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live wire
A KNOWLEDGE NOTE SERIES FOR THE ENERGY & EXTRACTIVES GLOBAL PRACTICE

A GIS approach to planning electrification in Afghanistan

THE BOTTOM LINE

A new database of geospatial information and a related model allow Afghani planners to estimate, analyze, and visualize the most cost-effective electrification options for the achievement of electricity access goals. The tool is focused on the assessment and deployment of primarily renewable technologies to "ensure access to affordable, reliable, sustainable and modern energy for all" (Sustainable Development Goal 7).

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Why is this issue important?

Electrification promises significant social and economic returns in Afghanistan

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. Per capita consumption averages 186 kilowatt-hours (kWh) per year, significantly less than the South Asia average of 707 kWh and far below the global average of 3,126 kWh (based on authors' calculations and 2014 World Bank data). Accessing the electricity grid remains a serious challenge in rural areas, where three-quarters of Afghans live and only 11 percent are connected to the grid (CSO 2016).

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.

The study summarized here (Korkovelos and others 2017) offers an initial, "quick pass" analysis of 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 so as to enable the national government to make energy investments that will widen 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:

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

The study on which this Live Wire is based corresponds to the fourth of these five parts. It aims to provide a sense of the scale of the investments needed to electrify the country and to inform a more detailed analysis.

How can access be improved?

Through careful planning and solutions that take into account "spatial diversity"

The recent experience of electricity utilities in many developing countries has shown that spatial diversity—that is, diversity in demographic attributes, terrain types, wealth levels, access to infrastructure, resource availability, and other factors—affects the planning of electrification. These factors need to be captured quantitatively and with local specificity using a data-modeling platform that will allow 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 compiling geospatial datasets, which, in turn, permit the rapid creation of electrification plans with quantitative and spatial specificity and accuracy.

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Recent global experience shows that the most effective and efficient way of achieving a rapid increase in electrification is through a sectorwide 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. Under such an approach, implementation relies on solutions aligned with a least-cost national electrification plan as well as financial and physical resources mobilized in a predictable and structured fashion, while allowing for uncertainty in security conditions.

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

Geospatial energy planning. Moving from planned, centralized, and expensive energy carriers toward fluctuating, decentralized, and cost-effective renewable energy production necessitates considerable modifications of energy infrastructure that must be carefully planned for optimal results. Because these modifications are most often motivated by geospatial concerns, ground-level geospatial data are of key importance in identifying the most effective electrification strategy. But acquiring energy-related data at the local level is a challenging task.

In 2017, the Division of Energy Systems Analysis of the KTH Royal Institute of Technology in Sweden (KTH dESA)[1] 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 options for the achievement of electricity access goals and "ensure access to affordable, reliable, sustainable and modern energy for all" (Sustainable Development Goal 7).[2] It can be used to assess options across population settlements in well-defined locations and to reveal patterns at the national or subnational levels. The tool's prime focus is the identification of the additional capacity and investment required to fulfill energy-planning goals.

KTH dESA and the World Bank have collected and processed the data on the various "layers" required to represent the present status of Afghanistan's energy sector with as much accuracy as possible given data constraints. Data were gathered for 2011–16 and are considered the best available as of December 2016. The layers populate a geodatabase available at https://energydata.info. The data layers are:

- Administrative boundaries
- Population distribution and density
- Nighttime light
- Land cover
- Digital elevation
- Mini/small hydropower potential (with restrictions)
- Solar irradiation (with restrictions)
- Wind power capacity factor (with restrictions)
- Travel time to nearest town
- Road network (existing and planned)
- Transmission network (existing and planned)
- Power plants (existing and planned)
- Substations (existing and planned)
- Quarries and mines

Identifying demand. Forecasting a population's size and purchasing power is central to any least-cost electrification analysis because the number of people in a given area, and their income, are key drivers of future demand for electricity and thus of the payback 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 as migratory patterns, a complex task.

[1] https://www.kth.se/en/itm/om/organisation/institutioner/energiteknik/forskningsavdelningar/desa. A preview of this work can be found in Mentis and others (2015) and Fuso Nerini and others (2016).

[2] UN Sustainable Development Goals: http://www.un.org/sustainabledevelopment/energy.

Table 1. 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 (e.g., food processing, refrigeration)	Tier 3 + medium-power or continuous appliances (e.g., water heating, ironing, water pumping, rice cooking, microwave)	Tier 4 + high-power and continuous appliances (e.g., 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 IEA and World Bank 2015.

In Afghanistan, a plan that relies solely on grid expansion can be expected to increase the rate of electrification only slowly. 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.

OnSSET uses five tiers for household electricity consumption, starting from very low to high (table 1). Urban population growth estimates are separated from rural, since these two groups usually follow slightly different growth profiles. The lowest assumed consumption allows no more than low-consumption tasks, such as turning on a light for a few hours or charging a mobile-phone. The highest consumption tier allows for energy services such as continuous lighting and running a refrigerator or air conditioner.

Electricity access targets in Afghanistan. It is estimated that approximately 29 percent of the Afghan population has access to the national electric grid, with the rate of access higher for urban households (approximately 88 percent) than for rural households (approximately 11 percent).[3] The consumption of connected households varies significantly across provinces. For example, annual 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 centers such as Kabul (3,000 kWh per household) and Herat (2,600kWh per household). Interestingly, households not connected to grid electricity seem to have access to some source of electricity, mostly solar and batteries. This electricity is used primarily for lighting or occasionally to power low-consumption household devices.

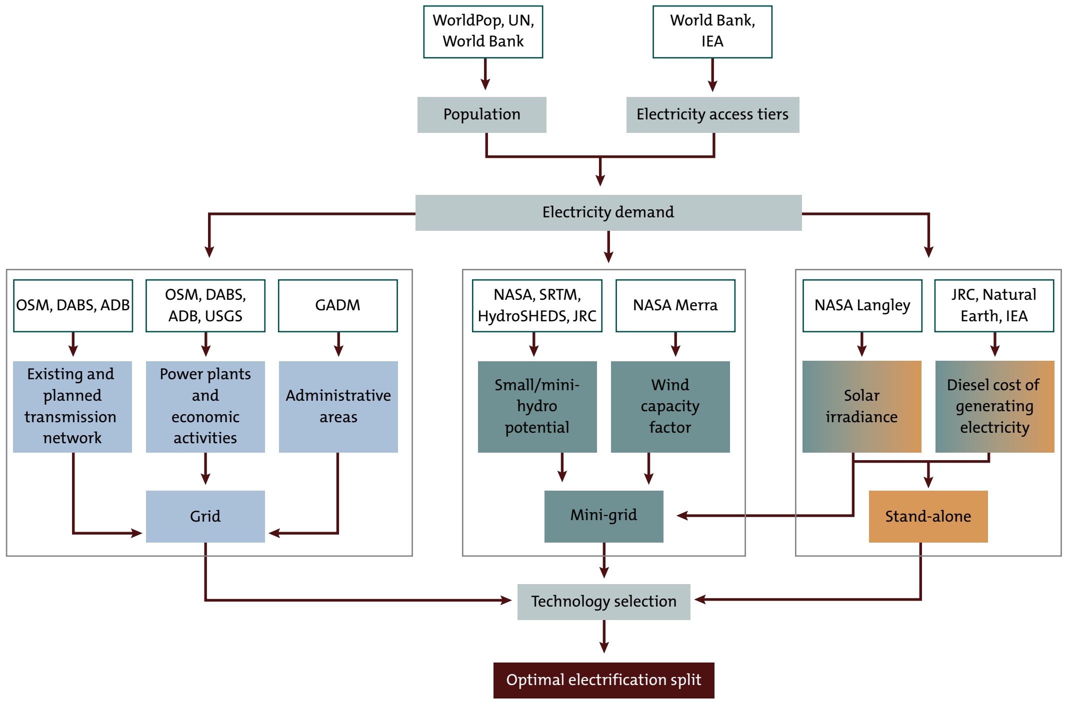
Based on the Power Sector Master Plan estimates, the average annual electricity consumption in Afghanistan by 2030 will be approximately 1,500 kWh/household. Using this estimate, tier 5 (4,190 kWh/household) and tier 3 (1,301 kWh/household) were selected as base electricity access targets for urban and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

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 (2030). Because every location has different characteristics, some of which might favor one technology over another, it is unlikely that using only one

3 The sources for the data presented in this section are ADB (2013), ANPDF (2016), CSO (2016), and Infrastructure Development Cluster (2012).

Forecasting a population's size and purchasing power is central to any least-cost electrification analysis and related capital plan. But estimating population growth is not a straightforward task. Changes in socioeconomic conditions make the estimation of future fertility and mortality rates, as well as migratory patterns, a complex task.

Figure 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.

technology could achieve this goal. The OnSSET methodology considers seven technological options. These are arranged into three main electrification categories: grid, mini-grid, and stand-alone systems.

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. 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 1 schematically represents the main methodological processes of OnSSET.

Generating scenarios. OnSSET makes it possible to investigate alternative pathways for electrification through the generation of scenarios. Thirty-two scenarios have been developed for Afghanistan that consider variations in electricity consumption (a function of the access target), diesel price, and grid cost (or cost of electricity)—the main input parameters considered in the construction of the scenarios.

According to the National Energy Supply Plan and the Power Sector Master Plan study, approximately 3,000 MW are planned to be added to the national system by 2025. This entails 2,500 MW from 13 hydropower projects and 600 MW from coal power plants. Solar and wind are additional sources with high estimated potential. 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.

- *Energy access target.* The level of electricity to be provided may vary significantly from area to area. In this study, we consider two population groups: urban and rural. Since 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 set assumes different access targets for urban and rural areas, while the second assumes the same access target for all settlements by 2030.
- *Diesel price.* Diesel generators are an established and reliable technology used for electrification, especially in remote areas but also as backup alternatives throughout Afghanistan. Despite the low capital investment required up front, diesel generators can entail high operating costs, depending on the fuel price. To account for price fluctuation, scenarios were constructed with low and high fuel price. One assumes that the price of diesel will remain close to the current low levels (at about $0.69/liter), while the second assumes an increase to $1/liter.
- *Price of electricity furnished by the national grid.* Previous electrification efforts have shown that the expansion of an electricity grid 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 does not distinguish between the different technologies in the grid's generation mix; instead, it sees the grid as a "black box." 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. 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; Shift Project Data Portal 2015). Based on this mix, the cost of generation was estimated at approximately $0.062/kWh.

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 and the Power Sector Master Plan study, approximately 3,000 MW are planned to be added to the national system by 2025 (ADB 2013; Infrastructure Development Cluster 2012). 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. Solar and wind are additional sources with high estimated potential (wind power is estimated at 158 GW) (ADB 2013). 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.[4]

Three alternative paths were created to incorporate the government's plans into OnSSET. The first assumes that electricity imports will remain stable, with the additional capacity to come primarily from hydropower, coal, and natural-gas-fired power plants. Reduced use of diesel generators is also included. This would force the generating cost (used as an input in the model run) up to $0.077/kWh. The estimated capital investment requirement would be $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 OnSSET. It was assumed that imports would remain the same, while 40 MW of solar and 26 MW of wind would replace the oil-based generators. This would result in a lower generation cost of approximately $0.075/kWh but a higher capital investment requirement ($1,989/kW).

The third path was developed to illustrate how the grid electricity cost would react if more imports were needed to cover the expected demand. To illustrate that, the planned domestic generation capacity was kept below 3,000 MW and imports were increased. The grid cost in this scenario was estimated at $0.075/kWh, with lower capital investment requirements than in the previous cases ($1,603/kW).

4 Interconnectivity is provided under the Turkmenistan-Uzbekistan-Tajikistan-Afghanistan-Pakistan (TUTAP) electricity project; the Turkmenistan-Afghanistan-Pakistan India (TAPI) gas pipeline; and the Central Asia South Asia Electricity Transmission and Trade Project (CASA).

KTH dESA has developed an online open interface to support the use of the Open Source Spatial Electrification Tool (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 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.

Table 2. Grid cost ($/kWh) under 32 electrification scenarios investigated for Afghanistan, by diesel price and electricity consumption tier

Twelve selected scenarios (highlighted in green) are discussed in the text

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; IM refers to increased imports from neighboring countries.

How can the geospatial tool OnSSET help planners?

OnSSET is a user-friendly online interface that helps planners decide whether a grid connection is the best option under various circumstances

To summarize, KTH dESA has developed 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 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.

As noted, 32 scenarios have been created for Afghanistan (table 2). Twelve of them, shaded in the table, are presented here to illustrate OnSSET's capabilities.

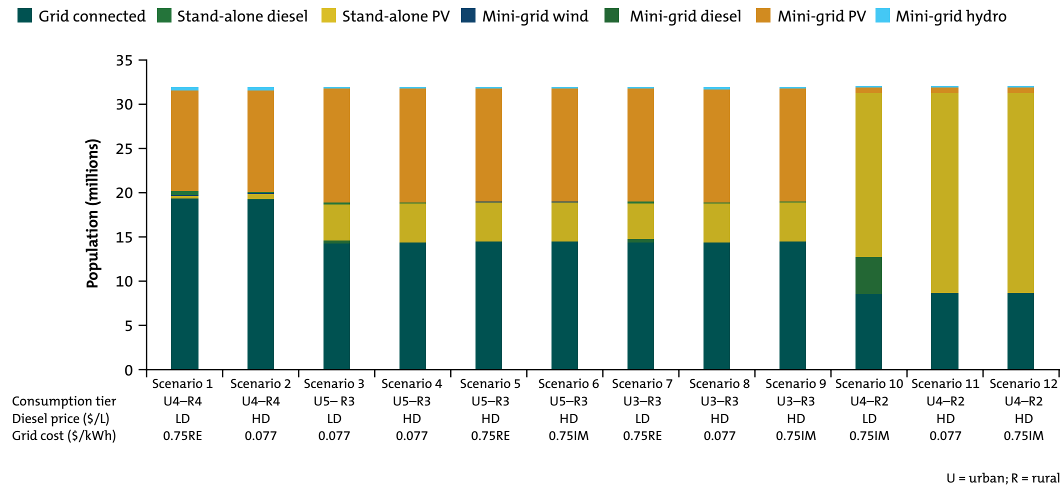
Figures 2, 3, and 4 provide a quick overview of some of the results for the 12 selected scenarios. The graphs allow for quantitative comparisons of the implications of each scenario for technology share, added capacity, and investment requirements.

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 settlement in the country according to the specified resolution (in this case 1x1 km). This file is used to retrieve location-specific information and to display the results on detailed maps. 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.[5]

[5] The files for all the scenarios developed for Afghanistan are available at the following link: https://energydata.info.

Assuming a midrange electricity consumption per household makes grid connection a more viable option (to the detriment of stand-alone options).

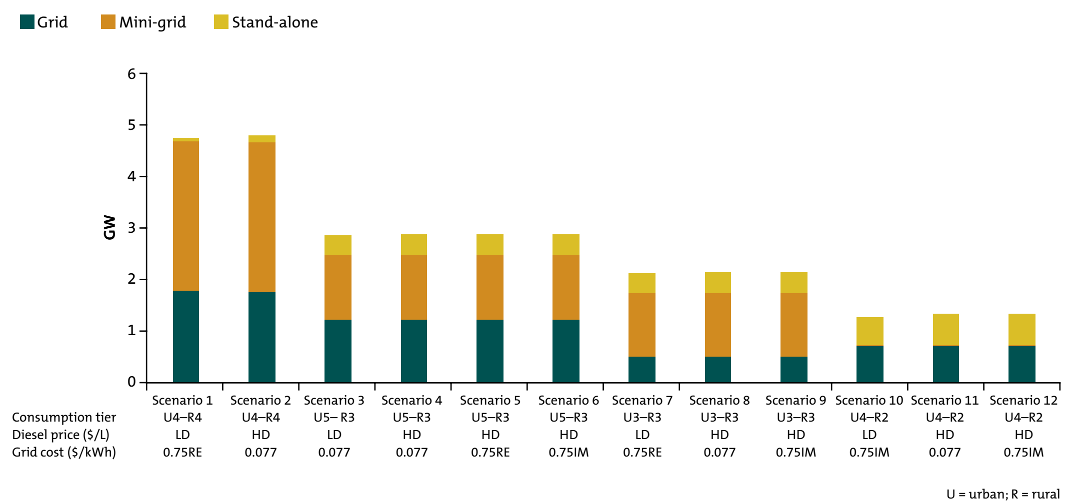
Figure 2. Newly electrified population, by technology



Source: KTH dESA.

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

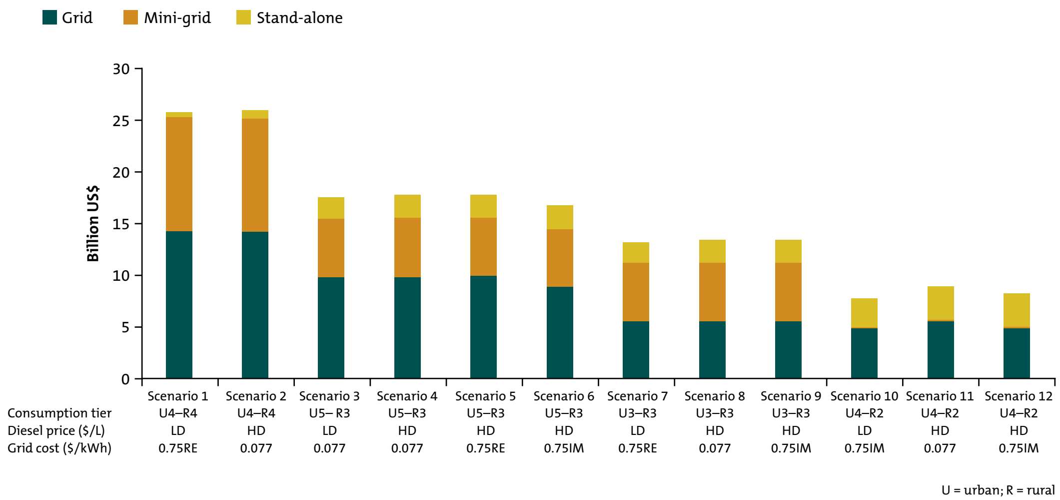
Figure 3. New capacity required, by system type



Source: KTH dESA.

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

Figure 4. Investment required, by system type



Source: KTH dESA.

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

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.

The maps, three samples of which are shown in figure 5, allow for qualitative comparisons of the parameters that most influence the penetration of different technologies in the generation mix.

OnSSET 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.

The cost of ensuring access to electricity for all Afghanis by 2030 lies between $7.82 billion and $26.04 billion. These figures include the up-front capital investments needed to extend the transmission and distribution network, build the mini-grid systems, and install the stand-alone solar and diesel technologies. The model finds that between 55 and 73 percent of the population may be receiving electricity through off-grid technologies.

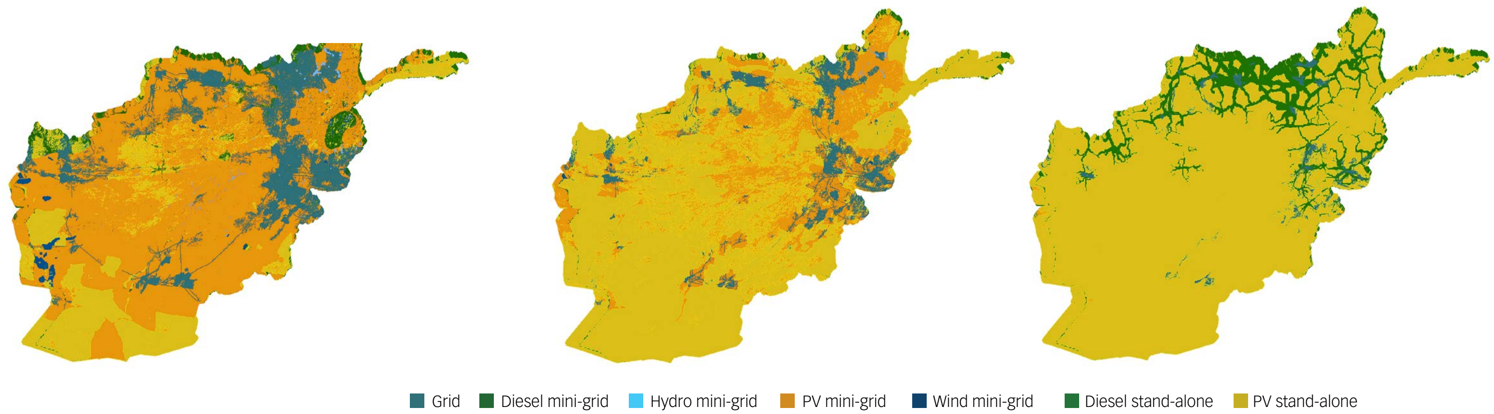
The lower a household's electricity consumption and the lower the diesel price, the lower the overall investment needed to reach universal access. The lowest-cost investment ticket for providing universal access corresponds to the case where consumption is assumed to be lowest (tier 4 for urban, tier 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 a high diesel price.

Figure 5. Summarized results

a. Scenario 1: U4–R4, LD, 0.075 RE

b. Scenario 8: U3–R3, HD, 0.077

c. Scenario 10: U4–R2, LD, 0.075 IM



Source: KTH dESA.

Note: Ux–Rx refers to the electrification tier for urban and rural settlements, respectively (see table 1); RE refers to the alternative path with increased penetration of renewable-based technologies (solar, wind); IM refers to the alternative path with increased imports from neighboring countries. LD = low diesel price; HD = high diesel price.

The cost of ensuring access to electricity for all Afghanis by 2030 lies between $7.82 billion and $26.04 billion. These figures include the up-front capital investments needed to extend the transmission and distribution network, build the mini-grid systems, and install the stand-alone solar and diesel 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 also increases the average contribution of renewable sources.

Caveats?

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 (Open Source Energy Modelling System) 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 impact the electrification mix.

A final word of caution: The model quantifies electrification targets for Afghanistan by 2030. It highlights the challenges ahead for policy and decision makers charged with implementing energy

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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. But it does not imply the implementation of the identified strategies or the provision of necessary finance.

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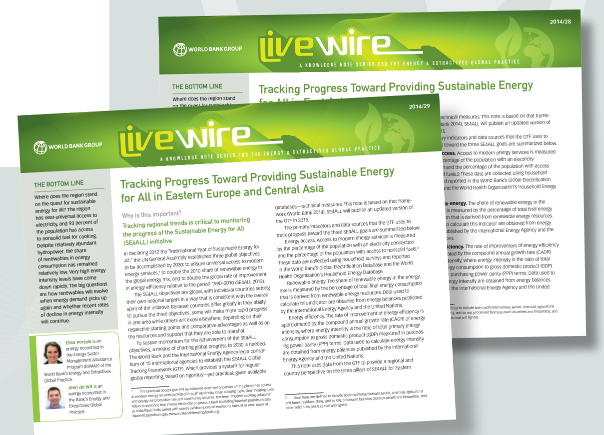

Contribute to livewire

Do you have something to say? Say it in *Live Wire!*

Those working on the front lines of energy and extractives development in emerging economies have a wealth of technical knowledge and case experience to share with their colleagues but seldom have the time to write for publication.

Live Wire offers prospective authors a support system to make sharing your knowledge as easy as possible:

- Trained writers among our staff will be assigned upon request to draft *Live Wire* stories with staff active in operations.
- A professional series editor ensures that the writing is punchy and accessible.
- A professional graphic designer assures that the final product looks great—a feather in your cap!

Live Wire aims to raise the profile of operational staff wherever they are based; those with hands-on knowledge to share. That's your payoff! It's a chance to model good "knowledge citizenship" and participate in the ongoing change process at the Bank, where knowledge management is becoming everybody's business.

If you can't spare the time to contribute to *Live Wire,* but have an idea for a topic, or case we should cover, let us know!

We welcome your ideas through any of the following channels:

Via the Communities of Practice in which you are active

By participating in the Energy and Extractives Global Practice's annual *Live Wire* series review meeting

By communicating directly with the team (contact Morgan Bazilian, mbazilian@worldbank.org)