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An Evaluation on the Cost Efficiency of Wind and Solar Hybrid Power System

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An Evaluation on the Economic Efficiency of
Wind and Solar Hybrid Power System

A Thesis submitted in partial satisfaction of the requirements
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in

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by

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ABSTRACT OF THE THESIS

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Tianhao Gu

Master of Science in Engineering Science (Mechanical Engineering)

University of California, San Diego, 2017

Professor Jan P. Kleissl, Chair

Solar energy generation is intermittent due to the limitation of night time and weather, so batteries are normally used to stabilize the solar energy output in the distributed generation system. However, batteries are still expensive and have relatively short life span. The motivation of this research is to evaluate if wind energy can be a more cost efficient solution to replace battery storage.

An algorithm is created to analyze the solar irradiance, wind speed and load data from two different cities, Atlantic City and San Diego. Then find the most cost efficient renewable energy solution for each city under different renewable energy penetration level. The result shows that the wind energy is not a good substitution for battery. The solar and wind hybrid system can reach higher renewable energy penetration level, but the cost of the system and the wasted energy percentage is also extremely high. In San Diego, the integration of wind energy does not bring any economic benefit to the solar system. In Atlantic City, where the wind energy resource is abundant, adding wind turbines to the solar battery system can lower the system cost while maintaining the same level of renewable energy penetration.

Chapter 1 Introduction

1.1 Background

Renewable energy generation is widely applied during the last decades in the United States. According to the U.S. Energy Information Administration, in the year of 2015, around 10% of the total energy consumption in the U.S is provided by renewable energy generation. In the future, more renewable energy will be added to the energy system to reduce the carbon emission and fight the global warming. Many cities in the United States have set their goal to reach high renewable energy penetration level, some of them even made the 100% renewable energy commitment. Among all the renewable energy consumption, hydro and biomass generation have the largest ratio of 74%, while solar and wind generation count for 6% and 19% of the total consumption (US Energy Information Administration , 2016). Hydro and biomass generation stations require a lot of construction and proper locations, thus most of them are utility scale projects that are not directly accessible to the energy customers. Solar and wind generation projects, on the other hand, are very flexible on size, they can be utilized in both utility scale system and distributed generation systems. In the U.S, wind generates over three times more electricity than solar in the energy market, but solar technology is more popular in the distributed generation market. There are over 8000 solar installation companies throughout the nation that install solar photovoltaic panels for the commercial and residential customers to reduce their energy bill (Solar Energy Industry Association, 2016). Despite the large amount of solar installation, one major problem remains with solar energy, that the energy output is intermittent. In most cases, solar energy users need to either connect their systems with the main grid or install battery storages to stabilize the energy output, store the over produced energy, and discharge it when underproduction of energy occurs. Another more cost efficient way to raise renewable energy penetration rate while achieve greater overall generation stability is installing wind turbines in addition to the solar system to form a wind-solar hybrid power system. Unlike solar, wind blows both day and night, thus wind turbines can keep generating as far as the wind is still blowing. In areas where wind resource is abundant, wind system could be a cheaper substitution for the battery storage.

1.2 Research Motivation

Current battery storage technology is still expensive and has many limitations; it is not always the most cost efficient way to solve the intermittency in a solar system, especially in a larger scale. With the integration of wind energy, it is possible to increase the renewable energy penetration while reducing the intermittency of the total delivered power from the renewable energy systems at the same time. Wind and solar co-generation could optimize the total project cost for customers by minimizing the size of expensive battery storage.

The motivation of this research is to compare the economic efficiency and feasibility of using wind-solar hybrid power system as an alternative method to replace battery storage under different renewable energy penetration level.

1.3 Research Objectives

The objective of this research is to find out if wind and solar hybrid system is more cost efficient than solar and battery system. An algorithm will be developed to analyze and optimize multiple segments of data including solar irradiation data, wind speed data and load data. It can help the energy investors or users work out the most cost efficient energy solution under different renewable energy penetration level goal.

Chapter 2 Technology Overview

2.1 Solar Panels

There are two major ways to generate electricity using solar power, solar photovoltaic, and solar thermal. In this research, the solar photovoltaic (PV) modules will be considered as the default solar generation module because it has been commercially applied to distributed systems. There are three types of technology utilized in the PV panels on the market, which are monocrystalline, polycrystalline, and thin film amorphous. For roof-top installation, monocrystalline and polycrystalline solar panels are commonly used because they have higher efficiency than thin film solar panels thus take less roof space.

Monocrystalline solar panels have an efficiency of 18% and polycrystalline solar panels' efficiency is around 12%. In this study, monocrystalline solar panels will be chosen because of the higher efficiency (Sendy, 2016).

The solar PV power output depends on many aspects, including local solar irradiation, solar PV panel efficiency, panel temperature, panel tilt angle, and the invertor's efficiency. Also, the shading on the solar panels from other objects could influence the output power of solar PV panel as well. In recent years, the price of monocrystalline solar panels has dropped rapidly. The price for solar panels alone can be less than $1 per Watts. In the first half of 2016, the cost for the entire PV system is $2.89 per Watts, including all cost from module (PV panel), EBOS, labor, permitting & interconnection, taxes, overhead & margin, inverter, SBOS, design & engineering, supply chain, logistics & misc. and origination (GreenTechMedia, 2016).

Solar energy is abundant, but only during the day time. The uneven output of energy has caused potential problems for the grid operators. In 2013, the California Independent System Operator (CAISO) published a “Duck Chart”, this graph shows the potential for “over generation” occurring at increased penetration of solar photovoltaics (PV). The over generation of solar energy could affect the performance of the generators and certain motors connected to the grid without intervention. To balance the supply and demand, the grid operators must carefully monitor the solar energy output, and reduce output from the conventional generation fleet if over generation occurs. The integration of other renewable energy sources such as wind and geothermal can effectively flatten the shape of “Duck Chart” (Denholm, 2015). Utilizing energy storage to store the over generated energy is another solution towards over generation.

2.2 Energy Storage

Energy storage is an effective way to reduce the fluctuation in the power grid caused by renewable generation. There are numbers of energy storage technologies on the market. For utility scale storage, mechanical methods such as pumped hydro, compressed air, and flywheel are commonly used, but in most cases where solar and wind energy are related, electrochemical batteries are the best choices. Lithium-ion batteries and lead acid battery are two most common electrochemical batteries. Lead acid battery is lower in cost, but also low in cycle number and energy density. The materials that are contained in the lead acid battery could cause serious pollution to the environment. Lithium-ion battery is higher in both cycle number and energy density, but cost more than lead acid battery. Although the cost of Lithium-ion battery went down rapidly in the past 5 years, the cost is still around $500/KWh in average. The typical life span of Lithium-ion battery is 10-15 years (Luo, 2014), which is half the life span of the generation modules like solar panels and wind turbines. The relatively short life span of the batteries further increases their cost in the renewable energy systems.

2.3 Wind Turbines

The wind turbines are divided into two groups based on the orientation of their rotation axis, the two groups are HAWT and VAWT. HAWT, also known as Horizontal Axis Wind Turbine is the most common type of wind turbine. It is good for both utility scale generation and distributed generation. VAWT, which stands or Vertical Axis Wind Turbine has completely different mechanical structure compare to HAWT (Pope, 2010). Wind turbines do not generate power under all wind speeds. At very low wind speeds, the torque exerted by the wind on the turbine blades is not enough to trigger the rotation. On the other hand, when the wind speed is too high, the wind turbine will stop generating to protect itself. The speed at which the turbine first starts to rotate and generate power is called the cut-in speed while the highest wind speed that could keep the turbine operating is called the cut-out speed (Acosta, 2012).

Different wind turbine could lead to different energy output even under the same wind speed. To develop a sample case in this study, the parameter of a VAWT produced by Ropatec. Inc was chosen to estimate the wind power output. This kind of VAWT has a rated power of 6kW at the wind speed of 14m/s and a cut-in speed of 2m/s. This type of wind turbine has no cut-out speed, instead, the turbine will stay at the rated power when the wind speed is over 14m/s. The advantage of this VAWT is that it can work under wider range of wind speed and capture more wind power than the wind turbines with cut-out speed (ROPATECH, 2012).

The unit cost per Watts of the wind turbine various bases on the types of turbine, total capacity, and the installation location. The costs of the commercial scale wind turbine range from about $1.3 million to $2.2 million per MW, which is $1.3 to $2.2 per Watts. However, the commercial scale wind turbine cannot be installed in urban area due to the lack of land. Smaller wind turbine that can be installed in the urban area has a higher unit cost. Wind turbines under 100 kW has a cost of around $4 per Watt (US Department of Energy, 2016). In this study, the sample wind turbine has a rated power of 6kW, thus the unit price for wind turbine was assumed to be $4 per Watt.

Chapter 3 Methodology

In this research, five different types of renewable energy generation systems will be discussed and compared. These five types are: solar panels only, wind turbines only, solar panels plus battery storage, solar panels plus wind turbines, and the combination of all three together.

MATLAB 2015b is used in this study to process the data and run the optimization. The first step is to load the time series files of annual energy consumption, annual solar energy production and annual wind speed into to the program manually.

For the solar panel only and wind turbine only situation, only one generation source exists. The enumeration method is used by listing all the possible numbers of capacity from 100kW to 50000kW with an interval of 100kW. The annual energy production per 1kW of solar panel and wind turbine is used as the unit production rate. As the capacity increase, the outputs would show the penetration level of solar energy or wind energy in the system at the current capacity. The percentage of wasted renewable energy is also calculated by dividing the unused energy by the total energy production.

For the solar-wind cases, the MATLAB commands *find* and *max* are used. The enumeration method is also used in this case. All combinations of solar panel and wind turbine capacity from 100kW to 50000kW are listed, the find-max command is able to select the cases that the most renewable energy is used under different penetration level.

For the case with battery, the size of battery needed for every hour in the entire year is calculated with different combination of solar or wind energy. The mean value of the battery size is outputted as the optimized battery size.

The MATLAB program can output the optimized capacity for solar, wind or/and battery under different renewable energy (including wind and solar) penetration levels from 10% to 100%. It also shows that how much energy is wasted under different penetration level.

3.1 Data Acquisition

The data that are required for this study are the load data, solar production data and wind production data. Among them, solar and wind data within the boarder of U.S were obtained from NREL（National Renewable Energy Lab, 2015）website. The data sets that are used in this study are the TMY3 data. The TMY3s are data sets of hourly values of solar radiation and meteorological elements for a 1-year period. The TMY3 data sets have the solar and wind data in 1020 locations across the United States from 1991 to 2005. TMY3s provide great convenience for the study of solar and wind energy nationwide (Gagnon, 2016).

In this study, the solar production data are obtained directly from the NREL PVWatts Calculator tool. The PVWatts Calculator provides PV generation data at the desired locations based on the atmospherically data from TMY3. The one-year time series of energy production of 1kW of solar panel at the two chosen locations are obtained from PVWatts Calculator. The annual generation of 1kW solar panel served as the unit production rate in this study.

The wind speed data are obtained from TMY3 as well. With the wind speed data, the wind production rate can be calculated based on the wind turbine parameters.

The load data are not as easy to obtain as the solar or wind data, because they are considered as private property. The load data of Scripps Institution of Oceanography (SIO) in year of 2014 is used in this study with the permission from UCSD. The load of SIO campus is quite consistent throughout the year.

To compare the performances of different renewable energy systems in different locations, two locations are chosen in this study to represent different situations. The city of San Diego and Atlantic City are used for the case study. San Diego is located at the “Sun Belt” of the United States where the solar irradiance is strong throughout the year. Atlantic City is a coast city on the north-east coast of United-States, where the wind resource is very abundant. The solar and wind data of the two cities are obtained from NREL website.

The data used in this study are collected in different range of time due to technical difficulties and data availability. Thus, this study does not reflect the actual situation in a timely manner. However, the MATLAB program made for this study is universal.

3.2 Data Processing

The first step of data processing is to convert all data into the time series that have same units and time interval. All the data, including load, solar production and wind production should be converted into the unit of kWh and the time interval of 1 hour.

The load data from UCSD and solar data from PVWatts Calculator already have the unit of kWh. The PVWatts time series gives the electricity produced by the solar panels in one hour time interval and the load data are also time series in 1 hour interval.

The wind speed data from TMY3 are collected at the altitude of 10 meter above ground. To get more wind power, wind turbines are normally elevated to higher altitude. In this study, an altitude of 80 meters is chosen. At this altitude, a calibration of wind speed must be made using MATLAB, the equation used for the calibration is:

$$v_w(h) = v_{10}.(\frac{h}{10})^a$$

Where v_w is the wind speed at desired altitude, v_{10} is the wind speed at 10m altitude and a is a constant called Hellmann Exponent. For urban area, a's value is normally 0.27 (Sunderland, 2014).

With the calibrated wind speed, the wind power can be calculated using the following equation:

$$\mathrm{P} = \frac{1}{2}\rho U^3 \frac{\pi d^2}{4}$$

Where P is the power of the wind turbine; ρ is the density of air; U is the speed of wind and d is the cross section of the wind turbine.

. In this study, the rated speed of the wind turbine was 14m/s, which means for each 1kW of wind turbine, 1kWh of electricity would be produced each hour if the wind speed is 14m/s. When the wind speed is under 14m/s, the power of the 1kW of wind turbine can be calculated based on the speed ratio.

$$P = \frac{U^3}{14^3}$$

With the time series of hourly solar energy production, hourly wind energy production and hourly load, the MATLAB program can run the optimization using the method explained in the methodology part. The outputs show the most cost efficient solutions for all five types of renewable energy system under the renewable energy penetration level from 10% to 100%.

Finally, the system total cost was calculated using the following equation:

$$\mathrm{T} = 1000\times(N_s p_s + N_w p_w) + N_b p_b$$

Where T is the total cost, $N_s$is the total capacity of solar panel (in kW), $N_w$is the total capacity of wind turbine (in kW), $N_b$is the total capacity of battery; p_s is the unit price per Watt for solar panel, p_w is the unit price for wind turbine and p_b is the unit price per kWh for battery. In this study, p_s has a value of $2.98/W, p_w has a value of $4/W and p_b has a value of $500/kWh.

Chapter 4 Result

I. Solar only

The result for solar only case shows that San Diego has a better solar resource than Atlantic City. For 20% penetration rate, San Diego only needs 850kW of solar penal to satisfy the demand of SIO while Atlantic City needs 1050kW. At the penetration level around 30%, there are some waste of energy occurs. The solar panel can only provide at most 48% of energy for the load in San Diego, and 46% of energy in Atlantic City.

Table 1 Solar Panel Capacity under Different Penetration Levels

	Atlantic City		San Diego	
Penetration	kW required	Energy Wasted	kW required	Energy Wasted
15%	1050	0	850	0
20%	1400	0	1100	0
30%	2500	16%	1800	8%
50%	N/A	N/A	N/A	N/A
75%	N/A	N/A	N/A	N/A
90%	N/A	N/A	N/A	N/A
100%	N/A	N/A	N/A	N/A

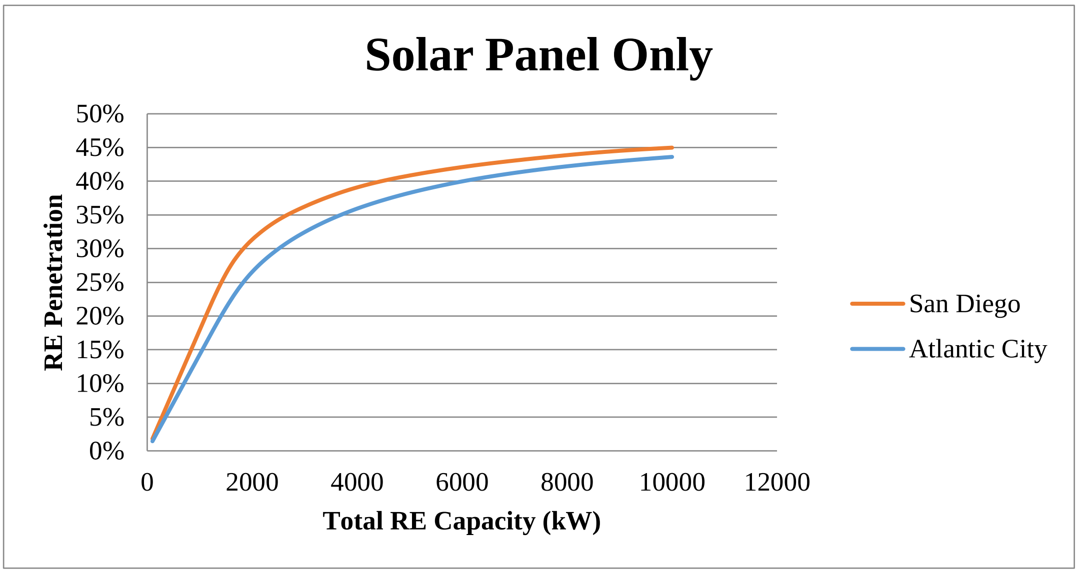

Figure 1 Total Renewable Energy Capacity in Solar Panel Only Situation

II. Wind Turbine Only

Atlantic city has a better performance if the energy system is using wind energy only. At 20% penetration level, Atlantic City only need 900kW of wind turbine while San Diego needs 3000kW. At 50% penetration level, the difference become even larger, Atlantic City needs 3900kW while San Diego needs 13200kW. In Atlantic city, wind energy can reach up to 90% of renewable energy penetration level. San Diego can only reach 50%. Using wind turbine to generate energy leads to large amount of wasted energy at high penetration level.

Table 2 Wind Turbine Capacity under Different Penetration Levels

	Atlantic City		San Diego	
Penetration	kW required	Energy Wasted	kW required	Energy Wasted
15%	650	0%	2200	5%
20%	900	0%	3000	10%
30%	1500	11%	5200	21%
50%	3900	44%	13200	48%
75%	15500	79%	N/A	N/A
90%	50000	92%	N/A	N/A
100%	N/A	N/A	N/A	N/A

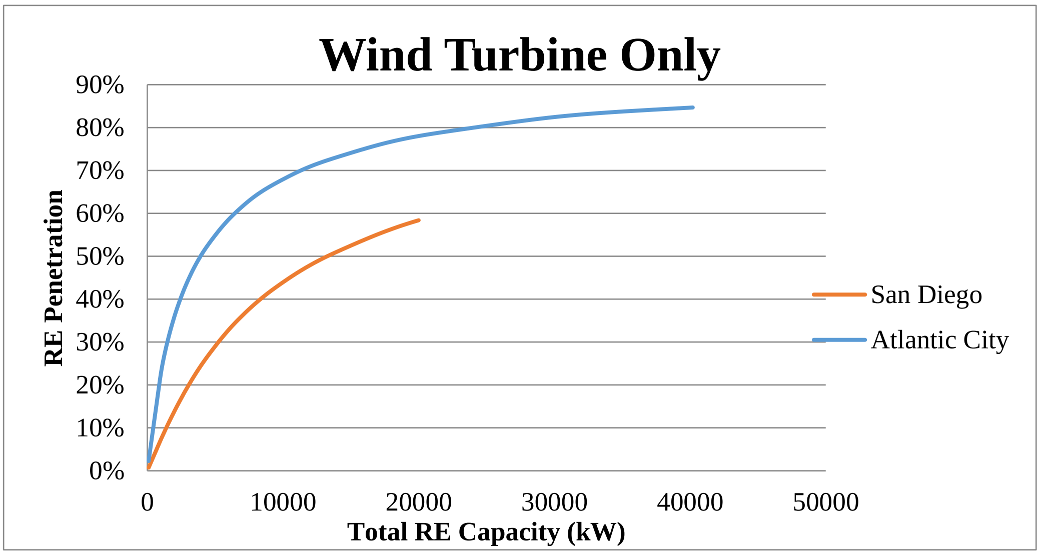

Figure 2 Total Renewable Energy Capacity in Wind Turbine Only Situation

III. Solar and Wind

The solar-wind hybrid system can reach higher penetration level than solar or wind only system. However, when the penetration goal is under 30%, there is no need to using both. In Atlantic City, using wind only is the most cost efficient method when the penetration level is less than 30%. In San Diego, using solar only system is the most cost efficient method when the penetration level is less than 30%. The capacity of wind turbines raises at an exponential rate as the penetration level increases. In Atlantic City, 45000kW of wind turbines are needed to reach a 90% penetration rate while the solar capacity is only 5000kW.

Table 3 Solar Panel & Wind Turbine Capacity under Different Penetration Levels

Solar+Wind	Atlantic City			San Diego		
Penetration	Solar (kW)	Wind (kW)	Wasted	Solar (kW)	Wind (kW)	Wasted
15%	0	650	0%	850	0	0%
20%	0	900	0%	1100	0	0%
30%	0	1500	11%	1800	0	8%
50%	1080	2520	32%	3200	4800	46%
75%	2820	11280	75%	3790	34110	77%
90%	5000	45000	92%	N/A	N/A	N/A
100%	N/A	N/A	N/A	N/A	N/A	N/A

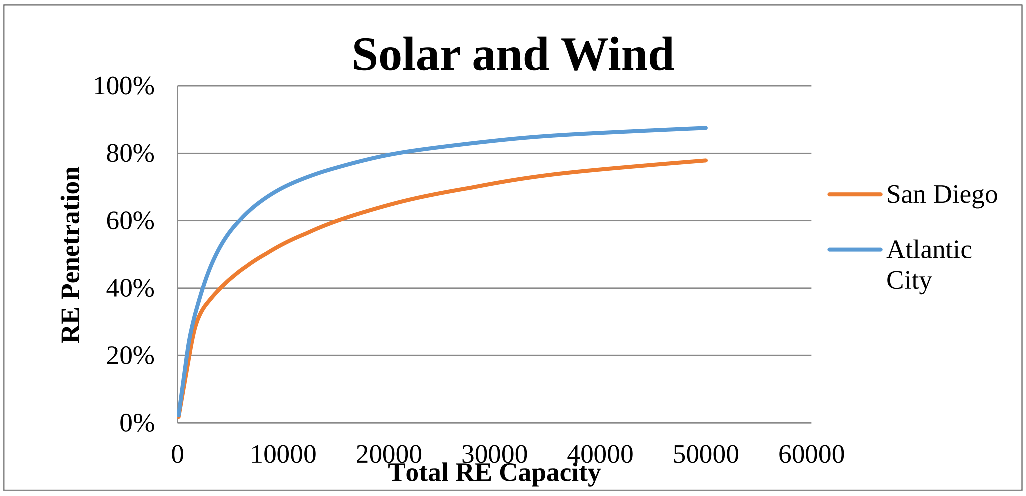

Figure 3 Total Renewable Energy Capacity in Solar Wind Hybrid Situation

IV. Solar and Battery

Using solar and battery system allows the system to reach 100% penetration level. In this case, the relationship between renewable energy penetration level and solar capacity is a linear relationship. In Atlantic City, 8100kW of solar and 23000kW of battery is needed to reach the 100% penetration rate. In San Diego, 6200 kW of solar and 21200kWh of battery is needed to reach 100% penetration rate.

Table 4 Solar Panel & Battery Capacity under Different Penetration Levels

Solar+Battery	Atlantic City			San Diego		
Penetration	Solar (kW)	Battery (kWh)	Wasted	Solar (kW)	Battery (kWh)	Wasted
15%	1050	0	0%	850	110	0%
20%	1400	0	0%	1100	150	0%
30%	2200	1421	3%	1700	700	2%
50%	3800	6645	8%	3000	5621	6%
75%	6000	14518	13%	4600	13244	9%
90%	7300	19800	14%	5600	18229	10%
100%	8100	23174	14%	6200	21242	10%

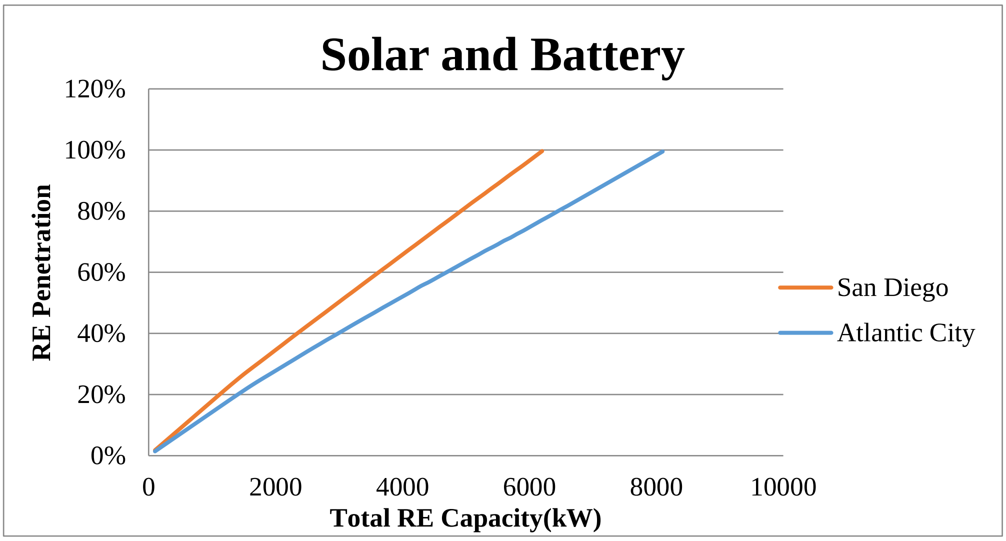

Figure 4 Total Renewable Energy Capacity in Solar and Battery Situation

V. Solar, Wind and Battery

The solar wind and battery system has a performance similar to the solar and wind system. When the renewable energy penetration level is under 30%, no solar panel is needed in Atlantic city while no wind is needed in San Diego.

At 100% penetration level, 1220kW of solar, 4880kW of wind and 19800kWh of battery is needed in Atlantic City. 2500kW of solar, 10000kW of wind and 18700kWh of battery is needed in San Diego. The relationship between renewable energy penetration level and renewable energy capacity is also a linear relationship.

Table 5 Solar Panel, Wind Turbine & Battery Capacity under Different Penetration Levels

Solar + Wind + Battery	Atlantic City			
Penetration	Solar(kW)	Wind(kW)	Battery (kWh)	Wasted
15%	0	700	338	0%
20%	0	900	674	0%
30%	0	1,400	1,586	6%
50%	840	1,960	4,484	12%
75%	1,350	3,150	10,685	18%
90%	1,650	3,850	15,433	19%
100%	1,220	4,880	19,805	23%
Solar + Wind + Battery	San Diego			
Penetration	Solar(kW)	Wind(kW)	Battery (kWh)	Wasted
15%	0	850	110	0%
20%	0	1,100	150	0%
30%	0	1,700	700	2%
50%	2,800	700	5,483	6%
75%	3,000	4,500	11,752	10%
90%	3,000	7,000	15,898	12%
100%	2,500	10,000	18,766	15%

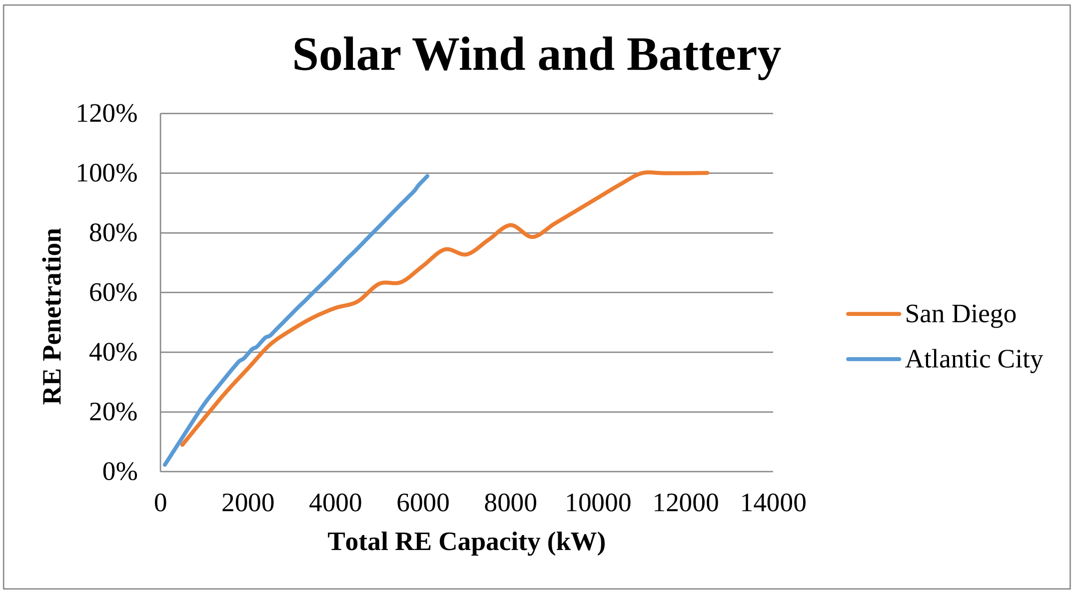

Figure 5 Total Renewable Energy Capacity in Solar Wind and Battery Situation

4.1 Cost Comparison

The total costs of the five different types of renewable energy systems under different penetration levels are shown in the table 6 and 7. The green number shows the most cost efficient system among the five. Table 6 shows that in Atlantic City, wind only system is the most cost efficient system when the penetration goal is under 30% and solar, wind and battery system is the most cost efficient system when the renewable energy penetration goal is 50% or more. Table 7 shows that in San Diego, the solar only system is the most cost efficient system when the penetration level is under 30% and solar battery system is the most cost efficient system when the penetration goal is 50% or more.

In San Diego, the renewable energy system cost less than the system of same renewable energy penetration level in Atlantic City

Table 6 System Cost in Atlantic City under Different Penetration Level

Atlantic City					System Cost (million $)
Penetration	Solar	Wind	Solar+Wind	Solar+Battery	Solar+Wind+Battery
15%	3.0	**2.6**	2.6	3.0	3.0
20%	4.0	**3.6**	3.6	4.0	3.9
30%	7.2	**6.0**	6.0	7.1	6.4
50%	N/A	15.6	13.2	14.3	**12.5**
75%	N/A	62.0	53.3	24.6	**21.8**
90%	N/A	200.0	194.5	31.0	**27.9**
100%	N/A	N/A	N/A	35.0	**32.9**

Table 7 System Cost in San Diego under Different Penetration Level

San Diego					System Cost (million $)
Penetration	Solar	Wind	Solar+Wind	Solar+Battery	Solar+Wind+Battery
15%	**2.5**	8.8	2.5	2.5	3.5
20%	**3.2**	12.0	3.2	3.3	4.5
30%	**5.2**	20.8	5.2	5.3	7.2
50%	N/A	52.8	28.4	**11.5**	13.6
75%	N/A	N/A	147.4	**19.9**	32.5
90%	N/A	N/A	N/A	**25.3**	44.6
100%	N/A	N/A	N/A	**28.5**	56.6

Chapter 5 Discussion

The result shows that using wind energy to replace battery storage does not necessarily lower the cost of the entire renewable energy system; it depends on the abundance of the local wind resource.

The Solar Only case shows that if only solar energy are installed, the total energy production in the two cities and maximum renewable energy penetration rate in the two cities are very close. In both cities, the solar energy alone can satisfy up to 45% of the building's energy demand. This is due to the daytime limit of solar power itself. Wind energy can reach higher renewable penetration rate than the solar energy, wind power penetration rate can reach 58% in San Diego and 90% in Atlantic City, but the waste would be huge if that percentage of penetration is reached. When reaching the highest wind energy penetration level, over 92% of wind energy would be wasted in Atlantic City and over 50% would be wasted in San Diego.

Using solar and wind hybrid generation system can raise the renewable energy penetration level. In each city, the hybrid system can reach higher penetration than solar or wind generation alone. However, the solar wind hybrid system is not economically efficient: at lower penetration level (under 30%), using solar or wind generation alone is the most cost efficient way; at higher level of renewable energy penetration (over 50%), using battery storage can greatly reduce the waste and system cost.

Introducing battery storage to the renewable generation system allows the renewable generation system to reach 100% penetration level, it also reduce the cost of the entire system at the high penetration level.

Although battery storage is the most effective aspect in reducing the system cost and raising the renewable energy penetration level, wind turbines could also contribute to make the system even more cost efficient. In Atlantic City, where wind energy resource is abundant, the implementation of wind turbine can make the solar battery system cost less than solar and battery system. The cost comparison table shows that as the renewable energy penetration goal goes higher than 50% in Atlantic City, the solar wind hybrid system with battery storage would become the most cost efficient system among all five types of system.

5.1 Limitation of the Study

The parameter of certain types of solar panel and wind turbine are used in this evaluation, using other modules may lead to different results. The renewable energy generation data acquired in this study were not the concurrent data, thus the evaluation only represent the general situation. Also, there were not enough load data to analyze in this study, the result can not reflect the situations of other buildings with different load types.

5.2 Future Work

To further study the economic efficiency of solar and solar hybrid system, more cases with different locations and different load types should be studied. In this study, due to the limitation of the load data, only distributed generation system was analyzed, if possible, the load data of the entire city should be used in the study so that the utility scale renewable energy generation method could be considered. Utility scale wind turbines have a much cheaper unit price, which may lead to different cost efficiency.

Chapter 6 Conclusion

In this study, the economic efficiency of five types of distributed renewable energy system was compared in two different cities, Atlantic City and San Diego. The result shows at a low renewable penetration level (<30%), the most cost efficient renewable energy system for San Diego is solar only system. For Atlantic City, wind only system cost the least. The combination of solar, wind and battery will not bring in additional benefits at the low penetration level.

Solar wind hybrid generation system is able to reach the renewable penetration goal of 50% or higher while either one alone could not. If the penetration goal is higher than 50%, the implementation of battery storage is recommended because otherwise the cost of the system and the wasted energy would both become extremely high. Lastly, if the government or investors are heading for the 100% renewable energy penetration goal, the battery storage is essential in the renewable energy system. In areas that are rich in wind energy resource, adding wind turbines to the solar and battery system could further optimize the system and lower the total cost, but wind turbine could not replace battery storage completely.

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