A Feasibility Analysis of Deploying Photovoltaic Array in a Remote Arctic Community

Ashish N. Agrawal, Vikas S. Sonwalkar, Richard W. Wies

***Abstract* – This paper presents a feasibility analysis of deploying a photovoltaic (PV) array in a remote arctic community. We have developed a MATLAB® Simulink® model that computes the annual solar flux at a given latitude. The Simulink® model is used to compute the annual solar flux at Wales Village (Latitude = 65.60917° N and Longitude = 168.0875° W), a small village in Alaska. For Wales Village, we compared the annual electrical load profile, the annual surface temperature profile, and the estimated annual solar flux profile. We found a strong positive correlation between the surface temperature and the solar flux, a strong negative correlation between the electrical load profile and the surface temperature, and a weak negative correlation between the electrical load and the solar flux. Since the correlation between the electrical load and the solar flux is negative and weak, and because the solar flux at Wales is low during the winter months, a PV array by itself is not an economically feasible option for supplying the electrical energy demand at Wales Village. Therefore, other sources of electricity, such as wind turbine generators, micro-hydro turbines, geothermal power, biomass, and a battery bank should be incorporated with the diesel electric generators and a PV array to supply the electricity demand for Wales Village.**

***Index Terms* – arctic energy, hybrid power systems, PV array, solar flux.**

I. INTRODUCTION

Diesel Electric Generators (DEGs) are the main source of electric power for more than 800 remote communities in Alaska [1]. Some of the challenges to supply economical electric power to the isolated remote communities in Alaska include: high fuel costs, complex terrains, remoteness of the site, new environmental standards, and the lack of utility grids. The State Government and the electric utility companies are constantly investigating new technologies to supply economical power to remote Alaskan communities. These technologies include: wind power, solar power, geothermal power, microhydro, and biomass.

The main focus of this paper is to investigate the feasibility of installing photovoltaic (PV) panels in remote Alaskan communities. One of the major advantages of using the PV array is that the energy production from the PV array does not cause environmental pollution, thus helping the utility companies to meet their environmental standards. Besides this there are number of federal and utility rebate programs available for installing and using the PV array. The energy production from the PV array is a major function of geographical location.

Fig. 1 shows the variation of annual average solar flux with latitude on the top of the atmosphere [2]. We observe that at latitudes close to equator the annual average solar flux is high and as we move away from the equator towards the poles the annual average solar flux decreases. Therefore, the annual average solar flux in arctic regions is low due to the high latitude.

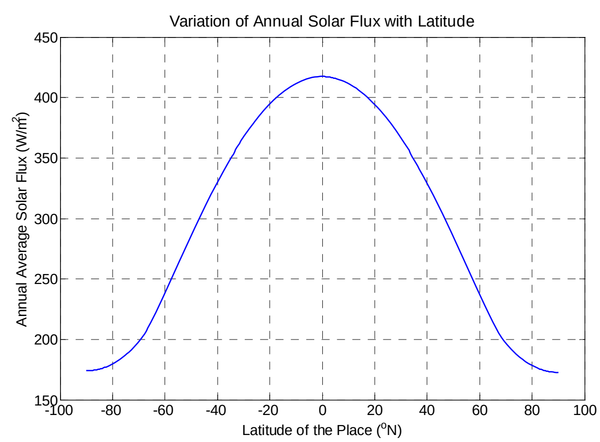

Fig. 1. Variation of Annual Average Solar Flux with Latitude on the Top of the Atmosphere.

In this paper we have used Wales, Alaska, as a sample village to investigate the feasibility of installing a PV array in order to meet the electrical power needs of the village. The reason for selecting Wales is that the power system data, the annual load data, and the annual surface temperature data were available for this village, which are in general difficult to obtain for Alaskan villages.

Wales Village is located at the tip of the Seward Peninsula, about 111 miles northwest of Nome, Alaska, at latitude 65.60917° N and longitude 168.0875° W. As per the US 2000 census, the area of Wales Village is about 2.8 square miles, with approximately 152 people, 50 households, and 28 residing families. There is one school attended by 49 students,

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and one local hospital – Wales Health Clinic [3]. The occupations of Wales Village residents include hunting, fishing, whale trapping, native arts and crafts, and mining [4]. The average summer temperature of Wales Village is about 40-50 °F, the average winter temperature is about –10 to 6 °F, the average precipitation is about 10 inches, and the annual snowfall is about 35 inches. Due to its coastal location, there are frequent fog and blizzard conditions in Wales Village [4].

The electricity in Wales Village is provided by the Alaska Village Electric Co-operative (AVEC) with the use of a hybrid wind-diesel-battery system. The hybrid system was installed in the summer of 2000 [1]. Before 2000, DEGs were the only source of electricity with a back-up battery bank.

Fig. 2 shows the details of the Wales Village, Alaska hybrid electric power system [5].

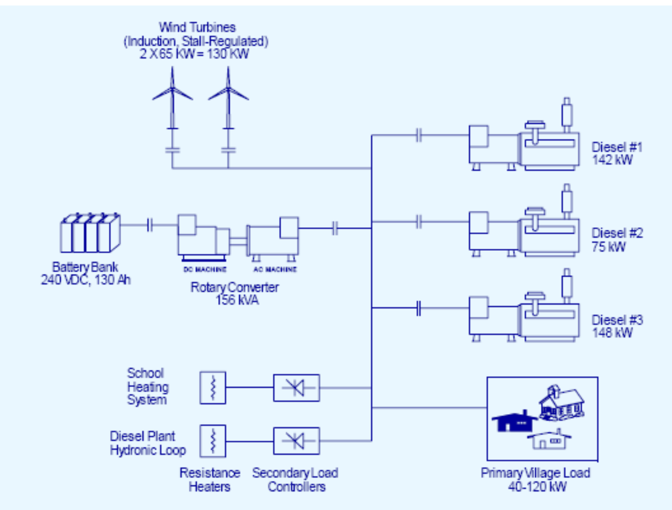


Fig. 2. Hybrid Power System of Wales Village Alaska [5].

The Wales Village hybrid power system consists of 3 DEGs:

- Diesel #1: 168 kW, 1200 RPM Cummins LTA10.
- Diesel #2: 75 kW, 1800 RPM Allis-Chalmers 3500.
- Diesel #3: 168 kW, 1800 RPM Cummins LTA10.

The Wales Village hybrid power system is operated as a single generator plant. DEG # 1 and DEG # 3 are cycled to supply the village load, in conjunction with wind turbine generators (WTGs). DEG#2, a less efficient generator, is brought online in case of scheduled maintenance or failures of either DEG#1 or DEG#3.

A detailed economic analysis of the hybrid wind-diesel-battery system for Wales Village, Alaska is available in [6] and a detailed economic analysis of the Lime Village PV-diesel-battery hybrid power system is available in [7], [8]. Currently, there is no PV array installed at Wales Village, Alaska.

II. OBSERVATIONS

Fig. 3 shows the annual load profile for Wales Village, Alaska from August 1st, 1993 through July 31th, 1994.

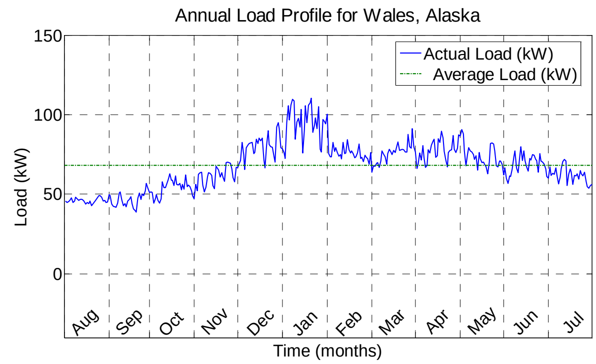


Fig. 3. Annual load profile for Wales Village, Alaska.

We obtained the electrical load data from Ms. Mari Shirazi in October 2002 when she was working for the National Renewable Energy Laboratory (NREL) on a hybrid power system project for Wales Village. The data were averaged over the period of 15 minutes and saved into a data logger. The sampling rate of the averaged data for Wales Village is unknown; generally it varies between 10 samples per second to 50 samples per second for such applications, depending on the desired accuracy. There is no additional filtering done if the data are averaged and saved with higher sample rates. From Fig. 3 it can be observed that the electrical load is higher in the winter months of December through April and lower for summer months with an average annual load of about 63 kW.

Fig. 4 shows the annual surface temperature profile for Wales Village, Alaska.

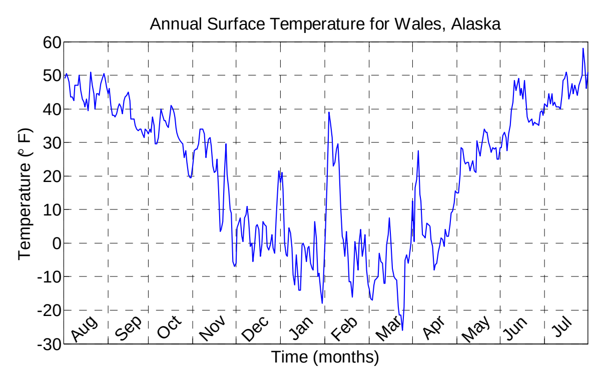
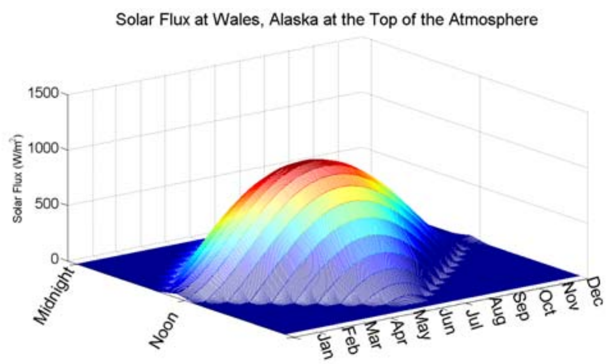


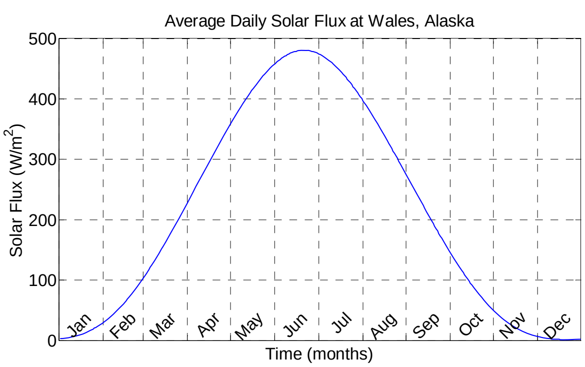
Fig. 4. Annual Surface Temperature profile for Wales Village, Alaska.

We obtained the temperature profile data from Ms. Martha Sulshi in March 2006 when she was working with UAF's weather department. The temperature profile data is for the same time interval as that of the electrical load profile. The actual data is the average of daily minimum and daily maximum temperatures recorded at Wales Village, Alaska.

Fig. 5 shows the annual hourly and average daily solar flux profile at Wales Village, Alaska.



(a)



(b)

Fig. 5. (a) Annual Hourly and (b) Annual Average Daily Solar Flux at Wales Village, Alaska.

We obtained the solar flux profile in Fig. 5 by developing a MATLAB® Simulink® model which can generate the solar flux profile for any place on the earth given the latitude of the location. It should be noted that, these solar flux values are the flux values above the top of the atmosphere at the latitude of Wales Village, Alaska. The actual solar flux reaching on the surface of the earth can be obtained for these flux values and knowing the clearness index of the place. The average solar flux for one day is calculated from the equation given in [2] as,

$$Q\_day = \frac{S_0}{\pi} * \left(\left(\frac{\bar{d}}{d}\right)^2 \left(h_0 \sin\phi \sin\delta + \cos\phi \cos\delta \sin h_0\right) \right), \qquad (1)$$

where Q_day (W/m^2) is the solar flux, S_o (W/m^2) is the maximum solar flux available at the surface of the earth, $\left(\frac{\bar{d}}{d}\right)^2$ is the squared ratio of the mean Earth-sun distance to the actual distance, h_0 is the hour angle (radian) at sunrise and sunset, ϕ (degree) is the latitude of the location (Wales, Alaska), and δ (degree) is the declination angle. The value of S_0 is generally given or can be assumed as 1360 W/m^2. The declination angle can be calculated by using the Fourier series,

$$\delta = \sum_{0}^{3} a_n \cos(n\theta_d) + b_n \sin(n\theta_d), \qquad (2)$$

where the coefficients are given as shown in Table I.

TABLE I
COEFFICIENTS FOR FOURIER SERIES OF DECLINATION ANGLE

N	a_n	b_n
0	0.006918	
1	-0.399912	0.070257
2	-0.006758	0.000907
3	-0.002697	0.001480

and θ_d is given by,

$$\theta_d = \frac{2\pi d_n}{365}, \qquad (3)$$

where 'd_n' is the day under consideration.

The angle of sunrise and sunset is given by,

$$\cos(h)_0 = -\tan\phi \tan\delta, \qquad (4)$$

and the Fourier series for the ratio $\left(\frac{\bar{d}}{d}\right)^2$ is given as,

$$\left(\frac{\bar{d}}{d}\right)^2 = \sum_{0}^{2} a_n \cos(n\theta_d) + bn \sin(n\theta_d) \qquad (5)$$

with the coefficients given as shown in Table II.

TABLE II
COEFFICIENTS FOR FOURIER SERIES OF SQUARED RATIO OF THE MEAN EARTH-SUN DISTANCE TO THE ACTUAL DISTANCE

N	a_n	b_n
0	1.000110	
1	0.034221	0.001280
2	0.000719	0.000077

Fig. 5(a) shows that there is high solar flux available during the summer months and low solar flux during the winter months for Wales Village, Alaska. The hourly values can be used to study the use of PV systems for projects which use power only during summer months. For example, a number of people use PV arrays for their cabins during the summer months. Fig. 5(b) shows the annual average daily solar flux. This figure can be used in computing the economics for projects which use PV arrays year round.

III. Data Analysis

Fig. 6 shows the weekend effect analysis for Wales Village, Alaska. We used the annual load profile to determine if there are any weekend effects observed in Wales Village, Alaska. Generally, in big cities, it is a common observation that the electrical load drops due to closure of a number of businesses. We did not observe the weekend effect for Wales Village, Alaska, but we did notice an approximate 5-10% decrease on Thursdays and Fridays.

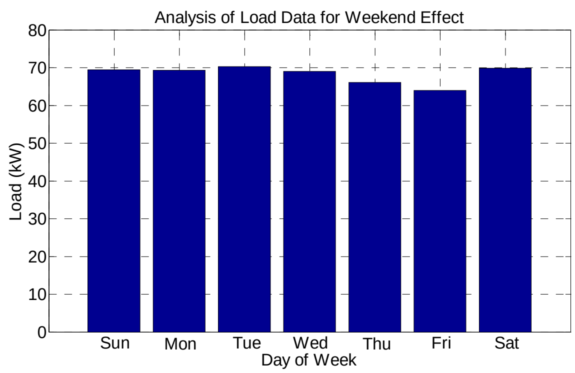


Fig. 6. Weekend Electrical Load Effect Analysis for Wales Village, Alaska.

Fig. 7 shows the annual variation of solar flux and surface temperature for Wales Village, Alaska. We observed a strong positive correlation between the solar flux and the surface temperature. The correlation coefficient is observed as 0.58. We note that there is a lag of about one month between the minimum solar flux and the minimum surface temperature.

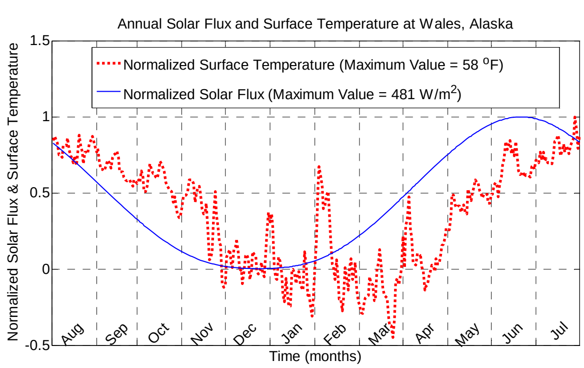


Fig. 7. Annual Variation of Solar Flux and Surface Temperature for Wales Village, Alaska.

Fig. 8 shows the annual variation of electrical load and solar flux at Wales Village, Alaska. We observed a negative correlation between the solar flux and the electrical load. The correlation coefficient between the load and the solar flux is obtained as -0.28. Here also we see a one month lag between the minimum solar flux and the maximum electrical load.

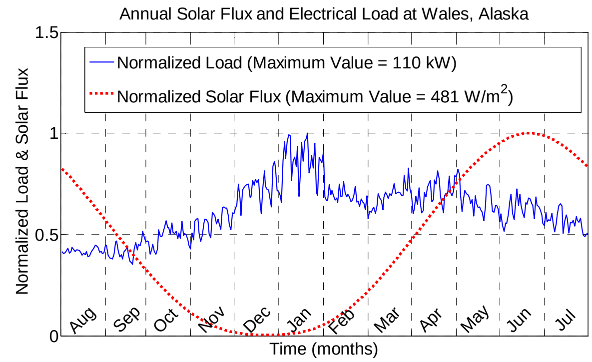


Fig. 8. Annual Variation of Solar Flux and Electrical Load for Wales Village, Alaska.

Fig. 9 shows the annual variation of the electrical load and the surface temperature for Wales Village, Alaska. We observed a strong negative correlation between the surface temperature and the electrical load. With the decrease in surface temperature, the demand for electricity increases. The correlation coefficient is obtained as -0.68.

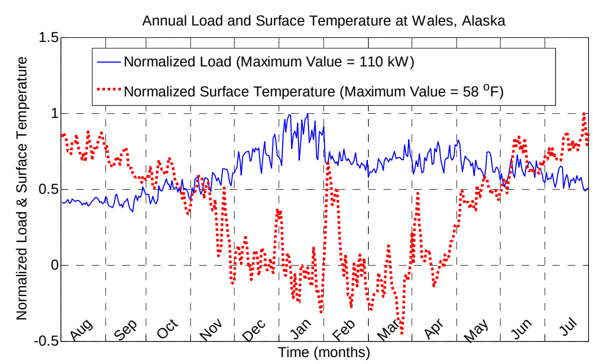


Fig. 9. Annual Variation of Electrical Load and Surface Temperature for Wales Village, Alaska.

IV. Conclusions

In this paper we presented a data analysis technique that can be used to study the feasibility analysis of installing PV arrays in remote villages of Alaska. To study this we developed a MATLAB® Simulink® model that can compute the solar flux above the top of the atmosphere for any given location on the earth. We used this solar flux profile and the surface temperature profile and compared them with the annual load profile of Wales Village, Alaska.

We observed a strong positive correlation between the solar flux profile and the surface temperature, a negative correlation between the annual solar flux profile and the annual load profile, and a negative correlation between the surface temperature and the annual load profile.

From our analysis we conclude that photovoltaic arrays, by themselves, are not a feasible option to supply electricity for Alaskan villages due to low electricity load demand during summer months when there is sufficient sunlight available and high load demand during winter months when there is very little sunlight available.

Therefore, we conclude that in addition to PV arrays and DEGs, other energy generation technologies such as wind turbines, micro-hydro turbines, geothermal, and bio-mass, should be considered for supplementing the electrical energy needs of the villages in Alaska as well as in other high latitude remote locations on the Earth.

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