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Analysis of Solar Photovoltaic and Wind Power Potential in Afghanistan

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Analysis of Renewable Energy Potential in Balkh and Herat Provinces of Afghanistan

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Abstract

We analyze the potential of solar and wind energy sources in Afghanistan's most populous provinces (Balkh and heart) for large scale grid-connected power generation to meet a fraction of the growing Afghan electricity demand. The analysis is performed by quantifying resource quality and variability. The quality of solar and wind resources are quantified by characterizing wind speed and solar radiation and calculating seasonal and annual net capacity factors and energy yields from hypothetical power plants using measured wind speed and typical solar radiation data. Variability of wind and solar resources are quantified by comparing their daily and seasonal profiles with electricity demand profiles, analyzing their impacts on load duration curves and determining their penetration and curtailment levels for various demands scenarios.

1. Introduction

Modern energy systems are a key factor in furthering development. Although the Millennium Development Goals [xxx] do not explicitly address energy, there is an implicit recognition of the critical nature of energy access. Perhaps more specifically, bringing electrification to developing countries is a clear prerequisite for development. However one defines sustainability with respect to energy systems, reliability and affordability over the long-term must be included as criteria. In addition, given the challenge of mitigating the effects of anthropogenic climate change, a truly sustainable energy system should respect the need for minimal carbon emissions.

Development paths of industrialized countries were enabled through the combustion of fossil fuels over the past two centuries (but especially during the past 50 years, a period in which over 75% of total historical emissions have occurred). Often, those countries with particularly large endowments of fossil fuels were also profligate in their use of these resources, with concerns about efficiency being secondary. Now there are also increasing concerns about not only the detrimental effects of climate change, but also about fossil fuel scarcity, as evidenced by consistently high and increasing prices over the past decade. Thus, the development path of choice, or rather, of chance, for the wealthiest countries today, may not be easily available for developing countries today. This would appear to be a very uncomfortable dilemma if not for the fortunate fact that the cost of renewable energy sources has declined dramatically over the past ten to twenty years. Therefore, it is possible that with careful planning and foresight, an alternate development path is possible, one that looks not only to the necessity of near-term improvements in standard of living, but also to the long-term viability of that chosen pathway.

Many integrated assessment models (IAMs) of climate change mitigation policy, and effectively, of energy system transformation, find relatively low costs for a process of reducing carbon emissions to near-zero levels over the course of this century. Although there is reason to be skeptical of the optimistic projections for increased wealth or development, while expecting very low levels of per capita energy consumption [xxx] the fact remains that options are available. In this work we present a detailed study of the most populous areas in Afghanistan where renewable energy sources, specifically solar PV and wind, can meet significant portions of electricity demand in the future.

In what follows, we first review current energy consumption and production in Afghanistan (Sec. 2) and previous studies regarding the potential of large scale solar PV or wind power plants in Afghanistan. (Sec. 3). In Sec. 4 we describe our methodology for assessing wind and solar resource potential, followed by a description of data sources in Sec. 5. Modeled outputs for potential wind and solar PV generating capacity are presented in Sec.6 and Sec. 7, respectively. The core of this work is the analysis of demand characteristics as related to the generation of wind and solar power (Sec. 8 and 9), followed by a discussion of results in Sec. 10.

2. Energy consumption and production in Afghanistan

Gross electricity consumption in Afghanistan was 140 kWh per capita in 2011, one of the lowest rates in the world [xxx]. The average household consumption rate varies from 3000 kWh/year in Kabul Province to 178 kWh/year in Ghor Province [xxx]. Currently, only 28% of the population is connected to the electricity grid [xxx]. On the other hand, gross electricity demand is estimated to grow at a rate of 8.7% per year by 2032 [xxx]. Annual gross demand for the whole country is projected to increase from 3,531 GWh (2011) to 18,409 GWh (2032) and annual peak demand from 742 MW (2011) to 3,502 MW (2032) [xxx]. Further grid connection of individuals is expected to reach about 83% by this time [xxx]. This growth in demand and electric connection means that Afghanistan would need about five times more electrical energy than was produced in 2011.

Afghanistan so far does not have an interconnected centralized power system, however, interconnection of all grid segments is proposed by year 2032 [xxx]. In addition, there are many decentralized local grid and stand-alone system such as solar PV and diesel generators providing electricity. Installed capacity (not operating capacity) of existing grid-connected electricity generation assets reaches about 1,338 MW including imports from Tajikistan, Uzbekistan, Iran and Turkmenistan [xxx]. Imports account for about 63% of total grid-connected capacity, while hydro power and thermal (diesel-fired) power plants make up the rest, with each having about the same share. Currently about 134 MW [xxx] of decentralized power generators are installed around the country mostly in rural areas, more than half of which are diesel generators. Solar PV (13 MW), micro-hydro power (36.65 MW), and wind power (~200 KW) comprise the rest of Afghan decentralized generating capacity.

Figure 1 shows the share of each energy producing source in the Afghan power system in 2011. Total generation was recorded to be 3,088 GWh [xxx]. Imports made up about 73% of total generation. The majority of imported power was thermal-based, with some hydropower from Tajikistan. Domestic hydropower and diesel fired power plants each contributed 26% and 1.3% respectively. It should be noted, though, that the share of diesel power plants could be higher due to missing and incomplete data.

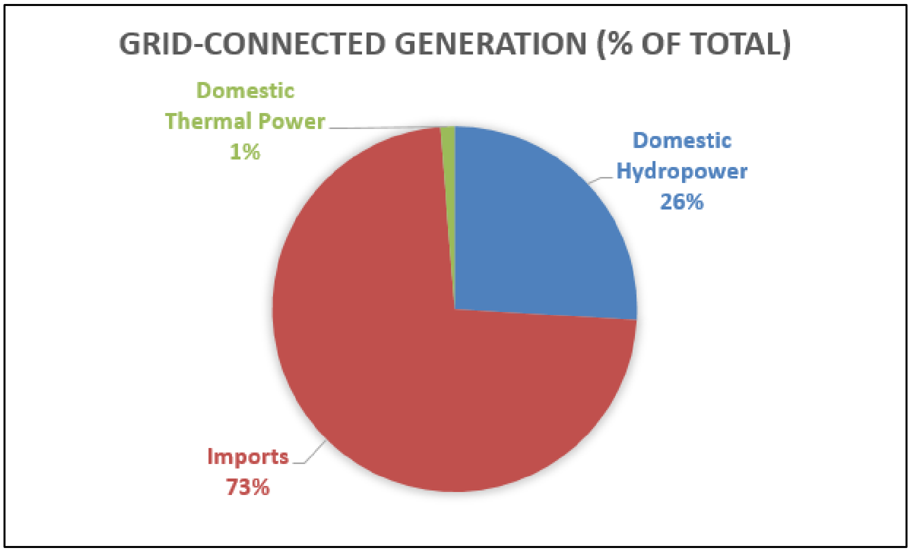


Figure 1 Share of energy generation sources in 2011

A majority of existing and planned hydropower plants use day storage rather than run-of-the river generation [xxx]. The main hydro plants with day storage are Naghlu (100 MW) and Mahipar (66 MW). Examples of run-of-the river hydro plants are Grishk (2.4 MW) and Puli-Khomri (8.2 MW). Thermal power plants are mainly reciprocating engines run by diesel fuel. The only two large-scale gas turbine generators are NW Kabul 21.8 MW and NW Kabul 23 MW.

Stand-alone off-grid solar and wind energy technologies have thus far been seen as a favorable solution to electrify rural areas in Afghanistan by the government, donor agencies and communities themselves. The main reasons are lower operating costs, technical simplicity, and short installation time. Currently, there are no utility-scale solar PV or wind power plants. The largest renewable energy system feeding a local grid is a 1 MW solar PV plant with battery storage in the central province of Bamyan. In the next section we review some of the main studies regarding the potential of large scale solar PV or wind power plants in Afghanistan.

3. Review of previous renewable energy studies for Afghanistan

The U.S. National Renewable Energy Laboratory (NREL) [xxx] published a 1-km resolution wind map at 50 m for Afghanistan in 2007 to quantify wind resource potential and identify possible locations for further on-site wind measurement campaigns. The dataset includes average monthly wind speeds together with some statistical parameters such as wind power density, A Weibull shape factor, windiest hour, diurnal strength, and an autocorrelation factor was established for each 1 km^2 grid in Afghanistan. NREL's estimates showed a resource potential of about 158 GW. While macroscopically useful, this dataset is insufficient to model the energy production of an actual wind farm since it ignores wind speed variations due particularly to terrain variation, which is significant in the Afghan provinces considered in this study.

Relative to solar energy, NREL [xxx] also produced high-resolution satellite-derived global horizontal and direct normal irradiance data for Afghanistan. The datasets are in a gridded format and have a ground resolution of 0.1 degrees latitude and 0.1 degrees longitude (8.5 km x 10 km). Irradiance datasets include monthly averages over a three year period from 2002-2005.

In another study, Tetra Tech [xxx] used multi-criteria geographic information system (GIS) analysis and identified a total of 10 sites located in the provinces of Herat (x3), Balkh (x5) and Kabul (x2) for future wind farm development, and subsequently installed wind measurement instruments to measure wind speed at these sites in order to estimate installed capacities and capacity factors. The study used NREL's modeled wind resource maps together with available GIS data to determine the technical and economic potential of these sites. No resource and demand matching exercise was conducted to analyze resource variability. The total economic potential of these sites was estimated to be about 1.045 GW of installed capacity.

Foster [xxx] assessed the feasibility of interconnecting a 10 MWe photovoltaic (PV) system in the Kandahar City utility as part of the USAID-funded Afghanistan Clean Energy Program (ACEP). This study assumed a 1-axis tracking PV system without storage connected to the local grid. Monthly solar radiation and air temperature were used to calculate system energy generation and capacity factor. A Life Cycle Cost (LCC) analysis was used to determine total installed cost, net present value, and amortized cost of energy. The annual average estimated capacity factor was 23%.

NRECA International [xxx] evaluated the response of transmission networks in the Balkh and Herat provinces to carry hypothetical levels of wind penetration and determined the maximum installed capacity of wind farms without disrupting the quality of the supplied power to the customers. This study showed that the Balkh and Herat power systems could handle wind power plant installed capacities of up to 85 MW and 16.5 MW(roughly respectively if these systems were to be upgraded. This capacity would only supplant a meager 4.7% of the current power capacity in the country.

Foster [xxx] compared a proposed 1 MW grid-tied solar PV power system with a potential 1 MW micro-hydro power in Bamyan Province. He concluded that it was a logical choice to install a 1 MW micro-hydro power plant rather than a 1 MW PV system due to lower capital cost, lower cost of energy per kWh, and production and demand profile matching for the particular communities in Bamyan. The annual average estimated capacity factor for solar PV was estimated to be about 13%.

Ershad [xxx] estimated Afghan resource potential of solar PV to be about 30,987 GW while its technical potential being about 29 GW. The study used a multi-criteria GIS analysis of the solar resource together with topographic and geographic constraints. Future solar PV farms were assumed to be located within 40 km of five major demand centers (Kabul, Mazar-e-Sharif, Herat, Kandahar and Jalalabad) and within 2 km of an existing transmission line. Topographic constraints included lands with less than 3% slope and land uses limited to only rangeland, bare soil and sand covered areas. No constraint was applied for solar radiation. The study did not include economic or market potential analysis.

Finally, the Afghan Power Sector Master Plan (APSMP) [xxx] concluded that solar PV and wind power plants could not achieve high penetration levels in the existing and future power system and their role in the mix of grid-connected power generation was said to be minimal. APSMP recommends developing distributed hybrid wind, solar and diesel power plants and off-grid solar home systems to meet the demand mainly in rural areas.

4. Methodology for Solar and Wind Capacity Assessment

The purpose of this study is to analyze the potential of solar PV and wind power plants in Balk and Herat Provinces, two of the most promising provinces for future renewable power generation. Western Herat and Eastern Balkh are said to be two of the major wind resource areas in the country [xxx]. In addition to wind, these provinces have excellent solar resources. Other factors that make these provinces very attractive to renewable energy deployment are their relatively high electricity demand, well developed power system, heavy reliance on imported power, and proximity to the western and northern borders, with access to imported power.

The potential for solar PV and wind power plants is analyzed by quantifying the quality and variability of potential power plants. Quality is quantified by characterizing solar and wind energy resources and determining seasonal and annual plant capacity factors and energy yields, whereas variability can be analyzed using three different methodologies. First, seasonal and diurnal profiles of power output from wind and solar PV power plants are correlated with temporal electricity demand profiles. Second, the impacts of power supply from solar PV and wind on various types of loads such as peak, cycling and baseload are studied by creating residual load duration curves, where the residual load duration method simply subtracts hourly power produced from solar PV or wind power plants or a combination of them from the required demand for that hour to get the residual load. The resulting residual load is then sorted from highest to lowest to obtain the residual load duration curve, as shown in Equation (1) below (RLDC) [xxx].

$$ResLDC(t') = sort[Load(t) - GenerationRES(t)] \quad (1)$$

Third, variability is measured in terms of curtailment and penetration. Curtailment is associated with times when the total capacity including that coming from renewable sources exceeds demand, and penetration refers to the fraction of total energy provided by renewable energy. Section 9 describes our effort to estimate penetration and curtailment levels of three solar PV and wind power plant sizes (50 MW, 100 MW, and 150 MW) interconnected to grid segments with varying peak loads (200 MW, 300 MW, 400 MW and 500 MW) are determined.

5. Data sources for this study

Historical measured wind and solar data is very limited in Afghanistan. In 2012 the Afghanistan Clean Energy Program (ACEP), funded by the United States Agency for International Development (USAID), conducted a wind monitoring campaign to measure wind data for a period of 12 months for commercial applications. Six sites were selected using NREL's modeled wind resource maps and other important criteria for wind farm siting such as proximity to transmission lines. Ten-minute interval wind speed and wind direction data at 30, 40 and 50 m elevations were collected for a period of one year in 2012 at each potential site. In addition, air temperature at 3 m and global horizontal solar radiation were also measured.

For the purpose of this study, the wind resource at Hotel Safid for Herat Province (latitude 34.4054°, longitude 61.8226°, elevation 958 m) and Uljato for Balkh Province (latitude 36.7212°, longitude 67.6222°, elevation 385 m) are characterized and later used for wind plant power output calculations. These two sites have the highest annual average wind speed among the monitored sites mentioned above and are in the proximity of the sites selected for further measurement by a previous study [xxx].

NREL's Typical Meteorological Year (TMY) weather files for Mazar-e-Sharif International Airport (OAMS) and Herat International Airport (OAHR) are used to calculate the energy production of solar PV power plants in both Balkh and Herat. For comparison, the output of a PV array in Balkh province using actual measured global horizontal irradiance (GHI) and ambient temperature from the Uljato wind monitoring station was calculated. Measured solar radiation data from Hotel Safid included errors due to the malfunctioning of the installed solar pyranometer and is not used in calculations.

5.1 Wind resources

Sites with higher wind speed in the winter are ideal for Afghanistan since electricity demand is highest and hydropower generation is lowest then. Uljato experiences windier winters than Hotel Safid. In contrast, long-term wind speed data from Mazar-e-Sharif Airport (OAMS) and Herat Airport (OAHR) show that summers are windier than winters. Figures 2a and 2b show the difference between measured wind speeds in Uljato and Hotel Safid and data measured at their nearest airports.

Average wind speeds at 50 m and power densities at 70 m in Uljato and Hotel Safid reach 6.34 m/s and 9.11 m/s and 426 W/m^2 and 879 W/m^2 respectively. A typical diurnal variation in wind speed shows an increase during the day and a decrease during the night. [xxx]. However, wind speeds in Uljato and at the Hotel Safid do not seem to depend strongly on time of the day. Annual average variation of daily wind speed in Uljato is within 10% of its peak, while at Hotel Safid it is within 30%. Uljato experiences multiple peaks during a typical day, while Hotel Safid seem to peak daily at around 5 p.m.

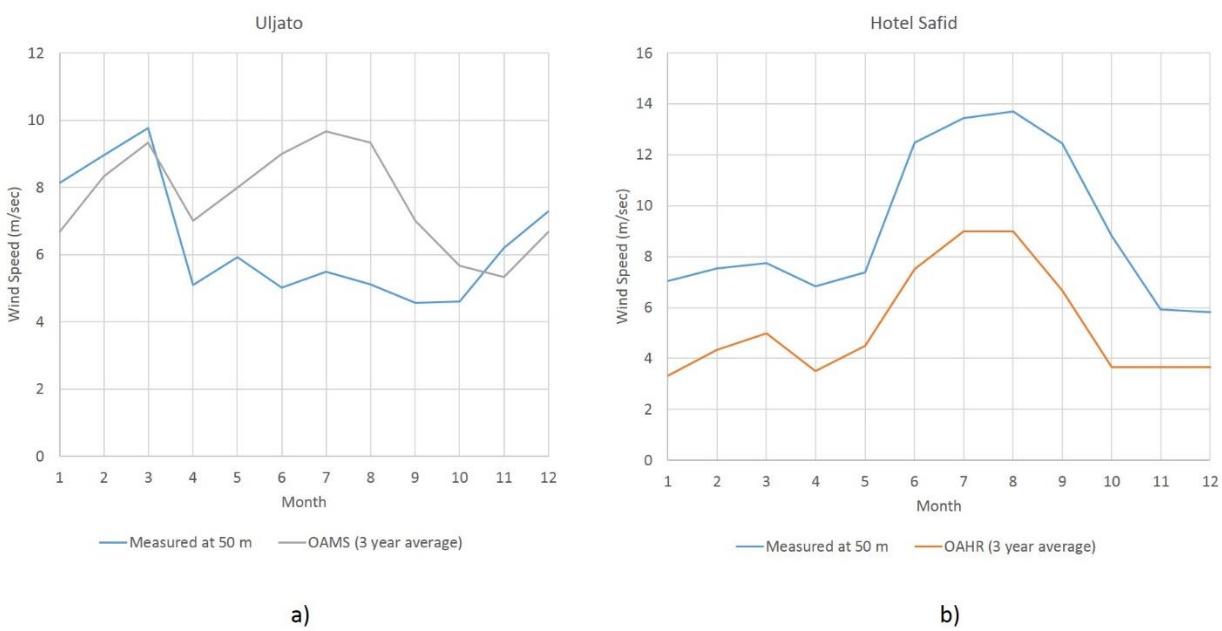


Figure 2 - Monthly wind speed in Hotel Safid and Uljato in 2012

5.2 Solar resource characteristics

Afghanistan receives on average about 5.3 kWh per square meter of horizontal surface on a clear day with a standard deviation of 0.42 kWh. This corresponds to an average annual Global Horizontal Irradiance (GHI) of 1,935 kWh/m^2. National average seasonal maximum and minimum GHI are 7.84 kWh/m2/day and 2.38 kWh/m2/day. Annual GHI for Herat and Balkh provinces are

1,726 kWh/m^2 and 1,967 kWh/m^2 respectively. Figure 3 show resource map of GHI for Afghanistan.

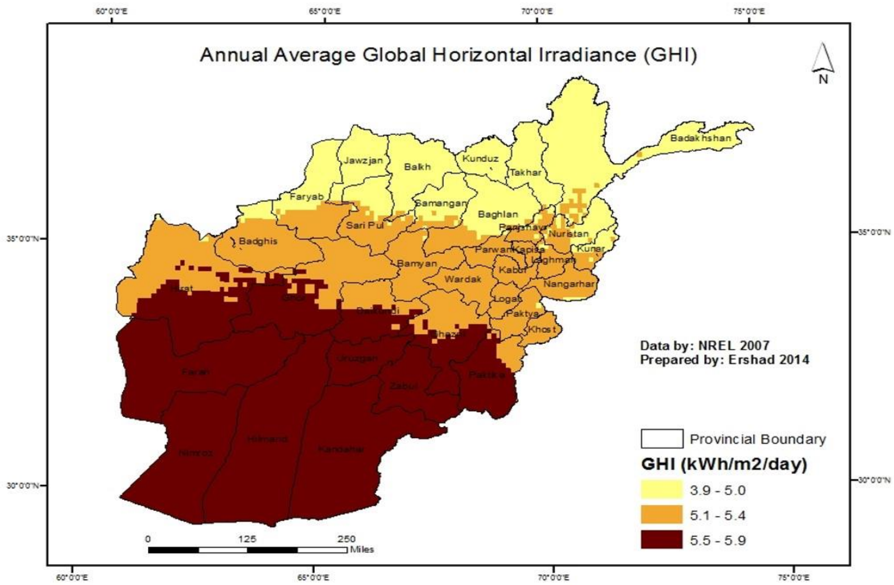


Figure 3 - Annual Average Global Horizontal Irradiance (GHI) in Afghanistan

Tables 1 and 2 show daily and annual average GHI data for OAMS and OAHR by various models. In addition, for comparison reasons, measured GHI from Uljato site which is about 40 km east of OAMS is also given.

Table 1 OAMS annual and daily average GHI

SOLAR RADIATION	SUNY Model	NASA SSE Model	NREL CSR Model	TMY	Uljato Measured Data
Daily Average (kWh/m^2/day)	4.69	4.83	4.86	4.82	4.80
Annual Average (kWh/m^2/year)	1,713	1,763	1,773	1,759	1,751

Table 2 - OAHR annual and daily average GHI

SOLAR RADIATION	SUNY Model	NASA SSE Model	NREL CSR Model	TMY
Daily Average (kWh/m^2/day)	5.378	5.041	5.520	5.383
Annual Average (kWh/m^2/year)	1,963	1,840	2,015	1,965

Figs. 4a and 4b show seasonal variation of the daily GHI for OAMS and OAHR from available datasets.

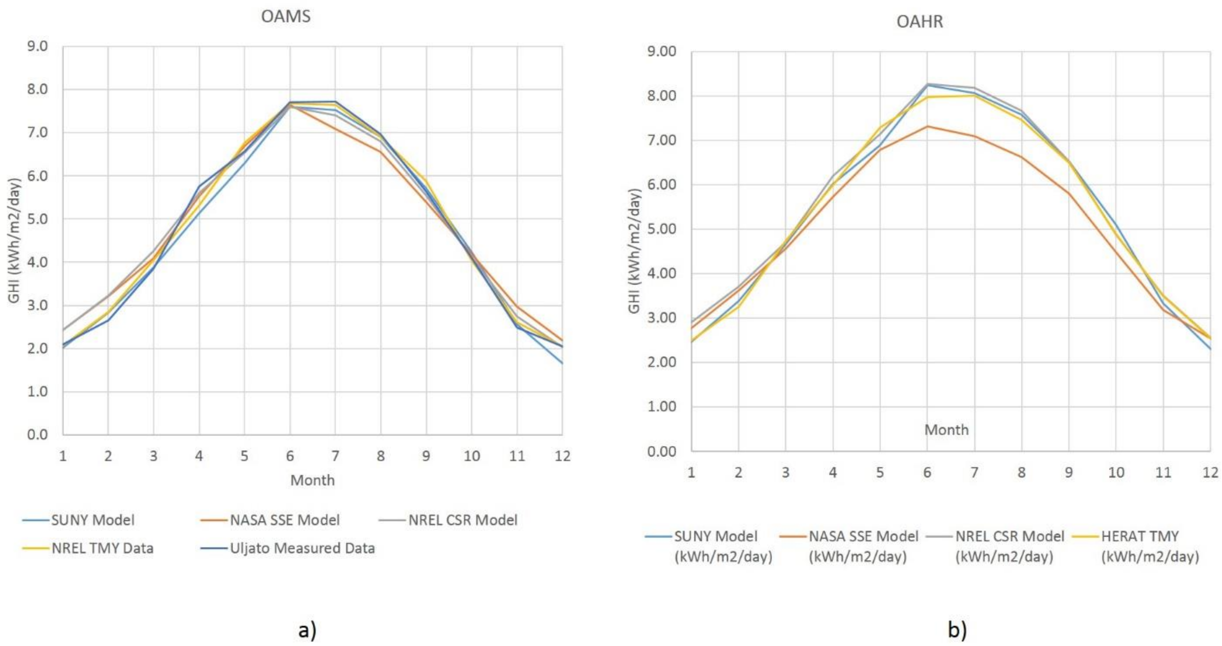


Figure 4 - OAMS monthly GHI by different modeled datasets and Uljato measured monthly GHI

6. Modeling of wind power output

The power output of potential wind farms is modeled using 10 minute-interval wind speed, wind direction, and air temperatures, together with the composite power curve of a 630 KW wind turbine with a rotor diameter of 48m. The composite power curve is created using power curves from commercial pitch-regulated wind turbines in the range of 275 kW – 1 MW which are deemed feasible for installation in Afghanistan [xxx]. Each turbine's power output was averaged over a 0.5 m/sec wind speed bin and the averaging process was performed over a range of air densities. The turbine considered has cut-in, rated and cut-out wind speeds of 3 m/s, 15 m/s, and 25 m/s, respectively.

Wind speeds are converted from the measured 50 m measurement height to 70 m equivalents using the wind shear coefficients determined from measured data. The average wind shear coefficient is 0.2 for Uljato and 0.11 for Hotel Safid. An adjustment is made for changes in air density as a function of altitude, and a correction is made for wake losses as a function of wind direction. In addition, a 3% electrical loss [xxx] and 13% plant availability loss [xxx] is also applied to the final output. Turbulence effects were not considered.

Table 3 shows the net annual energy production (AEP) and net capacity factor (CF) determined for both sites. Also included in this table is the typical annual capacity factor of wind power plants around the world [xxx]. Interestingly, the Hotel Safid site has the potential for a very high CF. Finally, Fig. 5 shows annual average daily net energy yield of both wind farms, representing the typical hourly time-series net energy production (MWh/MW) as a function of hour in the day.

Table 3 – Modeled output for the potential wind farms

Site	**AEP (MWh/MW)**	**CF (%)**
Hotel Safid	3,709	42.4
Uljato	2,418	27.6
World Typical	1,752-3,066	20-35

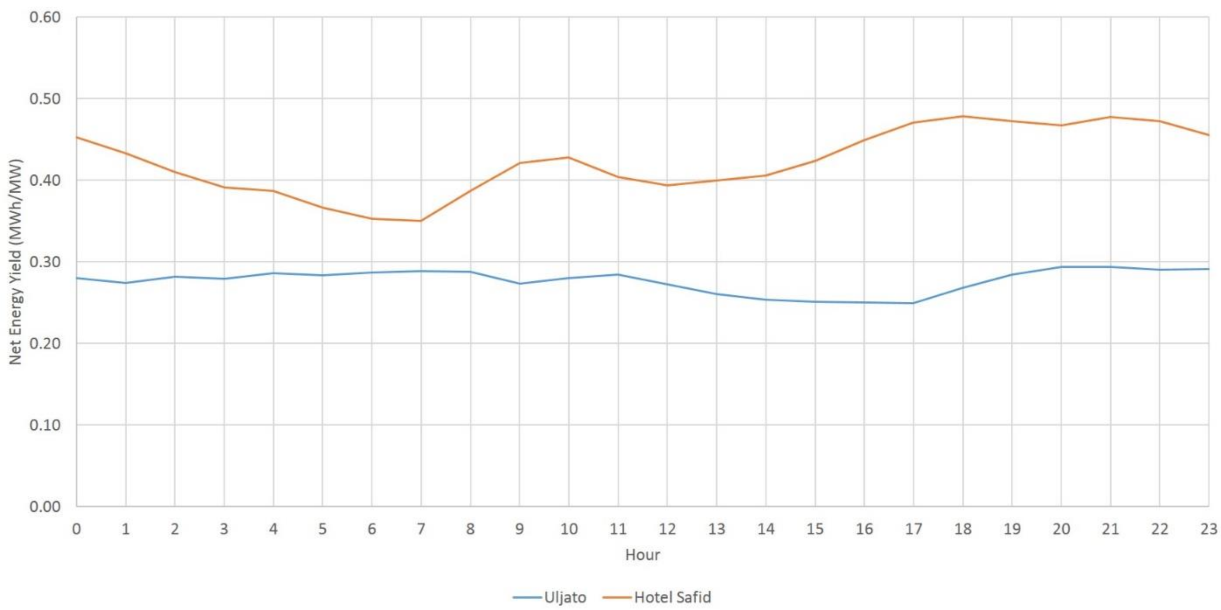


Figure 5 - Annual average daily wind farm net energy yield

7. Modeling of solar power output

NREL's System Advisor Model (SAM 9.20.2013) software is used to calculate PV array outputs. Hourly gross DC (P_{gdc}) output (accounting for effects of cell temperature) of a fixed 1000 KW_{dc} PV array made up of 250 W Sharp NU-Q250W4 panels with a 15.3% facing south tilted at an angle equal to the latitude of OAHR (34.217° N) and OAMS (36.7° N) is calculated using

TMY datasets from OAMS and OAHR. P_{gdc} in KW_{dc} is then converted to net AC (P_{acn}) output after applying an overall derate factor equal to 77% which is NREL's old (before 2014) default value for grid connected PV systems with crystalline modules and is a good approximation for conditions in Afghanistan. Loss from shading is not included. The derate factor accounts for PV modules nameplate derate, mismatch of PV modules in the array, DC and AC wiring losses, diodes and connections, soiling, and availability and interconnection losses from inverters and transformers. For a detailed proportion of losses from each category, refer to PVWatts website [xxx]. Corrections are also made for DC power loss or gain due to an increase or decrease in temperature of PV cells with respect to the reference cell temperature at Standard Test Conditions (STC) of 25 °C. The temperature coefficient of power is taken -0.5%/°C.

Net AC output of a PV array using measured hourly GHI and ambient temperature in 2012 from Uljato is calculated for a similar fixed 1000 KW_{dc} PV system installed at latitude tilt (36.7° N) facing south using procedures adopted by NREL's PVWatts hourly simulation model [xxx]. Hourly incident radiation on the tilted surface from measured global radiation is calculated using Homer's time-series import option. Homer uses algorithms developed by Erbs, Klein and Duffie [xxx] to estimate the horizontal diffuse and beam portions of the global horizontal radiation to model plane of the array radiation.

Table 4 shows the net annual energy production (AEP) and net capacity factor (CF) for the cases consider. The system requires about 16,000 m^2 of land. In addition, hourly time-series net energy production (MWh/MW) is also created for temporal analysis of demand and solar PV power. Table 4 also gives typical annual capacity factors of solar PV power plants around the world [xxx].

Site	AEP (MWh/MW)	CF (%)
OAHR	1,482	17
OAMS	1,339	15.3
Uljato	1,260	14.4
World Typical	876-1,752	10-20

Table 4 – Modeled output for solar PV system

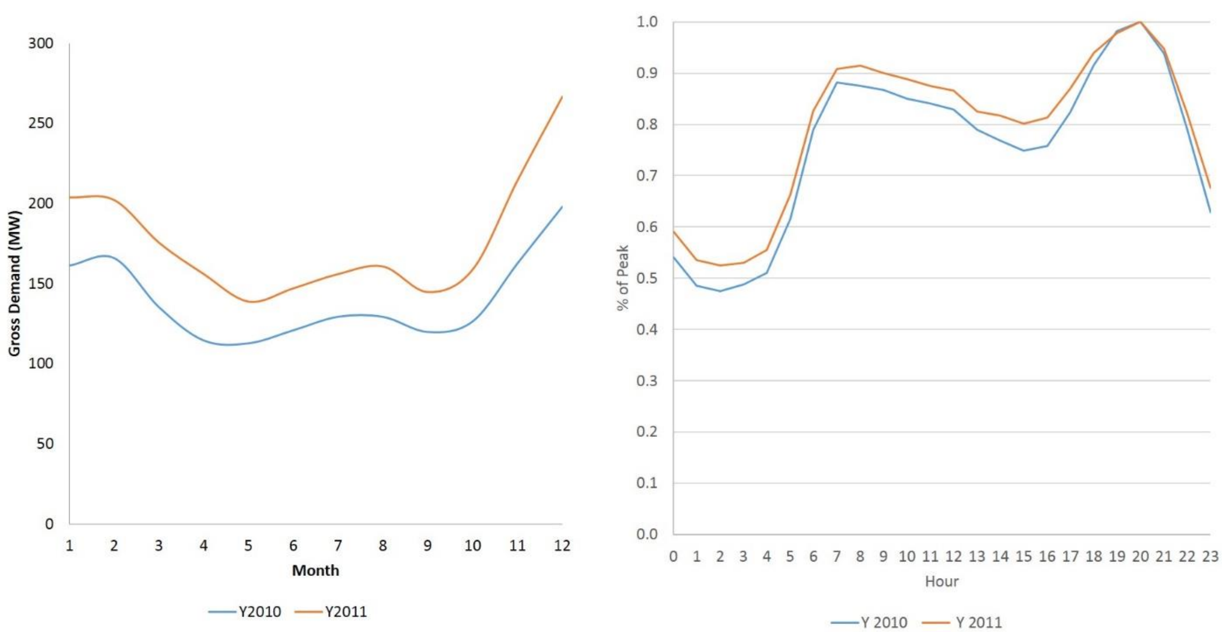
The PV array in Herat yields about 10% higher energy production than the one in Balkh due to a higher solar resource. The difference in energy production of Balkh PV arrays (OAHR and OAMS) could be due to differences in modeling approaches, possibly due to differences in the assumed inverter efficiency.

8. Demand characteristics

For the purpose of this study, it is assumed that grid segments in Herat and Balkh have the same profile as the one in Kabul. An Average Demand Profile (ADP) is created using Kabul demand data from 2010 and 2011. Hourly demand data from each year are normalized to the peak value and averaged over both years for all 8,760 hours in a year. Thus, for a given peak demand, the ADP is scaled to obtain the corresponding hourly demand data. The minimum load of ADP is 19% of its peak demand making its flexibility about 80%. A gross load factor of 55% is achieved when using the ADP as a demand profile.

It is assumed that the proposed solar and wind farms in Balkh and Herat Provinces will be connected to grids with similar temporal load characteristics. However, there exist some obvious consumptions differences between Kabul and Balkh and heart, such as higher load factors in Herat and Balkh provinces due to greater industrial activity and higher and longer summer demand due to their higher annual average temperatures and thus increased use of air conditioning. In spite of this, Kabul temporal demand could be a reasonable proxy for demand in other provinces for two main reasons. First, it takes into account generation from domestic hydro and thermal sources. Second, all of these provinces would be interconnected in the future and the single demand profile would be created dominated by Kabul consumption – as Kabul is by far the most populous region in the country.

Average 2010 gross electricity demand in winter (October-March) in Kabul was 35% higher than summer (April-September) demand. This seasonal variation in demand is validated with 2011 demand data. A 5% increase is noted between 2010 and 2011. One of the main reasons for higher winter electric consumption could be electric heating. Summer demand peaks in August and is about 63% of overall peak. Summer peaks in Herat and Balkh are about 82% and 87% of annual peak respectively. Fig. 6a shows average demand for 2010 and 2011 and depicts its seasonal variation. The month with the highest annual average demand was December both in 2010 and 2011. May and September months require the least electricity in Kabul with May being the overall minimum.



a) b)

Figure 6 - Kabul Province a) average monthly demand in 2010 and 2011 and b) annual average daily profile

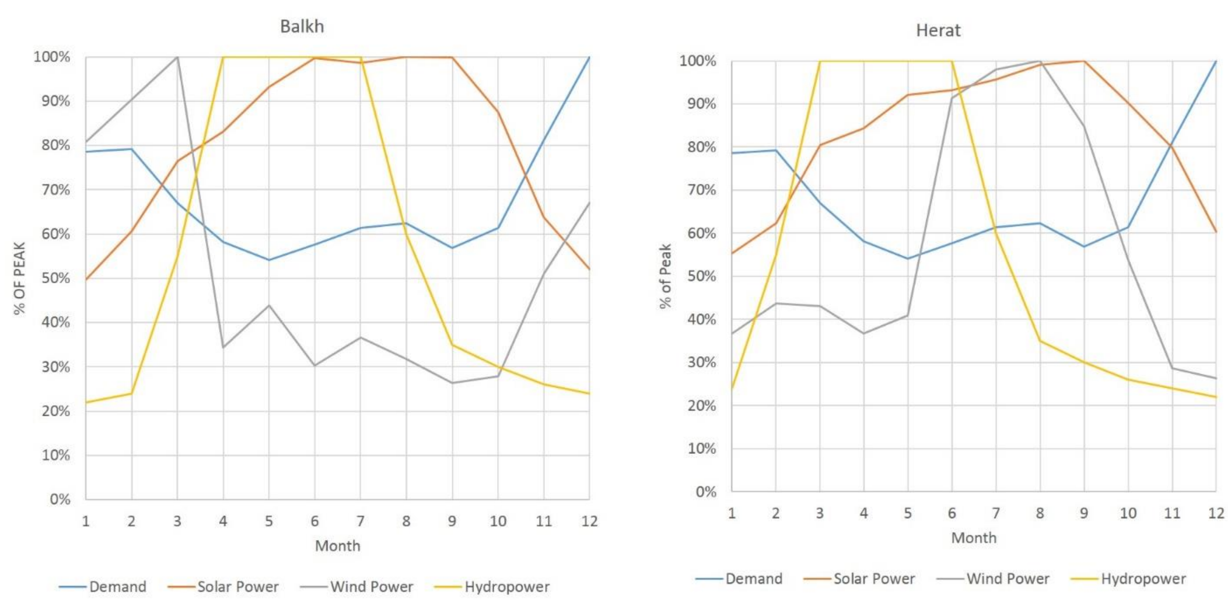
The normalized daily hourly load profile in Kabul Province for 2010 and 2011 (Figure 6b) is bimodal. This characteristic is observed thoughout the year. On average the hours with the highest electricity demand in 2011 were 8 a.m. and 8 p.m.. The hour with the lowest demand was 2 a.m. Demand dependancy on day of the week is assumed to be minimal since electricity is consumed mostly for ligting, cooking and heating as seen from the time of daily peak. Minimum average daily demand in 2011 was about 53% of daily peak. This figure was about 47% in 2010. The minimum daily load is higher in Herat and Balkh provinces since these provinces have higher load factors.

9. Resource Variability

The capacity of wind and solar power plants depends highly on the correlation and availability of wind and solar power with demand, flexibility of other units in the system, available storage and interconnection and the share of variable renewables. The goal of this section is to quantify the variability of wind and solar resources in Balkh and Herat provinces by: 1) comparing their daily and seasonal profiles with ADP; 2) analyzing their impacts on load duration curves; and 3) determining their penetration and curtailment levels under various peak demands using ADP.

As noted in the previous section, demand for electricity in Afghanistan is higher in winter (October through March) than summer (April through September). This period of high demand does not coincide with the strongest period of the wind resource in Herat or with peak solar radiation anywhere in the country. However, the wind resource in Uljato for the months of October through March is higher than April through September, which closely matches the demand. In addition to wind and solar resources, the Afghan hydro resource also peaks in spring and early summer. On average, existing and future hydropower plants produce 100% of their rated power capacity in the months of May and June with the lowest production coming in January (_% of peak).

Figs. 7a and 7b show seasonal variations of potential wind and solar PV power plants together with electricity demand and hydro power plants. Seasonal production profile (% of nameplate capacity) of Salma (Herat) and Mahipar (Kabul) hydropower plants are compared with solar and wind power profiles in Balkh and Herat respectively. Of the three power plant types, solar PV experiences the least seasonal variation, while hydro experiences the most. This is true for Herat as well. Hotel Safid wind power complements Salma hydropower supply pretty well since hydro power peaks during March through June, while wind power peaks during June through August



a) b)

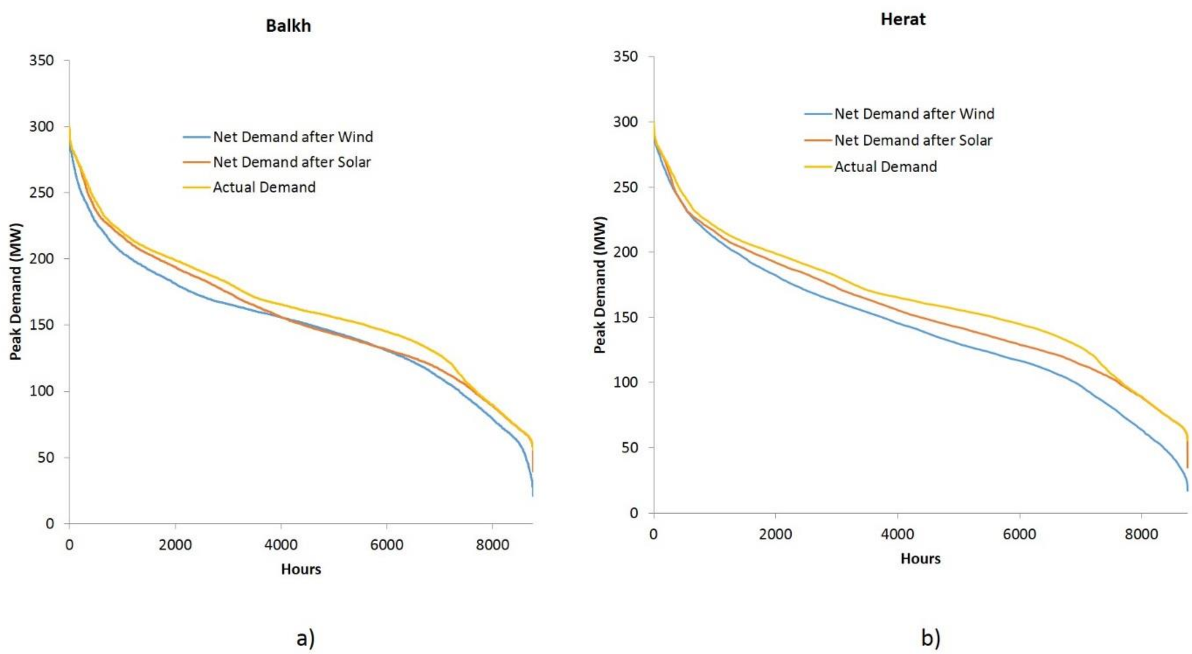
Figure 7 - Seasonal variation of intermittent renewables and electricity demand for a) Balkh and b) Herat provinces

On a daily basis, electricity demand is highest in the evenings with another lower peak in the mornings. Hotel Safid and Uljato wind farms would produce more power in the mornings than evenings during the months of November through March. During summer, high wind power occurs during mid-day through the evening. This difference in winter and summer winds causes the wind resource to not depend on time of day during a year. Power output of solar PV plants plays little role in meeting peak daily demand since the peak demand occurs in the evenings.

The type and geographic location of intermittent power sources could have different impacts on the remaining load requirements. To understand the effects of Balkh and Herat solar PV and wind power on typical Afghan electricity load, the method of Residual Load Duration Curves is used. One can easily understand the temporal impact of renewables on the residual demand profile. Although Herat wind and solar PV power plants achieve higher annual average capacity factors or number of full load hours than the ones in Balkh, their contribution in meeting various types of loads such as peak, cycling (intermediate) or baseload differ. In both locations, solar power plants reduce cyclic loads, but do not effectively address afternoon minimum loads or morning and evening peaks loads. This is true for Herat solar plants as well.

Uljato wind reduces all three types of loads. It has the same effect as solar PV for cyclic loads. The greatest contribution of Uljato wind is in reducing operational hours of near peak load. Herat wind, on the other hand, has a significant impact on reducing cyclic and base loads since it is strongest in the summer and in the afternoons and evenings. Figures 8a and 8b show the residual load duration curves of ADP for 300 MW peak loads, after introducing 50 MW solar and 50 MW wind.

If synergistic effects of solar PV and wind are considered, 50 MW solar and 50 MW wind plants in Herat would have the same effect as 50 MW wind and 50 MW solar in Balkh in reducing near peak loads. However, Herat combined solar and wind plants would contribute more in reducing the baseload. Figure 9 shows residual load duration curves of ADP for 300 MW peak demand in Herat and Balkh when both sources are connected to the grid.



a) b)

Figure 8 – Residual load duration curves of a) Balkh and b) Herat grid

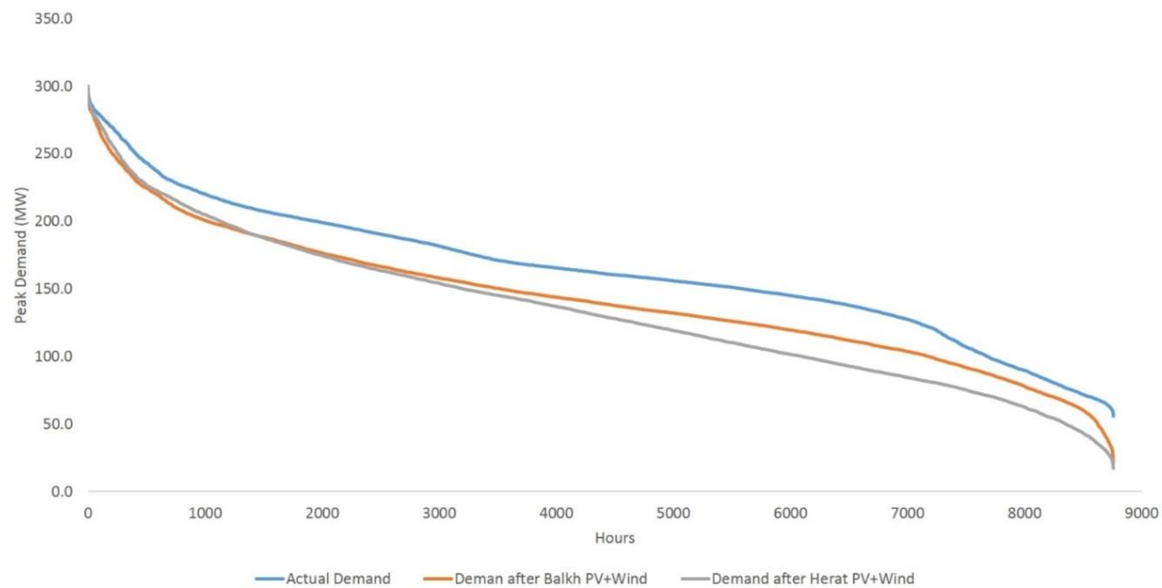
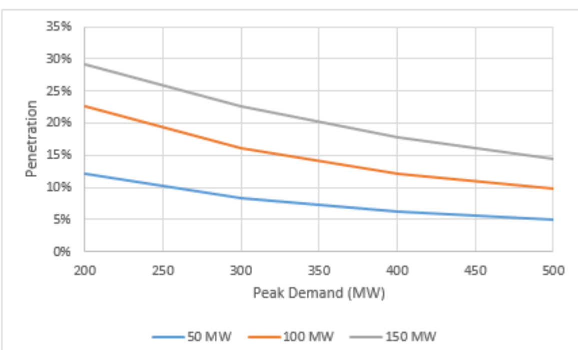


Figure 9 - Residual load duration curves of Balkh and Herat including effects of combined solar and wind

Lastly, penetration and curtailment curves of three sizes of wind and solar PV power plants (50 MW, 100 MW, and 150 MW) are created for four ADP peak demands (200 MW, 300 MW, 400 MW and 500MW). Different demand scenarios are considered due to the growing demand and values are roughly based on demand growth projections of Herat and Balkh power systems. Wind or solar PV penetration is the ratio of total annual utilized power from these power plants divided by total annual demand of the grid. Curtailment on the other hand is the ratio of total annual wind or solar power that is not used, divided by the total annual wind or solar PV power generated. Hourly utilized power is calculated by subtracting solar and wind power from replaceable demand (actual demand minus minimum demand or base load). Hourly curtailment is calculated using the same procedure as utilized power whenever production from solar or wind is higher than replaceable demand. Results are presented with Figures 10 a-d through 11 a-d.

For example, Figs.10a and 10b show that Balkh wind farm would achieve penetration levels of 12% to 30% for the range of installed capacities at 200 MW peak demand and decreases almost linearly to 5% to 15% at 500 MW peak. The highest curtailment loss of about 23% occurs when installing 150 MW wind power when the peak demand is 200 MW. For the rest of the combinations, curtailment losses are about 10% or less.

Wind power plants achieve higher penetration levels than solar PV in Balkh and heart (_ % versus _%) provinces for a given installed capacity and grid demand. Both solar PV and wind power plants in Herat achieve higher penetration levels than the ones in Balkh (_ % versus _%). Although wind power plants could achieve higher penetrations levels than solar PV, they have higher curtailment losses. This fact is due to mismatch of wind resource with demand especially during the night times. Wind power curtailment losses are higher in Hotel Safid than in Uljato due to the greater mismatch between between load and wind generation transients.



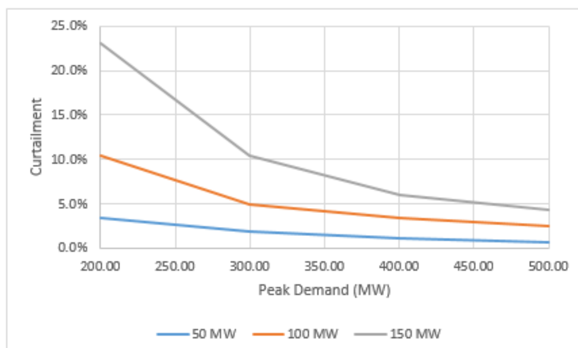


Figure 10a) Balkh wind penetration

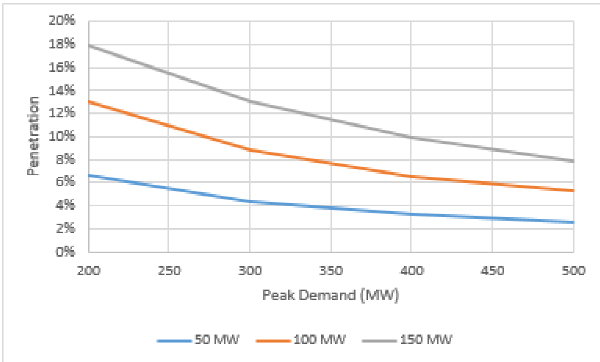


Figure 10b) Balkh wind curtailment

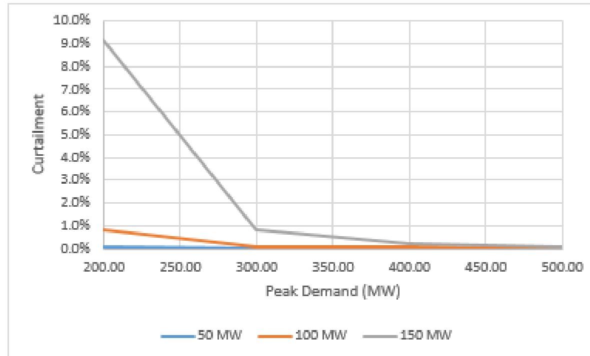


Figure 10c) Balkh solar PV penetration

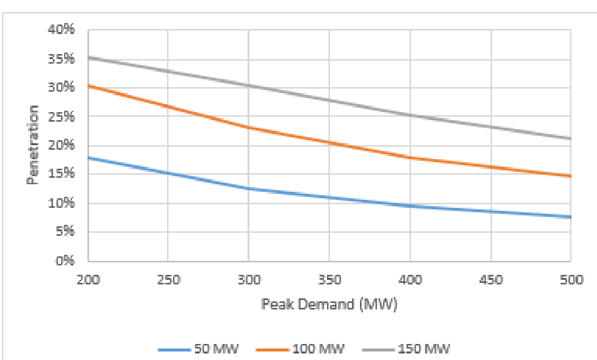


Figure 10d) Balkh solar PV curtailments

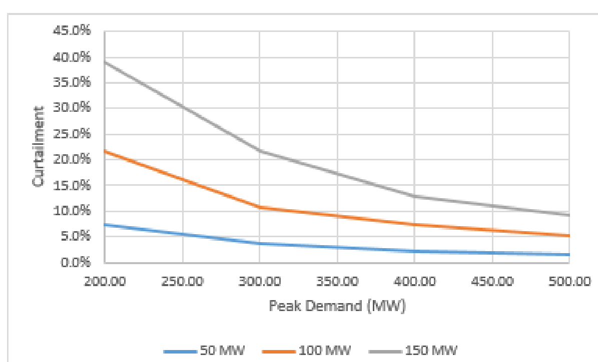
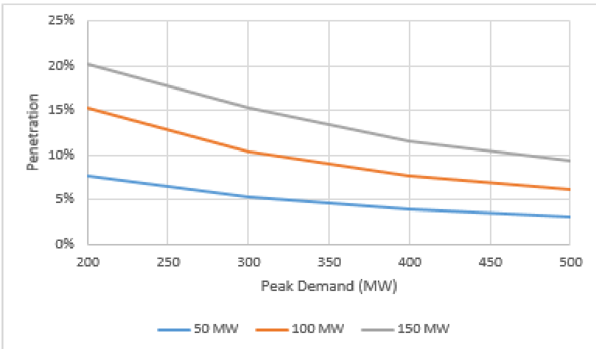


Figure 11a) Herat wind penetration

Figure 11b) Herat wind curtailment



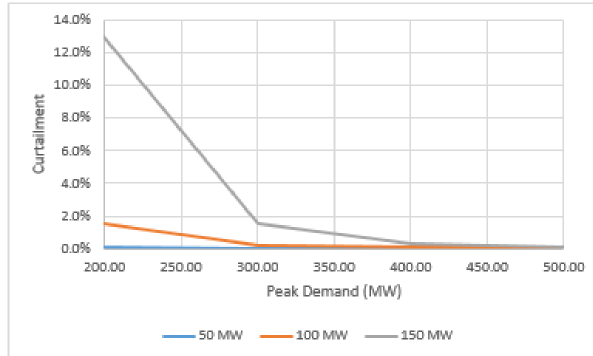


Figure 11c) Herat solar PV penetration

Figure 11d) Herat solar PV curtailment

It is unlikely to see a cumulative installed capacity of solar PV and wind turbines in the near future that would surpass limits of significant curtailment losses. However, it is wise to take advantage of the modular nature of solar PV and wind turbines. Installed capacity could be increased in parallel with increase in demand or export opportunities. In addition, excess power from solar PV and wind power plants could be used to complement hydropower plants especially during summer months by pumping back water leaving the turbines to the reservoirs during the night when the load is minimal.

10. Conclusions

Afghanistan unfortunately has not yet taken advantage of its vast resources of renewable energies such as solar radiation and wind on a scale large enough to meet a significant fraction of its electricity demand. Two of the most promising provinces for renewable energy deployment are Balkh and Herat provinces. Annual average global horizontal solar radiation in Herat and Balkh are 1,726 kWh/m^2 and 1,967 kWh/m^2 respectively. Fixed axis solar PV power plants tilted at angles equal to the latitudes achieve 14% and 17% annual net capacity factors including modest losses in Balkh and Herat respectively. Typical global capacity factors of solar PV power plants are in the range of 10% to 20%.

Average wind speeds at 50 m in Uljato and Hotel Safid reach 6.34 m/s and 9.11 m/s. Average power densities at 70 m wind turbine hub height reach 426 W/m^2 and 879 W/m^2 in Uljato and Hotel Safid respectively. Sites with power densities greater than 400 W/m^2 are considered commercially viable for wind farm development. Wind power plants in Uljato and Hotel Safid yield annual net capacity factors of 27.6% and 42.3% respectively. Typical onshore wind power plants around the world achieve capacity factors in the range of 20% to 35% with exceptional plants achieving 45%.

Electricity demand in Afghanistan is highest in the winter while power supplied from wind power plants in most of locations and solar PV power plants everywhere would be highest in the summer. Uljato is one of the locations that experiences stronger wind speeds in winter months (November – March). Hotel Safid on the other hand experiences higher winds in summer. Wind speed diurnal profile varies from month to month and it turns out that on average wind speed in both locations do not quite depend on time of day. Solar PV and wind power plants in Balkh and Herat have the potential to reduce the load on all types of domestic generation schemes and imports. For example, solar PV can reduce the number of operating hours of power plants responsible for providing cyclic power especially to meet mid-day demands. Wind power plants would contribute in reducing near peak and in to some extent peak load and baseload.

Although these sources alone would not be ideal to be used as the main or only source of electricity supply due to their higher capital costs, intermittent nature, requirement for substantial storage, and uncertain power supply, they could well achieve significant penetration levels in the

Afghan grid especially when all of the islanded grid segments are interconnected and could possibly export power. In the meantime, these sources are environmentally friendly sources of power generation and offer power with stable prices.

In most developed countries, the best way to increase the share of intermittent renewables in the existing grid is to improve the flexibility of either the grid or the dispatchable sources of power. On the other hand, developing countries like Afghanistan still have the opportunity to think ahead and design power systems that could accommodate higher levels of variable power sources as they are still growing and taking shape. In the meantime, shares of renewables could go higher if the Afghan government sets national targets and designs effective policies. In the end, higher solar PV and wind penetration means less reliance on unpredictable and unstable power purchase agreements with neighboring countries, longer life of limited domestic fossil fuel resources such as coal and natural gas, and less imports of diesel fuel with rising costs and unfriendly environmental impacts.

References