Journal of Energy and Power Engineering 11 (2017) 85-94
doi: 10.17265/1934-8975/2017.02.003

Hybrid PV/Wind/Diesel Based Distributed Generation for an Off-Grid Rural Village in Afghanistan

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Received: October 17, 2016 / Accepted: October 31, 2016 / Published: February 28, 2017.

Abstract: Afghanistan has a tremendous resource potential of renewable energy especially solar and the wind. Therefore, utilization of these resources has a special rule for the remote areas where access to the electrical grid or secure power supply is a dream for most of the people. This paper presents a feasibility and usefulness of hybrid power generation based on PV/wind/diesel generator for an off-grid rural village that feeds the load at a rate of average 7.9 kWh/day with 1.32 kW peak load. GsT (geospatial toolkit) is used to obtain the solar and wind data of the site. Windographer software is used to analyze the wind resource data of the site. HOMER Pro software package is used to select the suitable and reliable hybrid generation system and calculate the optimal capacities and costs of the components. Through the study, it is found that this state of the art adaptation could provide vast opportunities for off-grid rural communities such as in Afghanistan where enough high penetration of renewable energy is available.

Key words: Rural village electrification, hybrid power generation, solar, wind, diesel generator.

1. Introduction

Access to energy is the backbone of socio-economic development of each country. It was estimated that 80% of the people in developing world do not have access to electricity with most of them located in Africa and South Asia [1, 2]. Afghanistan with totally about 31 million population, located in South Asia where only 30% of the total people population has access to electricity. More than 75% people live in rural areas where only 10% of them have access to the power and about 35% live under the absolute poverty line in the country [3, 4]. Economic growth that raises incomes and reduces poverty is strongly correlated with increased energy use. Besides, the provision of adequate and reliable energy services at affordable and cost-based prices, in a secure and environmentally sustainable manner, and in conformity with social and economic development needs, is an essential element of sustainable development. Furthermore, a sufficient energy supply is a vital input for eradicating poverty, improving human welfare and raising living level. On the other hand, it is well-known that living standard of each country is indicated by GDP (gross domestic product) of that country which is claimed to be about 90% dependent on per capita energy consumption. Based on the data available for 2012, Afghanistan with its $687 GDP per capita and 7.6 kWh per capita energy consumption ranks among the lowest in the world [5]. The main concern is the resources from which we can achieve optimum energy and electric power. The conventional way of electricity generation from traditional fuels causes severe environmental problems and seems not relevant to 21st century any more [6, 7]. On the other hand, the major portion of supplied electricity in Afghanistan is imported power from the neighboring countries, which is claimed to be very expensive especially for those who live in the rural areas with the lowest income. Also, having imported power is considered unreliable due the

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concerns related to energy security. The main disadvantage of the strategy is reliance on politically unstable neighbors, limited enforceability of commercial contracts, and lack of certainty about future price trends. Besides, the internal electric power generation where hydropower plants account the largest share of capacity with imports in second place and growing, are not adequately developed.

Although, since 2001 the primary focus of energy sector in the country has been on reconstruction and expansion of national grid. However, given that the national grid is being developed almost from scratch, it is accepted that there are swathes of the country that the national electrical network will not be able to serve them in the next 20 years [5, 8].

Renewable energy for electric power generation is gaining attention in the world. For Afghanistan, these resources could not only fulfill the current and future energy demand but also will decrease poverty by creating various jobs. Furthermore, if compared to the conventional energy sources, the environmental impact from renewables is also considerably small [9].

Afghanistan has a huge potential of renewable energy specifically solar and the wind. There are more than 300 annual sunny days, and the total technical potential of solar power is estimated 222 GW [10, 11]. According to NREL (2007) Afghanistan with average 6.5 kWh/m^2/day solar irradiance on a horizontal plane is the possible place for installing stand-alone and grid-connected photovoltaic systems. Similarly, there are provinces with good and excellent wind resource utility scale. In good scale areas the wind speed is about 6.8-7.3 m/s (wind power of 400-500 W/m^2) and in excellent scale areas the wind speed is about 7.7-8.5 m/s (600-800 W/m^2) [12]. The total technical potential of wind power is estimated 66.726 GW. Based on the data above, installation of wind towers can also be feasible in several provinces of the country.

It is obvious that additional essential requirements regarding rural electrification such as socio-economic benefits, reliable power supply, security, durability and so on should be taken into account. Due to the intermittent nature and low efficiency (18 to 60%) [13] of renewable energy generators, it becomes tough to get the average necessary and consistent electric power from a single source.

Distributed power generation which is also called dispersed or embedded generation, is the optimum and directly energy supply method for off-grid rural electrification that would not only fulfill the requirements mentioned above but also can provide clean and cost-effective power for rural households, and it can avoid extra investment for lines and other instruments [14, 15].

Besides, distributed generation could increase the application of renewable energy technology and other carbon-less generation systems such as microturbines, fuel cells, etc. Currently, renewable energy excluding hydropower constitutes only about 3% of the total installed capacity in Afghanistan, and it is projected to increase this amount to 10% of the total demand by 2032 [8]. A few types of research exist in the field of rural electrification in Afghanistan. In Ref. [16] a hybrid power system based on PV and micro-hydro power for a rural community in Bamian northern Province of Afghanistan is proposed. Danish et al. [17] also indicated the importance of rural electrification through renewable sources using hybrid technology.

This paper presents the availability of solar and wind power resources and feasibility of hybrid power system based on solar and wind energy for a rural community in the country. GsT (geospatial toolkit) developed by NREL is used to achieve the monthly solar irradiance and wind speed data of the site. Besides, Windographer as an industry leading software is used to analyze the wind data of the site. HOMER Pro software which means hybrid optimization model for multiple energy resource is used to evaluate the suitable and cost-effective small hybrid power system based on the different available resources such as solar, wind and diesel generator.

The rest of the paper is organized as follows: Section 2 describes the location of the village under study. In Section 3 the load profile is presented, resource significance and availability is defined in Section 4, Section 5 presents the windographer analysis for the wind characteristics, Section 6 describes system configuration, sizes and costs, Section 7 is organized for optimal system choice. Finally, Section 8 describes the significance and advantages of the optimized system with barriers to rural electrification in Afghanistan outlined in Section 9 followed by conclusion in Section 10.

2. Site Location

Qarabagh district is located 56 km to the southwest of Ghazni in central-east of Afghanistan [18]. The landscape varies in different parts of the region-deserts in the Southwest, plains in the southeast and mountains in the north. The proposed village is located in the north-west area of the district with longitude and latitude of 68°3′51.28″ and 33°13′16.92″ respectively. The village is called qala-i-Kaka which currently does not have access to electricity. The topography of the site is characterized as woodland, farmland and surrounding by extensive deserts with reasonable wind speed and solar irradiance.

3. Electrical Load Demand

A short time site survey has been done, and the daily load of the village Qala-i-Kaka is estimated and assumed for optimization and simulation in this paper. There are totally 12 houses and a mosque with their primary loads, constitute of compact fluorescent lamps, TVs and mobile battery chargers. There is no commercial and industrial load demand. On the other hand, as the people are poor and also due to the moderate weather, there is no need for electrical fans. The daily load profile of the village is shown in Fig. 1. During the day time, there is no energy consumption, as the residents go outside either for farming or menial jobs for 7 to 8 hours. Therefore, the peak consumption is usually in the evening.

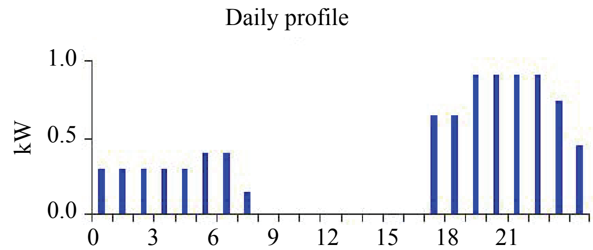

Fig. 1 Daily load profile of the village.

4. Resource Significance and Availability

It is well-known that rural electrification has a particular role in socio-economic development of a country. In Afghanistan, as the majority of people live in the rural area under the poverty line with lower income; only from livestock and agriculture. Thus, deployment of renewable energy could not only supplement the increasing energy demand but also will decrease the poverty level and provide other opportunities mainly employing of poor and jobless people in the rural areas of the country [19].

Afghanistan has an enormous renewable energy potential especially solar and wind throughout the country. Most of the south, east, south-eastern and south-western parts of the country are indicated that they have high solar irradiance and wind speed. Details of renewable potential in Afghanistan are described by Ludin et al. in Ref. [8]. Solar and wind power potential of proposed site is presented below.

4.1 Solar

Solar energy constitutes the major portion of renewable energy potential in Afghanistan. Besides, as it is clean, abundant, offers zero input cost and distributed throughout the country, it is a prerequisite sustainable source especially for remote off-grid locations [20]. Solar energy potential data are achieved using GsT, which records the data from GIS (geographic information systems) and provides monthly solar irradiance of each province and site of

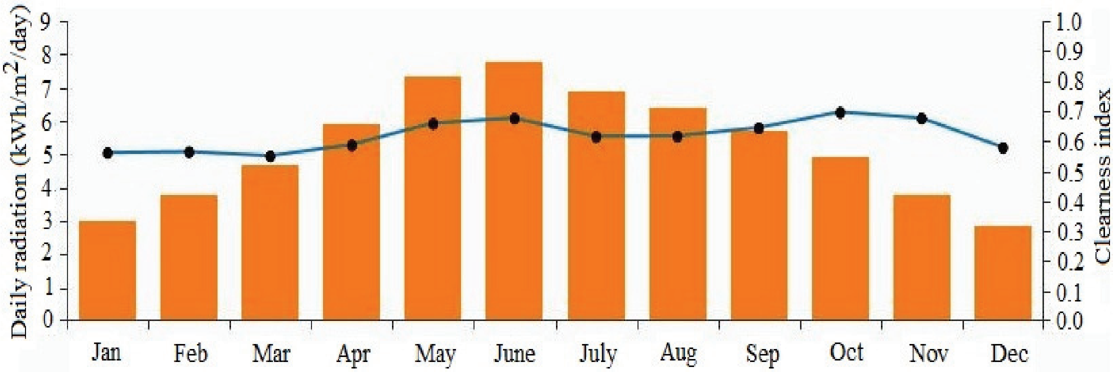

Fig. 2 Monthly solar irradiation and clearness index.

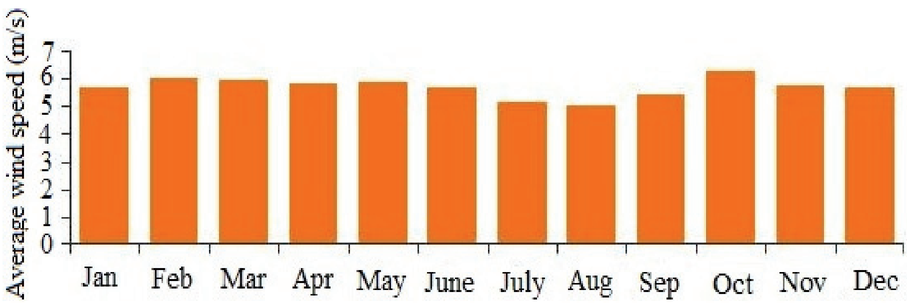

Fig. 3 Monthly average wind speed of the village.

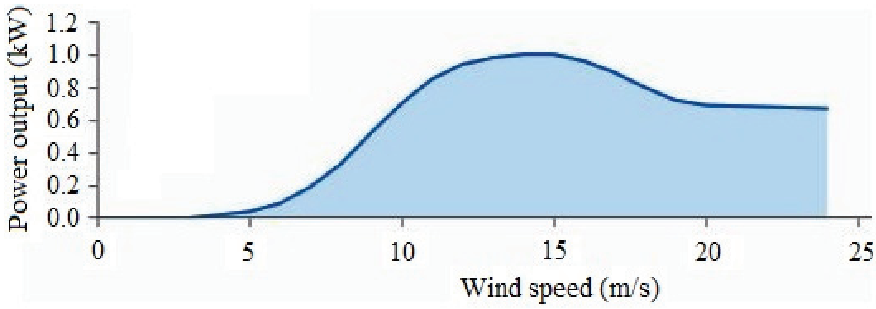

Fig. 4 Wind generator output power curve.

the country. The average daily solar irradiance with clearness index plot of the Qala-i-Kaka village is shown in Fig. 2. As it is apparent from Fig. 2, the solar irradiance varies between 2.87 kWh/m^2/day in December and 7.75 kWh/m^2/day in June with an annual average of 5.25 kWh/m^2/day.

4.2 Wind

In recent years, wind energy due to the lower environmental and economic costs is gaining attention. Although currently about 35 million people in the world meet their energy demand by wind power which constitutes 0.4% of total global electricity demand, it is estimated that wind energy in many countries is already competitive with fossil fuel and nuclear power if social/environmental costs are considered [21]. Furthermore, according to the EWEA (European Wind Energy Association), wind energy which needs strong global commitment, will make about 12% of the world total energy supply by 2020 [21].

The wind data of the site are obtained using GsT as well. Besides, the geographical location indicators i.e. longitude and latitude of the site is given to the Homer Pro window, in both cases, the same results for the wind speed obtained which are plotted in Fig. 3. As it is evident, the wind speed varies between 5.15 m/s in

July and 6.28 m/s in October with an annual average of 5.69 m/s.

The power output curve of the wind turbine generator is shown in Fig. 4.

5. Windographer Analysis

Windographer is an industry leading software that analyzes the quality of wind characteristics and statistical data [22]. Besides, it provides a wide range of graphs and tables to display and visualize not only the data from the original data file but also can calculate the quantities such as air density and turbulence intensity. The flexible filter is available to provide a high degree of quality control such as tower shading, icing events, sensor malfunctions, or low signal-to-noise ratio [23]. However, in this paper only the following items have been analyzed using windographer software [24].

5.1 Monthly Wind Speed Profile

Monthly wind speed profile, based on the wind speed variation of the site from January to December is shown in Fig. 5. As it is evident, the wind speed is higher between January and July.

5.2 Box Plot

Boxplot of the wind speed is shown in Fig. 6, which indicates the maximum, mean and minimum wind speed of the site. The higher speed means that maximum wind power could be extracted. As it is apparent from Fig. 6, the wind speed is higher from January to July for Qala-i-Kaka.

5.3 Wind Rose Analysis

A wind rose is a circular showing of wind speed and direction that are distributed at a given location for a particular time [25]. The circular forms of the wind speed rose also present the frequency of the winds blowing from specific directions. Wind speed rose of six months with higher wind speeds which presented in subsection A and B are plotted in Fig. 7. It can be seen that, maximum and minimum wind speed direction changes with time variation. Besides, for instance in the wind rose plot for the month of February the wind is blowing from the north direction to south-west, tend to be the strongest averaging more than 6 m/s. Contrariwise the wind blowing from west to the east becoming the lowest averaging less than 2 m/s.

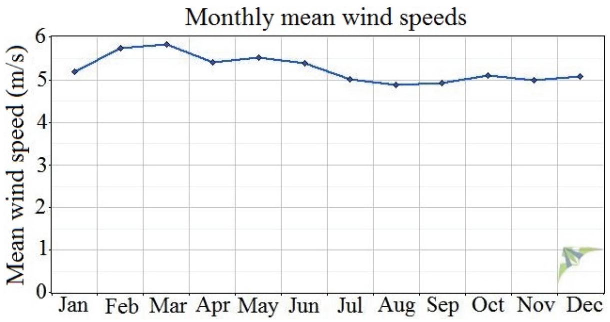

Fig. 5 Monthly wind speed profile.

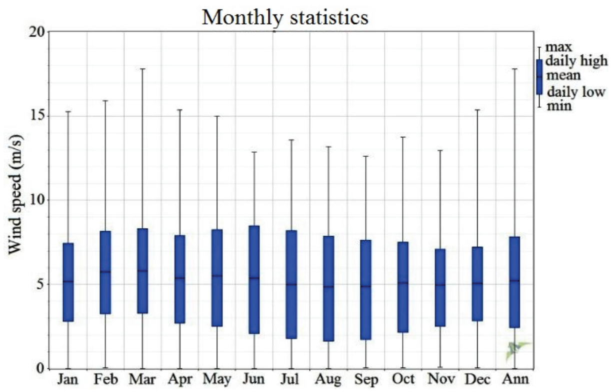

Fig. 6 Box plot of wind speed for 50 m height for Qala-i-Kaka.

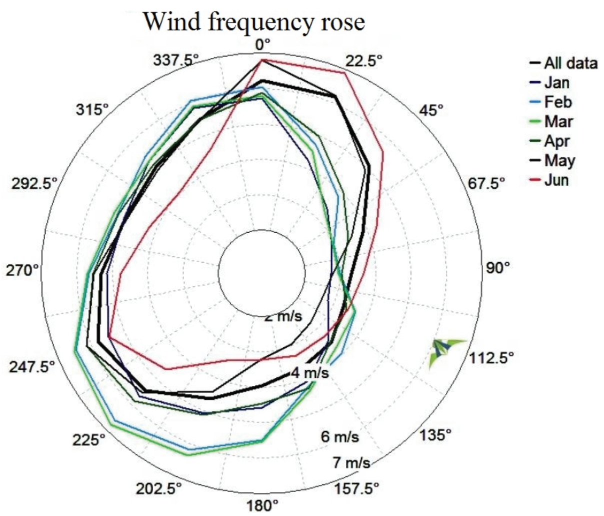

Fig. 7 Monthly wind speed rose at 50 m height from January to June.

5.4 Wind Scatter Plot Analysis

A polar plot of data points drawing with *x* marks is called the wind scatter plot [24]. When in any direction the wind flowing is stronger, the x points increase accordingly. In the scatter plot of site wind speed as shown in Fig. 8, the strongest wind flowing is from north-east direction than the others.

Finally, as a comparison, according to the monthly wind speed plot and box plot, the average wind speed is 5.26 m/s or above especially from January to July, and it is greater than 4 m/s. It means that during this interval of time it is possible to extract adequate power from wind energy. However, according to the wind speed rose and scatter plot analysis it is concluded that flowing of wind does not follow a particular direction.

6. System Configuration, Size and Costs

In order to implement and select the optimal parameters of the hybrid power system, HOMER Pro optimization software is used. The proposed system comprises primary renewable energy sources (PV/wind) which are supported by standby auxiliary conventional sources (diesel generator/batteries) as backup systems. The power converter is included in the system to connect the AC and DC links and controller unit.

The components related characteristics such as load and resources information, economic information such as fuel cost, the capital cost of equipment and O&M (operation and maintenance) costs as shown in Table 1 [22, 26, 27], have been given as input to the software. HOMER Pro selects the optimal and suitable component sizes based on the lower net present cost. Different system combinations of the available energy resources are simulated as shown in Table 2 [26]. The output of the simulation is including capital cost, NPC (net present cost), per kWh energy cost, component sizes and other characteristics. The configuration of the system is shown in Fig. 9. Fig. 10 depicts the optimal size of each element in the system that is simulated by HOMER Pro. The simulated optimized size of each component is highlighted by yellow color in the search space which is called overall winner. The

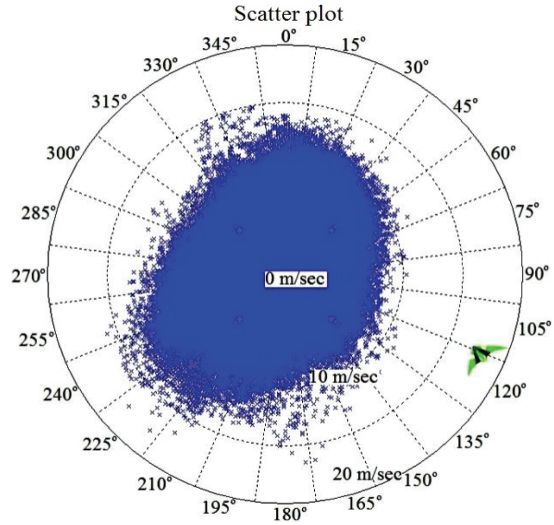

Fig. 8 Scatter plot of wind speed at 50 m height for Qala-i-Kaka.

Table 1 Components costs.

Name	Capacity (kW)	Capital ($)	Replacement ($)	O&M ($/year)
PV (flat plate)	1	2,200	2,200	0
Wind (generic)	1	5,000	5,000	50
Autosize generate	1	500	500	0.03
Lead acid battery	1	270	270	10
Generic converter	1	300	300	0

Table 2 Combination of systems.

No.	System
I	PV + wind + generator + battery
II	Wind + generator + battery
III	Wind + generator
IV	PV + wind + generator

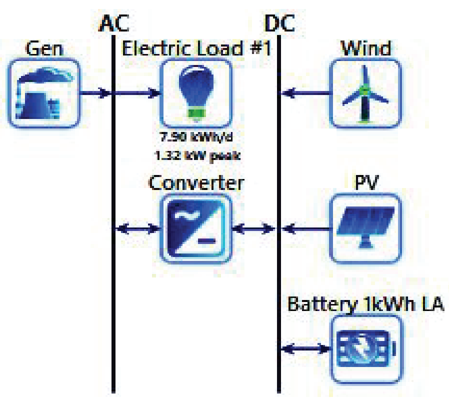

Fig. 9 Hybrid system configuration with its elements.

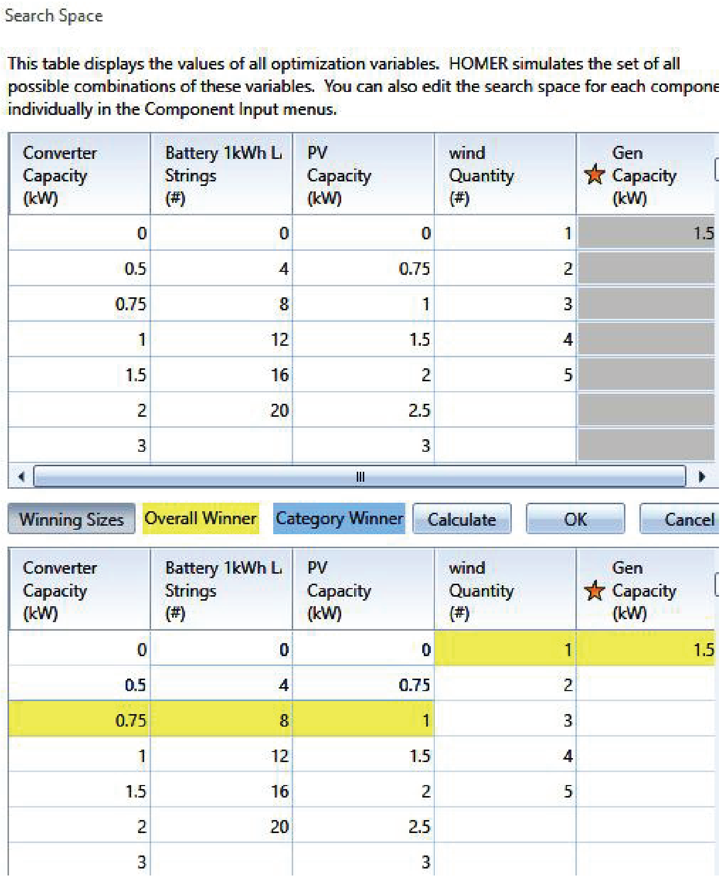

Fig. 10 Optimized elements sizes.

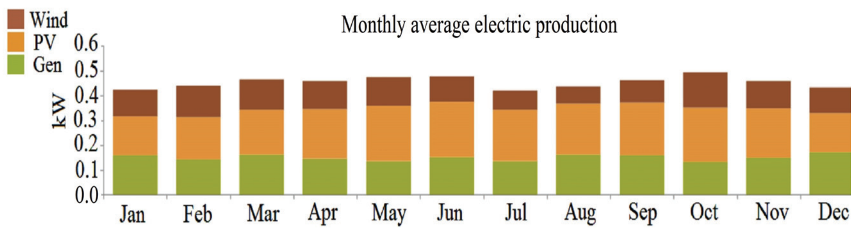

Fig. 11 Monthly average electric power production by the resources.

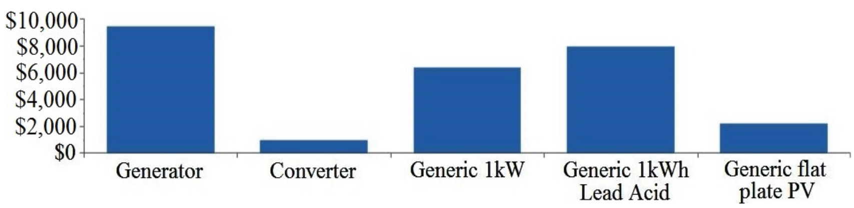

Fig. 12 Net present cost by the resources.

Table 3 Output results of cost calculations.

System	Capital ($)	NPC ($)	Operating cost ($)	COE ($/kWh)	RF (%)
I	10,845	26,846	1,238	0.720	54
II	7,320	27,846	1,588	0.747	21
III	6,240	31,449	1,950	0.844	0.0
IV	7,890	32,498	1,904	0.872	1.2

share of electricity generation by resources is plotted in Fig. 11, and Fig. 12 shows the net present cost of each component. Output results for cost comparison are shown in Table 3. As mentioned in Table 3, autosize genset is selected as a generator. Hence, its size is selected by software and examining of more generators in the search space is not needed. Finally, the software has selected a 1 kW PV, 1 kW wind, 1.5 kW diesel generator, eight units 83.4 Ah battery and 0.75 kW converter.

7. Optimal System Choice

It is obvious that a system with more components has higher initial capital cost. On the other hand, to supply reliable and secure power to the loads especially in the rural areas far from the electrical grid, further effective factors should be analyzed. As shown in Table 3, although system I has higher initial capital cost than other choices but the cost of energy, NPC and operating costs are lower. Renewable fraction is another valuable factor that shows the share of renewables i.e. the ratio of renewable energy generation to the total production [22]. As depicted in Table 3, this factor is also higher (54%) in System I than others. Besides, the software simulates and selects the system based on total and lower NPC which is called life-cycle costs. Hence, the system I is selected as an optimum choice.

8. Significance and Advantages of System I

Rural electrification is a second priority after the rule of law in Afghanistan. Besides, due to the importance of rural electrification through renewable energy and sustainable energy, ministry of energy and water has established an independent organization in 2009, called renewable energy department. Also, due to the availability of sufficient potential of renewable energy especially solar and wind in the remote areas of the country, renewables with the System I could be more advantageous where both resources are used in an optimal way. Furthermore, it can maintain both balance and security in the system. For example, solar insulation is usually higher in summer and wind is usually relatively strong in winter. Thus, a hybrid photovoltaic/wind system provides optimized and stable output power and minimizes the seasonal dependency of renewable energy sources [28]. Utilization of renewable sources such as solar and wind for remote power generation needs incorporation of energy storage systems as an effective means to enhance power smoothening and quality [29]. The battery is added to the system as a storage device. Besides, when there is excess power from solar and wind, it is stored in the battery and can be used in some critical conditions such as during the fault or during the shortage of PV or wind power. The conventional diesel generator is also added to the system as an ancillary and backup service, not as an option but to guarantee the power supplying during the PV and wind energy shortage or to provide the load power for a particular time. Besides, based on the accessibility to solar and wind power, diesel generator could be scheduled to manage the renewable energy output and fulfill the load requirement for a given time [9]. Furthermore, as shown in Fig. 12, the NPC of the diesel generator is higher than other components. Hence, it is recommended to use generator just in critical conditions when it is needed. As discussed in the wind rose analysis that wind speed and direction vary seasonally. Hence, when the extracted power from wind is insufficient, then PV can supply the load. Vice versa, during the winter and cloudy season when there is insufficient solar radiation, the load can be feed by wind power.

9. Barriers to Rural Electrification in Afghanistan

The deployment and utilization of renewable energy could have a major rule in enlightenment and socio-economic development especially in rural areas of Afghanistan. But some significant local and national challenges are hampering their uptake and proliferation which are addressed below:

(1) Poor institutional framework and infrastructure at the sub-national level for rural energy promotion.

(2) Infrastructural barriers such as large distance, inadequate infrastructures and lack of distribution networks.

(3) Local and social barriers such as political instability, poverty, low population density and lack of skilled personnel.

(4) Economic challenges such as higher initial costs for both end-users and providers, reliance on government financing and policy and lack of market.

(5) Lack of co-investment and private sector involvement.

(6) Lack of consumer awareness and public opinion on the benefits and opportunities of renewable energy.

10. Conclusions

This paper presents the feasibility of hybrid power generation based on solar and wind as renewable energy generation for a rural village in Afghanistan. The new version of HOMER software, HOMER Pro is used to simulate the hybrid system and select the optimal and reliable system. A conventional diesel generator is added to the system to ensure reliable and secure load power supply in some rare and critical conditions. It is found that the life cycle cost and cost of energy with System I is lower than others. Finally, small scale hybrid power generation is an optimal choice for rural poor and off-grid communities especially in developing countries such as Afghanistan but will entails the support of private sectors, governmental and non-government organizations in the country.

Acknowledgment

The authors thankfully acknowledge the supports and cooperation of University of the Ryukyus, JICA and the Electrical Power Engineering Department of Kabul Polytechnic University for this research.

References

[1] Akinyele, D. O., and Rayudu, R. K. 2013. "Distributed Photo-Voltaic Power Generation for Energy-Poor Households: The Nigerian Perspective." *IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC)*. DOI: 10.1109/APPEEC.2013.6837165.

[2] Xu, D., and Kang, L. 2015. "Optimal Dispatch of Unreliable Electric Grid-Connected Diesel Generator-Battery Power Systems." *International Journal of Emerging Electric Power Systems* 16 (3): 253-63.

[3] *Ministry of Energy and Water, Ministry of Rural Rehabilitation and Development*. Afghanistan Rural Renewable Energy Policy, Islamic Republic of Afghanistan: Final Draft. 2013.

[4] Alamyar, K. M. 2014. *Renewable Energy for Sustainable Development*.

[5] ADB. 2013. *Power Sector Master Plan*. Technical Assistance Consultants report, Islamic Republic of Afghanistan: Project Number 43497.

[6] Thabit, S. N., Senjyu, T., and Yona, A. 2015. "Enhancement of Voltage Stability of DC Smart Grid During Islanded Mode by Load Shedding Scheme." *International Journal of Emerging Electric Power Systems* 16 (5): 491-501.

[7] Abegaz, B. W., Mahajan, S. M., and Negeri, E. O. 2016. "Optimal Energy Management for a Smart Grid Using Resource-Aware Utility Maximization." *International Journal of Emerging Electric Power Systems* 17 (3): 251-66.

[8] Ludin, G. A., Amin, M. A., Aminzay, A., and Senjyu, T. 2016. "Theoretical Potential and Utilization of Renewable Energy in Afghanistan." *AIMS Energy Journal* 5 (1): 1-19.

[9] Bhandari, N. M., Burt, G., Dahal, K. P., Galloway, S., and McDonald, J. 2007. "Dispatch Optimization of Renewable Energy Generation Participating in a Liberalized Electricity Market." *International Journal of Emerging Electric Power Systems* 8 (3): Article 1.

[10] *Ministry of Energy and Water*. 2014. Afghanistan National Renewable Energy Policy, Final Draft.

[11] *Ministry of Energy and Water, Ministry of Mines, Ministry of Rural Rehabilitation and Development*. 2013. Energy Sector Strategy, Islamic Republic of Afghanistan: Afghanistan National Development Strategies.

[12] *Ministry of Energy and Water*. 2015. Renewable Energy Department Database, Islamic Republic of Afghanistan.

[13] Zamora, I., Martin, J. I. S., Mazn, A. J., Martn, J. J. S., and Aperribay, V. 2005. "Emergent Technologies in Electrical Microgeneration." *International Journal of Emerging Electric Power Systems* 3 (2): Article 1092.

[14] Su, Y., Zhao, C., Xu, L., and Liu, X. 2013. "Distributed Generation Application in the Rural Areas of West China." In *Proceedings of the IEEE PES Asia-Pacific Power and Energy Engineering Conference,* 167-70.

[15] Akinyele, D. O., and Rayudu, R. K. 2014. "Decentralized Energy Generation for End-Use Applications: Economic, Social and Environmental Benefits Assessment." *IEEE Innovative Smart Grid Technologies: Innovative Smart Grid Technologies Asia (ISGT ASIA)*, DOI: 10.1109/ISGT-Asia.2014.6873769.

[16] Mahdi, S., Anil, P., and Miller, R. D. 2012. "Basic Design and Cost Optimization of a Hybrid Power System for Rural Communities in Afghanistan." *IEEE North American Power Symposium (NAPS)*, DOI: 10.1109/NAPS.2012.6336333.

[17] Danish, M. S. S., Yona, A., and Senjyu, T. 2014. "Pre-design and Life Cycle Cost Analysis of a Hybrid Power System for Rural and Remote Communities in Afghanistan IET." *Journal of Engineering* 7. DOI: 10.1049/joe.2014.0172.

[18] https: //en:wikipedia:org/wiki/Qarabagh district, Ghazni/.

[19] Ministry of Energy and Water, Ministry for Rural Rehabilitation and Development. 2013. "Afghanistan Rural Renewable Energy Strategy." For the Government of the Islamic Republic of Afghanistan: Action Plan until 2018, Development Objectives until 2024, Draft version 1, 08 May 2013.

[20] Anurag, A., Bal, S., and Sourav, S. 2014. "A Comparative Study of Mathematical Modeling of Photovoltaic Array." *International Journal of Emerging Electric Power Systems* 15 (4): 313-26.

[21] Bansal, R. C., Zobaa, A. F., and Saket, R. K. "Some Issues Related to Power Generation Using Wind Energy Conversion Systems: An Overview." *International Journal of Emerging Electric Power Systems* 3 (2): Article 1070.

[22] Bergey Windpower Co. http://www.bergey.com/bergey/pages/packages.html.

[23] https://www.awstruepower.com/products/software/windographer/.

[24] Hasan, K., Fatima, K., and Mahmood, S. 2011. "Feasibility of Hybrid Power Generation over Wind and Solar Standalone System." In *Proceedings of the IEEE 5th International Power Engineering and Optimization Conference,* 139-43.

[25] http://www.mtavalanche.com/weather/windrose.

[26] Yuenio, S. 2010. Machinery & Electronics Import & Export Co Ltd. http://www.yueniao.com.

[27] Solar Panel Store (SPS). http://www.solarpanelstore.com.

[28] ElMoursi, M. S., and Sharaf, A. M. 2006. "Novel STATCOM Controllers for Voltage Stabilization of Stand Alone Hybrid (Wind/Small Hydro) Schemes." *International Journal of Emerging Electric Power Systems* 7 (3): Article 5.

[29] Prabhakar, J. R., and Ragavan, K. 2014. "STATCOM-Based Wind-Solar-Hydro Electric Power System with Modified Real and Reactive Power Controls." *International Journal of Emerging Electric Power Systems* 15 (1): 45-58.