Proposal of an Ecofriendly Powered University Concept

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Abstract

In the current report, solar and wind energy were analyzed quantitatively and compared against each other to determine which renewable energy (RE) was a better option to annually offset 8GWh from New Mexico State University (NMSU) total consumption. It was noted that regardless of the farm size, the solar photovoltaics (PV) system's Levelized cost of energy (LCOE) remained constant while the wind farm's LCOE fluctuated. Wind energy reported a better capacity factor (Cp~22.8%) than solar (Cp~16.55%). By the same token, for the availability factor (Af), which was computed assuming a 1MW battery energy storage system (BESS) and a minimum supply of 500kW, wind energy (Af~49%) was also superior to solar PV farm (Af~44%). If the required availability factor is more than 70%, solar PV farm would not be an option. Contrastingly, the maximum theoretical limit for Wind farm ended up being around ~95%. This means that if Af is the priority, wind farm in tandem with a good BESS are the solution. Regardless of the previous values, solar (PV) system performed somewhat better than the wind farm, reporting an LCOE of 8.46 and 8.68 cents/kW respectively, this was translated to a more solid investment opportunity with potential revenue of more than $20M dollars after a 30 years period. All the above plus the high New Mexico state' solar potential made the solar PV system a plausible solution to supply the required brute energy.

All the calculations were later compared against System Advisor Model (SAM) National Renewable Energy Laboratory's (NREL) software to determine if the values were within a realistic range.

Keywords: *solar, wind, LCOE, PV, renewable energy, Cp, Af, BESS, SAM, NREL.*

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Problem Summary

To give a feasible ecofriendly solution designed specifically to supply a certain amount of energy to an institution, in this case New Mexico State University (NMSU). By accomplishing this general purpose, it is meant to show that this same proposal could be performed for any institution which is willing to become ecofriendly.

This paper was conceived with renewable energy, mainly solar energy, in mind; and considering all the available land owned by NMSU. It must be remarked that the specific goal of this paper is to give two valid solutions to deliver 8GWh of solar energy annually.

- The first solution should be the cheapest possible
  - Supplying the 8GWh of energy is the sole constraint, ideal assumptions are valid as long as the energy requirement is satisfied.
- The second solution should consider solar energy in tandem with another alternative given that supplying this amount of energy could not be attained with solar power only.
  - The solution shall offer a minimum of 500kW for at least 50% of the hours of each year.
  - Look for further solutions that can guarantee a minimum of 500kW for 75% and even 100% of the hours of each year.

All the required concepts and theory will be described and applied in the following sections (Introduction and Design).

Introduction

Alternative energy propose a cheaper and cleaner solution to current and subsequent pollution problems. The most attractive and feasible energy sources for New Mexico state are: Solar and Wind Energy (3^{rd} and 11^{th} respectively for Nation's potential ranking) (EIA, 2019). Both options are currently competing in levelized cost of energy (LCOE) with coal plants and in some cases even beating them (U.S. Energy Information Administration, 2019), this improvement in solar and wind energy is expected to continue (see Table 1).

Table 1: Estimated levelized cost of electricity (unweighted average) for new generation resources entering service in 2023 (2018 $/MWh) . Table retrieved from: (U.S. Energy Information Administration, 2019)

Plant type	Capacity factor (%)	Levelized capital cost	Levelized fixed O&M	Levelized variable O&M	Levelized transmis-sion cost	Total system LCOE	Levelized tax credit[1]	Total LCOE including tax credit
Dispatchable technologies								
Coal with 30% CCS[2]	85	61.3	9.7	32.2	1.1	104.3	NA	104.3
Coal with 90% CCS[2]	85	50.2	11.2	36.0	1.1	98.6	NA	98.6
Conventional CC	87	9.3	1.5	34.4	1.1	46.3	NA	46.3
Advanced CC	87	7.3	1.4	31.5	1.1	41.2	NA	41.2
Advanced CC with CCS	87	19.4	4.5	42.5	1.1	67.5	NA	67.5
Conventional CT	30	28.7	6.9	50.5	3.2	89.3	NA	89.3
Advanced CT	30	17.6	2.7	54.2	3.2	77.7	NA	77.7
Advanced nuclear	90	53.8	13.1	9.5	1.0	77.5	NA	77.5
Geothermal	90	26.7	12.9	0.0	1.4	41.0	-2.7	38.3
Biomass	83	36.3	15.7	39.0	1.2	92.2	NA	92.2
Non-dispatchable technologies								
Wind, onshore	41	39.8	13.7	0.0	2.5	55.9	-6.1	49.8
Wind, offshore	45	107.7	20.3	0.0	2.3	130.4	-12.9	117.5
Solar PV[3]	29	47.8	8.9	0.0	3.4	60.0	-14.3	45.7
Solar thermal	25	119.6	33.3	0.0	4.2	157.1	-35.9	121.2
Hydroelectric[4]	75	29.9	6.2	1.4	1.6	39.1	NA	39.1

These two energy (solar and wind) work in a very peculiar and different way and therefore propose very interesting advantages as well as drawbacks which are more or less remarkable depending on the geographical region of interest.

Solar Energy

The solar energy, which is produced via nuclear fusion inside the sun, represents the most reliable energy source given that sun will keep shining for a long time and even though there are cloudy days, this does not interrupt the sun's electromagnetic radiation hitting our planet. The sun's radiation intensity is about 70,000 to 80,000 kW/m^2, only a small portion arrives to earth (~200,000,000 billion kWh) which is approximately 10,000 times more than the current energy need of the whole world (Institute of Sustainable Technologies, 2009). To better understand how solar energy is exploited, it is of extreme importance to understand how sun interacts with our planet. It is known that earth is displaced from sun explaining why only a small amount of sun's energy strike the earth's surface (Stine & Geyer, 2001). Another interfering factor is the earth's rotation around its own axis which causes that a given region on earth can only receive sun's direct energy for about half a day (Stine & Geyer, 2001). The last relevant factor is earth's atmosphere which protect us from this electromagnetic radiation given that without this protection human kind could not exist, this protection accounts for a 30% reduction in the sun's energy (Stine & Geyer, 2001).

To determine if a place is favorable for a solar energy system, being Photovoltaics (PV) and/or Concentrating Solar Power (CSP), the rate of energy that reaches a unit of area (referred as solar irradiance or insolation) in a certain place is measured (Stine & Geyer, 2001). This solar irradiance is also used to determine the size of the plant to avoid over/under sizing.

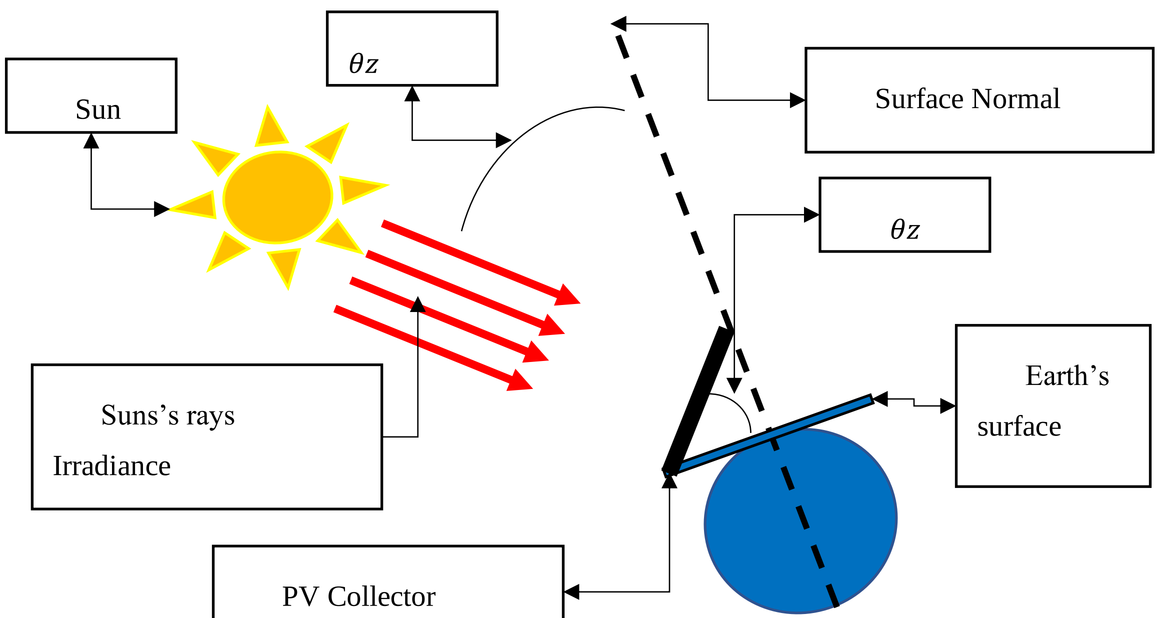


Figure 1: Simplified System for a Solar collector

What can be seen from Figure 1, is that the optimal surface angle is equal to the angle between the surface normal and the irradiance because it means the surface is synced with the sun increasing the amount of sun's rays hitting the surface.

When the solar irradiance is known, important calculations can take place to determine the ideal system according to the budget, available land or other relevant inputs/constraints. As it was mentioned previously, when developing the solar collector system, it is required to know where the sun is with respect to our system. If the desired collector posses a sun-tracking system, the design must ensure that the collector is being as optimal as possible during the 8-12 hours of the 365 days of the year. Similarly, if the collector has a fixed position, this position should be the position that let the system gather the most energy possible. This sun's position can be described simply by two components: the zenith angle (θ_z) and the angle of the sun with respect to the vertical (Paul Gauché, 2017); however, these components are dependent of various parameters that will be described in the following paragraphs.

In order to attain the optimum position, several terms have to be defined because what may be useful for the quotidian basis may not be convenient for precise and absolute calculations. One of the first things that needs to be corrected is time and to do it, designers use the solar time (t_s) to compute the hour angle (ω) which is used to give earth's rotation based on the hour (Stine & Geyer, 2001).

$$\omega = 15(t_s - 12) \quad (degrees\ °) \qquad \text{[Eqn. 1]}$$

Where:

ω=hour angle, (°)

t_s=solar time, ranging from 0 to 24

Continuing with the procedure, the next correction to perform is called Equation of Time (EoT) which represents the difference between the mean t_s and the true solar time on a given date. This correction is required due the earth's elliptical orbit around the sun which causes a fast movement at the perigee (shortest distance) and slow movement at the apogee (longest distance). This correction is computed utilizing the angle generated by the earth's translation around the sun at a certain date. Therefore, if it is known that this translation takes 365.242 days to take place, and the rotation corresponds to 2π (360°) we get the following equation for the angle (x) which in a few words is just the conversion of day number to an angular value (Paul Gauché, 2017):

$$x = \frac{360(N-1)}{365.242}\ (degrees\ °) \qquad \text{[Eqn. 2]}$$

Where:

x=day of the year-angle equivalence, (°)

N=number of day (ranging from 1 to 365 (366 in leap-year)

Utilizing Eqn. 2, the EoT can be now found. The level of accuracy depends on the used type of system; however, according to (Paul Gauché, 2017) Eqn. 3 has been found to be accurate enough to correct the time.

$$EoT = 229.2\big(0.000075 + 0.001868\cos(x) - 0.32077\sin(x) - 0.014615\cos(2x) - 0.04089 sin(2x)\big) \quad (minutes) \qquad \text{[Eqn. 3]}$$

Where:

EoT=Equation of Time, (minutes)

x=day of the year-angle equivalence, (°)

Figure 2, corresponds to a typical EoT distribution, we can see that the correction occurs mainly during the perigee (winter season- November and February) given that the earth is translating faster due the high gravity force generated by the sun.

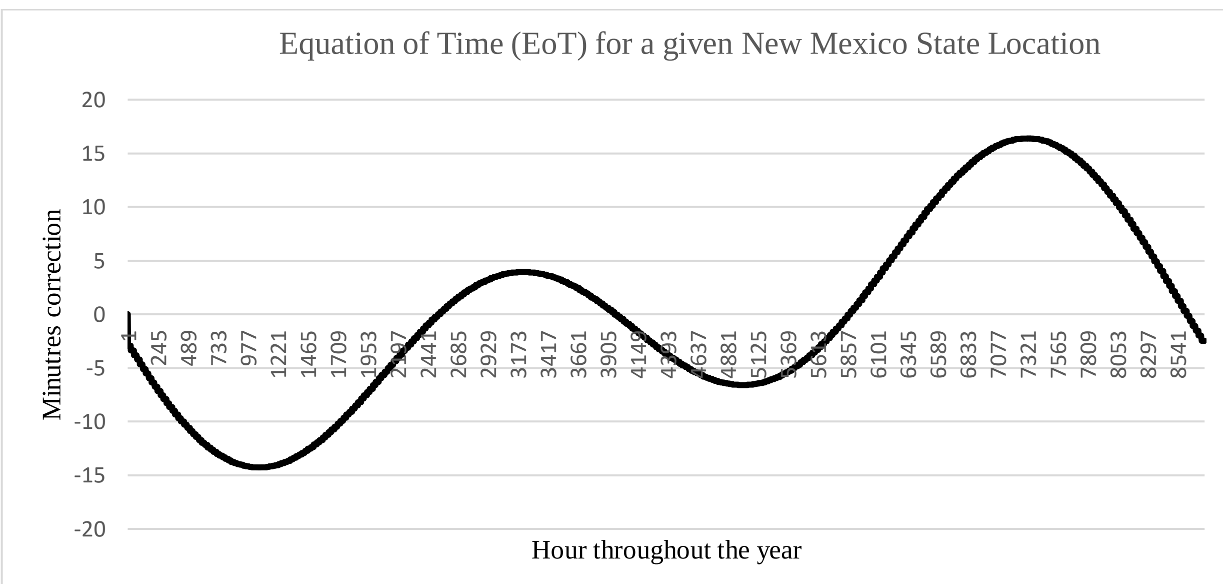


Figure 2. Equation of Time behavior for 32.29° and -106.74° location

Having calculated the minutes correction required for each hour/day of the year, a “real” solar time can be found which is in grosso modo the sum of the standard time, a longitude correction depending on the geographical position and the EoT correction (Paul Gauché, 2017).

$$Solar\ time = Standard\ time + 4(L_{st} - L_{loc}) + EoT \qquad \text{[Eqn. 4]}$$

Where:

Solar time= absolute time

Standard time = time displayed by local clock

L_{st} *=standard longitude, (hour difference times 15°) (°)*

L_{loc} *=Local longitude, (°)*

EoT= Equation of time, (minutes)

The last parameter to be computed in order to be able to describe sun’s displacement with respect to our given position is the declination angle (δ). The δ represents the angle between the zenith and the equator due to the tilted earth’s rotation axis (Paul Gauché, 2017).

$$\delta = 0.006918 - 0.399912\cos(x) + 0.070257\sin(x) - 0.006758 * \cos(2x) + 0.00907\sin(2x) - 0.002679\cos(3x) + 0.00148\sin(3x) \quad (degrees\ °) \qquad \text{[Eqn. 5]}$$

Where:

δ*=declination angle, (°)*

x=day of the year-angle equivalence, (°)

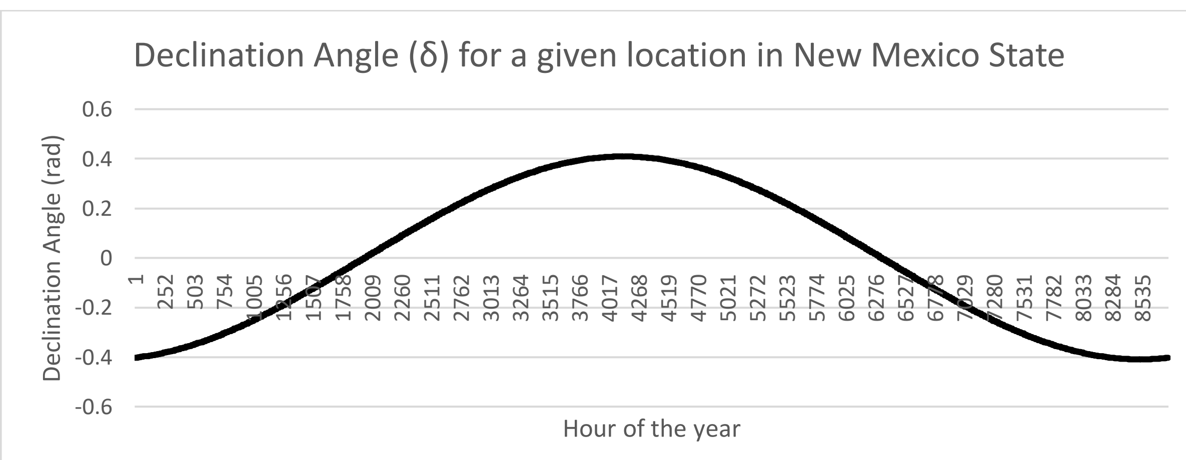


Figure 3: Declination Angle (rad) Equation of Time for 32.29° and -106.74° location

It can be seen in Figure 3 that the maximum declination angles of the year correspond to both solstices (which corresponds to ~+/- 23.43° for New Mexico state 32.29° and -106.74° location). What is very interesting from these results is that the negative value (~-23.43°) is the lowest position the sun will have in the sky which is at the same time the longest shade the collectors will generate in the whole year; therefore this day (winter solstice) is often used to size solar collectors in often to avoid efficiency decrease due shading.

Recalling the two required components: the zenith angle (θ_z) and solar azimuth (γ_s) which are given by the following two equations (Paul Gauché, 2017).

$$\cos\theta_z = \cos\emptyset\cos\delta\cos\omega + sin\emptyset\sin\delta \quad \text{[Eqn. 6]}$$

Where:

θ_z=zenith angle, (°)

$\emptyset$=latitude, (°)

δ=declination angle, (°)

ω=hour angle, (°)

$$\gamma_s = \mathrm{sign}(\omega)\left|\cos^{-1}\frac{\cos\theta_z\sin\emptyset - \sin\delta}{\sin\theta_z\cos\emptyset}\right| \quad \text{[Eqn. 7]}$$

Where:

γ_s=azimuth angle, (°)

θ_z=zenith angle, (°)

$\emptyset$=latitude, (°)

δ=declination angle, (°)

ω=hour angle, (°)

Non-concentrating Apertures

The schematic for a fixed collector can be seen in Figure 4. For this type of collectors, which are not "synced" with the sun's movement, the total incident irradiation (I_t) is mainly obtained between

10 AM and 3:00 PM. For a non-concentrating system, the I_t is only due the Direct normal irradiation (DNI) (I_b) leading to the following simplified equation.

$I_t = I_b \cos\theta$ (W/m^2) [Eqn. 8]

Where:

I_t=total incident irradiation, (W/m^2)

I_b=direct normal irradiation, (W/m^2)

θ= angle between aperture's normal and sun's rays, (°)

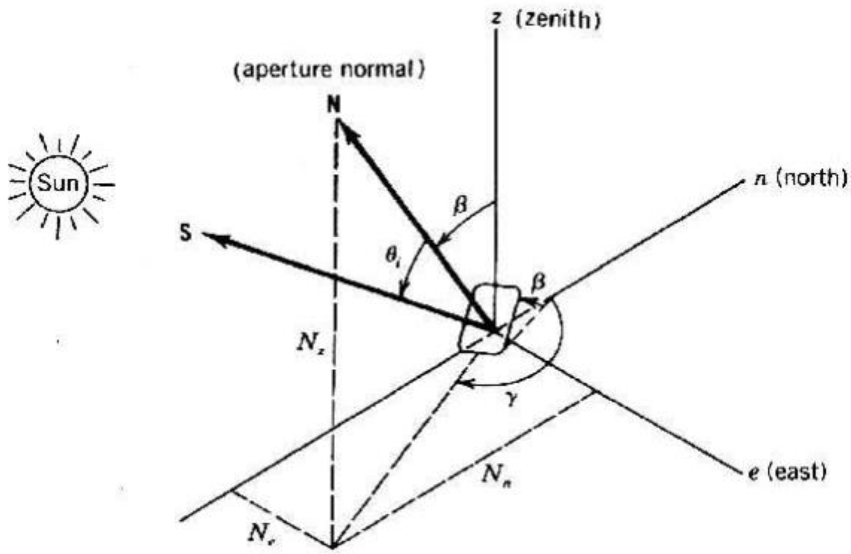


Figure 4. Fixed aperture with its orientation defined by the tilt angle (ß) and the aperture azimuth angle (γ). The aperture normal (N) and sun position vectors are also included. Image retrieved from: http://powerfromthesun.net/Book/chapter04/chapter

Concentrating Apertures

Contrastingly, for a concentrating aperture which can take better advantage of sun throughout its entire transition in the sky, the I_t is bigger and therefore a different equation containing more terms is required.

$I_t = I_b \cos\theta + [I_d \left(\frac{1+\cos\beta}{2}\right) + \rho I_g \left(\frac{1-\cos\beta}{2}\right)]$ (W/m^2) [Eqn. 9]

Where:

I_t=total incident irradiation, (W/m^2)

I_b=direct normal irradiation, (W/m^2)

θ= angle between aperture's normal and sun's rays, (°)

I_d=diffuse horizontal irradiation (DHI), (W/m^2)

I_g=global horizontal irradiation (GHI), (W/m^2)

β= panel tilt angle with respect to horizontal, (°)

ρ=surface reflectivity

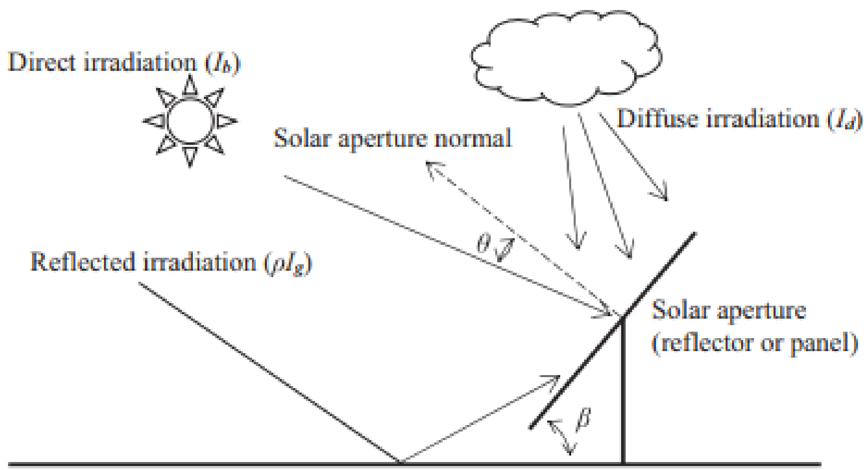


Figure 5: Typical system for a concentrating-solar collector. Image retrieved from: (Paul Gauché, 2017)

Wind Energy

Wind Energy is one of the fastest growing energy sources in the world. It is the simplest conversion of mechanical power (via a turbine) into electrical power (Mehmet Kanoglu, 2019). This mechanical power is extracted from a fluid's, ideally, linear kinetic energy. The current cost of wind power, including capital and operating costs is about $0.082 /kWh which makes it one of the cheapest options (Mehmet Kanoglu, 2019).

As it was mentioned in the previous paragraph, wind energy is generated by converting fluid's kinetics energy (which is dependent of object's velocity squared) into mechanical power. Therefore, the direct parameter to determine if a location has good potential for wind energy is wind speed. According to the experience, and calculations, if a location has a year wind speed average of 6 m/s it is a good location to invest in wind energy production (Mehmet Kanoglu, 2019).

To understand wind energy, wind turbines' working principle has to be understood. A turbine can only operate within a velocities range. This range is marked by the minimum operating velocity (cut-in-speed) and the maximum operating velocity (cut-out-speed). Before the cut-in-speed, the velocity is to low to move the turbine's blade, and after the cut-out-speed the velocity is to high generating a high-stress condition at the blades; therefore, an automatic brake is turned on to prevent damage (Mehmet Kanoglu, 2019). Somewhere between the cut-in and cut-out speeds lays the rated speed, which is the speed at which the maximum power is delivered by the turbine. (See Figure 6)

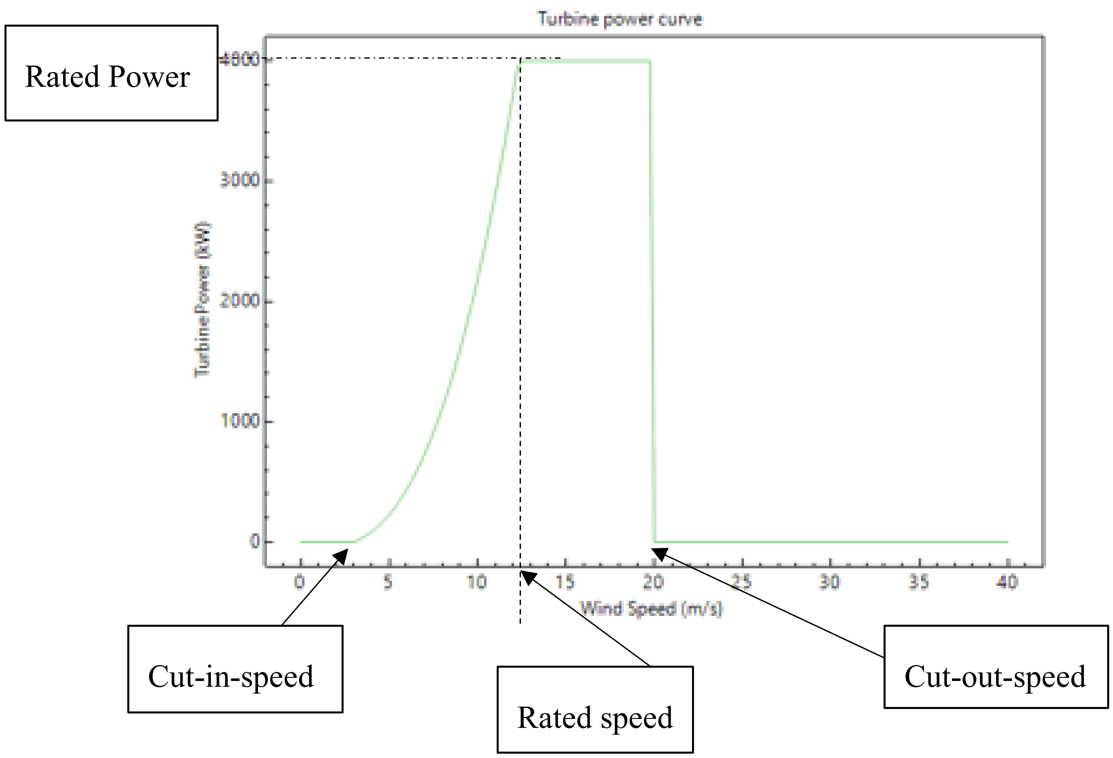


Figure 6:Typical Turbine power curve for a 4000kW turbine.

Having understood Figure 6, it must be understood how the maximum power can be computed and delivered. Knowing that the mechanical energy of a flowing fluid is (Mehmet Kanoglu, 2019):

$$\dot{E_{mech}} = \dot{m}\left(\frac{P}{\rho} + \frac{V^2}{2} + gz\right) \quad (Joules,\ J) \quad \text{[Eqn. 10]}$$

Where:

$\dot{E_{mech}}$ *=total mechanical energy, (J)*

$\dot{m}$*=mass flow rate, (kg/s)*

$\frac{P}{\rho}$*= flow energy, (J)*

V=flow speed, (m/s)

gz=potential energy, (J)

Assuming that all the flow posses the same potential and flow energy Eqn. 10 reduces to (Mehmet Kanoglu, 2019):

$$\dot{E}_{mech\_avaialble} = \dot{m}\left(\frac{V^2}{2}\right) = \frac{1}{2}\rho A V^3 \ \ (Joules/s,\ \ W) \qquad \text{[Eqn. 11]}$$

Where:

$\dot{E}_{mech\_available}$ =available power, (W)

V=flow speed, (m/s)

$\dot{m}$=mass flow rate, (kg/s)

ρ=fluid's density, (kg/m^3)

A=area, (m^2)

Knowing that the mass flow rate is equal to the amount of a fluid passing through an area per time. It can be concluded that the available power by a wind turbine is a function of wind speed and the projected area (circle) by the wind turbine's rotating blades.

Regardless of the available energy, the thermodynamics limits the performance of any mechanical device. Even though, a wind turbine possesses high-efficiency elements (oscillating around the 80% and 90%), the product of all these elements' efficiencies results in a relatively low (but still good enough) efficiency of 30% to 45%. There exists a maximum possible efficiency of any wind turbine which is 59.26% (Mehmet Kanoglu, 2019), this theoretical limit is known as "Betz limit". This limit represents the thermodynamic limitation regardless of the elements' efficiency. Human kind will never surpass this limit because it would simply imply a thermodynamics' laws violation.

$$\eta_{overall=} \prod(\eta_{electric\,conversion}\ \eta_{mechanical}\,\eta_{gearbox\ldots}) \quad \text{[Eqn. 12]}$$

Combining Eqn. 11 and Eqn. 12, the real electric power generated by the wind turbine can be computed.

$$\dot{E}_{real\_electric} = \eta_{overall}\dot{m}\left(\frac{V^2}{2}\right) = \frac{1}{2}\eta_{overall}\rho A V^3 \ \ (W) \ \text{[Eqn. 13]}$$

Where:

$\dot{E}_{real\_electric}$ =*real electric power delivered, (W)*

V=*flow speed, (m/s)*

$\dot{m}$=*mass flow rate, (kg/s)*

ρ=*fluid's density, (kg/m³)*

A=*area, (m²)*

$\eta_{overall}$=*wind turbine's overall efficiency*

Even though, wind energy is relatively free and renewable, wind turbines are very expensive given that its structure is massive and has to be very efficient (low structure drag, high environment resistance, etc.). Another obvious drawback is wind's intermittence which makes wind energy a not-so-reliable source of energy, a possible solution will be described further in the report.

Capacity Factor

The capacity factor (Cp) describes how intensively a power generation plant worked according to its production availability during a certain time (Energy Information Administration, 2019). This parameter allows designers to determine how reliable an energy production system is. If a system has a Cp of 0.2 it means that system was exploited only a 20% of its total potential during that specific time (second, day, month, year, decade, etc.) (University of Colorado Denver, 2019). The obvious conclusion from this concept is that the more Cp approaches 1 (100%) the better because it means it is being utilized at its maximum potential. Even in coal, geothermal and nuclear plants the Cp is not 100% given that maintenance and safety protocols are always required (Energy Information Administration, 2019).

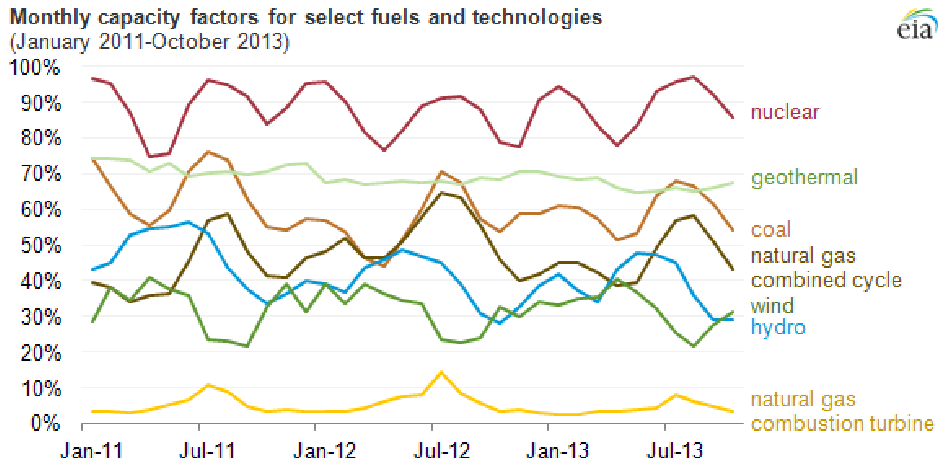


Figure 7: Monthly capacity factor for various energy power plants. Image retrieved from: (Energy Information Administration, 2019)

Having explained the Cp definition in English, its mathematical definition is now included.

$$Cp = \frac{\dot{W}_{delivered\ in\ certain\ time}}{\dot{W}_{potential\ in\ certain\ time}} \qquad \text{[Eqn. 14]}$$

In the other hand, the availability factor is the amount of time that a given system is available to produce energy. With this concept in mind, it can be said that the Cp can never surpass the availability factor (University of Colorado Denver, 2019).

According to the (Energy Information Administration, 2019), the average Cp of Solar PV and wind energy are as shown in Table 2.

Table 2: Average Cp per year for Wind and Solar PV big-scale plants. Information Retrieved from: (Energy Information Administration, 2019)

Year	**Wind Cp (%)**	**Solar PV Cp (%)**
2013	32.4	N/A
2014	34.0	25.9
2015	32.2	25.8
2016	34.5	25.1
2017	34.6	25.7
2018	37.4	26.1

Energy Storage

One of the most important drawbacks that can be mentioned about renewable energy is their inconsistency. This is very obvious given that sun sets every day and sometimes wind does not blow at all. It is for this reason that renewable energy are not yet a feasible and realistic solution for current human's energy problems; however, there exist several ways to reduce the impact of this issue: Energy storage.

Energy storage consists in absorbing energy and storing it for a finite period of time for then release it (International Energy Agency, 2014). Energy can be stored in several ways, depending on the chosen way the stored time and storing efficiency may vary and be better for one type of energy or another (International Energy Agency, 2014). One good advantage about energy storage is that it can be sized according to the energy plant size and type. As it is widely known energy can be manifested as electricity and thermal energy (International Energy Agency, 2014), according to the purpose of this report only electricity storage will be included.

Electricity Storage

This type of energy storage can be divided in three main categories which make a distinction in the required stored time (International Energy Agency, 2014). This categorization is:

- Short-term: seconds-minutes.
- Long-term: hours-seasons.
- Distributed battery storage: both short and long-term storage.

Among the short-term storage alternatives, supercapacitors which use electric or magnetic fields can store electricity. Also, utilizing a very basic mechanical principle flywheels can store and the release the stored energy by spinning for then return to an original position while releasing the potential energy. These two options present a solution for systems that require only a short impulse of energy.

Talking about the long-term solutions, pumped-storage hydroelectricity (PSH) is the best and more mature option. It consists on storing electricity in the form of gravitational potential energy (International Energy Agency, 2014). By pumping water from a lower reservoir to a high-elevation reservoir energy is immediately stored and able to be released when desired by just releasing the stored water and driving a turbine to produce energy. It must be said that for evident reasons, this storing system has many efficiency leaks which may degrade the quality of the energy; nonetheless, this alternative is extremely reliable and widely applied (International Energy Agency, 2014).

There exists also another very popular but complex way of energy storage which is the hydrogen storage. It consists on converting electricity into hydrogen and then stored in a cryogenic tank or utilizing a packed-bed. This method could be very good and attractive for many industrial applications due its large-scale application; nonetheless, it is extremely expensive and dangerous (International Energy Agency, 2014).

Battery storage

Talking about battery storage, which seems to be the most known alternative in the world consists on storing the excessive power generated by a given system, via chemical reactions that enable the flow of electrons in other words they enable the flow of energy (International Energy Agency, 2014). (the most popular is lithium-based). Batteries can be installed in every system regardless of its size; however, batteries present an issue when lifetime, cost and energy density come to the discussion (International Energy Agency, 2014).

Battery storage has been found to be highly-performant and reliable for renewable energy systems (Cole & Frazier, 2019). According to NREL projections, the cost of batteries is expected to decrease substantially due the R&D and the increasing demand.

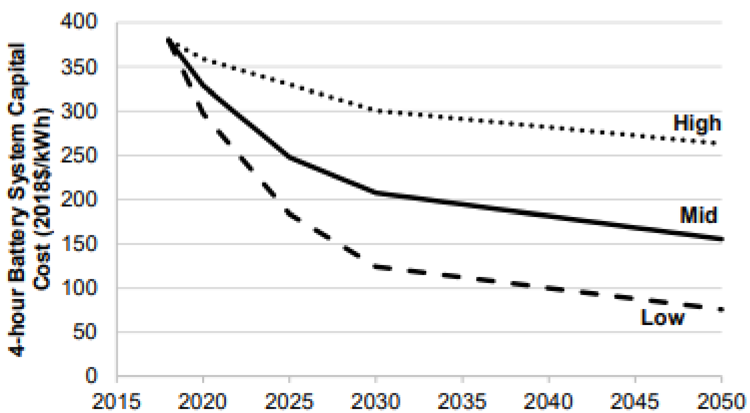


Figure 8: Battery cost projections for 4-hour lithium ion systems. Image retrieved from: (Cole & Frazier, 2019)

In order to estimate the cost depending on the desired storing duration, a different cost for the energy and power has to be assigned. Having done this, the total cost ($/kWh) of the battery can be approximated.

$$Total\ Cost\ \left(\frac{\$}{kWh}\right) = Energy\ Cost\ \left(\frac{\$}{kWh}\right) + Power\ Cost\,\frac{\frac{\$}{kW}}{Duration(hr)} \qquad \text{[Eqn. 15]}$$

Once the excess of energy is determined the size of the battery can be determined, with these two values a very good approximation of the battery's cost could be obtained.

Economics and profitability

It was mentioned in previous sections that the worse drawbacks of renewable energy were: intermittence (which could be solved with a good energy storing system) and extremely high initial investment (which can be solved doing the correct design and the right accounting plan).

A technical analysis has to be accompanied by an economic analysis. Once the design analysis is performed, it can be determined if the system is profitable or not by comparing the obtained LCOE with the current/concurrence's LCOE. If it is lower then a deeper, more optimized and extensive analysis can be done.

The standard method to determine the LCOE for a given energy plant was included in (Paul Gauché, 2017).

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \quad \left(\frac{\$}{kWh}\right) \qquad \text{[Eqn. 16]}$$

Where:

LCOE=levelized cost of energy, $\left(\frac{\$}{kWh}\right)$

t= investment cost in year, ($)

M_t*=operating and maintenance cost in year, ($)*

F_t*=fuel cost in year, ($)*

E_t *= electricity produced in year t, (kWh)*

r=discount rate

n=lifetime of the plant

With the LCOE found, further and more detailed analysis can be done. For instance, the initial investment of a renewable energy project can be compared against investing the same amount of money and calculating the revenues in the future (Mehmet Kanoglu, 2019).

An economic analysis allows the comparison of a given project and another. It is very useful for stakeholders or any person willing to invest in a renewable energy project (Mehmet Kanoglu, 2019).

It is known that money's value varies through time, this means that lending $100.00 today and getting the same $100.00 in 5 years is not the same given that there exist many factors like interest (i), inflation (e) and taxation (t). It is for this reason that predicting the future value (F) of your present value of a certain amount of money (P) taking into consideration every factor (to be as accurate as possible) is extremely important (Mehmet Kanoglu, 2019).

Table 3: Summary of basic equations used for an economic analysis.

$\boldsymbol{i_{adjusted} = \frac{(1-t)i-e}{1+e}}$ $(\boldsymbol{interest\ rate\ adjusted\ for\ taxation\ and\ inflation})$	[Eqn. 17]
$\boldsymbol{F = P(1 + i_{adjusted})^n}$	[Eqn. 18]
$\boldsymbol{U = P(\frac{i_{adjusted}}{1-(1+i_{adjusted})^{-n}})}$	[Eqn. 19]
$\boldsymbol{Benefit - cost\ ratio = \frac{Total\ benefits\ in\ present\ time}{Total\ costs\ in\ present\ time}}$	[Eqn. 20]

Where:

$i_{adjusted}$ *= interest rate adjusted for taxation and inflation*

t=taxation

e=inflation

F=future value

P=present value

n= time

U=uniform series amount

Methodology

It was understood that the methodology required to design and analyze the problematic was compound by several stages:

1. The first stage was to gather all the information regarding the available resources- Literature Review.
2. The second stage was to design ideas based on the existing knowledge and resources (i.e. weather, land, existing renewable facilities, agreements with energy suppliers)-Design.
   2.1. An extensive design analysis was performed to determine if the resources were being used as good as possible, taking into consideration several aspects. (i.e. if strong winds are in the area, probably Eolic energy might be more attractive.)-Design Analysis.
   2.2. Evaluating the options based on the cost, time needed to perceive benefits, feasibility and in overall importance of constraints was required to determine the best option-Design Evaluation and selection.
3. Then (third stage), a design validation was performed, based on all the assumptions and requirements it was determined if the idea was completely satisfying-Design Validation.
4. Finally, a discussion about the results was conducted to gather all useful information and improve the existing design by returning at some earlier stage-Iteration.

All the developed calculations (ideas) were compared against System Advisor Model (SAM) software results to determine if the results are within a reasonable interval.

Design

Starting to solve the first project's objective: to find the cheapest solution to offset 8GWh for New Mexico State University, utilizing renewable energy.

Three possibilities were analyzed: PV panels, concentrating PV panels and wind energy. Utilizing a weather file corresponding to the characteristic year in 32° 17' 24" N, 106° 44' 24" W position which is in Las Cruces, New Mexico.

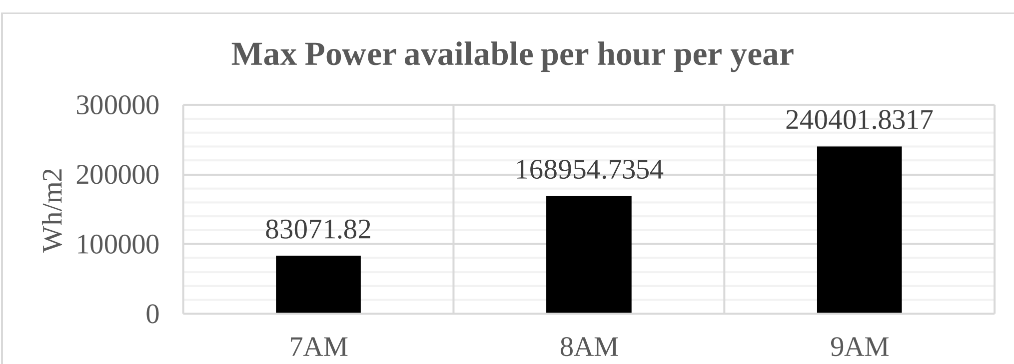
After having applied Equations included in Introduction section for Solar and Wind energy respectively the maximum power delivered was found. All the first stages of the design analysis were made without including energy storage, this part will be included later in this section.

Solar Energy

After having determined the maximum deliverable power by square meter (W/m^2) utilizing Equations given in Introduction-Solar energy section, arrangement criteria had to be delimited given that the PV panels cannot be placed one after another without leaving any empty space for people to do maintenance and to avoid shading between the panels. In order to do this, the maximum shade distance has to be computed. This maximum distance will occur during the winter solstice (December 21st) given that this day the sun has its shortest trajectory throughout the visible sky; therefore, the designing has to be done for this particular day, by doing this shading issues will be avoided.

Once the date has been defined, the hour is the following to be defined. It was found that at 7:00 AM of the whole year the gathered power was minimal compared with 8:00 and 9:00 AM (See Table 4). For this general dimensioning section, non-concentrating PV panels will be assumed for the total power (Eqn. 8). Same procedure was followed for the Concentrating PV panels but, utilizing Equation 9 instead.

Table 4: Maximum Obtainable Power per square meter at 7,8 and 9:00 AM



The hour is critical because the earlier in the day the lower the sun, the larger the PV shade. Now, that 7:00 AM was discarded, the analysis was performed for 8:00 AM and 9:00 AM. Most of the solar analysis was performed based on a PANASONIC Photovoltaic Module HIT N325 (See Appendix A for specs). With the dimensions and a solar chart (See Appendix B for Solar chart) for the analyzed position the following diagrams were constructed.

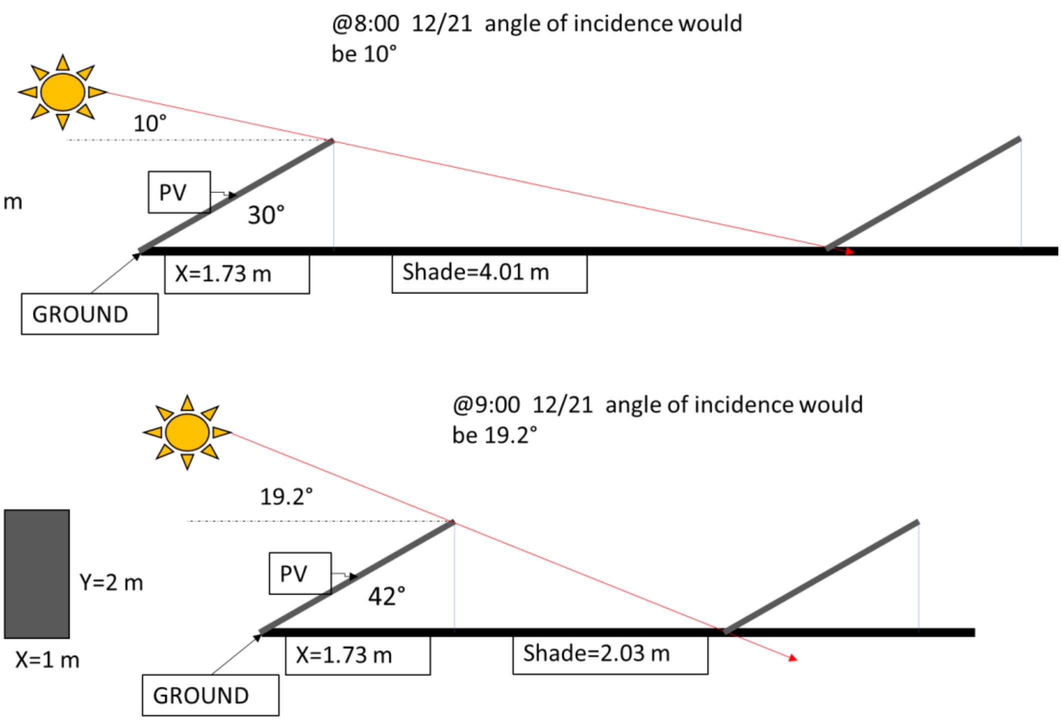


Figure 9: PV's shade to determine optimal spacing

Having calculated the shade length for both times, the ground coverage was now possible to be determined.

Table 5: Ground coverage and resulting power at 8:00 AM and 9:00 AM

Time	**Ground Coverage (%)**	**Power per surface (WH/m2)**
8:00	14.33	63,674.737
9:00	22.6%	100,581.536

As it can be quickly seen, even though more power could be gathered by the PV panels, if the 8:00 AM is included, its optimal design would reduce the ground coverage and therefore the total power because more land would be “wasted”, this is why the 9:00AM was the chosen option regardless of the concentrating or regular PV .

A positive point that has to be done about PVs in general is that all the required land could be “recycled” from unused roofs, parking lots, or small land from many places which make solar PV a very attractive option if no open land is available.

Non-Concentrating PV

It was determined by iteration that the optimal PV tilting angle for the given location was: 42°. This angle would end up giving the maximum Power throughout the year for a non-tracking system.

With the given specifications for the previously mentioned PV, it was determined that 97505m2 are required in order to supply the 8GWh, utilizing Equation 8, which would correspond to 13180 modules for a total 22068.089 m2 of aperture. Contrary to the PANASONIC PV, the chosen PV only has to have a rated power of 250W which would reduce the total cost substantially (more detail will be given in later sections).

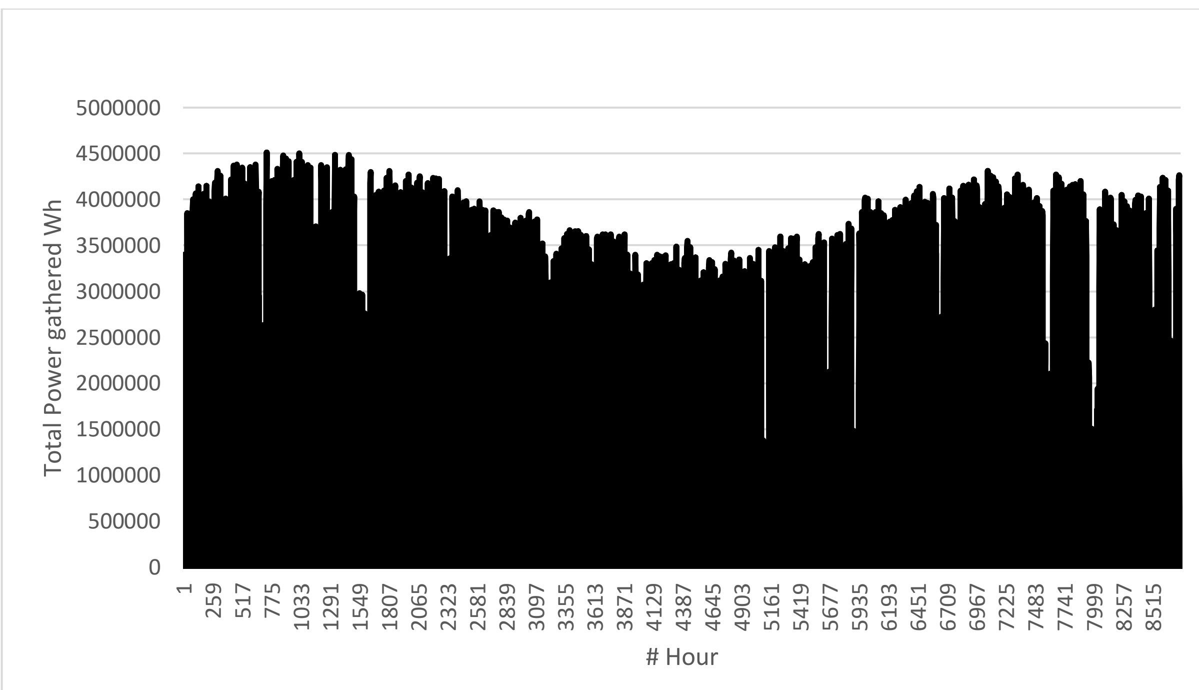


Figure 10: Power delivered by the non-concentrating PV system throughout the year.

It cannot be seen so clearly in Figure 10 that the system has a low Capacity factor around 16.55% which means that this system is not so reliable and probably cheaper PV panels (with a lower rated power) could be used. Still, even with cheaper PV panels, the sun will keep setting therefore; the capacity factor would only increase a couple of percentile points.

Table 6: Non-concentrating PV panel summary

Non-concentrating PV Summary	**Value**
Aperture m^2	22068.08975
Total_PV_Land m^2	97505
Capacity Factor	16.55%
Total Modules @9AM	13180
Total Power Wh	**8,000,007,587.77**

Concentrating PV

By the same token, utilizing the same equations as for the Non-concentrating PV (Equation 9 was used instead of Equation 8 to compute the total Power available) but changing some values according to the concentrating PV panels (CPV). Given that the non-concentrating PVs and the CPVs are too different from each other in size, the optimum tilt angle for the panels decreased from 42° (non-concentrating PV) to 27° because given that CPV also includes GHI and DHI it can gather energy in moments in which the non-concentrating PV cannot, leading to a lower tilting angle and therefore a higher ground factor because the generated shade would be shorter. This generates Figure 10 and 11 to look slightly different.

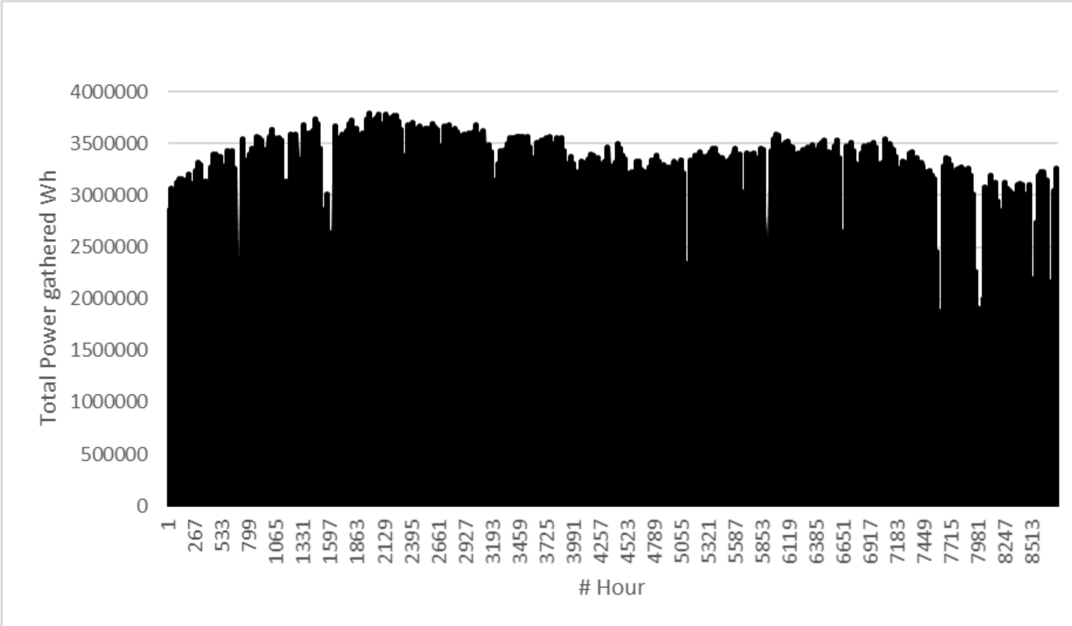


Figure 11: Power delivered by the Concentrating PV system throughout the year.

The main thing that changes from one and the other is the cell efficiency. For a CPV the average cell efficiency is around 30-40%; higher values have been reported in High-technology CPV in Laboratories measurements (as high as 46%) (Maike Wiesenfarth, 2017) but a realistic efficiency of 38% will be used instead.

For the ground coverage, the same shade analysis was performed but with the typical CPV dimensions (See Appendix C for CPV Specs). It was found that for the new height and dimensions in overall, the resulting ground coverage was 31.8% which would require about 28024m2 of total land to supply the 8GWh.

As it can be seen in Table 7, the Cp for the CPV is just slightly higher than the regular PV and this is because CPV are meant to be used with a 1-axis or more tracking system to take more advantage of it. Given that the performed analysis did not include this tracking variable the CPV ends up being somewhat wasted.

What is very interesting, is that the total amount of cells required diminished from 13180 to only 52. This give us a small insight of the CPV power and panels' size compared with the non-concentrating PV.

Table 7: Concentrating PV panel summary

Concentrating PV Summary	**Value**
Aperture m^2	8911.623

Total_PV_Land m^2	28024
Total Modules @9:00 AM	52
Capacity Factor (Cp)	20.5%
Cell efficiency	38%
Total Power Wh	**8,000,261,194.34**

Wind Energy

In order to obtain the maximum wind power available for the location of interest, the equations given in Introduction-Wind Energy section were used. The first parameter that had to be fixed was the wind turbine’s height, the higher the turbine the higher the wind speed and therefore the higher the available power and indeed, the velocity is the best thing to play with. It was thought that the main structure would not vary excessively given that at the end it just a structural element to elevate the turbine therefore, it was opted that 100m was a good value and also a common value used wide world.

The density was computed utilizing the ideal gas law which relates the density of a gas with its temperature and pressure (Mehmet Kanoglu, 2019). It is a very good approximation of the behavior of many gases.

$\rho = PRT$ [Eqn. 21]

Where:

ρ = Density (kg/m3)

P = Atmospheric pressure (kPa)

T=Temperature (K)

R = Gas constant (287 $JKg{\cdot}K$)

Both the pressure and the temperature were given by the weather spreadsheet and the density was found at each hour of the year to make the analysis more accurate. Once all the cells were programmed, it was just a matter of iterating changing some design variables (i.e. rotor diameter and rated power within realistic values found in literature) until the demand of 8GWh was attained (for the final specifications see Appendix C-Wind Turbine configuration).

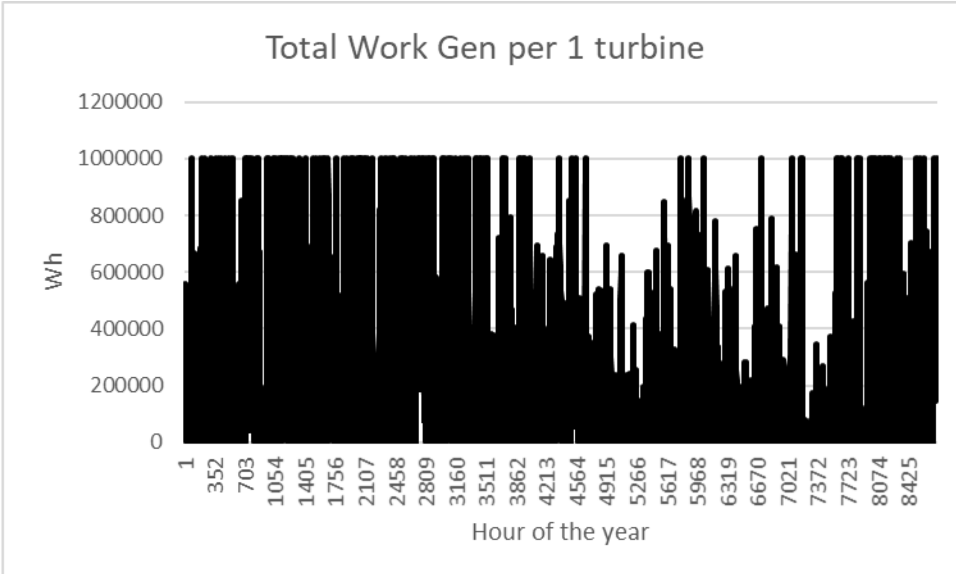


Figure 12: Total Work generated by 1 Turbine

As it can be seen in Figure 12, at some hours the wind turbine is working at its maximum capacity but as it is expected at some other times specifically from hour 3511 to 7723 (From May to November) the wind turbine is not even close to its maximum Cp. In despite of this, this wind turbine would generate 2,004,697,409.735 Wh in that year (2.004 GWh) therefore the wind turbine farm would require 4 turbines of this kind to generate 8,018,789,638.94 Wh (8.018GWh).

According to (Uk government, 2015) a wind turbine shall be placed at least 6 diameters apart from another turbine against the prominent wind direction in that location and at least 4 diameters towards the other directions in order to avoid wind turbine shadowing. To avoid this, 7 diameters were used to determine the total farm size. It ended up being 316,200 m2 or 78.13 Acres total land. In contrast to Solar PV, the land used for the wind farm has to be relatively apart from urban regions due possible safety issues. This could be a major drawback for wind energy if no open land is available.

Profitability Analysis

Given that the project itself is not so big to justify the installation of CPV with the proper tracker system besides it was found that CPV has a relatively short lifespan and high maintenance costs; therefore, it will be let down for the next design steps.

For this stage, PV panels (non-concentrating) and the wind turbine farm will be analyzed separately to determine which is cheaper. The resulting option will be selected as the solution for the first objective.

All the calculations for this section were made utilizing equations given in Introduction-Economics and Profitability section. According to the (U.S. Energy Information Administration , 2016) there exist a regional cost adjustment to estimate the total cost of an energy project.

For New Mexico, these cost adjustments are the following:

Table 8: Regional cost adjustment for New Mexico

Energy	**Cost Adjustment**
Solar PV	99%
On-shore Wind	103%

What can be seen in Table 8 is that installing a Solar PV farm in New Mexico state is cheaper by 1% compared to the nation's average cost. By the same token, a wind farm in New Mexico is expected to cost about 3% more than the average cost. Therefore, the final project cost should be multiplied by this factor to have the actual cost.

Equation 16 was used to estimate the LCOE, the Capital Expenditure value was obtained from (National Research Laboratory, 2019)'s spreadsheet which contains many of the relevant values for the LCOE estimation. It must be remarked that this estimation involves some maintenance costs which were estimated based on literature. With the CAPEX value, the project size, the Cp, the regional correction and future values regarding taxing and projected years the LCOE ended up being:

Table 9: Capex Value, Maintenance costs, Project cost and LCOE for Solar PV and Wind Energy

Energy	**Capex ($/KW)**	**Maintenance Cost per year**	**Total Project ($)**	**LCOE ($/KW)**
Solar PV	1111	2% of total project cost	6,068,117.81	0.08467
Wind Energy	1590	$48000 per MW=$76800	6,550,800.00	0.08443

As it can be seen both of them are almost identical, 8.4 cents/KW. With the LCOE and the total project cost a profitability analysis was performed because it is well-understood that people and companies are not going to switch/invest in renewable energy if they do not present any advantage at all.

By estimating how much money an entity would earn if the total cost of the project was invested today in a bank with a solid 6% of revenue per year, which end up being lower taking into consideration some corrections such as: taxation, inflation and depreciation, it is intended to motivate a given investor (in this case NMSU) to take a step to the front and opt for one of these ideas based on available land or better profitability.

It can be seen from figure 13 that investing in the Solar PV farm (even taking into consideration maintenance costs) would be a better alternative at long term; after 21 years of having invested the same amount of money the solar farm would outstand the bank investment, and after 30 years (PV farm lifespan) it would even generate ~$10 millions more than the bank investment.

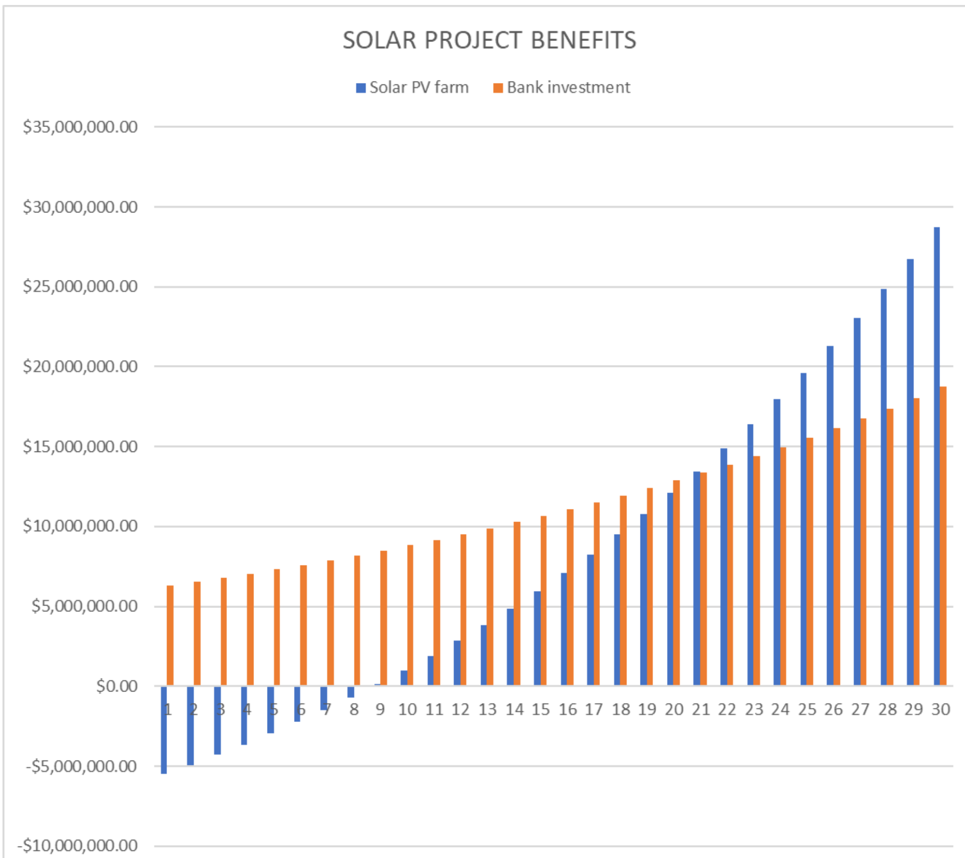


Figure 13: Solar Project vs Bank Investment benefits

Another useful parameter to determine if a project is worthy or not is the benefit-to cost ratio. Figure 14 emphasizes the fact that the solar PV farm would start to be profitable after the eight year and that it would generate ~5 times more money than its total dispenses at the end of the project.

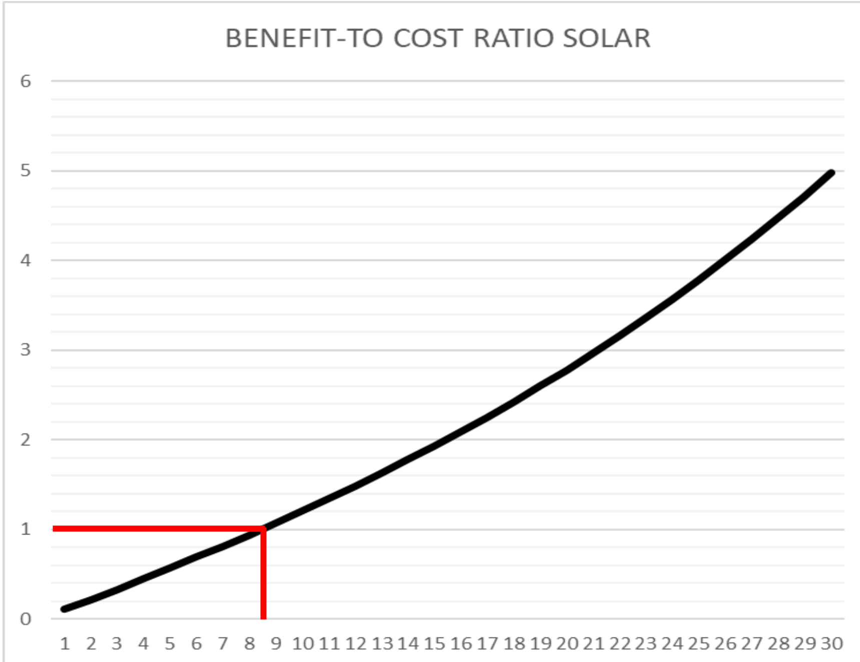


Figure 14: Benefit to cost Ratio for Solar Project

By doing the same analysis for the wind farm, almost same results are obtained, with the small difference that at the end of the 30 years lifespan the wind farm would "only" outstand the bank investment for ~$8.77 million and that the investment would be worthy after year 22 instead of 21. This is understandable because the wind farm is somewhat more expensive and even though its maintenance is cheaper the first investment (bank case) or expense (wind farm) represent to much because is a present value which is only increasing with time. If it is an investment is advantageous, in the other hand if it is an expense it is a bad new because it means the debt is only increasing with time.

Continuing with the benefit-to cost, it can be mentioned that after the ninth year the wind farm would start to be profitable and that it would generate ~4.7 times more money than what it would dispense.

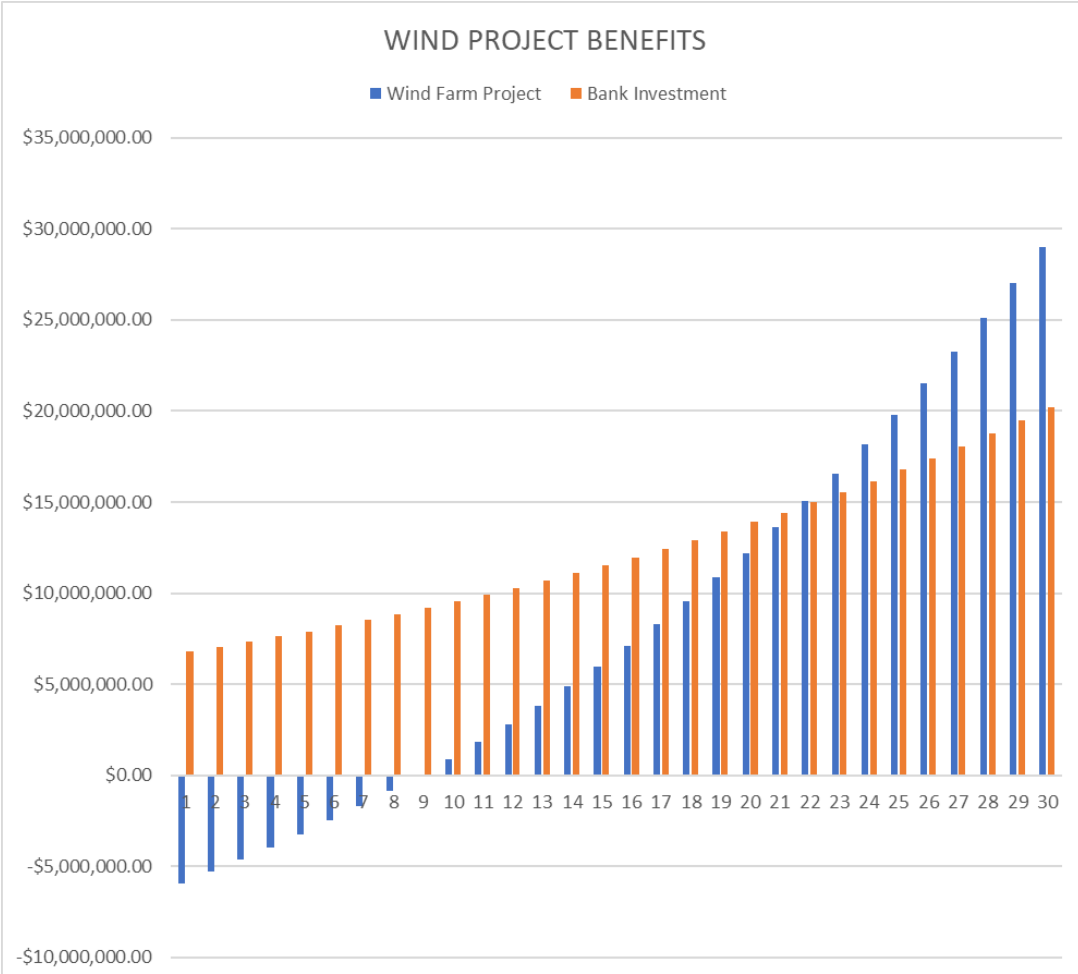


Figure 15: Wind farm Project vs Bank Investment benefits

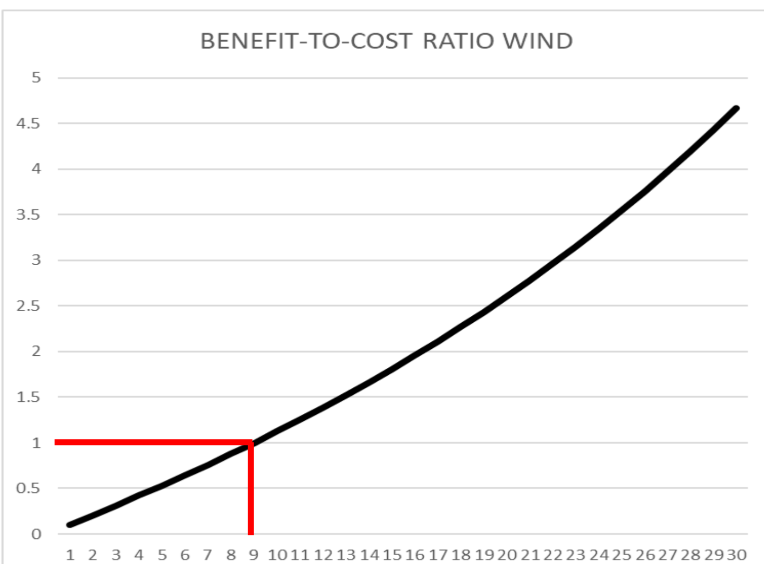


Figure 16: Benefit to cost Ratio for Wind Farm Project

In order to validate what has been done so far, a quick SAM software validation will be provided for both projects.

For the Solar PV farm all the parameters used were also used in the SAM program and the following results were obtained:

Table 10: SAM for Solar PV farm-Summary

Metric	Value
Annual energy (year 1)	9,292,065 kWh
Capacity factor (year 1)	19.2%
Energy yield (year 1)	1,684 kWh/kW
Performance ratio (year 1)	0.69
PPA price (year 1)	8.53 ¢/kWh
PPA price escalation	1.00 %/year
Levelized PPA price (nominal)	9.30 ¢/kWh
Levelized PPA price (real)	7.25 ¢/kWh
Levelized COE (nominal)	8.39 ¢/kWh
Levelized COE (real)	6.54 ¢/kWh
Investor IRR	11.00 %
Year investor IRR acheived	19
Investor IRR at end of project	11.37 %
Investor NPV over project life	$256,724
Developer IRR at end of project	NaN
Developer NPV over project life	$700,367
Net capital cost	$7,110,203
Equity	$3,267,639
Debt	$3,842,564

It can be said that even though both approaches present some differences the results are within a valid range given that for SAM software the economics analysis is way more complicated, it involves depreciation and system degradation also the excess of energy produced is due the higher Cp probably because the software applies different correlations for the sun's position or because the program really optimizes. Besides the program did not include the same values that were assumed for the PV panel of reference; therefore, all these are possible sources of error that might explain the variation. What can be remarked is that the LCOE (nominal) is extremely close to the obtained value which causes the total revenue to also be very similar to the obtained revenue.

Regarding the wind farm, the weather spreadsheet could not be imported to the SAM program and the included New Mexico state location is not similar; therefore, only the total cost analysis will be included given that this cost does not involve power generation or location.

It was found that the total cost of project would be around $6,864,596.50 dollars which is indeed very approximated to the estimated cost ($6,550,800.00)

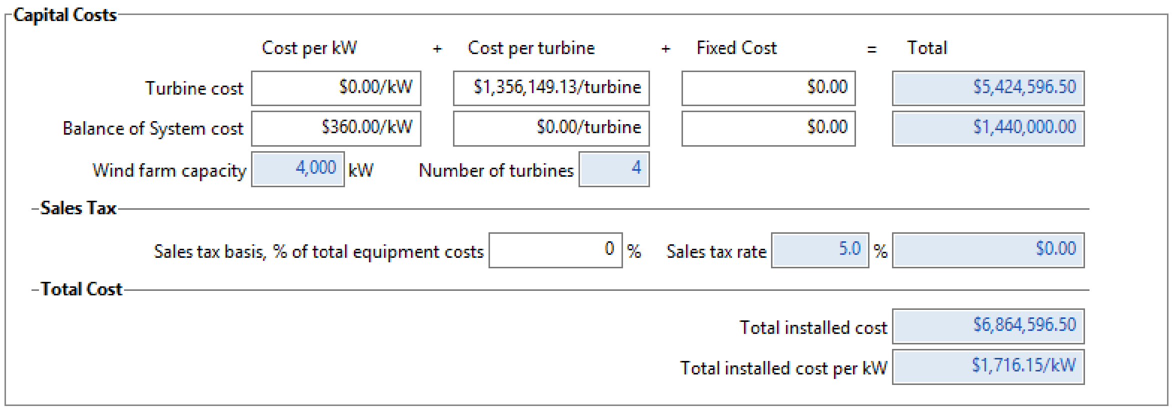


Figure 17: SAM for wind farm-project cost summary

By verifying that both analyses showed acceptable values, it can be concluded that the better alternative would be the solar PV farm given that it is more profitable than the Wind farm (regardless of the almost null LCOE difference). Besides the economical point of view, as it was stated before, PV panels can be installed in a smaller scale, if the client (NMSU) wants to install 100 PV panels more, they can be installed almost immediately no matter where. In the other hand, given that the wind turbines are so massive and expensive (~$1,637,700.00) they required way more planning and investment to become a reality.

Battery Storage

For this part of the design, the system shall guarantee a maximum energy output of no more than 2MW and not less than 500kW (still giving a total of 8GWh per year) and solutions for an availability factor (Af) of 50,75 and even 100% throughout the entire year.

The first part of the design, the cheapest and smallest PV panels and wind turbines were took into consideration given that for that particular goal having an excess of energy was a waste of money and hence a more expensive system; nonetheless, to achieve a high availability factor a lot of excess of energy in tandem with very good batteries are required.

50% availability factor

To attain this availability factor is not very complicated given that sun stays in the profitable sky window for more than 8 hours, therefore batteries are only required to retain and supply 500kW for four more hours; hence, it could be possible just to keep adding more and more solar PV panels and a huge battery nonetheless, this would end up being to expensive and not realistic. It was found that the previously developed solar and wind systems reported an Af of 44% and 49% respectively which is already very close to the 50%. The easiest solution would be just use one or the other alone and then use a 1MW battery. This was found to increase the Af enough to attain the goal.

Nonetheless, a more interesting option would be to combine both wind turbines and solar PV panels systems given that nature usually blows air when sun is not too shiny. To be able to accomplish this goal of >50% of availability, batteries with the following specifications would be required:

Table 11: Battery specifications for >50% Af

Battery SPECS 50%	
U_Limit (2MW)	2000000
L_Limit (500kW)	500000
battery cap W	1000000
Batt charge rate W	500000
Batt discharge rate W	500000
battery eff	0.95

As mentioned, not only the battery will be required, also an effective aperture of 12448.028 m2 (7434 modules with the specifications given in Appendix A) in tandem with 3 wind turbines of the same kind used in part 1.

Table 12: Project summary for >50% Af

>50% availability factor	
Solar PV	
Aperture	12448.02765 m2
Total Modules	7434
Total Power	4,467,467,444.27 Wh
LCOE	$0.0846729
Cost of Project	$3,388,636.63
Wind Farm	
Rated Power	1000kW
# of Wind turbines	3

Total Power	6,014,092,229.21 Wh
LCOE	$0.0820385
Cost of Project	$4,913,100.00
Battery	
Curtailed	**2,625,235,766.04 Wh**
Availability factor	***61.08%***
Total Power supplied	***8,001,222,336.10 Wh***

75% availability factor

Regarding the 75% Af, which starts to be a complicated system, it was found that for the wind farm a 2.5 MW BESS and 10 turbines could supply the required minimum energy for 76% of the time (Cf~76%). In the other hand it was found that for the PV this goal is already unattainable not even doubling the effective aperture nor adding a more powerful BESS, the problem with the regular solar PV farm is that it is exposed to its source too short to be able to gather and store the energy for so long.

Table 13: Battery specifications for 75% Af

Battery SPECS 75%	
U_Limit (2MW)	2000000
L_Limit (500kW)	500000
battery cap W	2000000
Batt charge rate W	500000
Batt discharge rate W	500000
battery eff W	0.95

Table 14: Project summary for 75% Af

75% availability factor

Solar PV	
Aperture	14749.78113
Total Modules	8809
Total Power	5,347,012,917.23 Wh
LCOE	$0.0846729
Cost of Project	$4,055,784.19
Wind Farm	
Rated Power	1000 kW
# of Wind turbines	5
Total Power	10,023,487,048.68 Wh
LCOE	$0.0868272
Cost of Project	$8,188,500.00
Battery	
Curtailed	**6,180,663,070.19 Wh**
Availability factor	**75%**
Total Power supplied	**9,432,507,410.47 Wh**

100% availability factor

It was mentioned that solar PV system was too weak even for 75% Af therefore it is obvious it could not give a 100% Af. Regarding wind farm, not even 20 Wind turbines and a 15MW BESS would be enough, this configuration would only give an Af of 97.6%, which is very solid but still does not attain the goal.

To attain 100% availability factor, batteries would not be enough, it would be needed a small power station capable to store more than 10MW for at least 3 hours to get a 98% of availability factor.

Table 15: Battery specifications for ~100% Af

Battery SPECS ~100%	
U_Limit (2MW)	2000000
L_Limit (500kW)	500000
battery cap W	10000000
Batt charge rate W	500000
Batt discharge rate W	500000
battery eff	0.95

Table 16: Project summary for ~100% Af

100% availability factor	
Solar PV	
Aperture	22632.77755 m2
Total Modules	13517
Total Power	8,204,715,232.82 Wh
LCOE	$0.0846729
Cost of Project	$6,223,391.43
Wind Farm	
Rated Power	1000kW
# of Wind turbines	5
Total Power	18,042,276.69 Wh
LCOE	$0.0868272
Cost of Project	$10,023,487.05
Battery	
Curtailed	**8,605,942,851.76**
Availability factor	**98%**

Total Power supplied	**10,609,908,157.28**

As the Af increases, the total cost and curtailed energy increase but in a very abrupt manner, and even for 100% which ends up being almost impossible to attain, only with high-quality and performance storing system is barely possible.

Conclusion

Solar PV farm and wind farm were analyzed and compared against each other and the results are interesting. Regarding the required space, solar PV farm showed that it is very versatile when no free space is available because roofs, parking lots or any other unused space could be filled with PV panels of any size and start making/saving money. Contrastingly, the wind farm requires an empty wide space to position massive structures that shall not shadow its neighbors. In this area, PV panels proved to be superior.

Economics point of view usually summarizes the entire picture of a project given that in order to determine the total cost, all the factors shall be considered. It was determined that regardless of the project's size, the Solar's LCOE remained constant while the wind's LCOE fluctuated based on several aspects such as: project size and maintenance costs. Nonetheless, given that the LCOE is greatly dependent of the capacity factor, a well-optimized and justified wind farm could reduce its costs substantially. In this aspect both options performed very well and similar.

When comparing the Af for both systems separately, the wind farm gave better numbers than the solar PV farm meaning that it is more constant throughout the year than the solar PV system; nonetheless, both of them resulted low to be used as a primary energy production.

Considering the previous three aspects and the client in regard (NMSU), the solar PV farm was considered to be better given that not too much space is available and also because New Mexico state has extremely good solar energy potential which even makes all solar projects cheaper (therefore more profitable) than the nation's average. Besides, the fact that solar PV panels can be installed one by one, spending only hundreds of dollars instead of having to spend ~$1.64M to install a turbine is another extra for solar energy.

Having stated positive points about solar and wind energy, drawbacks have also been identified. It was evident that both alternatives present a serious availability factor problem, while Nuclear power plants can ensure a 99% of Af, solar and wind sources struggle to supply 50% combined (without any storing system) which makes them a non-reliable primary energy source.

The Af issue can be reduced combining renewables with any storing system; nonetheless, these storing systems have a theoretical (and economical) limitation when energy is curtailed. If the Af has to be increased too much, the cost of the storing system as well as the curtailed energy (Total energy produced) are just tot high to be worthy. This is why renewables currently are very good just as a secondary alternative or probably as a first alternative but without totally quitting Coal and Nuclear options because at some point they will be needed.

Renewable energy showed that they are performant and profitable regardless of the size of the project. Investing money in renewables is not only a solid long-term business, but also a helpful and green alternative for the world. The transition towards renewables is imminent and as soon as it happens the better.

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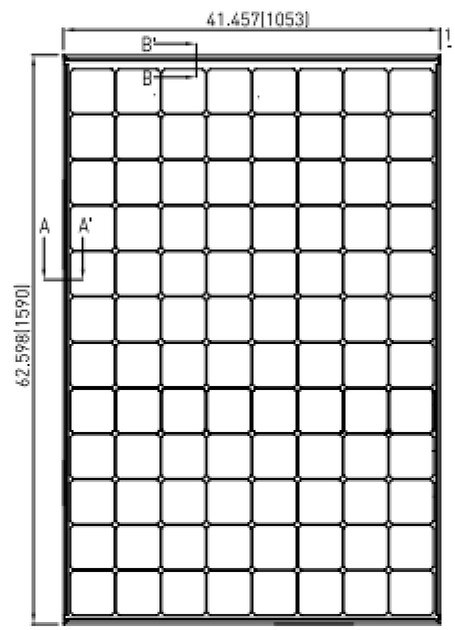
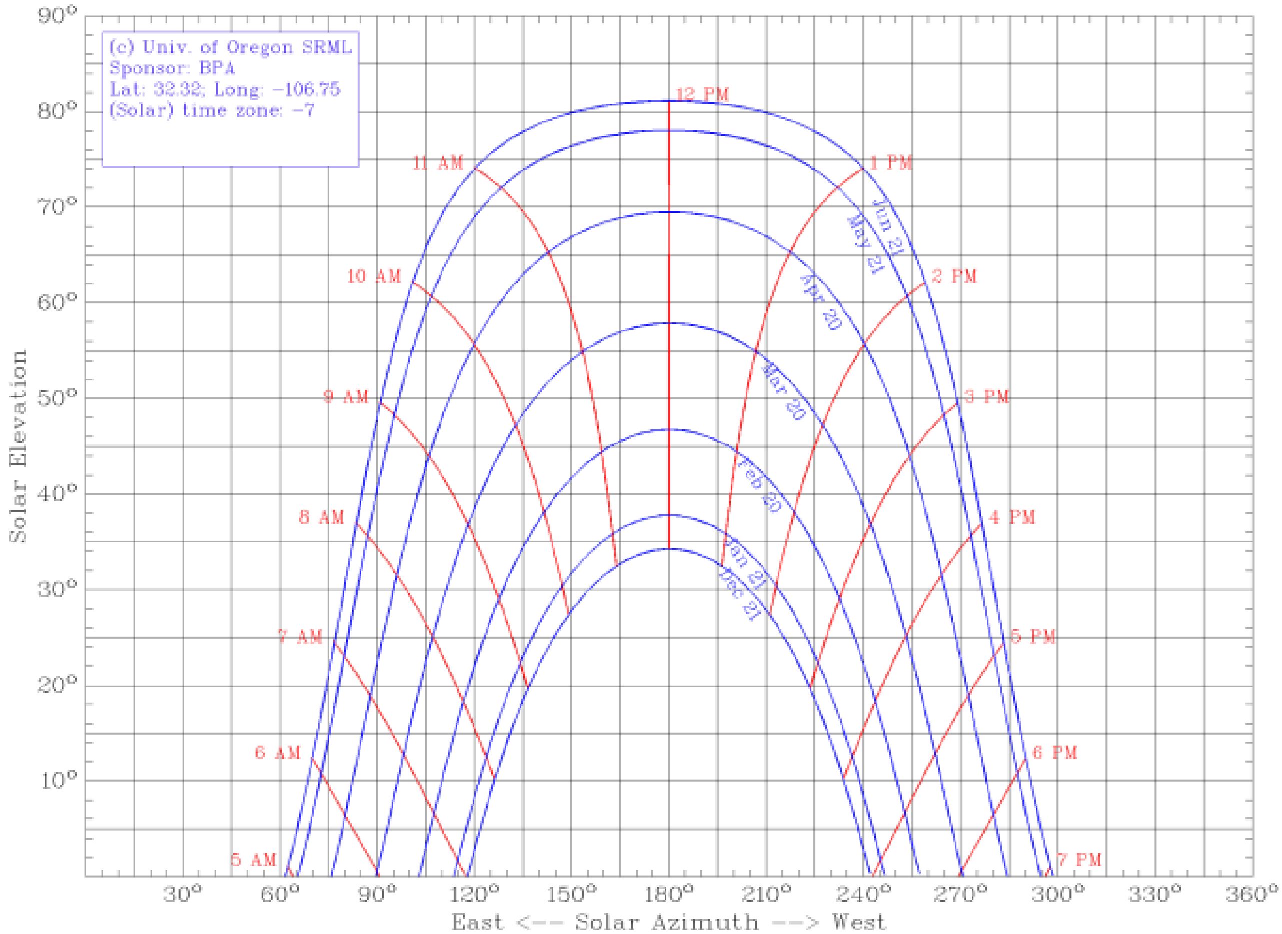
Appendix A- PV Specifications

Photovoltaic module hit n325	**value**
X	1.053 m
Y	1.59 m
efficiencies	19.4%
Rated power	325 W
Operating Temp	-40°C to 85°C
Hail Safety impact velocity	25mm at 23m/s
Warranty	25 years Power Output (MIN)



Appendix B-Solar Chart



Appendix C- CPV Specifications

CPV Collector SPECS

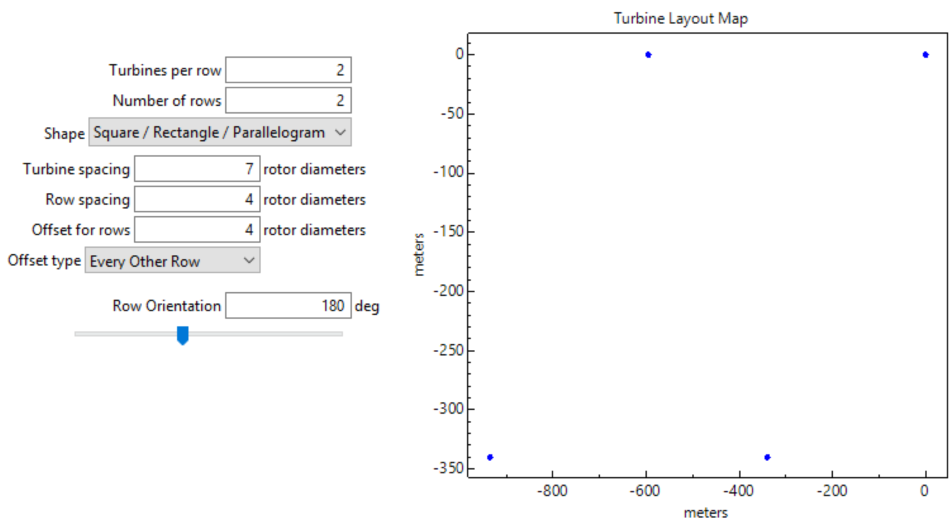
Width Maximal	12.44m
Height Maximal	12.73m
Weight	1.600 tons
Overall Surface	2679.33 m2
Cells efficiency (typical)	38%

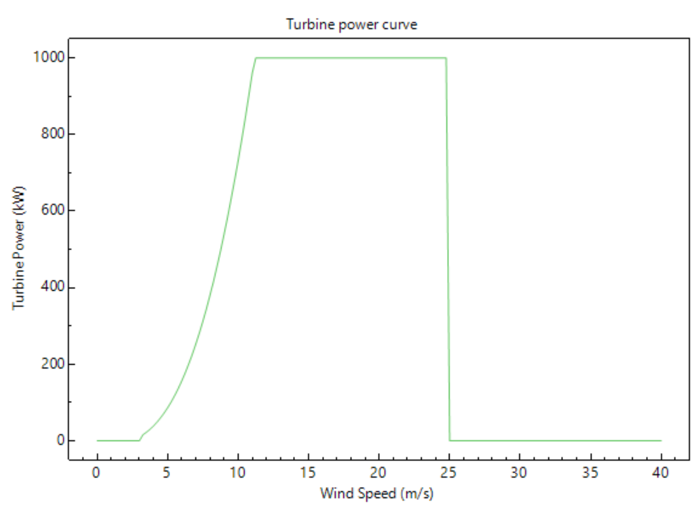
Information retrieved from http://www.airlightenergy.com/cpv-collector-specifications/

Appendix D-Wind Turbine Configuration

Wind Turbine specs

alpha	0.211
Diameter m	85
Area m2	5674.5017
Cut in Speed m/s	3
Cut out speed m/s	20
Rated Power ***kw***	1000
efficiency	0.45
R_Gas	287
#_Wind turbines	4





Images taken from SAM software