Review

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Review

Design of Photovoltaic System for Green Manufacturing by Using Statistical Design of Experiments

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Abstract: Overcoming the negative impacts on the environment and other problems associated with fossil fuels has forced many countries to inquire into and change to environmentally friendly alternatives that are renewable to sustain the increasing energy demand. Solar energy is one of the best renewable energy sources with the least negative impacts on the environment. Different countries have formulated solar energy policies to reduce dependence on fossil fuels and increase domestic energy production by solar energy. According to the 2010 BP Statistical Energy Survey, the world cumulative installed solar energy capacity was 22928.9 MW in 2009, a change of 46.9% compared to 2008. In this study, a PV generation system has been modeled and installed considering uncertain weather based on the hourly wind speed data of New York City (NYC) in the year 2014. Regression models have been used to forecast the hourly, weekly, and monthly wind speed of NYC year 2014. The design of experiment (DOE) has been used to determine the optimal panel size (area), the battery capacity size, and other levels of factors.

Keywords: solar PV system; regression model; DOE; solar energy

1. Introduction

Energy policy is a strategy in which the government decides to address the issues of energy development along with the development of the energy industry to sustain its growth, including energy production, distribution, and consumption [1,2]. The attributes of energy policy may include legislation, international treaties, and investment incentives [3]. It plays a vital role in mitigating the impacts of global warming and the crisis of energy availability [4].

Solar energy is one of the cleanest energy resources that does not compromise or add to global warming. The sun radiates more energy in one second than people have used since the beginning of time [5–7]. Solar energy is often called "alternative energy" to fossil fuel energy sources such as oil and coal [8]. The availability of cheap and abundant energy with minimum environmental and ecological hazards associated with its production and use is one of the important factors for desired improvement in the quality of life of the people [9,10]. The growing scarcity of fossil fuels has raised global interest in the harnessing of solar energy [11]. Solar power is a type of energy with great future potential though at present it covers merely a minor portion of global energy demands (0.05% of the total primary energy supply); now PV power generates less than 1% of the total electricity supply [12–15]. This is due to solar power still being considered the most expensive type of renewable energy. However, in remote regions of the earth, it may very well constitute today's best solution for a decentralized energy supply. According to the 2010 BP Statistical Energy Survey, the world cumulative installed solar energy capacity was 22928.9 MW in 2009, a change of 46.9% compared to 2008.

World primary energy demand is projected in the Reference Scenario to expand by almost 60% from 2002 to 2030, an average annual increase of 1.7% per year. Demand will reach 16.5 billion tons of oil equivalents (toe) compared to 10.3 billion toes in 2002 which is shown in Table 1. On the other hand, fossil fuels will continue to dominate global energy use. They will account for around 85% of the increase in world primary demand over 2002–2030. And their share in total demand will increase slightly, from 80% in 2002 to 82% in 2030. The share of renewable energy sources will remain flat at around 4%, while that of nuclear power will drop from 7% to 5% [16–19].

Table 1. World total final consumption.

	1971	**2002**	**2010**	**2030**	**2002–2030 (%)**
Coal	617	502	516	526	0.2
Oil	1893	3041	3610	5005	1.8
Gas	604	1150	1336	1758	1.5
Electricity	377	1139	1436	2263	2.5
Heat	68	237	254	294	0.8
Biomass and waste	641	999	1101	1290	0.9
Other renewable	0	8	13	41	6.2
Total	4200	7075	8267	11, 176	1.6

Solar photovoltaic technology could harness the sun's energy to provide large-scale, domestically secure, and environmentally friendly electricity [20–22]. In 2005, global solar markets reached US$ 11.8 billion, up 55% from 2004. Solar installations are expected to provide 15 GW in 2010 versus 2.7 GW in 2006. In April 2007, Photon Consulting forecasted 2010 revenues from sales of solar energy equipment of US$ 90 billion, up from US$ 20 billion in 2006. Demand for silicon for solar cells is expected to increase from 41,000 tons in 2006 to 120,000 tons in 2010 and 400,000 tons in 2014. Table 2 shows the expected development and installation of solar photovoltaic electricity in the USA, Europe, Japan as well as worldwide until 2030.

Table 2. Development and installation of solar photovoltaic electricity in various countries.

Year	**USA (MW)**	**Europe (MW)**	**Japan (MW)**	**Worldwide (MW)**
2000	140	150	250	1000
2010	3000	3000	5000	14,000
2020	15,000	15,00	30,000	70,000
2030	25,000	30,000	72,000	140,000

Table 3. World carbon dioxide emissions by region, 1990–2025.

Region	**1990**	**2002**	**2010**	**2015**	**2020**	**2025**
Mature market economics	10,465	11,877	13,080	13,745	14,392	15,183
North America	5769	6701	7674	8204	8759	9379
Western Europe	3413	3549	3674	3761	3812	3952
Mature market Asia	1284	1627	1731	1780	1822	1852
Transitiona l economics	4894	3124	3643	3937	4151	4386
Emerging economics	6101	9408	13,478	15,602	17,480	19,222

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Asia	3890	6205	9306	10,863	12,263	13,540
Middle east	845	1361	1761	1975	2163	2352
Africa	655	854	1122	1283	1415	1524
Central and south America	711	988	1289	1280	1639	1806
Total world	21,460	24,209	30,201	33,284	36,023	38,790

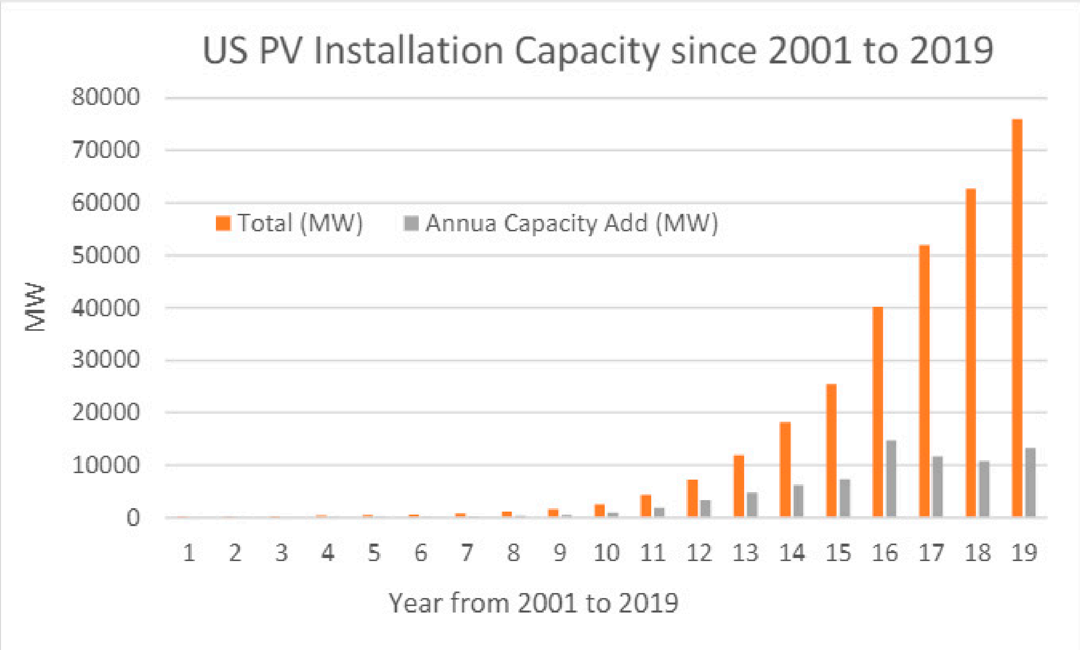

Figure 1. Solar PV Installation in the US from 2001 to 2019 (cumulative vs annual addition).

With growing aspects of this emerging area, the future of solar energy technology promises a transition to greener, more sustainable, and energy-efficient manufacturing processes [23]. As solar technologies continue to evolve and become more accessible, manufacturers will have the tools and incentives needed to make a substantial positive impact on both the environment and their bottom lines [24–26]. This shift towards solar-powered manufacturing is not only a testament to the industry's commitment to sustainability but also a strategic move towards long-term economic competitiveness [27].

The modern industrial landscape is witnessing a paradigm shift towards more sustainable and environmentally conscious practices, with a growing emphasis on green manufacturing. In this context, the utilization of solar energy stands as a pivotal and transformative component in the pursuit of cleaner, more energy-efficient production processes [28,29]. Solar energy offers not only a renewable and abundant source of power but also aligns with the principles of green manufacturing, which prioritize reduced environmental impact, energy efficiency, and resource conservation [30].

In the realm of green manufacturing, the integration of circular economy principles offers a wealth of advantages by culminating in a holistic and sustainable approach [31–35]. Green manufacturing, grounded in its commitment to reducing environmental impact and conserving resources, harmoniously dovetails with the foundational principles of the circular economy [36]. By blending these two paradigms, manufacturers stand to benefit in multiple dimensions [37]. Through the infusion of manufacturing process improvement principles, operations are streamlined, leading to increased efficiency, cost savings, and minimized waste generation. Furthermore, the incorporation of additive manufacturing techniques introduces unprecedented levels of flexibility, enabling on-demand production of intricate, sustainable components, and reducing material waste [38–41]. Simultaneously, the synergy of human-robot collaboration optimizes production processes by enhancing precision and speed, ultimately leading to cost reductions and heightened product

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quality [41–44]. This amalgamation promotes the life extension of products, facilitated by eco-design principles, and reduces the demand for virgin materials. The adoption of circular economy practices also entails the establishment of closed-loop systems and partnerships with suppliers and customers, which further enhances the overall sustainability of the supply chain, while enabling manufacturers to extract value from their waste materials. The reintegration of these materials into production operations, through waste-to-energy or upcycling approaches, not only minimizes environmental impact but also bolsters the circular economy's commitment to reducing waste. Sustainability metrics and reporting are integral to tracking progress, and the shift toward sustainable packaging materials and practices completes this sustainable loop [37]. Ultimately, the integration of circular economy principles within green manufacturing exemplifies a win-win scenario: manufacturers benefit from enhanced operational efficiency, cost savings, and reduced environmental impact, while simultaneously contributing to global sustainability efforts by reducing waste and conserving resources. This dynamic synergy represents a pivotal step toward a greener, more responsible, and economically prosperous future for both businesses and society at large.

Particularly, the inclusion of Solar energy in the circular economy-based green manufacturing domain stands as an unequivocal environmental champion in the realm of sustainable development, serving as the linchpin of responsible energy generation [45–48]. Unlike conventional energy sources, it operates without depleting precious natural resources or releasing harmful gaseous emissions like CO2, NOx, SO2, or particulates, thus contributing to a reduction in greenhouse and toxic gases. Additionally, solar energy projects can play a vital role in land reclamation, breathing new life into previously degraded areas. Notably, the decentralized nature of solar energy production reduces the need for extensive electricity grid transmission lines, mitigating energy losses and infrastructure requirements [49]. Simultaneously, solar power systems can enhance the quality of local water resources by conserving water traditionally consumed by cooling processes in conventional power plants. Solar energy further fosters regional and national energy independence by diversifying the energy mix and reducing dependence on centralized power sources. In turn, this diversification bolsters energy supply security and accelerates rural electrification efforts in developing nations, extending the benefits of clean energy access to underserved communities.

2. Methodology

The hourly wind speed data of NYC from the year 2014 to 2016 has been provided for the project. We are working for the year 2014 on this project. We have used Minitab, Excel, and Python to complete project work. For cleaning the data, we have used Python. As output, we received CSV format data and then converted the data into excel format. Data where the last number was not 51 eliminated by python software. We got 8744 hours of data and the rest 16-hour missing data we have calculated and finally, we get 8760 hours of wind speed. For statistical distribution, we have used Minitab software.

3. Result and Discussion

3.1. Question 01

For determining the mean and standard deviation, by month filter was applied and then the average and standard deviation of every month was taken. For the yearly mean and standard deviation, 8760 data were analyzed to get the values for 2014, 2015, and 2016.

Mean speed for 2015 = 4.875 m/s
Mean speed for 2014 = 5.07 m/s
Mean speed for 2016 = 5.15 m/s
Standard Deviation for 2015 = 2.6585
Standard Deviation for 2014 = 2.73
Standard Deviation for 2016 = 2.79

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For the yearly mean and standard deviation for the year 2014, the rand () function in Excel was used to create a random sample and then 1000 data points were collected from that group. From the 1000 random data points, the month wise mean and standard deviation for 2014 was calculated and they are as follows:

Month	Mean (M/S)	Standard Deviation
January	6.09	2.93
February	5.93	3.27
March	5.29	2.86
April	5.36	2.84
May	4.41	2.75
June	4.56	2.2
July	4.18	2.09
August	4.27	2.09
September	4.10	2.09
October	5.22	2.34
November	4.49	2.52
December	5.49	1.54

3.2. Question 02

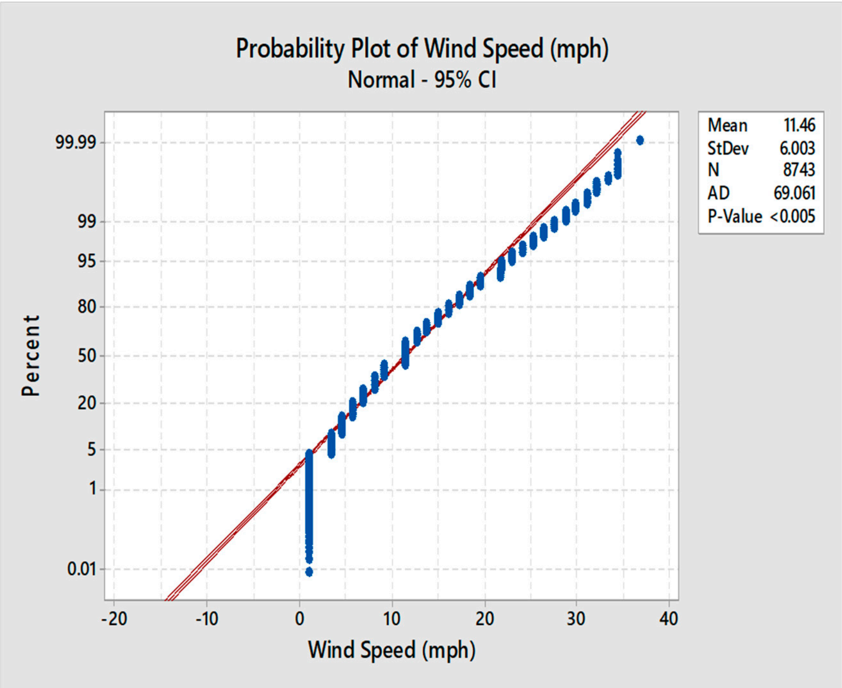

Figure 2. Probability plot of wind speed with normal distribution.

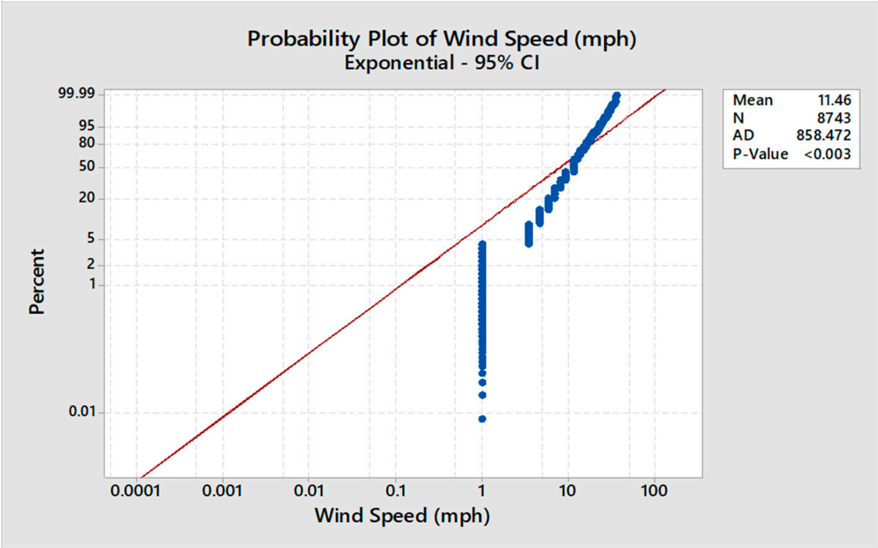

Figure 3. Probability plot of wind speed with exponential distribution.

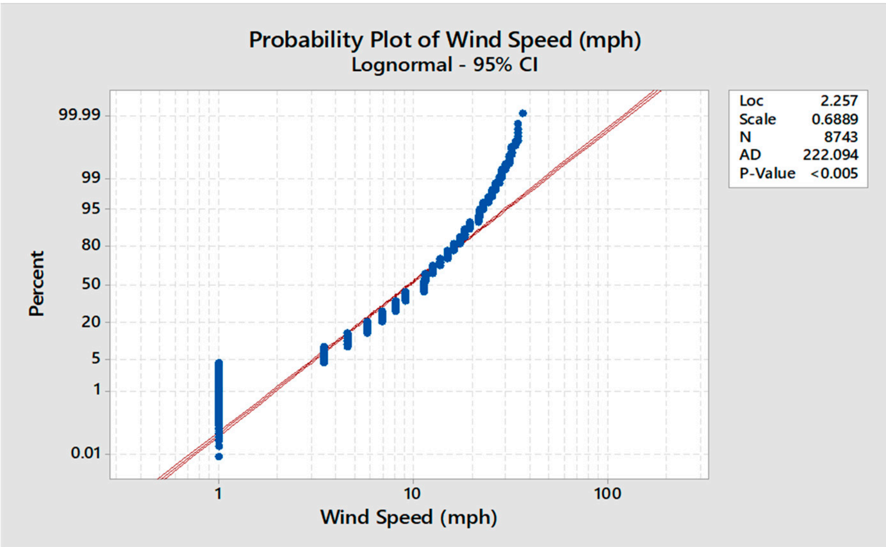

Figure 4. Probability plot of wind speed with lognormal distribution.

Using Minitab to fit a random sample of 1000, we concluded that the Weibull distribution is the best fit but still has a low p-value of <0.01. The second-best distributions were normal distribution with a p-value <0.005.

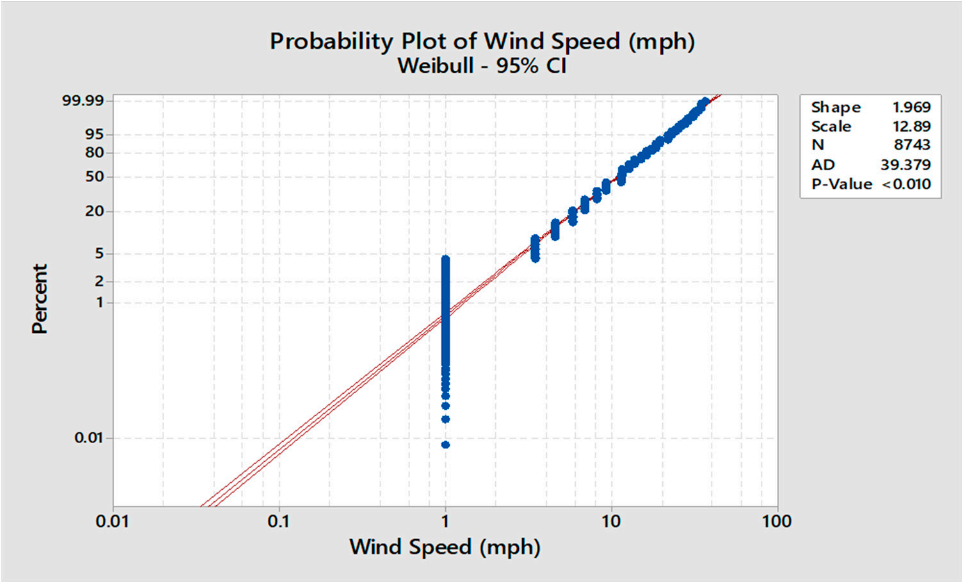

Figure 5. Probability plot of wind speed with Weibull distribution.

3.3. Question 03

- ✓ Hypothesis testing on windspeed means, Null Hypothesis: H_O: $u_O = u1$
- ✓ Alternative hypothesis: $H1$: $u_O \neq u1$
- ✓ The mean of the 1000 random value of wind speed of 2015 is = 4.85 m/s
- ✓ The variance of the 1000 random value of wind of 2015 speed is = 7.05
- ✓ Standard deviation = 2.64
- ✓ The mean of the 1000 random value of wind speed of 2016 is = 5.05m/s
- ✓ The variance of the 1000 random value of wind of 2016 speed is = 7.78 m/s
- ✓ Standard deviation = 2.78 m/s
- ✓ Sp= 2.72
- ✓ $t_O = -0.51$
- ✓ t_O falls in between the range. Hence, we fail to reject the null hypothesis. So, the mean wind speed is not significantly different between two adjacent years.

Here, F value is less than the F critical value, so we fail to reject the null hypothesis using 95% confidence level.

F-Test Two-Sample for Variances		
	Variable 1	*Variable 2*
Mean	12.10640641	12.7750501
Variance	41.42845591	46.31230566
Observations	1000	1000
df	999	999
F	0.894545312	
P(F<=f) one-tail	0.03929353	
F Critical one-tail	0.901037809	

Figure 6. F-test of two samples for variances.

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3.4. Question 04

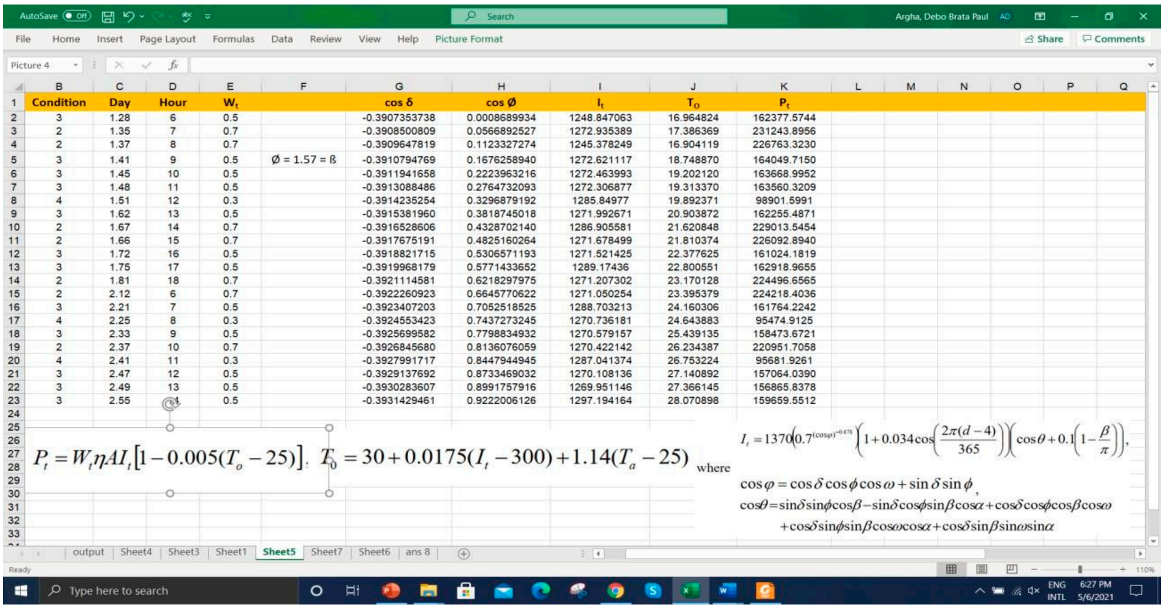
We have taken 1000 sample data from the 8760 data to estimate the yearly wind speed. We have used $V_h = V_g (80/8)^3$ to find the wind speed at turbine height. We have also removed the data which are unable to operate wind turbine. So, we have eliminated the wind speed less than 2m/s and greater than 25m/s. This gives us 330 data where wind turbine can operate between wind speed 12 m/s to 25 m/s.

The output will be = 2 MW/h*330 hrs. = 650 MWh. Between 0 to 2m/s numbers of samples = 32 Between 2 to 4m/s numbers of samples = 106 Between 4 to 6m/s numbers of samples = 134 Between 6 to 8m/s numbers of samples = 196 Between 8 to 10m/s numbers of samples = 150 Between 10 to 12m/s numbers of samples = 52

Wind Speed (m/s)	12-25	10-12	8-10	6-8	4-6	2-4
Power (MW)	2	1.75	1.5	1.25	0.75	0.25

From 1000 random data we have calculated total power =
(330Hrs x 2MWh) + (52Hrs x 1.75MWh) + (150Hrs x 1.5MWh) + (196Hrs x 1.25MWh) + (134Hrs x .75MWh) + (106Hrs x .25MWh) = 1348 MWh total
For total 8760 data it will be = (1348/1000) *8760 = 11,808.48 MWh total
So, the number of homes wind turbine could power = (11,808.48*1000)/7300 = 1618 homes

3.5. Question 05



	Condition	Day	Hour	W_t		cos δ	cos Ø	I_t	T_O	P_t
2	3	1.28	6	0.5		-0.3907353738	0.0008689934	1248.847063	16.964824	162377.5744
3	2	1.35	7	0.7		-0.3908500809	0.0566892527	1272.935389	17.386369	231243.8956
4	2	1.37	8	0.7		-0.3909647819	0.1123327274	1245.378249	16.904119	226763.3230
5	3	1.41	9	0.5	Ø = 1.57 = ß	-0.3910794769	0.1676258940	1272.621117	18.748870	164049.7150
6	3	1.45	10	0.5		-0.3911941658	0.2223963216	1272.463993	19.202120	163668.9952
7	3	1.48	11	0.5		-0.3913088486	0.2764732093	1272.306877	19.313370	163560.3209
8	4	1.51	12	0.3		-0.3914235254	0.3296879192	1285.84977	19.892371	98901.5991
9	3	1.62	13	0.5		-0.3915381960	0.3818745018	1271.992671	20.903872	162255.4871
10	2	1.67	14	0.7		-0.3916528606	0.4328702140	1286.905581	21.620848	229013.5454
11	2	1.66	15	0.7		-0.3917675191	0.4825160264	1271.678499	21.810374	226092.8940
12	3	1.72	16	0.5		-0.3918821715	0.5306571193	1271.521425	22.377625	161024.1819
13	3	1.75	17	0.5		-0.3919968179	0.5771433652	1289.17436	22.800551	162918.9655
14	2	1.81	18	0.7		-0.3921114581	0.6218297975	1271.207302	23.170128	224496.6565
15	2	2.12	6	0.7		-0.3922260923	0.6645770622	1271.050254	23.395379	224218.4036
16	3	2.21	7	0.5		-0.3923407203	0.7052518525	1288.703213	24.160306	161764.2242
17	4	2.25	8	0.3		-0.3924553423	0.7437273245	1270.736181	24.643883	95474.9125
18	3	2.33	9	0.5		-0.3925699582	0.7798834932	1270.579157	25.439135	158473.6721
19	2	2.37	10	0.7		-0.3926845680	0.8136076059	1270.422142	26.234387	220951.7058
20	4	2.41	11	0.3		-0.3927991717	0.8447944945	1287.041374	26.753224	95681.9261
21	3	2.47	12	0.5		-0.3929137692	0.8733469032	1270.108136	27.140892	157064.0390
22	3	2.49	13	0.5		-0.3930283607	0.8991757916	1269.951146	27.366145	156865.8378
23	3	2.55	[illegible]	0.5		-0.3931429461	0.9222006126	1297.194164	28.070898	159659.5512

$$P_t = W_t \eta A I_t [1 - 0.005(T_o - 25)]. \quad T_0 = 30 + 0.0175(I_t - 300) + 1.14(T_a - 25)$$

where

$$I_t = 1370\left(0.7^{(\cos\varphi)^{-0.678}}\right)\left(1 + 0.034\cos\left(\frac{2\pi(d-4)}{365}\right)\right)\left(\cos\theta + 0.1\left(1 - \frac{\beta}{\pi}\right)\right),$$

$$\cos\varphi = \cos\delta\cos\phi\cos\omega + \sin\delta\sin\phi,$$

$$\cos\theta = \sin\delta\sin\phi\cos\beta - \sin\delta\cos\phi\sin\beta\cos\alpha + \cos\delta\cos\phi\cos\beta\cos\omega + \cos\delta\sin\phi\sin\beta\cos\omega\cos\alpha + \cos\delta\sin\beta\sin\omega\sin\alpha$$

Figure 7. Sample calculation for question 5.

For PV output all-night data have been deleted and set the PV angle to the same as the latitude of NYC to maximize output. After calculating the sunrise and sunset time, excel was used to find solar irradiance at every hour. To find the power output I mapped the given data condition range of 1-9 to the required 1-0. Then the power output at every hour could be established for the panels. After power output at every hour was found the sum has been calculated and found the yearly power output.

In total, the solar panels generated 867.37 MWh.

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3.6. Question 06

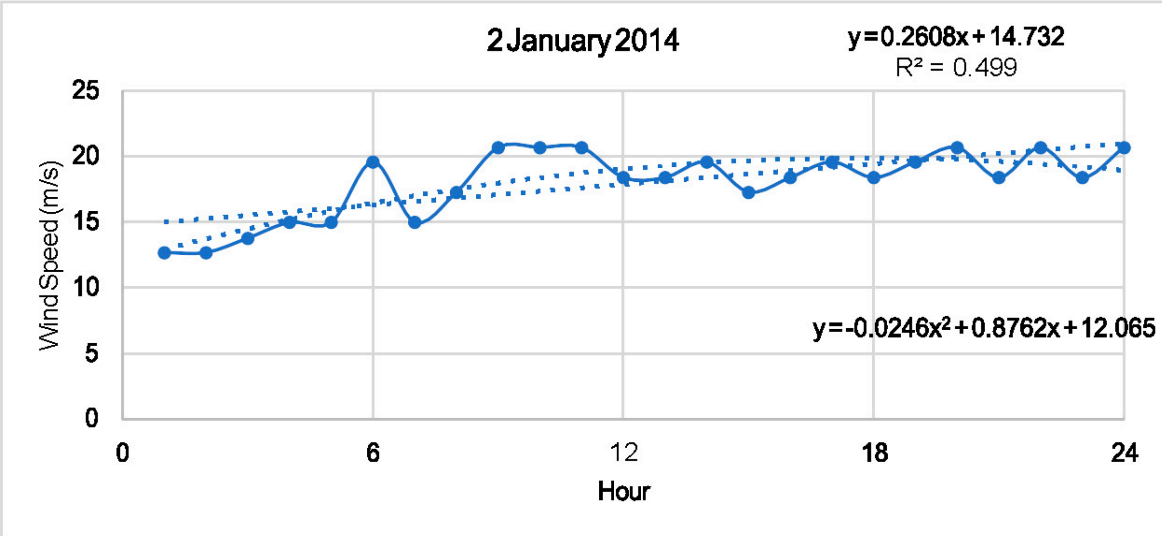

Figure 8. Hourly wind speed forecasting for January 02, 2014.

Using the second order of polynomial line, the equation for forecasting is:

$$y = -0.0246x^2 + 0.8762x + 12.065$$

For the linear fit model, equation is, $y = 0.2608x + 14.732$.

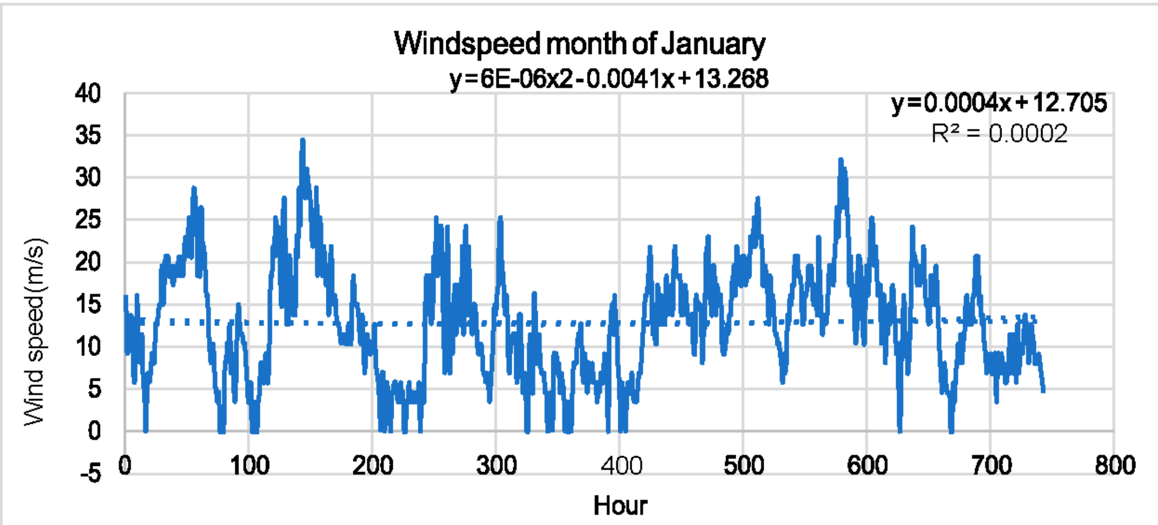

Figure 9. Monthly wind speed forecasting for January 2014.

For monthly wind speed estimation, we averaged the daily windspeed for January 2014, using this data then plotted the daily windspeed average vs the day of the month. For a second-order polynomial trend line, the equation obtained is, $y = 6E\text{-}06x^2 - 0.0041x + 13.268$

A linear trend line gives the equation: $y = 0.0004x + 12.705$.

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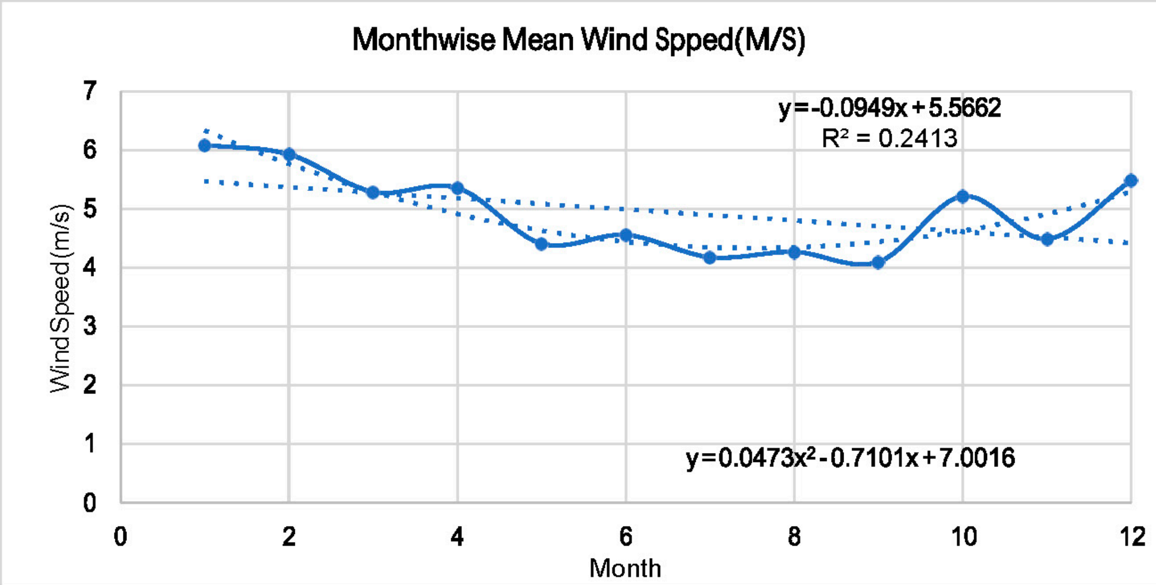

Figure 10. Yearly wind speed forecasting for January 2014.

For yearly wind speed, the average wind speed for every month for the year 2014 was calculated and plotted vs the number of the month. The formula for the second-degree polynomial is $y = 0.0473x^2 - 0.7101x + 7.0016$

Using a Linear line of fit we got, $y = -0.0949x + 5.5662$.

3.7. Question 07

Factors that are significant and/or correlated:

Factor 1. The Size of PV system: The size of the PV is one of the important factors. The energy generation will increase with the PV size.

Factor 2. PV Capacity Cost: The cost is the most important factor that can be calculated by the multiplication of the number of PV panels and the installation cost. The equation is 106x. Here, x = PV size in MW.

Factor 3. PV Efficiency: The PV efficiency has been selected as maximum as 25%. If we don't care much about cost, the efficiency can be increased in a limited size.

Factor 4. Weather Condition: In perfect weather conditions, the factory needs 100,000 m2 panels to handle roughly 27 MW assuming each panel generates 270 W/m2. The angle of the sun and weather conditions have a great effect on the fluctuation of power, on average in NYC is 130 W/m2.

In January 2014 average weather condition in New York is 0.412 representing the solar cells generate about 41% of their maximum output during the day in winter. Whereas in summer the value is 0.453 or 45% of maximum generation

Factor 5 and 6. Ambient Temperature and Wind Speed: Ambient temperature and wind speed have also an effect on panel efficiency. Both are helping to cool down the PV systems, making them run more efficiently.

Factor 7. Hour of a Day: The power can be generated in daytime, not at night and the maximum power can be found at noon. Based on the formula, in January (winter) it is 1274.76 W/m2 and in summer it is 1468.6 W/m2.

Factor 8 & 9. Utility Pricing Scheme and Government Incentives: Utility scheme could offer an income possibility if the PV system is generating more power than it is consuming, and Government incentives could drastically lower the upfront price of panel installation.

Factor 10. The batter capacity: battery capacity can reduce the size of the PV system by storing energy when power generation is over the factory power usage and discharging it during bad weather or at night.

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In winter, the factory has a peak energy draw of 17.4 MW during hours 13 and 16. So the expected power generation in January 1274.76 W × 25% × 1m2 × 0.412 × 1.0309 (from temperature) = 135.4.

In summer, 1468.6 W × 25% × 1m2 × 0.453 × 0.8621 = 143.4.

In winter, factory draws an average of 14.78 MW with a peak of 17.4 MW. Minimum we need 17.4 × 106/ 135.4 = 128,509 panels at 1 m2 each. In summer, minimum we need 22.6 × 106/143.4 = 157,602 panels at 1 m2 each.

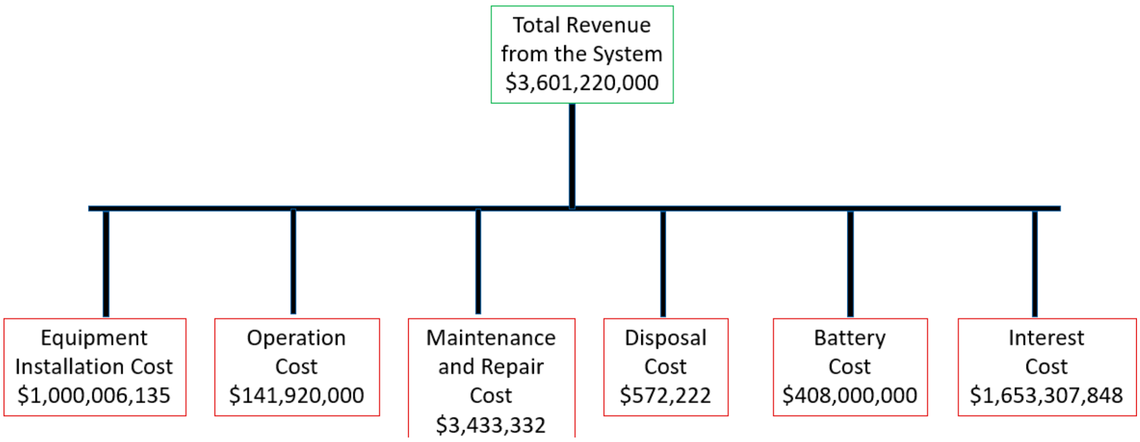
If the panels make an average of 17.4 MW during the daytime (from hour 7 to 17), we can create 17.4 × 10 = 174 MWh per day. The factory needs 14.78 × 24 = 354.8 MWh. So, the system would need an average of 35.48 MW/hour for 10 hours to generate enough energy for daytime power draw peaks and night usage.

If we use a 60 MW system, simulation gives us average excess energy storage of 62.3 MW/day.

If a 510 MW battery is installed, it would take 510/62.3 = 8.2 day to fully charge and can be capable of providing a little over one day of full power outage.

3.8. Question 08

Life cycle cost analysis



Cost of Electricity by source in US

Power Plant Type	Cost (LCOE)
	$/kW-hr
Coal with CCS	$0.12-0.13
CC Natural Gas	$0.04
CC with CCS	$0.08
Nuclear	$0.09
Wind onshore	$0.04
Wind offshore	$0.11
Solar PV	$0.04
Solar Thermal	$0.17
Geothermal	$0.04
Biomass	$0.09
Hydro	$0.03

(Levelized cost of electricity, LCOE) Source: Adapted from US DOE

4. Conclusion

Solar power is an immense source of directly useable energy and ultimately creates other energy resources: biomass, wind, hydropower, and wave energy. Most of the Earth's surface receives sufficient solar energy to permit low-grade heating of water and buildings, although there are large variations with latitude and season. At low latitudes, simple mirror devices can concentrate solar energy sufficiently for cooking and even for driving steam turbines. The energy of light shifts electrons in some semiconducting materials. This photovoltaic effect is capable of large-scale electricity generation. However, the present low efficiency of solar PV cells demands very large areas to supply electricity demands. Direct use of solar energy is the only renewable means capable of ultimately supplanting the current global energy supply from non-renewable sources. It is cheaper compared to all other sources of source. In the coming days production will be less and solar energy will be more feasible comparative to the present days.

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