.0	0.047	-
Iran	up to 150	770.0	22.0	0.054	-
Indigenous generation		**11,027.7**	**75.9**	**0.078**	
Hydro	2,767.5	7,757.8	71.2	0.091	2,230.0
Oil	0.0	0.0	0.0	0.300	500.0
Gas	267.0	994.0	9.1	0.037	1,000.0
Coal	400.0	2,102.4	19.3	0.055	1,500.0
Solar	40.0	105.1	1.0	0.060	1,130.0
Wind	26.0	68.3	0.6	0.065	1,600.0
	3,500.5	**14,527.7**	**100.0**	**0.075**	**1,989.0**

Source: ADB (2013), Infrastructure Development Cluster (2012), ANPDF (2016), Shift Project Data Portal (2015).
Note: GWh = gigawatt-hours; kWh = kilowatt-hours; MW = megawatts.

Table 2.8. Forecast of national power grid with increased imports, 2030

	End year 2030—Alternative path to government goal making greater use of imports				
Power System in Afghanistan	MW	GWh	(%)	USD/kWh	Investment (USD/kW)
Imports		**5,680.0**	**39.1**	**0.063**	**-**
Turkmenistan	up to 90	738.4	13.0	0.038	-
Uzbekistan	up to 300	2,556.0	45.0	0.081	-
Tajikistan	up to 300	1,136.0	20.0	0.047	-
Iran	up to 150	1,249.6	22.0	0.054	-
Indigenous generation		**8,847.8**	**60.9**	**0.083**	
Hydro	2,254.0	6,318.3	58.0	0.091	2,230.0
Oil	199.6	131.1	1.2	0.300	500.0
Gas	150.0	558.5	5.1	0.037	1,000.0
Coal	350.0	1,839.6	16.9	0.055	1,500.0
Solar	0.1	0.3	0.0	0.060	1,130.0
Wind	0.0	0.0	0.0	0.065	1,600.0
	2,953.7	14,527.8	100.0	0.075	1,603.4

Source: ADB (2013), Infrastructure Development Cluster (2012), ANPDF (2016), Shift Project Data Portal (2015).
Note: GWh = gigawatt-hours; kWh = kilowatt-hours; MW = megawatts.

Finally, the third path was developed to illustrate how the grid electricity cost would react in case increased imports are needed to cover the expected demand. To illustrate that, the planned domestic generation capacity was kept below 3,000 MW.[12] Imports were increased. The grid cost was estimated at $0.075/kWh, with lower capital investment requirements than in the previous cases, at $1,603/kW. Table 2.8 presents the basic parameters of this path.

2.6. Running the model

2.6.1. Option 1: Using the online interface of OnSSET

Over the past few months KTH dESA has been developing an online open interface to support the use of OnSSET by professionals without experience in the use of geospatial software. The interface allows the user to conduct an electrification analysis of a selected country, based on few key input parameters (energy access targets, population characteristics, technology costs, and so on). The results can be visualized quickly in an embedded map that show "at a glance" the most cost-effective electrification pathways. This interface is accessible at OnSSET.org, and the only requirement for its use is a stable Internet connection.[13]

12. As of spring 2017, 513 MW of hydropower projects had not come through; gas (Sheberghan) and coal projects (in Aynak and Hajigak) were delayed.
13. For access credentials refer to appendix B.

A space in OnSSET.org has been specially created to accommodate model runs that investigate various electrification pathways for Afghanistan. More information on how to navigate and properly conduct an electrification analysis using the online interface is accessible at https://energydata.info.

2.6.2. Option 2: Stand-alone software

OnSSET has been developed as an open-source tool; that is, the code and all the functions behind the model are accessible by any user and can be customized to serve the objectives of any analysis. The requirements for a fully customizable version of OnSSET are as follows.

GIS environment

OnSSET is a spatial electrification tool and as such relies on the use of GIS. A GIS environment is therefore necessary to:

1. Extract trivial characteristics for the electrification analysis from GIS layers and combine them together in a format easy to read by the Python code (a comma-separated-value file with all the attributes per population point).
2. Visualize the final results in maps.

At present, OnSSET relies on ArcGIS; however, any alternative GIS environment can be used (for example, Qgis and/or Grass).

Python—Anaconda package

OnSSET is written in Python, an open-source programming language used widely in many applications. Python[14] is a necessary requirement for OnSSET to work.

Programming in Python usually relies on the use of predefined functions that can be found in so-called modules. To work with OnSSET, certain modules need to be installed/updated. The easiest way to do so is by installing Anaconda, a package that contains various useful modules. Anaconda can be downloaded for free from https://www.continuum.io/anaconda-overview. Please make sure that you download the version that is compatible with your operating system (for example, Windows 32-bit). After the installation, you can use the Anaconda command line to run Python. Anaconda includes all the modules required to run OnSSET.

Python interfaces

Integrated Development Environment programs are used in order to ease programming process when multiple or long scripts are required. Many such programs have been

14. Python itself can be downloaded and installed for free using the official website: https://www.python.org/downloads/.

developed for Python.[15] KTH dESA has been using PyCharm as the standard one to run OnSSET.[16]

Jupyter notebook is a console-based, interactive computing approach to providing a web-based application suitable for capturing the whole computation process: developing, documenting, and executing code, as well as communicating the results. Jupyter notebook is used for the online onset interface, and is recommended for small analyses and exploring code and results.

GitHub

GitHub is a Web-based Git repository hosting service. It provides access control and several collaboration features such as bug tracking, feature requests, task management, and wikis for every project. The open-source code behind OnSSET is called "PyOnSSET" and is available in KTH dESA's Github space (https://github.com/KTH-dESA/PyOnSSET). A GitHub account will allow you to propose changes, modifications, and upgrades to the existing code.

2.7. Results and visualization

In total, 32 scenarios have been created for Afghanistan. A few of them (highlighted with green in table 2.9) are presented here as a showcase of OnSSET's capabilities.

OnSSET yields two comma-separated-value files as an output for each scenario. The first file contains the information acquired from the electrification analysis for every single settlement in the country according to the specified resolution (in this case 1x1 km). This file is used to retrieve location-specific information but also to illustrate the results on detailed maps through a GIS environment. The second file contains the summarized results for the scenario, providing information about the total capacity needed, by technology, and the relative investment level required to achieve the electrification target.[17]

Figures 2.2–2.8 provide a quick overview of the results for the 12 selected scenarios. The graphs allow a quantitative approach to the comparison of the aggregated results showing technology share, added capacity, and investment requirements per scenario. The maps, meanwhile, are organized in such a way as to allow a more qualitative comparison between the parameters that most influence the penetration of different technologies in the generation mix. A more detailed description of the results for each scenario is available in appendix A.

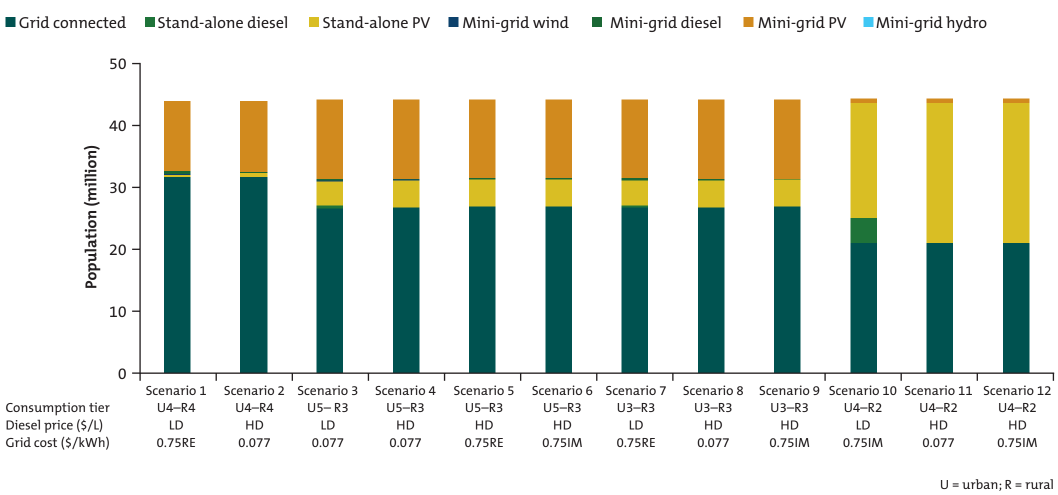
15. You can find a few at: http://noeticforce.com/best-python-ide-for-programmers-windows-and-mac.
16. It can be downloaded from https://www.jetbrains.com/pycharm/.
17. The files for all the scenarios developed for Afghanistan are available through the following link: https://energydata.info.

Table 2.9. Grid cost ($/kWh) under 32 electrification scenarios investigated for Afghanistan, by diesel price and electricity consumption tier

Diesel price ($/L)		Urban and rural electricity consumption tier and average weighted household consumption			
		U4–R4 (3,247 kWh/year)	U5–R3 (2,433 kWh/year)	U4–R2 (1,378 kWh/year)	U3–R3 (1,232 kWh/year)
Low	0.69	0.062	0.062	0.062	0.062
	0.69	0.077	0.077	0.077	0.077
	0.69	0.075 RE	0.075 RE	0.075 RE	0.075 RE
	0.69	0.075 IM	0.075 IM	0.075 IM	0.075 IM
High	1	0.062	0.062	0.062	0.062
	1	0.077	0.077	0.077	0.077
	1	0.075 RE	0.075 RE	0.075 RE	0.075 RE
	1	0.075 IM	0.075 IM	0.075 IM	0.075 IM

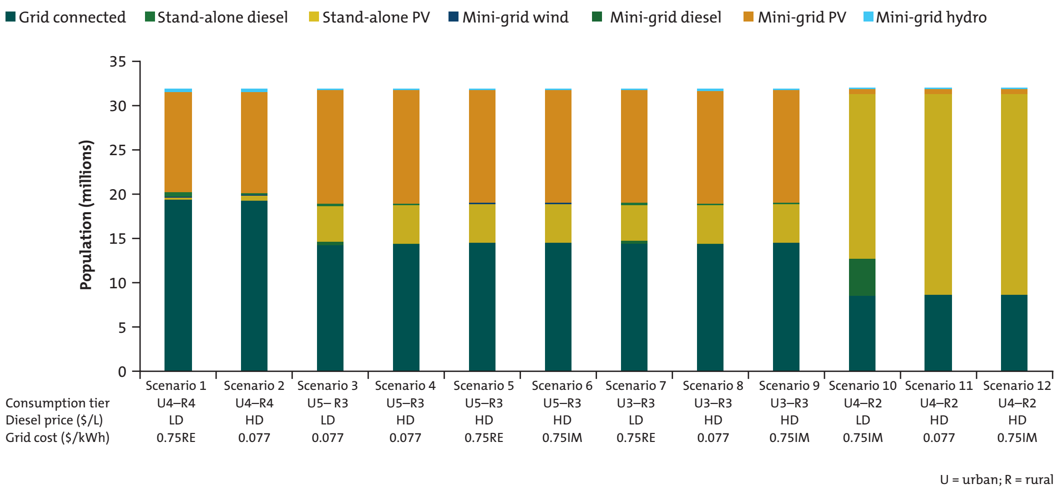
Source: KTH dESA.
Note: RE refers to increased penetration of renewable-based technologies (see table 2.7); IM refers to increased imports from neighboring countries (table 2.8). 12 selected scenarios (highlighted in blue) are presented in the report.

Figure 2.2. Total population electrified, by technology



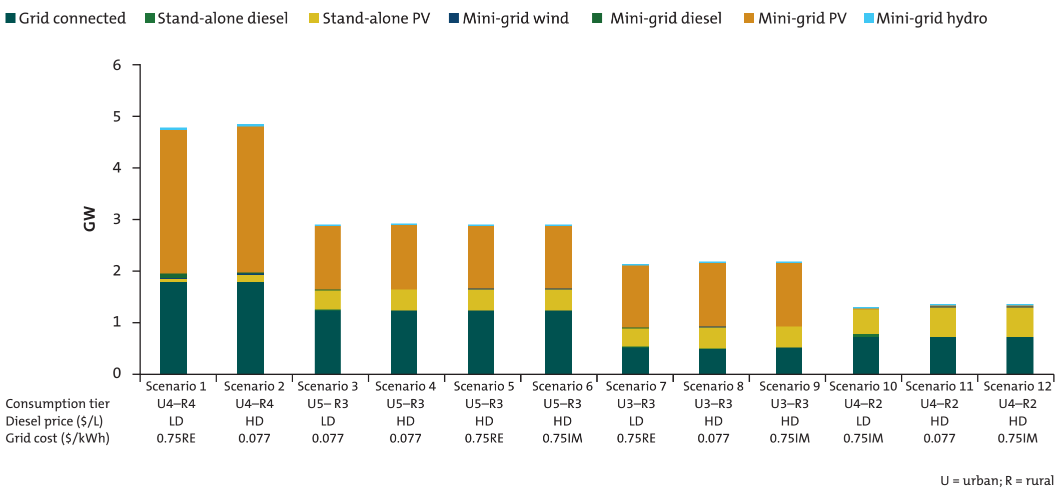
Source: KTH dESA.
Note: Ux–Rx refers to the electrification tier for urban and rural settlements, respectively (see table 2.2); RE refers to the alternate path with increased penetration of renewable-based technologies (solar, wind) (see table 2.7); IM refers to the alternative path with increased imports from neighboring countries (see table 2.8). kWh = kilowatt-hours; LD = low diesel price; HD = high diesel price.

Figure 2.3. Newly electrified population, by technology



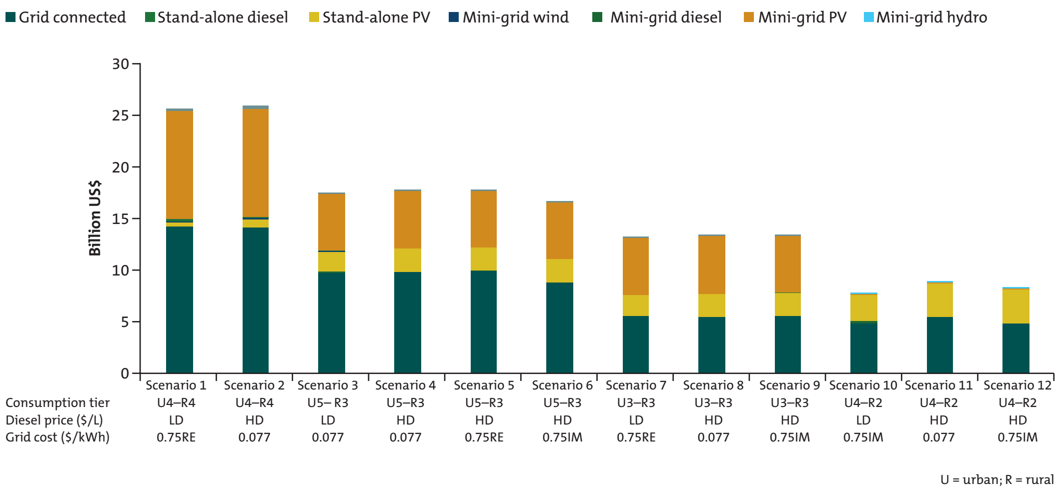
Source: KTH dESA.
Note: Ux–Rx refers to the electrification tier for urban and rural settlements, respectively (see table 2.2); RE refers to the alternative path with increased penetration of renewable-based technologies (solar, wind) (see table 2.7); IM refers to the alternative path with increased imports from neighboring countries (see table 2.8). kWh = kilowatt-hours; LD = low diesel price; HD = high diesel price.

Figure 2.4. New capacity to be added, by technology



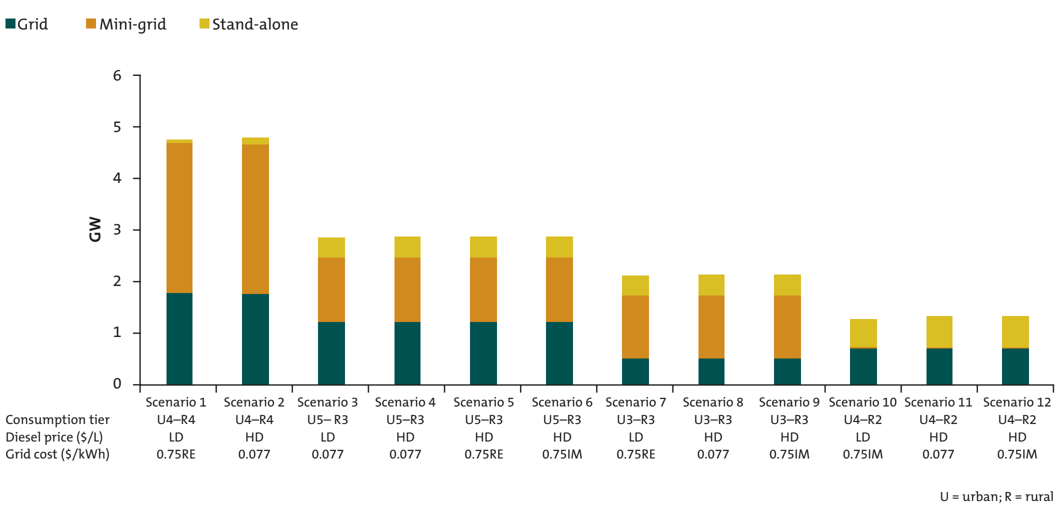
Source: KTH dESA.
Note: Ux–Rx refers to the electrification tier for urban and rural settlements, respectively (see table 2.2); RE refers to the alternative path with increased penetration of renewable-based technologies (solar, wind) (see table 2.7); IM refers to the alternative path with increased imports from neighboring countries (see table 2.8). kWh = kilowatt-hours; LD = low diesel price; HD = high diesel price.

Figure 2.5. Investment requirements, by technology



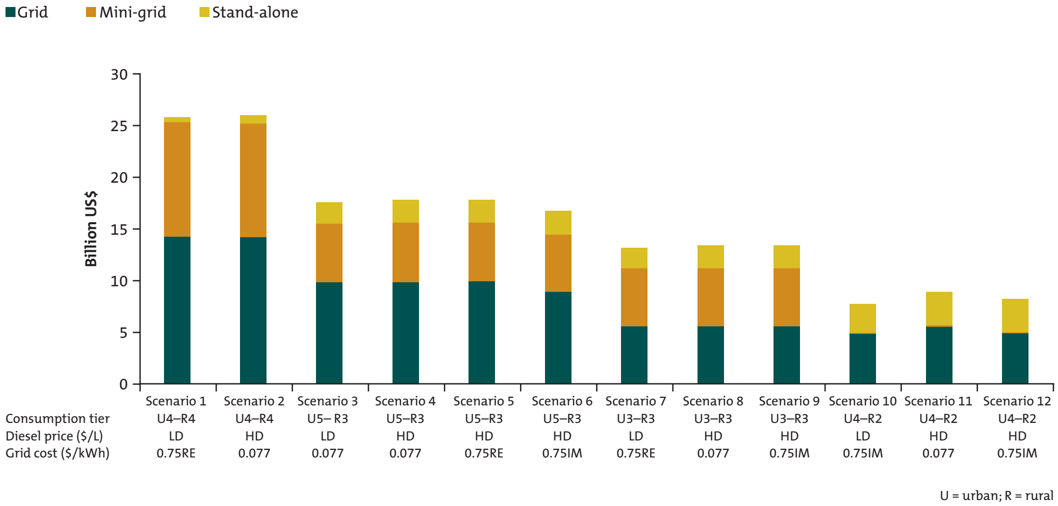
Source: KTH dESA.
Note: Ux–Rx refers to the electrification tier for urban and rural settlements, respectively (see table 2.2); RE refers to the alternative path with increased penetration of renewable-based technologies (solar, wind) (see table 2.7); IM refers to the alternative path with increased imports from neighboring countries (see table 2.8). kWh = kilowatt-hours; LD = low diesel price; HD = high diesel price.

Figure 2.6. New capacity required, by system type



Source: KTH dESA.
Note: Ux–Rx refers to the electrification tier for urban and rural settlements, respectively (see table 2.2); RE refers to the alternative path with increased penetration of renewable-based technologies (solar, wind) (see table 2.7); IM refers to the alternative path with increased imports from neighboring countries (see table 2.8). kWh = kilowatt-hours; LD = low diesel price; HD = high diesel price.

Figure 2.7. Investment required, by system type



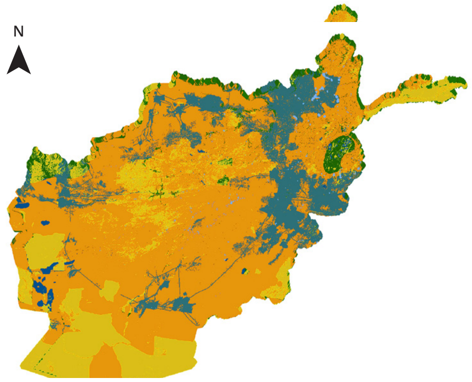
Source: KTH dESA.

Note: Ux–Rx refers to the electrification tier for urban and rural settlements, respectively (see table 2.2); RE refers to the alternative path with increased penetration of renewable-based technologies (solar, wind) (see table 2.7); IM refers to the alternative path with increased imports from neighboring countries (see table 2.8). kWh = kilowatt-hours; LD = low diesel price; HD = high diesel price.

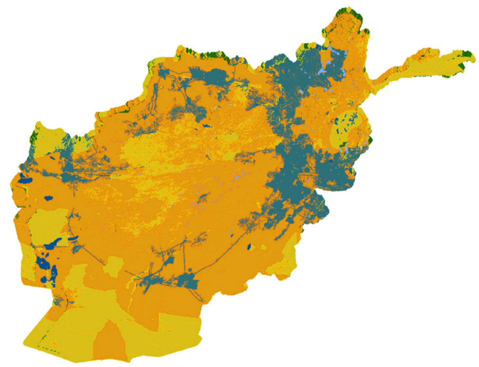
Figure 2.8. Summarized results

Grid | Diesel mini-grid | Hydro mini-grid | PV mini-grid | Wind mini-grid | Diesel stand-alone | PV stand-alone

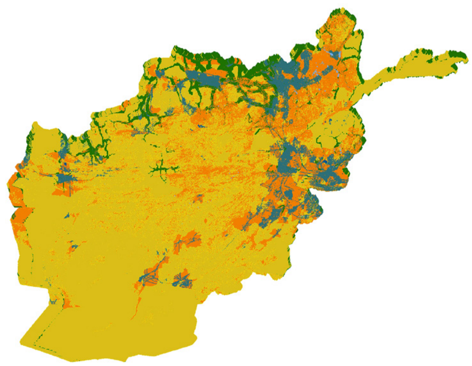
a. Scenario 1: U4–R4, LD, 0.075 RE



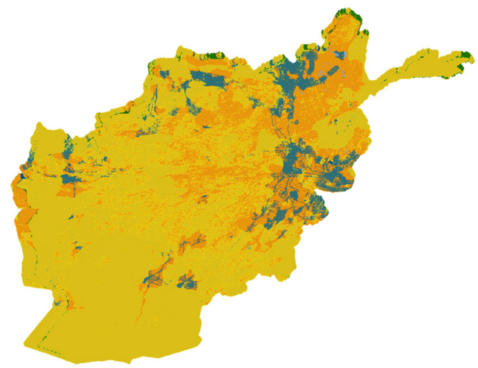
b. Scenario 2: U4–R4, HD, 0.077



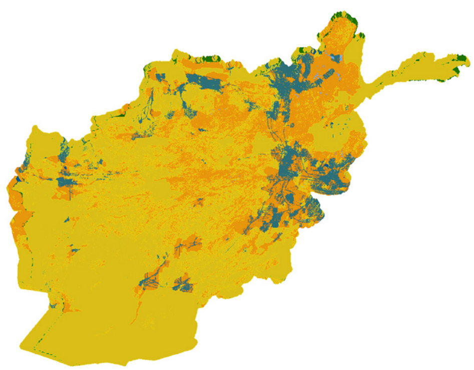
c. Scenario 3: U5–R3, LD, 0.077



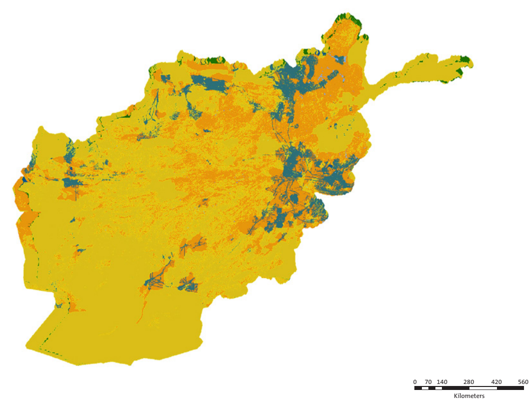
d. Scenario 4: U5–R3, HD, 0.077



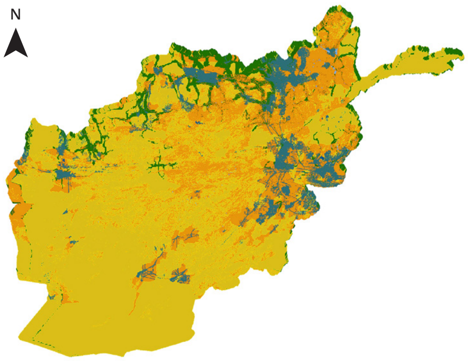
e. Scenario 5: U5–R3, HD, 0.075 RE



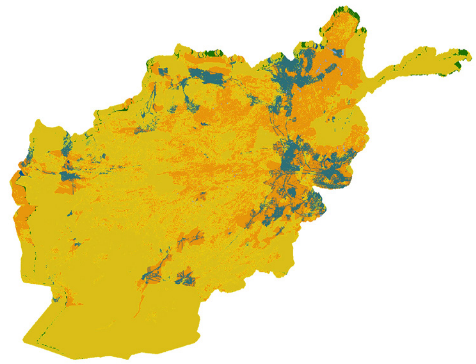
f. Scenario 6: U5–R3, HD, 0.075 IM



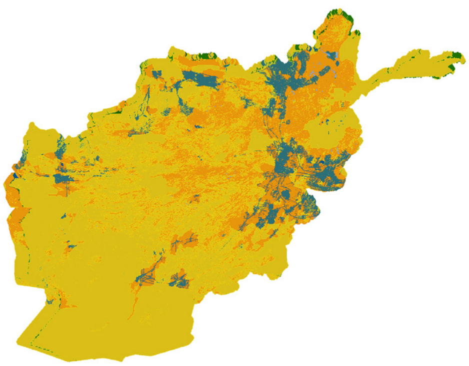
g. Scenario 7: U3–R3, LD, 0.075 RE



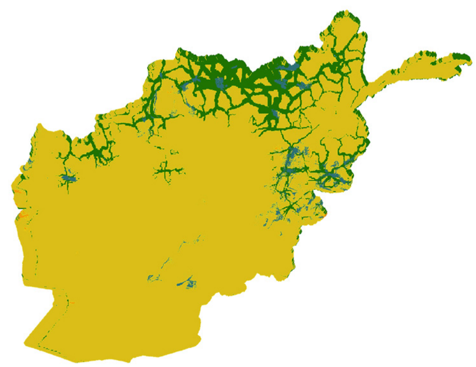
h. Scenario 8: U3–R3, HD, 0.077



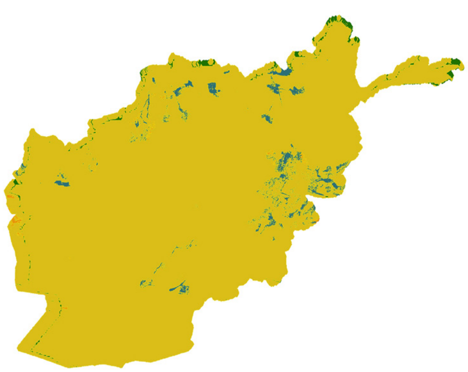
i. Scenario 9: U3–R3, HD, 0.075 IM



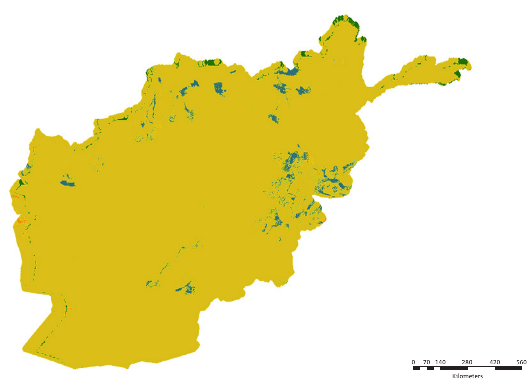
j. Scenario 10: U4–R2, LD, 0.075 IM



k. Scenario 11: U4–R2, HD, 0.077



l. Scenario 12: U4–R2, HD, 0.075 IM



Source: KTH dESA.
Note: Ux–Rx refers to the electrification tier for urban and rural settlements, respectively (see table 2.2); RE refers to the alternative path with increased penetration of renewable-based technologies (solar, wind) (see table 2.7); IM refers to the alternative path with increased imports from neighboring countries (see table 2.8). kWh = kilowatt-hours; LD = low diesel price; HD = high diesel price.

2.8. Bridging science and policy: Interpretation of OnSSET's results

OnSSET's results clearly show that the assumed level of electricity demand per household in the settlements in each of the GIS cells is an important factor determining which technology offers the lowest cost. At the lowest consumption levels, most population settlements close to already-electrified villages and transmission lines will find that connecting to the central electricity grid is the lowest-cost option. Elsewhere, most settlements will find that stand-alone systems are the most economical option (with PV panels a better option than diesel gensets, especially when diesel prices are high). At this low level of consumption, mini-grids play only a minor role.

Assuming a midrange electricity consumption per household makes grid connection a more viable option (to the detriment of stand-alone options). Assuming high consumption levels furthers the viability of increasing connections to the central grid; but, interestingly, high consumption levels imply that mini-grids become an economically attractive option and replace stand-alone technologies in many settlements. Shifting between low and high diesel prices not only has the expected result of reducing the importance of diesel generators for mini-grids or stand-alone systems, but it also increases the overall contribution of renewable-based mini-grids to achieving universal access to electricity.

The model finds that between 55 and 73 percent of the population may be receiving electricity through off-grid technologies. Where the assumed electricity consumption is relatively high (above 1,500 kWh/hh/year), off-grid technologies might be responsible for between 40 and 50 percent of households gaining access to electricity.

What is the cost of ensuring access to electricity for all by 2030? The total investment required ranges between $7.82 billion and $26.04 billion over the entire period in question, 2015–30. These figures include the up-front capital investments for extending the transmission and distribution network, building the mini-grid systems, and installing the stand-alone solar and diesel technologies. The lower a household's electricity consumption and the lower the diesel price, the lower the overall investment needed to reach universal access. The lowest-cost investment ticket for providing universal access corresponds to the case where consumption is assumed to be lowest (tier 4 for urban, tier 2 for rural), and the diesel price is low. The highest ticket corresponds to the highest household consumption (tier 4 for urban, tier 4 for rural) at the high diesel price (see table 2.2 for tier definitions).

The model identifies the role of renewable sources of energy in off-grid technologies. The role of renewables critically depends on the price of diesel. When diesel prices are low, renewable sources will be used to provide electricity to an average of 51 percent of the population. However, increasing the price of diesel to $1/liter (Af 66.5/liter) also increases the average contribution of renewable sources, which rise to 57 percent of the population.

In summary:

- Grid extension is the least-cost solution in densely populated areas that are already close to the existing grid network.
- Low diesel prices allow for a small market capture (1–2 percent)[18] of diesel gensets in the electrification mix. Increased diesel prices, on the other hand, give a competitive advantage to solar PV systems.
- Other renewables (wind, hydropower) capture a significant percentage in areas where these resources are available; their share is moderate across Afghanistan.
- As electricity demand levels rise, the most favorable electrification option shifts from (i) stand-alone systems to (ii) mini-grids to (iii) a grid connection.
- The share of renewable energy sources in total electricity generation can reach more than 60 percent by 2030.[19]

18. An exception is the U4–R2, LD, 0.075IM where stand-alone diesel generators are found to be the most economic electrification option for 13 percent of the newly electrified population.
19. Depending on the share of grid-connected renewables.

3. Conclusion and Final Remarks

OnSSET provides useful insights that may be used to assess electrification options across population settlements in well-defined locations; aggregate results reveal patterns at the national or subnational levels. The tool's prime focus is the identification of additional capacity and investment required to fulfill energy access goals.

OnSSET offers policy and decision makers support in identifying least-cost electrification strategies. Most important, the model specifically addresses the needs of the energy poor and offers tangible solutions. Its open-source features allow energy experts to refine results resolution and explore additional scenarios. When linked to OSeMOSYS, it becomes an extremely powerful analysis and planning tool.

Like most open source models, OnSSET is a work in progress, especially as new satellite imagery and GIS data become available. The current analysis has several limitations, which may be overcome as follows:

- The electrification mix is shown only for the end year (here 2030). Thus, the electrification mix and status in the intervening years (that is, today through 2030) are not considered. To include the whole period, it would be necessary to decide which areas need to be electrified in what order.
- The breakdown of the generation mix used to consider different grid electrification costs is not detailed. It would be necessary to link OnSSET with OSeMOSYS to obtain the optimal generation mix based on the country's resources, demand, and trade with other countries.
- Another critical issue is the various resolutions of the datasets used. For example, population density data are given at 1 km while the wind speed is at 5 km. The datasets need to be harmonized to ensure better accuracy.
- The analysis considers only household electrification. Other productive uses of electricity (such as in health services, schools, rural enterprises, agriculture and so on) should also be considered. These would increase the demand levels and therefore the electrification mix.
- A final word of caution: the model quantifies electrification targets for Afghanistan by 2030. It considers the least-cost mix and what the required aggregate investment would be. But it does not imply the implementation of the identified strategies or the provision of necessary finance. It highlights the challenges ahead for policy and decision makers charged with implementing energy strategies to achieve access targets, allows an analysis of trade-offs between competing demands for financial resources, and thus supports the prudent prioritization of available financial resources.

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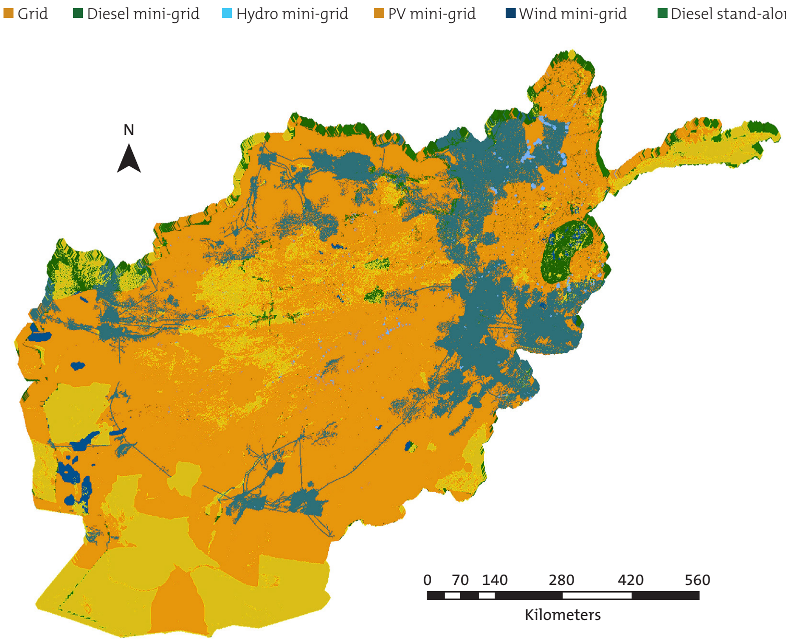
Appendix A

Detailed results of 12 representative electrification scenarios for Afghanistan (Map and tabular format)

Figure A.1. Scenario 1: U4–R4, LD, 0.075RE—Electrification results under the scenario defined by urban demand at tier 4, rural demand at tier 4, low diesel price, grid cost at 0.075 $/kWh, and higher penetration of renewable-based technologies in the grid mix



Source: KTH dESA.

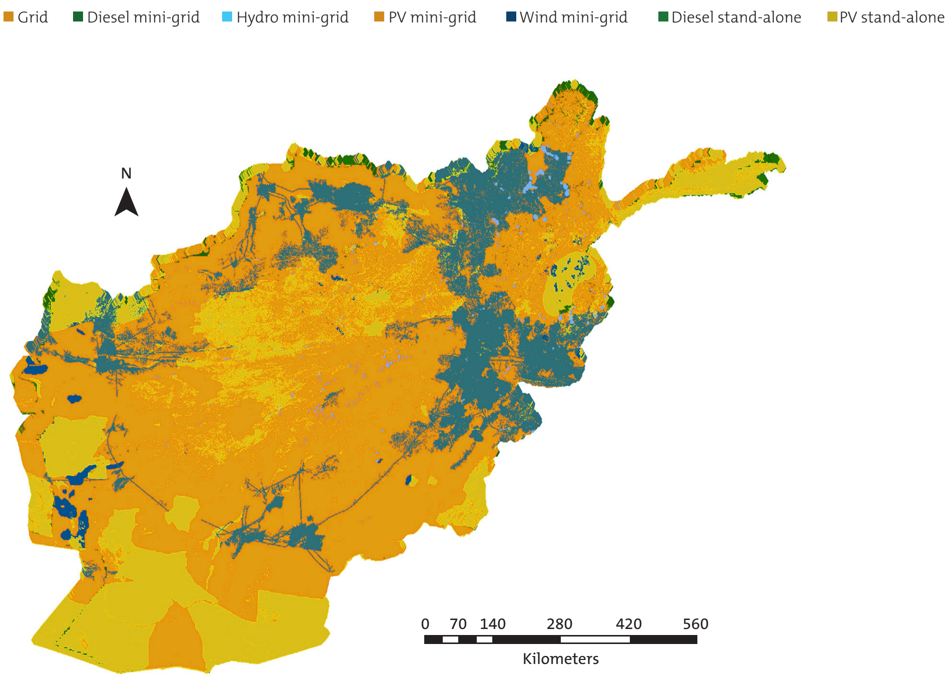
Table A.1. Scenario 1: Electrification results under the scenario defined by urban demand at tier 4, rural demand at tier 4, low diesel price, grid cost at 0.075 $/kWh, and higher penetration of renewable-based technologies in the grid mix

People to receive electricity by 2030: 31,999,487

By technology type	Share (%)	Capacity (MW)	Investment ($ billion)
Grid extension	60.7	1,773	14.3
Mini-grids	38.3	2,921	11.07
Diesel genset	1.5	65.9	0.198
PV system	35.4	2,798	10.6
Wind turbines	0.3	23.8	0.089
Mini–small hydro	1.1	33.3	0.217
Stand-alone	1.0	73	0.4
Diesel genset	0.053	2.4	0.006
PV systems	0.9	70.6	0.388
Total	**100**	**4,767.4**	**25.76**

Source: KTH dESA.
Note: kWh = kilowatt-hours; MW = megawatts; PV = photovoltaic.

Figure A.2. Scenario 2: U4–R4, HD, 0.077—Electrification results under the scenario defined by urban demand at tier 4, rural demand at tier 4, high diesel price, and grid cost at 0.077 $/kWh



Source: KTH dESA.

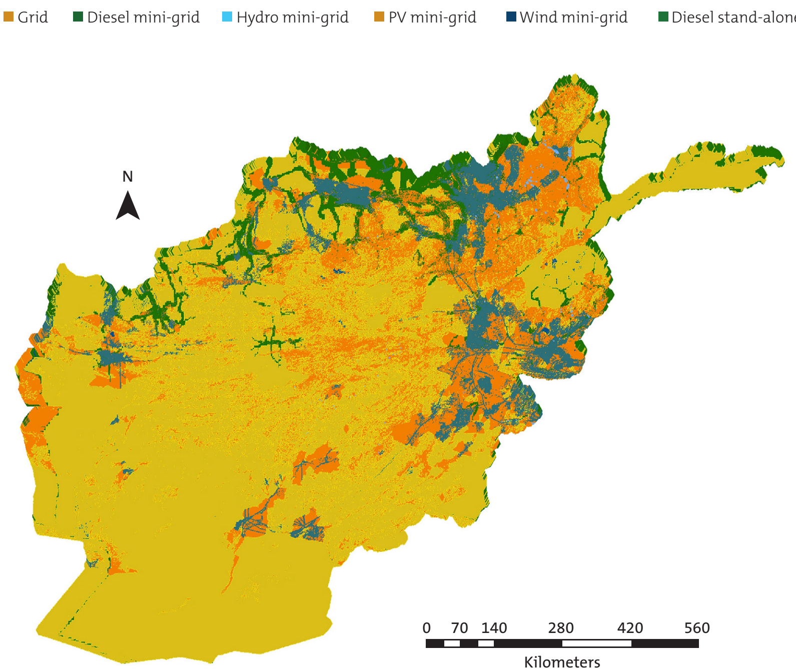
Table A.2. Scenario 2: Electrification results under the scenario defined by urban demand at tier 4, rural demand at tier 4, high diesel price, and grid cost at 0.077 $/kW

People to receive electricity by 2030: 31,999,487

By technology type	Share (%)	Capacity (MW)	Investment ($ billion)
Grid extension	60.6	1,769	14.22
Mini-grids	37.6	2,899	11.01
Diesel genset	0.5	20.03	0.052
PV system	35.7	2,815	10.6
Wind turbines	0.3	30.2	0.11
Mini–small hydro	1.1	34.2	0.22
Stand-alone	1.9	148	0.82
Diesel genset	0.003	0.13	0.038
PV systems	1.9	148.2	0.082
Total	**100**	**4,816.4**	**26.04**

Source: KTH dESA.
Note: kWh = kilowatt-hours; MW = megawatts; PV = photovoltaic.

Figure A.3. Scenario 3: U5–R3, LD, 0.077—Electrification results under the scenario defined by urban demand at tier 5, rural demand at tier 3, low diesel price, and grid cost at 0.077 $/kWh



Source: KTH dESA.

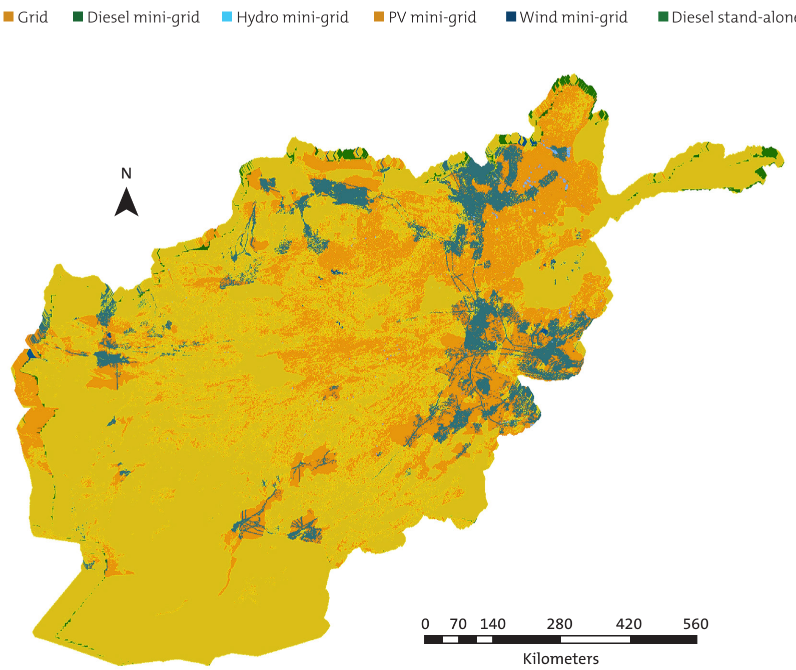
Table A.3. Scenario 3: Electrification results under the scenario defined by urban demand at tier 5, rural demand at tier 3, low diesel price, and grid cost at 0.077 $/kWh

People to receive electricity by 2030: 31,999,487

By technology type	Share (%)	Capacity (MW)	Investment ($ billion)
Grid extension	44.9	1,225	9.84
Mini-grids	41.4	1,252	5.7
Diesel genset	0.8	12.8	0.052
PV system	40.0	1,228	5.6
Wind turbines	0.1	4.8	0.021
Mini–small hydro	0.5	6.6	0.055
Stand-alone	13.7	383	2.1
Diesel genset	1.2	20.6	0.06
PV systems	12.5	362.3	2.0
Total	**100**	**2,860**	**17.58**

Source: KTH dESA.
Note: kWh = kilowatt-hours; MW = megawatts; PV = photovoltaic.

Figure A.4. Scenario 4: U5–R3, HD, 0.077—Electrification results under the scenario defined by urban demand at tier 5, rural demand at tier 3, high diesel price, and grid cost at 0.077 $/kWh



Source: KTH dESA.

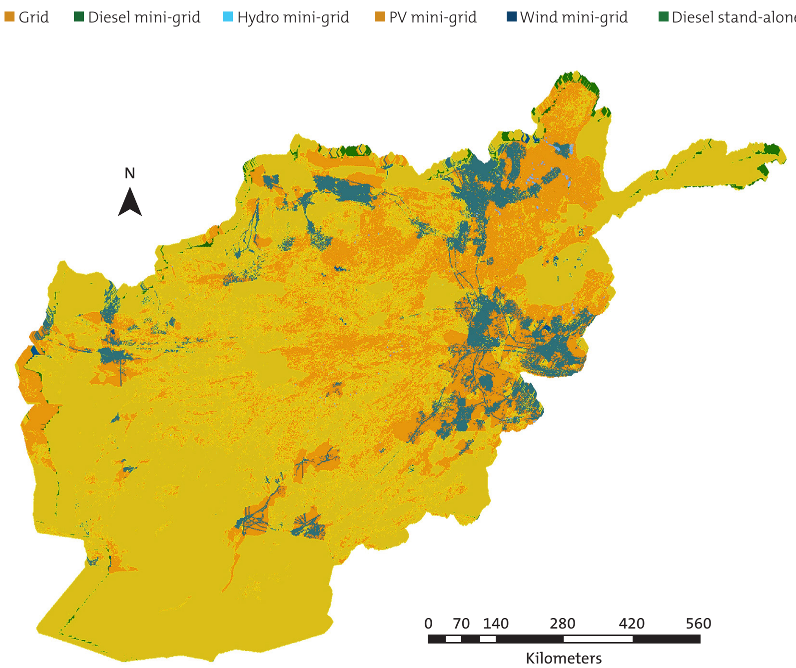
Table A.4. Scenario 4: Electrification results under the scenario defined by urban demand at tier 5, rural demand at tier 3, high diesel price, and grid cost at 0.077 $/kW

People to receive electricity by 2030: 31,999,487

By technology type	Share (%)	Capacity (MW)	Investment ($ billion)
Grid extension	45.1	1,228	9.9
Mini-grids	41.0	1,249	5.7
Diesel genset	0.1	2.2	0.01
PV system	40.2	1,233	5.6
Wind turbines	0.2	6.6	0.027
Mini–small hydro	0.5	6.6	0.056
Stand-alone	13.9	407	2.3
Diesel genset	0.03	0.486	0.014
PV systems	13.9	406	2.2
Total	**100**	**2,883.4**	**17.82**

Source: KTH dESA.
Note: kWh = kilowatt-hours; MW = megawatts; PV = photovoltaic.

Figure A.5. Scenario 5: U5–R3, HD, 0.075RE—Electrification results under the scenario defined by urban demand at tier 5, rural demand at tier 3, high diesel price, grid cost at 0.075 $kWh, and higher penetration of renewable-based technologies in the grid mix



Source: KTH dESA.

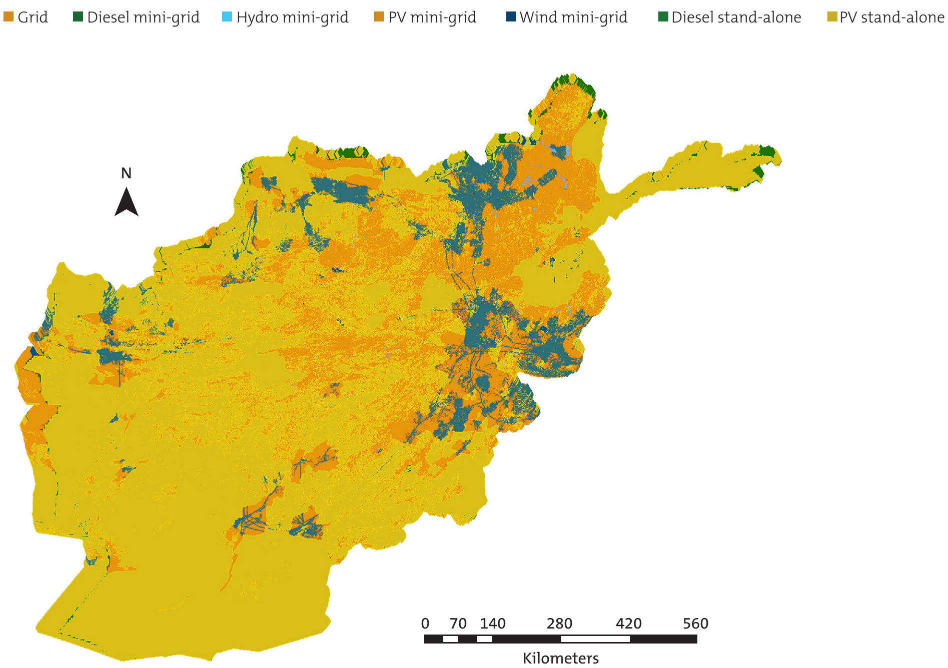
Table A.5. Scenario 5: Electrification results under the scenario defined by urban demand at tier 5, rural demand at tier 3, high diesel price, grid cost at 0.075 $/kWh, and higher penetration of renewable-based technologies in the grid mix

People to receive electricity by 2030: 31,999,487

By technology type	Share (%)	Capacity (MW)	Investment ($ billion)
Grid extension	45.5	1,233	10.02
Mini-grids	40.6	1,236	5.64
Diesel genset	0.1	2.2	0.01
PV system	39.8	1,221	5.5
Wind turbines	0.2	6.5	0.026
Mini–small hydro	0.5	6.6	0.056
Stand-alone	13.9	406	2.23
Diesel genset	0.03	0.48	0.014
PV systems	13.9	405.5	2.2
Total	**100**	**2,875.3**	**17.89**

Source: KTH dESA.
Note: kWh = kilowatt-hours; MW = megawatts; PV = photovoltaic.

Figure A.6. Scenario 6: U5–R3, HD, 0.075IM—Electrification results under the scenario defined by urban demand at tier 5, rural demand at tier 3, high diesel price, grid cost at 0.075 $/kWh, and increased imports in the grid mix



Source: KTH dESA.

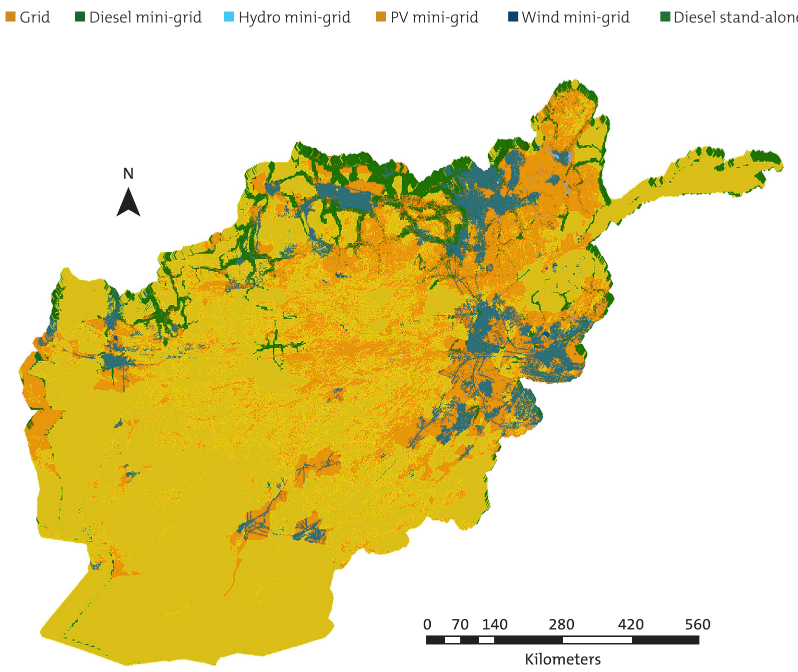
Table A.6. Scenario 6: Electrification results under the scenario defined by urban demand at tier 5, rural demand at tier 3, high diesel price, grid cost at 0.075 $/kWh, and increased imports in the grid mix

People to receive electricity by 2030: 31,999,487

By technology type	Share (%)	Capacity (MW)	Investment ($ billion)
Grid extension	45.5	1,233	8.9
Mini-grids	40.6	1,236	5.64
Diesel genset	0.13	2.2	0.01
PV system	39.7	1,221	5.5
Wind turbines	0.2	6.5	0.026
Mini–small hydro	0.5	6.6	0.056
Stand-alone	13.9	406	2.23
Diesel genset	0.03	0.5	0.014
PV systems	13.8	405.5	2.2
Total	**100**	**2,875**	**16.77**

Source: KTH dESA.
Note: kWh = kilowatt-hours; MW = megawatts; PV = photovoltaic.

Figure A.7. Scenario 7: U3–R3, LD, 0.075RE—Electrification results under the scenario defined by urban demand at tier 3, rural demand at tier 3, low diesel price, grid cost at 0.075 $/kWh, and higher penetration of renewable-based technologies in the grid mix



Source: KTH dESA.

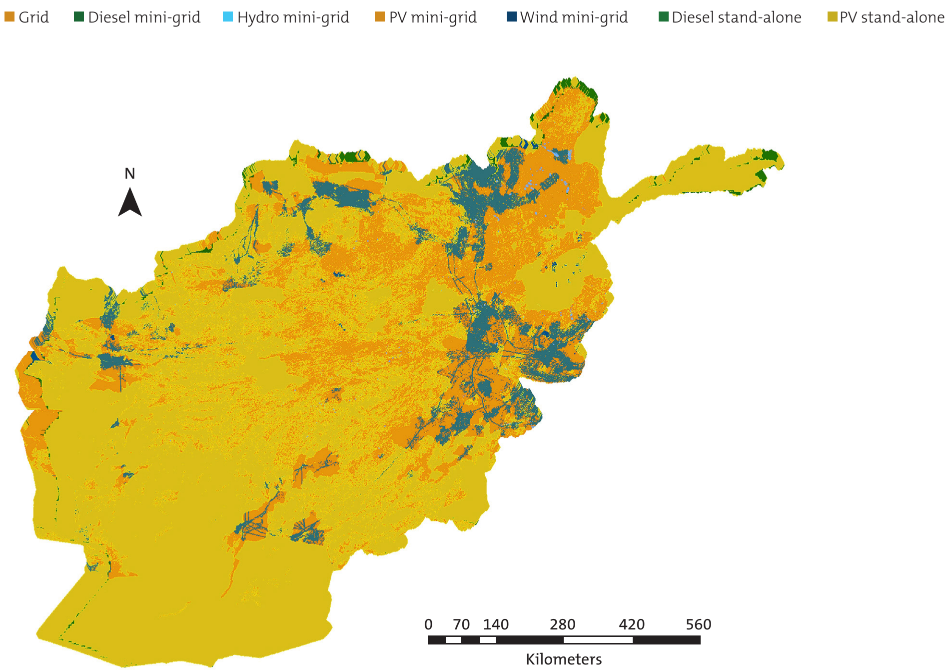
Table A.7. Scenario 7: Electrification results under the scenario defined by urban demand at tier 3, rural demand at tier 3, low diesel price, grid cost at 0.075 $/kWh, and higher penetration of renewable-based technologies in the grid mix

People to receive electricity by 2030: 31,999,487

By technology type	Share (%)	Capacity (MW)	Investment ($ billion)
Grid extension	45.2	501	5.57
Mini-grids	41.0	1,236	5.63
Diesel genset	0.8	12.8	0.051
PV system	39.6	1,212	5.5
Wind turbines	0.1	4.7	0.021
Mini–small hydro	0.5	6.4	0.056
Stand-alone	13.7	383	2.05
Diesel genset	1.2	20.5	0.061
PV systems	12.5	362.2	1.99
Total	**100**	**2,119.2**	**13.25**

Source: KTH dESA.
Note: kWh = kilowatt-hours; MW = megawatts; PV = photovoltaic.

Figure A.8. Scenario 8: U3–R3, HD, 0.077— Electrification results under the scenario defined by urban demand at tier 3, rural demand at tier 3, high diesel price, and grid cost at 0.077 $/kWh



Source: KTH dESA.

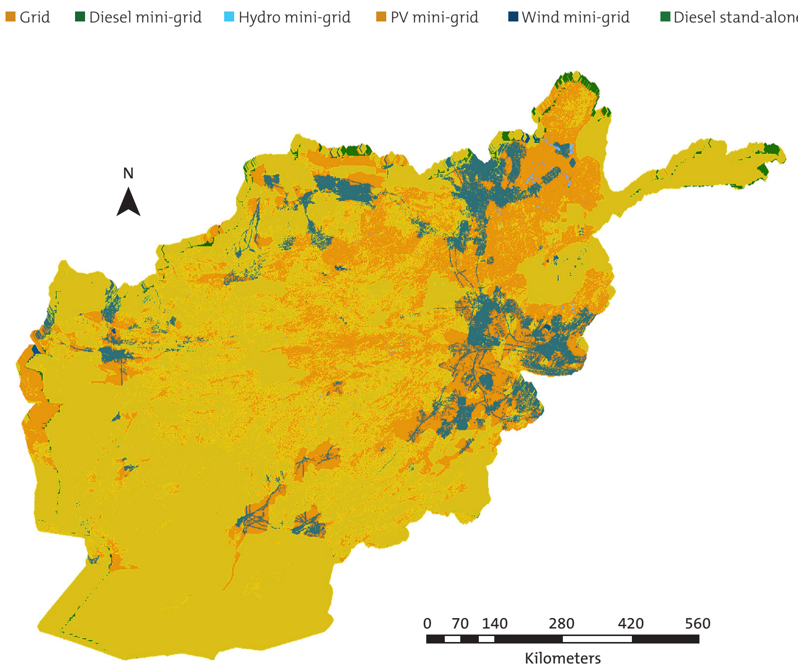
Table A.8. Scenario 8: Electrification results under the scenario defined by urban demand at tier 3, rural demand at tier 3, high diesel price, and grid cost at 0.077 $/kWh

People to receive electricity by 2030: 31,999,487

By technology type	Share (%)	Capacity (MW)	Investment ($ million)
Grid extension	45.1	499	5.53
Mini-grids	41.0	1,245	5.68
Diesel genset	0.1	2.2	0.01
PV system	40.2	1,229	5.6
Wind turbines	0.2	6.6	0.027
Mini–small hydro	0.6	6.5	0.056
Stand-alone	13.9	407	2.23
Diesel genset	0.029	0.486	0.014
PV systems	13.9	406	2.23
Total	**100**	**2,150.9**	**13.45**

Source: KTH dESA..
Note: kWh = kilowatt-hours; MW = megawatts; PV = photovoltaic.

Figure A.9. Scenario 9: U3–R3, HD, 0.075IM—Electrification results under the scenario defined by urban demand at tier 3, rural demand at tier 3, high diesel price, grid cost at 0.075 $/kWh, and increased imports in the grid mix



Source: KTH dESA.

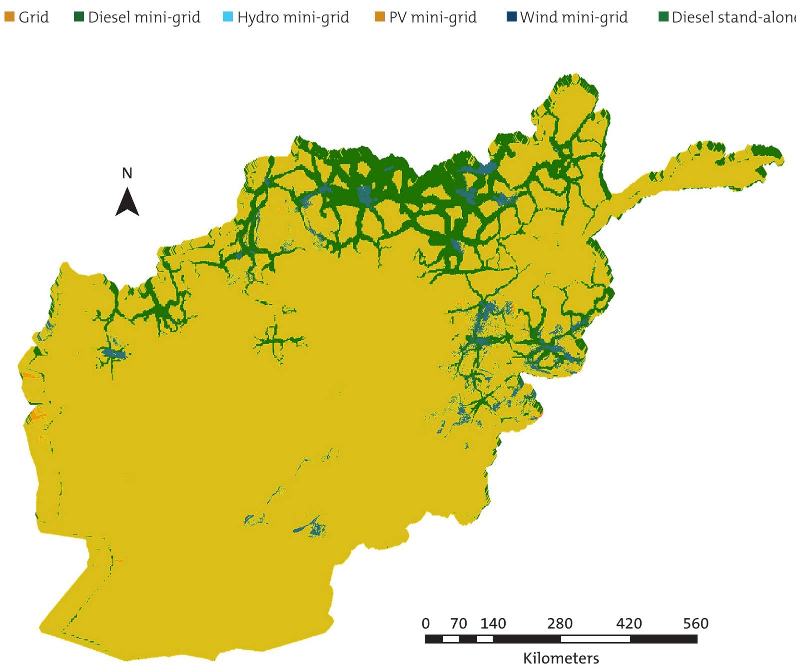
Table A.9. Scenario 9: Electrification results under the scenario defined by urban demand at tier 3, rural demand at tier 3, high diesel price, grid cost at 0.075 $/kWh, and increased imports in the grid mix

People to receive electricity by 2030: 31,999,487

By technology type	Share (%)	Capacity (MW)	Investment ($ billion)
Grid extension	45.5	504	5.62
Mini-grids	40.6	1,233	5.63
Diesel genset	0.1	2.2	0.010
PV system	39.8	1,217	5.5
Wind turbines	0.2	6.5	0.027
Mini–small hydro	0.5	6.5	0.056
Stand-alone	13.9	406	2.23
Diesel genset	0.03	0.486	0.0014
PV systems	13.9	405.8	2.2
Total	**100**	**2,142.8**	**13.48**

Source: KTH dESA.
Note: kWh = kilowatt-hours; MW = megawatts; PV = photovoltaic.

Figure A.10. Scenario 10: U4–R2, LD, 0.075IM—Electrification results under the scenario defined by urban demand at tier 4, rural demand at tier 2, low diesel price, grid cost at 0.075 $/kWh, and increased imports in the grid mix



Source: KTH dESA.

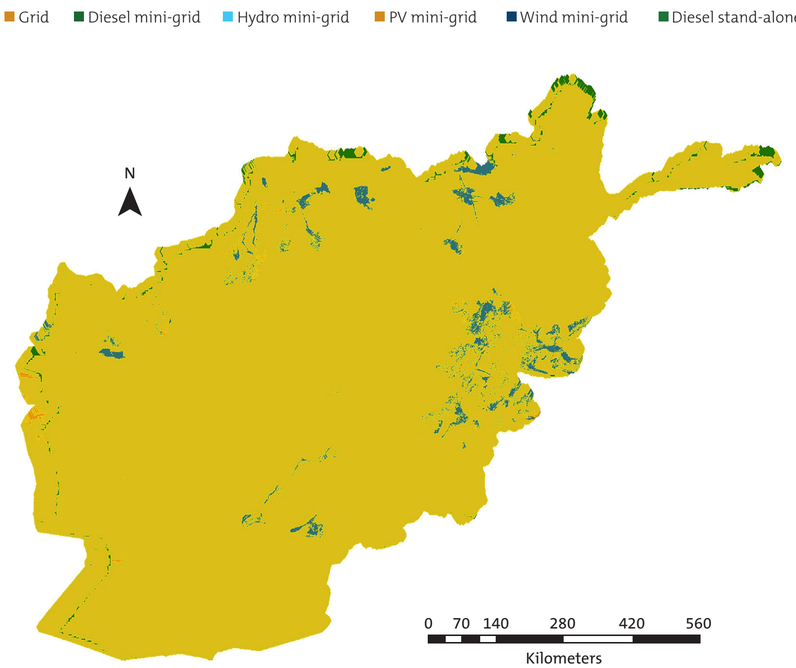
Table A.10. Scenario 10: Electrification results under the scenario defined by urban demand at tier 4, rural demand at tier 2, low diesel price, grid cost at 0.075 $/kWh, and increased imports in the grid mix

People to receive electricity by 2030: 31,999,487

By technology type	Share (%)	Capacity (MW)	Investment ($ billion)
Grid extension	27.1	707	4.89
Mini-grids	1.9	32	0.13
Diesel genset	0.044	0.594	0.0018
PV system	1.8	30.2	0.122
Wind turbines	0.001	0.017	0.001
Mini–small hydro	0.073	1.38	0.0057
Stand-alone	71.0	536	2.79
Diesel genset	12.9	59.4	0.173
PV systems	58.1	476.2	2.62
Total	**100**	**1,275.1**	**7.82**

Source: KTH dESA.
Note: kWh = kilowatt-hours; MW = megawatts; PV = photovoltaic.

Figure A.11. Scenario 11: U4–R2, HD, 0.077—Electrification results under the scenario defined by urban demand at tier 4, rural demand at tier 2, high diesel price, and grid cost at 0.077 $/kWh



Source: KTH dESA.

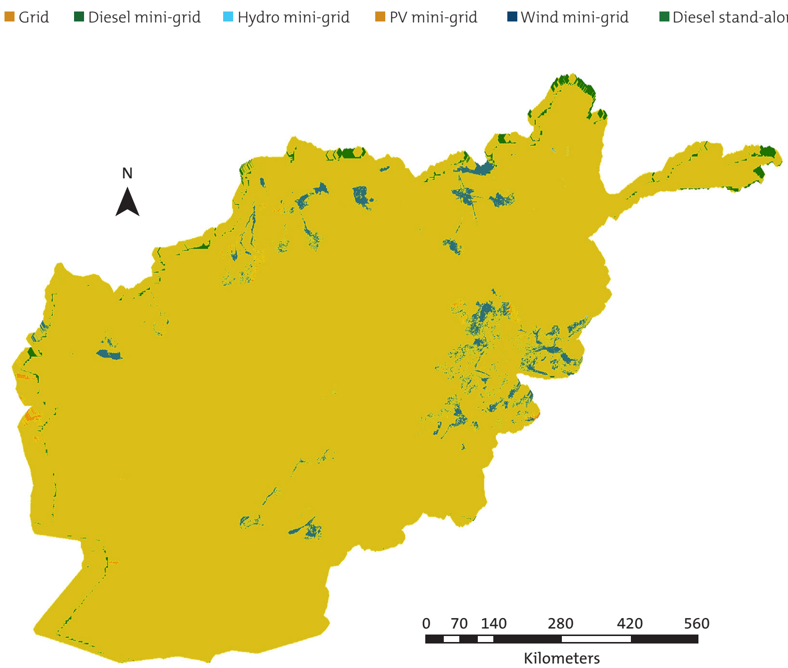
Table A.11. Scenario 11: Electrification results under the scenario defined by urban demand at tier 4, rural demand at tier 2, high diesel price, and grid cost at 0.077 $/kW

People to receive electricity by 2030: 31,999,487

By technology type	Share (%)	Capacity (MW)	Investment ($ billion)
Grid extension	27.2	708	5.56
Mini-grids	2.0	33	0.13
Diesel genset	0.05	0.631	0.002
PV system	1.9	30.6	0.124
Wind turbines	0.01	0.165	0.0007
Mini–small hydro	0.09	1.4	0.006
Stand-alone	70.8	590	3.24
Diesel genset	0.14	0.641	0.01
PV systems	70.6	889.1	3.24
Total	100	1,330.4	8.93

Source: KTH dESA.
Note: kWh = kilowatt-hours; MW = megawatts; PV = photovoltaic.

Figure A.12. Scenario 12: U4–R2, HD, 0.075IM—Electrification results under the scenario defined by urban demand at tier 4, rural demand at tier 2, high diesel price, grid cost at 0.075 $/kWh, and increased imports in the grid mix



Source: KTH dESA.

Table A.12. Scenario 12: Electrification results under the scenario defined by urban demand at tier 4, rural demand at tier 2, high diesel price, grid cost at 0.075 $/kWh, and increased imports in the grid mix

People to receive electricity by 2030: 31,999,487

By technology type	Share (%)	Capacity (MW)	Investment ($ billion)
Grid extension	27.3	708	4.9
Mini-grids	2.0	33	0.13
Diesel genset	0.05	0.631	0.002
PV system	1.84	30.3	0.122
Wind turbines	0.01	0.165	0.0008
Mini–small hydro	0.09	1.4	0.007
Stand-alone	70.8	590	3.24
Diesel genset	0.14	0.641	0.0018
PV systems	70.6	588.9	3.24
Total	**100**	**1,330.1**	**8.28**

Source: KTH dESA.
Note: kWh = kilowatt-hours; MW = megawatts; PV = photovoltaic.

Appendix B

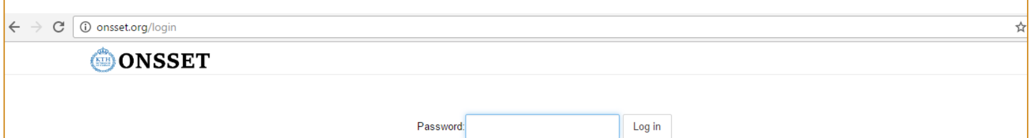
Introduction to the online interface of OnSSET
An example analysis for Afghanistan

Workshop presentation – February 1–2, 2017, New Delhi

Hands on experience with the online ONSSET tool

ONSSET - The **O**pe**N** **S**ource **S**patial **E**lectrification **T**ool

Welcome to ONSSET.org



Login password: ********

This page contains the full code for the **O**pe**N** **S**ource **S**patial **E**lectrification **T**oolkit. The designed modules will guide you through the code, as well as the various parameters that can be set to explore any scenario of interest. The code is split up into blocks, and each one has a preceding block of text to explain its function.

* Password may be made available upon request.

2

ONSSET in 6 Steps

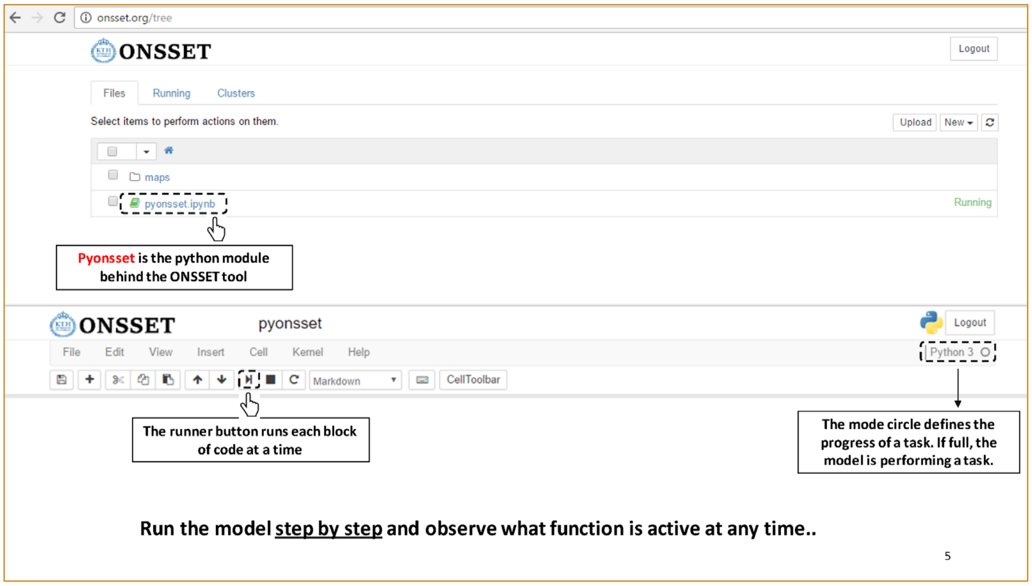
Step 1. Acquire the necessary GIS data for the area of interest[1]
Step 2. Use python techniques to extract useful information[2]

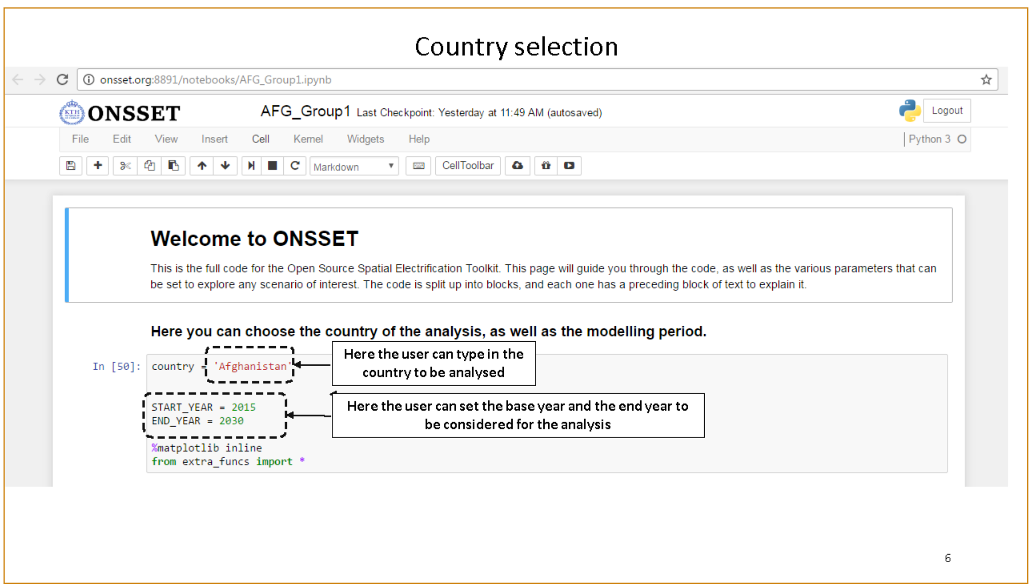
A GIS environment (ArcGIS, QGIS, GRASS) is required

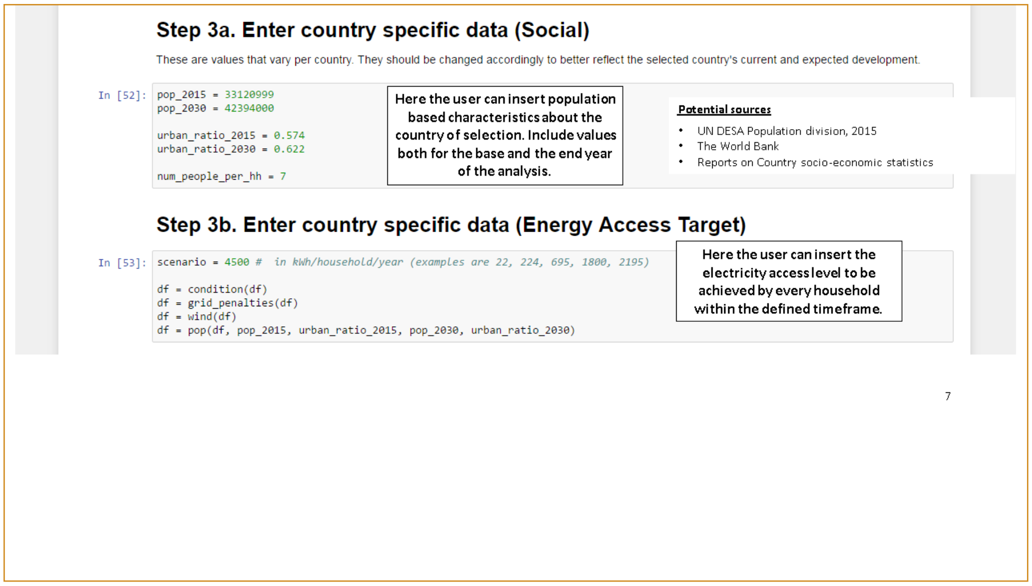
Due to the complexity involved in GIS processing and time limitations of this session, a csv file with all the necessary GIS information has already been prepared by KTH dESA. The csv files are available in the shared folder.

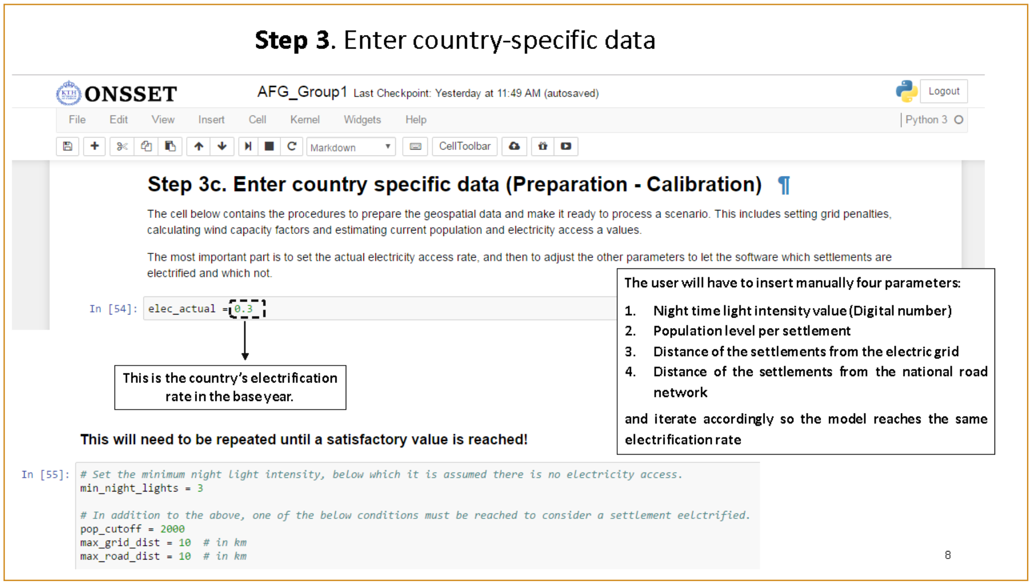
1) The list of Datasets and potential sources are available .
2) A sample GIS to CSV extraction code is available .

4


onsset.org/tree
ONSSET
Logout
Files
Running
Clusters
Select items to perform actions on them.
Upload
New
maps
pyonsset.ipynb
Running
Pyonsset is the python module behind the ONSSET tool
ONSSET
pyonsset
Logout
File
Edit
View
Insert
Cell
Kernel
Help
Python 3
Markdown
CellToolbar
The runner button runs each block of code at a time
The mode circle defines the progress of a task. If full, the model is performing a task.
Run the model step by step and observe what function is active at any time..
5


Country selection
onsset.org:8891/notebooks/AFG_Group1.ipynb
ONSSET
AFG_Group1 Last Checkpoint: Yesterday at 11:49 AM (autosaved)
Logout
File
Edit
View
Insert
Cell
Kernel
Widgets
Help
Python 3
Markdown
CellToolbar
Welcome to ONSSET
This is the full code for the Open Source Spatial Electrification Toolkit. This page will guide you through the code, as well as the various parameters that can be set to explore any scenario of interest. The code is split up into blocks, and each one has a preceding block of text to explain it.
Here you can choose the country of the analysis, as well as the modelling period.
In [50]:
country = 'Afghanistan'
Here the user can type in the country to be analysed
START_YEAR = 2015
END_YEAR = 2030
Here the user can set the base year and the end year to be considered for the analysis
%matplotlib inline
from extra_funcs import *
6


Step 3a. Enter country specific data (Social)
These are values that vary per country. They should be changed accordingly to better reflect the selected country's current and expected development.
In [52]:
pop_2015 = 33120999
pop_2030 = 42394000
urban_ratio_2015 = 0.574
urban_ratio_2030 = 0.622
num_people_per_hh = 7
Here the user can insert population based characteristics about the country of selection. Include values both for the base and the end year of the analysis.
Potential sources
UN DESA Population division, 2015
The World Bank
Reports on Country socio-economic statistics
Step 3b. Enter country specific data (Energy Access Target)
In [53]:
scenario = 4500 # in kWh/household/year (examples are 22, 224, 695, 1800, 2195)
df = condition(df)
df = grid_penalties(df)
df = wind(df)
df = pop(df, pop_2015, urban_ratio_2015, pop_2030, urban_ratio_2030)
Here the user can insert the electricity access level to be achieved by every household within the defined timeframe.
7


Step 3. Enter country-specific data
ONSSET
AFG_Group1 Last Checkpoint: Yesterday at 11:49 AM (autosaved)
Logout
File Edit View Insert Cell Kernel Widgets Help
Python 3
Markdown
CellToolbar
Step 3c. Enter country specific data (Preparation - Calibration)
The cell below contains the procedures to prepare the geospatial data and make it ready to process a scenario. This includes setting grid penalties, calculating wind capacity factors and estimating current population and electricity access a values.
The most important part is to set the actual electricity access rate, and then to adjust the other parameters to let the software which settlements are electrified and which not.
In [54]: elec_actual = 0.3
This is the country's electrification rate in the base year.
The user will have to insert manually four parameters:
1. Night time light intensity value (Digital number)
2. Population level per settlement
3. Distance of the settlements from the electric grid
4. Distance of the settlements from the national road network
and iterate accordingly so the model reaches the same electrification rate
This will need to be repeated until a satisfactory value is reached!
In [55]:
# Set the minimum night light intensity, below which it is assumed there is no electricity access.
min_night_lights = 3
# In addition to the above, one of the below conditions must be reached to consider a settlement eelctrified.
pop_cutoff = 2000
max_grid_dist = 10 # in km
max_road_dist = 10 # in km
8

Step 3. Enter country-specific data

ONSSET AFG_Group1 Last Checkpoint: Yesterday at 11:49 AM (autosaved) Logout

File Edit View Insert Cell Kernel Widgets Help | Python 3

Step 3d. Enter country specific data (Technology specifications & costs)

The cell below contains all the information that is used to calculate the levelised costs for all the technologies, including grid. These should be updated to reflect the most accurate values.

The following values can be provided by KTH dESA, based on OSeMOSYS, the open source optimization model for long-run integrated assessment and energy planning.

In [56]:

```
grid_price = 0.077 # This is the grid cost electricity USD/kWh a
grid_capacity_investment_cost = 1898.98  # The cost in USD/kW to
grid_losses = 0.21  # The fraction of electricity lost in transm
base_to_peak = 0.5296 # The ratio from peak grid demand to base
```

Here the user can insert pricing/costing information related to the national grid of the selected country. Grid_price refers to the cost at which the national grid is expected to be producing electricity over the modelling period.

This is the diesel price USD/liter as expected in the years of the analysis

In [57]:

```
diesel_price = 0.65
```

This is the expected diesel price over the modelling period.

These are the capital costs in USD/kW for each different technology.

In [58]:

```
sa_diesel_capital_cost = 1500
sa_pv_capital_cost = 5000
mg_diesel_capital_cost = 1000
mg_pv_capital_cost = 4000
mg_wind_capital_cost = 3000
mg_hydro_capital_cost = 5000
```

Here the user can insert Capital costs for the off-grid technologies.

9

Step 4. Calculate the LCoE per technology for every settlement in the country

Here is an example of how the different technologies perform under certain assumptions:

- **Distance from the National Electricity grid:** 20 km
- **Global Horizontal Irradiation:** 1500 kWh/m2/year
- **Hydro Availability:** Positive
- **Wind capacity factor: 40%**
- **Diesel price:** 0.345 USD/liter

LCoE Tables

Example of LCoE variation per technology depending on number of people per settlement

	grid	sa_diesel	sa_pv	mg_diesel	mg_pv	mg_wind	mg_hydro
10 people	22.343413	0.202476	0.543061	4.174740	4.144666	3.892932	3.855849
500 people	1.183240	0.202476	0.543061	0.739085	0.943454	0.691720	0.645202
1000 people	0.763193	0.202476	0.543061	0.573335	0.789014	0.537280	0.499585
2000 people	0.502091	0.202476	0.543061	0.456132	0.679809	0.428075	0.397133
5000 people	0.333594	0.202476	0.543061	0.352134	0.582908	0.331174	0.306582
10000 people	0.257903	0.202476	0.543061	0.299719	0.534070	0.282335	0.261071

Grid LCoE reduces in areas with high population density and proximity to the national grid

Mini-grid LCoEs depend usually on resource availability and fuel costs

Stand alone systems LCoEs change on later stage according to transportation costs

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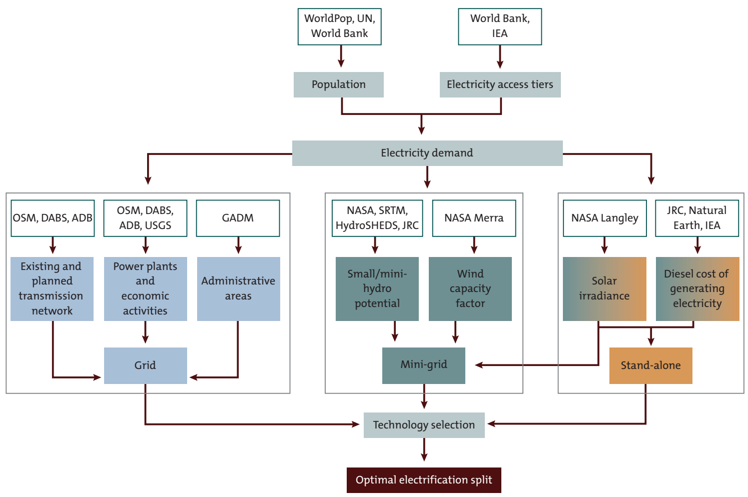
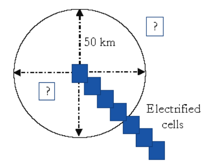
Step 5. Grid extensions - The electrification algorithm





1. Is the total additional MV line less than **50 km**?

2. Is there **adequate amount of people** (thus demand) to justify an extension of the grid?

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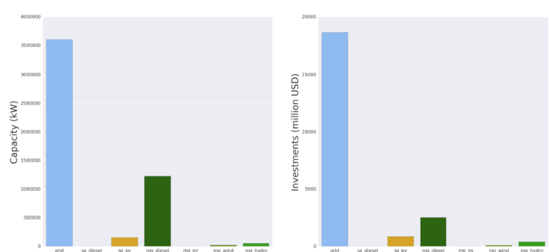
Step 6. Results, Summaries and Visualization

Based on the optimal split identify per technology:

- New connections by 2030
- Additional capacity needed
- Investments requirements

	Population	New connections	Capacity (kW)	Investments (million USD)
grid	36062520	26023100	3605964	18648.91
sa_diesel	0	0	0	0.00
sa_pv	447335	447335	155630	855.97
mg_diesel	5861689	5861689	1229037	2531.54
mg_pv	2117	2117	708	4.10
mg_wind	63415	63415	22833	98.41
mg_hydro	369643	369643	54252	405.53
Total	42806722	32767302	5068427	22544.46



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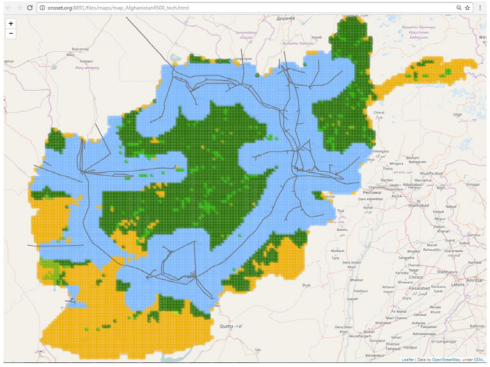
Step 6. Results, Summaries and Visualization

Map of technology split

Colour coding for technology split:

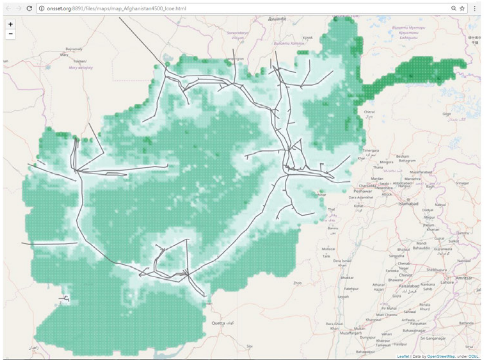
•Grid •SA Diesel •SA PV •MG Diesel •MG PV •Wind •Hydro



Map of electricity cost

Colour coding for LCOE, in USD/kWh

0.077 0.6



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