ASSESSMENT OF VARIOUS ENERGY STORAGE OPTIONS IN SAO VICENTE

Vaibhav R. Paraashar | *vrp2113*

Sagar Vinodababu | *sv2414*

INTRODUCTION

Several islands around the world have a significant potential of adding energy from renewable sources to their electric grid. However, the varying nature of these renewable sources adds uncertainty and unreliability to energy security of the island. Since the ever varying demand must be met a constant source of baseload generation must be coupled with renewable sources of generation of all times. This baseload generation is usually in the form of fossil fuel generators. This arrangement creates essentially two drawbacks: 1) There is still a huge dependency on fossil fuels despite the presence of large renewable energy potential; and 2) There is a need to balance the combined output of both the baseload and renewable source with the demand to avoid dangerous operating conditions for the grid. The second point is enforced generally by curtailing the generated renewable energy delivered to the grid at times of off-peak demand. This results in a significant waste of potential.

This repot studies the case of Sao Vicente Island, which has a large potential for harnessing wind energy, and attempts to propose a mechanism where:

1. Baseload generation and curtailed wind energy are optimized to a levels that bring about maximum efficiency.
2. Excess energy storage and utilization options are explored and feasibility is analyzed.

BACKGROUND

Sao Vicente is an island in the archipelago of Cape Verde, in the Atlantic Ocean off the coast of mainland Africa. It had a population of 79,374 in 2010 and has an area of 227 km^2. The highest point on the island is Mount Verde. It does not receive a terribly high amount of rainfall annually. The island has successfully integrated wind and solar power into its electricity grid.

Electrochemical batteries have long been used as storage mediums of energy. However, batteries of large capacities tend to expensive and dangerous to operate. Therefore, it makes sense to explore mechanical methods of storing vast amounts of energy.

Of the several options available, this report examines two main technologies that may be feasible to implement on the island of Sao Vicente:

1. Pumped Hydropower Energy Storage (PHES)
2. Underwater Compressed Air Energy Storage (UWCAES)

To a smaller extent, we also examine the possibility of utilizing excess wind energy to produce drinking water for the island by the process of desalination of sea water by reverse osmosis (RO).

To get an understanding of the above mentioned technologies, three technical publications were researched. A summary of each of the papers are printed below.

Wind powered pumped hydro storage systems, a means of increasing the penetration of renewable energy in the Canary Islands
C. Bueno, J.A. Carta

The Canary Islands are an archipelago belonging to the Spanish State in the Atlantic Ocean, off the coast of Africa. Due to its small size, it has traditionally depended on import of fossil fuels to meet its energy requirements. However, it has a huge potential for renewable energy in the form of wind power. A total of 41 wind farms were in operation in 2002 with an installed power of 105.6 MW and a total generation of 243 GWh of energy. This has brought about a reduction of 200,208 tonnes in CO2 emissions and an overall primary energy saving of 61,785 tonnes in 2002. Despite its small size Canary Islands accounted for 34.66% of the total wind power installed in Spain in 1994.

However, the unpredictability of wind power often causes wastage in the generated power during surge times and has increased the reliance on fossil fuel based power plants during lulls in winds. It is therefore practical to store the surplus wind power during off peak times and feed it back to the grid during times of peak demand. The variation in wind speeds lead to dangerous operating conditions as the grid is also in sync with the baseload generators.

The Canarian government is therefore keen to implement solutions that will help utilize wind power to its highest potential. These solutions aim to:

a. guarantee the energy supply

b. reduce the degree of vulnerability of the supplies by diversifying the sources
c. promote the rational use of energy
d. reduce energy dependence on external sources by increasing as much as possible the use of new energy sources
e. guarantee a stable and safe energy supply
f. minimize energy costs
g. contribute to the protection and conservation of the environment

With this aim, two possibilities are explored: of having a wind-diesel hybrid generating system and of installing a pumped hydropower energy storage system to store surplus wind energy.

Design and testing of Energy Bags for underwater compressed air energy storage
Andrew J. Pimm , Seamus D. Garvey, Maxim de Jong

Compressed air energy storage mechanism refers to the technology of storing excess generated electrical energy in the form of compressed air till such time as there is a demand for this energy, at which point the compressed air is made to expand and run a turbine to regenerate electricity.

The compressed air storage system cycle can be either isochoric (constant volume) or isobaric (constant pressure) in nature. However, it is preferable to employ an isobaric system as it presents two main advantages:

1. The expander efficiency is generally higher in this kind of system since the pressure of the air at the input of the expander can be roughly constant throughout the discharge of the air without the need to throttle it.
2. Energy density is higher as no cushion gas is necessary to be left in the vessel to support the external pressure.

There are two possible thermodynamic cycles that may be employed in the compressed air system, which govern the energy density of the system. They are isothermal and adiabatic. Since a lot of heat is lost in an isothermal process, adiabatic systems are preferred as they offer better efficiency.

Further, compressed air storage system may be implemented in two forms: underground and underwater. In underground compressed air energy storage system the lithostatic pressure in the surrounding rock provides resistance to the high pressure of the stored, compressed air. According to a United Nations study, underground air storage can be cost effective when storage is done in aquifers, depleted gas fields or salt caverns. However, structural feasibility and geological implications of such a system is the subject of further analysis and may even prove to be impediments to successful implementation of the system.

In underwater compressed air energy storage (UWCAES), on the other hand, the hydrostatic pressure of the surrounding water provides the pressure restraint. It is practical to maintain the pressure inside the storage vessel at a value roughly equal to that of the hydrostatic pressure, rather than higher, so that the strength requirements of the containment structure are minimal. As a result, the capacity of the energy storage system becomes a function of depth. Deeper the storage vessel, greater is the hydrostatic force and, hence, greater the pressure capacity of the vessel. This adds greatly to the advantages of this kind of energy storage system.

For an adiabatic CAES, the recoverable energy per cubic meter is given by:

$$u_{\text{adiab}} = rP_{\text{atm}}\left(r^{((\gamma-1)/\gamma)} - 1\right)\left(\frac{\gamma}{\gamma-1}\right)$$

Where, Patm = atmospheric pressure = 101.325 kPa

Γ = ratio of specific heats = 1.4 for dry air

r = ratio of storage pressure to atmospheric pressure = P / Patm

P = hydrostatic pressure + atmospheric pressure

= ρgd + Patm

where ρ = density of sea water = ,1.025kg/m^3 *g = accl. due to gravity & d = depth*

Several prototypes of UWCAES have been installed for testing in several sites around the world. University of Windsor, with partnership with Hydrostor, have set up a test location on Lake Ontario in Canada. The results from these experiments show promising signs that such a systm can be implemented in large scale in the future.

Energy storage for desalination processes powered by renewable energy and waste heat sources
Veera Gnaneswar Gude

The importance and value of water has exploded as a result of rising global population and depletion of water resources. One of the methods of artificially obtaining drinking water is desalination. Historically, the desalination technique was complicated, expensive and prohibitive. However, desalination much more viable these days because: 1) dramatic improvements in energy consumption by many desalination technologies; and 2) reduced investment costs for desalination technologies.

There are a variety of technologies available for desalination:

1. Multi-stage flash distillation (MSF)
2. Multi-effect evaporation/distillation (MSD)
3. Vapor compression (M/TVC)
4. Reverse Osmosis (RO)
5. Electrodialysis (ED)
6. Membrane Distillation (MD)

Reverse osmosis (RO) is a non-phase operation process in which a semi-permeable membrane is used to separate the water from the salt. A semi-permeable membrane allows water from the saline water to pass but not the salt. An external pressure is required to be applied to force the saline water through the semi permeable membrane. The amount of energy required for the mechanical pumping of the feed water through the membrane depends on the concentration of the feed water. This process does not require heating or phase-change of the feed water.

The amount of energy required to desalinate unit cubic meter of water (kWh/m^3) by the RO process is known as specific energy consumption (SEC). The SEC for a commercial RO plant can lie between 1 kWh/m^3 to 10 kWh/m^3. The highest SEC's are for plants that do not employ energy recovery devices (ERD). For a plant that uses ERD, such as pelton wheels or work exchangers, the SEC is around 3 to 5 kWh/m^3.

ANALYSIS, RESULTS AND DISCUSSION

PART 1: Assessment of Appropriate Storage Capacity

Analysis of Original Dispatch Data

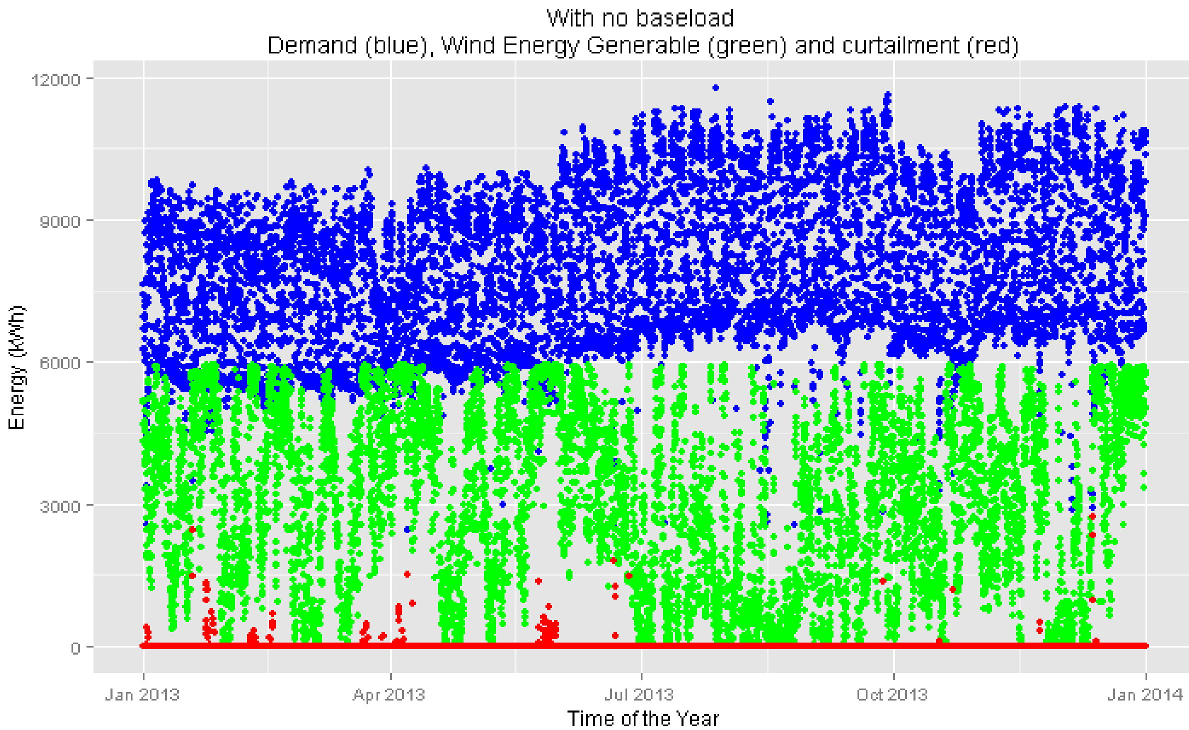
1. ***Calculate the uncurtailed capacity factor of the wind farm over the course of this year in the absence of any energy storage options, as per the turbine power curve and wind speed.***

   Capacity factor = 52.03%

2. ***Calculate the curtailed capacity factor of the wind farm over the course of the year in the absence of energy storage, using dispatched power values. How much energy is lost over the course of the year due to curtailment?***

   Curtailed energy = 52442.29 kWh

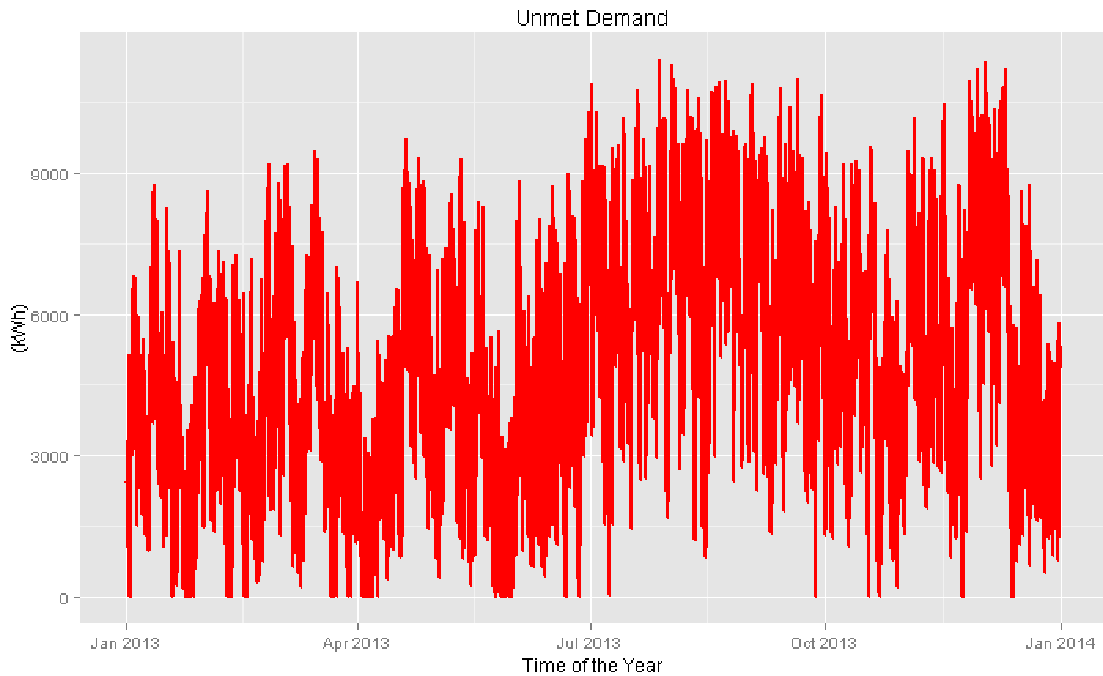
   Capacity factor = 51.93%

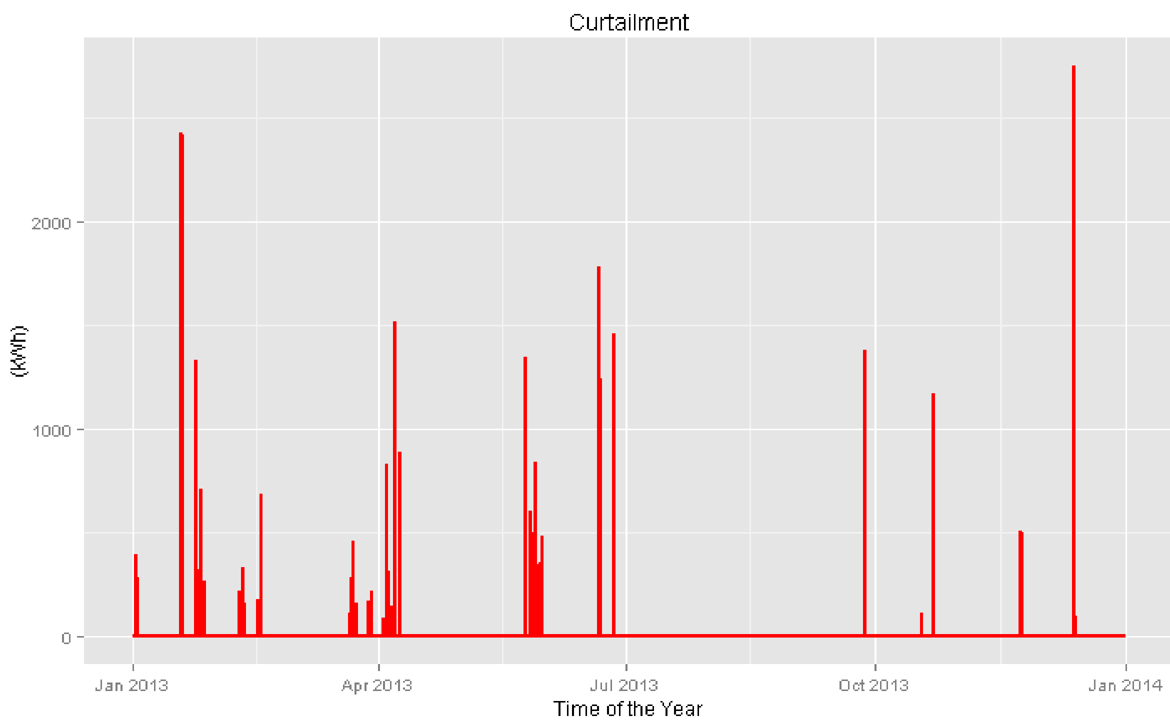


As can be seen, curtailment is very less as no baseload has been applied and demand is consistently more than generation.

3. What periods of the year have the greatest amount of curtailment over the year? What parts of the year have the highest amount of unmet demand?

As can be seen from the plots below**,** maximum curtailment occurs in the first half of the year.





Application of Constant Baseload Generation

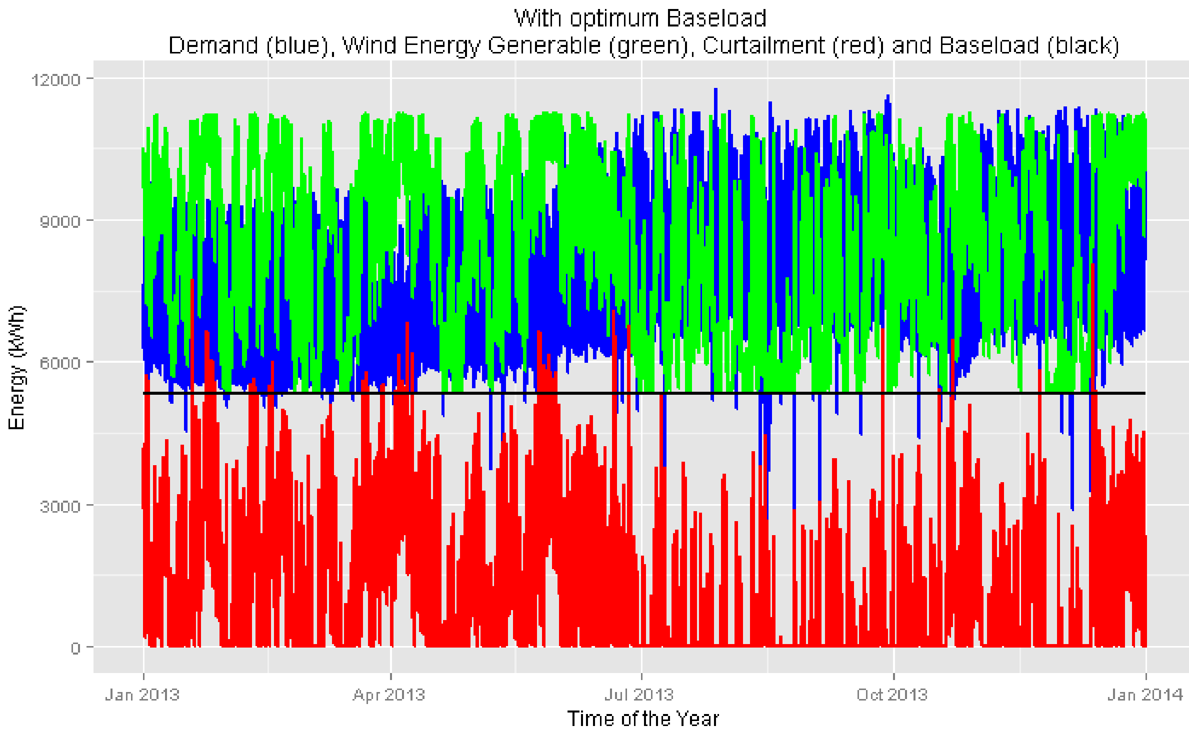
1. ***Consider the overall range of demand values over the course of the year. What would be a reasonable value for baseload generation? Why?***

   The following baseload value was chosen as the ratio of the unmet demand to the curtailment equals 0.64.

   Baseload = 5320 kWh

   This implies that all of the curtailed energy can be recovered to meet the unmet demand provided that the storage capacity is large enough, and taking into account 80% efficiencies in and out of the storage. Realistically, since there is a limit on storage capacity the net efficiency will be lesser than 0.64. In this case the baseload will have to be higher so that the curtailment is higher to compensate for this lower storage efficiency. Therefore, we recommend that baseload is at least 5320 kWh under these simple constraints considered.

The following is a plot for the 5320 kWh baseload scenario:



In the above plot the area under the blue curve above the green curve is 0.64 times the area under the red curve.

2. ***Given this baseload value, calculate the new curtailment and capacity factor of the wind farm.***

Curtailment = **11061748.37 kWh** and Capacity factor = **31.04%**

<u>Refining System Setpoints</u>

1. ***Propose a reasonable set of setpoints for wind farm generation and baseload generation. How do these values affect the curtailment and capacity factor?***

In this section, we calculate setpoints for baseload and wind generation such that curtailment and wastage are minimized, and operators have a concrete schedule such that there are no surprises.

We first define three time zones for each day:
a. Evening (1700 to 2100)
b. Late Night (2200 to 0500)
c. Day (0600 to 1600)

We find the annual average of demand for each of these time zones:
a. Evening (9026 kWh)
b. Late Night (6595 kWh)
c. Day (8475 kWh)

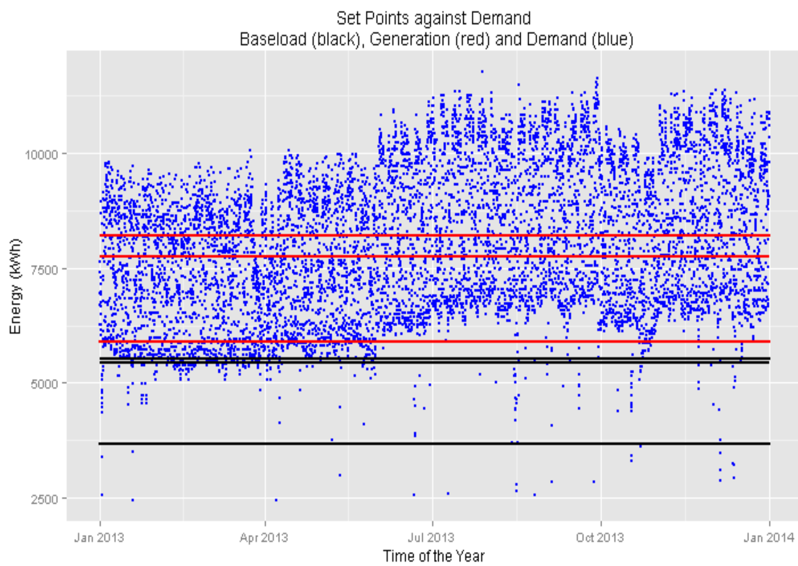
Then, we find the annual average of wind generation data for each of these timezones:
a. Evening (3504 kWh)
b. Late Night (2929 kWh)
c. Day (3032 kWh)

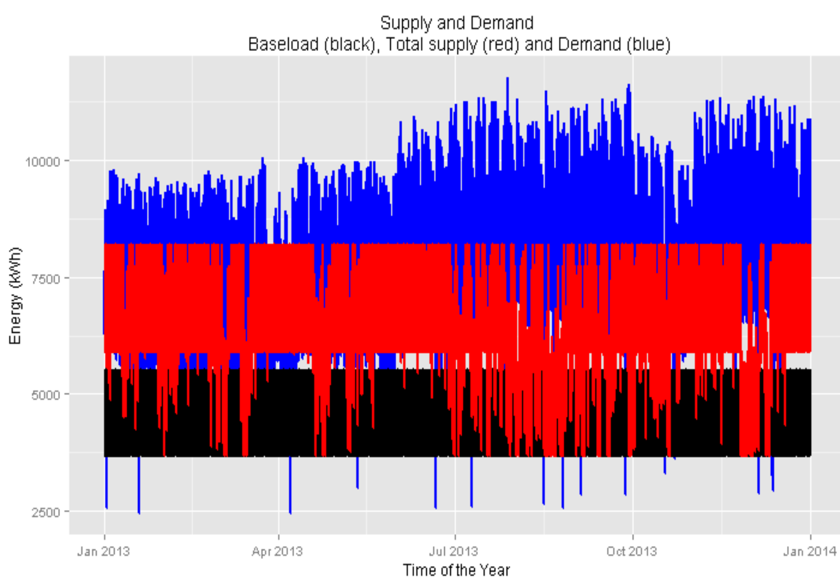
After this, we find the difference between the average demand and average generation to obtain **setpoints for baseload generation** and it falls in the vicinity of 5500kWh, our optimum baseload:

a. **Evening (5522 kWh)**
b. **Late Night (3666 kWh)**
c. **Day (5443 kWh)**

To find the setpoints for wind generation, we find the difference between average demand and baseload setpoints for each time zone. We know that the generation setpoints must be a function of this difference, but not equal to it. (If it is equal to it, we will end up approximating the wind generation data we already have.) We decide to take a fraction of this difference. As this fraction decreases, curtailment decreases (which is good, because of less wastage), but capacity factor also decreases (which is bad, because we're not using as much of wind energy in the mix as we should.) Again, we set an expectation of at least 30% for the capacity factor. We try to minimize curtailment while keeping the capacity factor at 30% or more. Through many trials, we find that the least fraction that satisfies this condition is 0.76 times the difference between average demand and baseload setpoints, and hence we find our **generation setpoints** to be:

a. **Evening (2672 kWh)**
b. **Late Night (2228 kWh)**
c. **Day (2313 kWh)**





We find the curtailment to be 1280196 kWh. This is half the curtailment (2.6 million kWh) that occurs using 3MW baseload, as seen earlier.

The capacity factor is **30.15%**.

Storage Capacity Effects on Capacity Factor

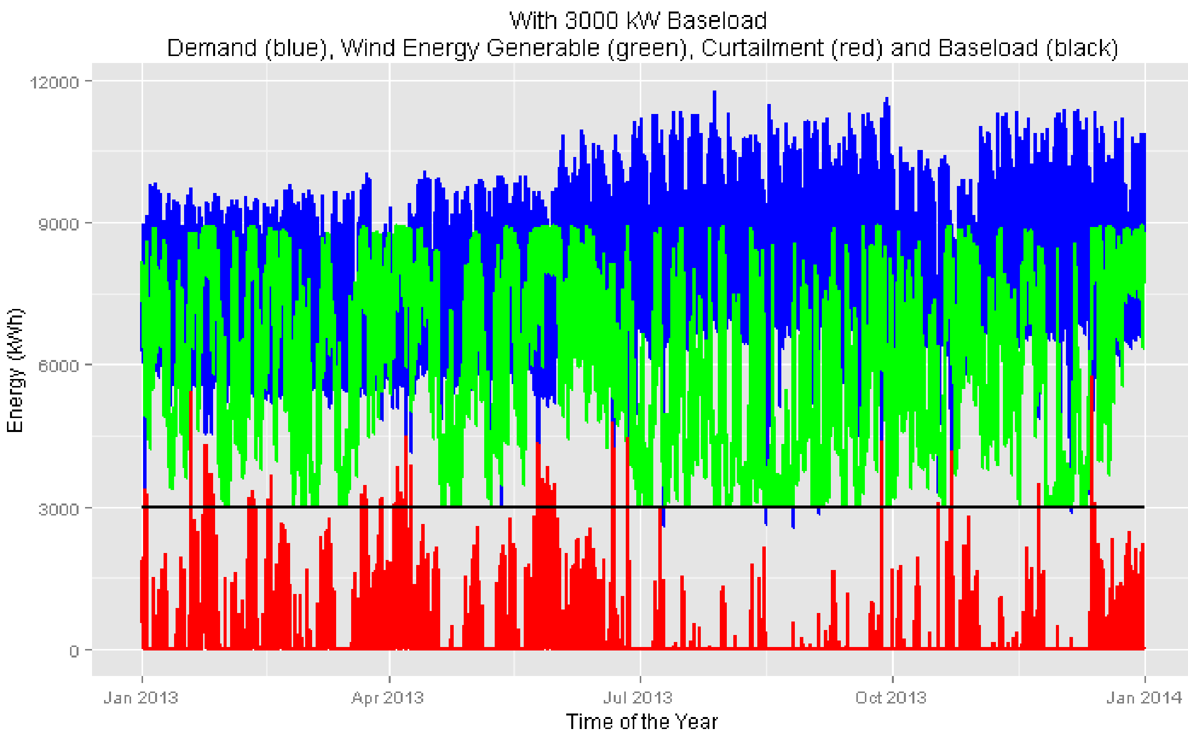
1. ***Perform an energy balance on the system over the entire year, assuming no energy storage.***

    a. ***How much non-baseload energy is not met by the wind farm (and must be met by extra diesel energy) over the course of the year?***

    18987535.14 kWh

    b. ***How much energy is lost over the year due to excess generation (i.e. what is the curtailment over the year?)***

    2637279.01 kWh



2. ***Now, using a simple loop (see the previous projects) and creating a running capacity total over each hour of the year, estimate the amount of recoverable energy possible by implementing this 10MWh storage. How much energy is recovered compared to the amount of non-baseload energy not met by wind over the course of the year? What is the new effective capacity factor of the wind farm?***

    913555.73 kWh (4.81 percent) of non-baseload energy not met by the wind farm earlier, 18992842.52 kWh, can be met by adding storage.

    Capacity factor with storage is 48.74 per cent.

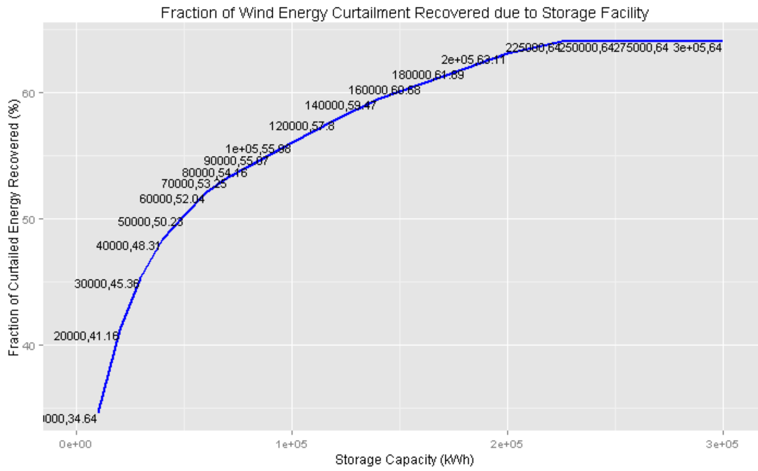
3. ***Perform analogous calculations for a variety of different storage capacities for 3MW constant baseload power or the proposed setpoint-defined baseload generation curve. What point would be considered optimum, to deliver the highest fraction of unmet non-baseload capacity with storage discharged energy? Explain your reasoning.***

AND

4. ***Perform analogous calculations for a variety of different baseload power for the 10MWh storage system. What point would be considered optimum, to deliver the highest fraction of unmet non-baseload capacity with storage discharged energy? Explain your reasoning.***

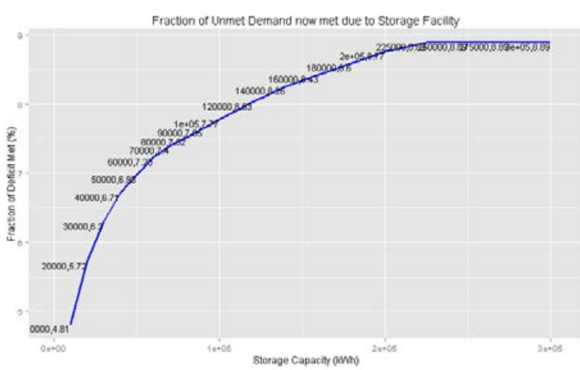
We have modeled the 3MW baseload scenario for a variety of storage capacities. This forms the first step in estimating our optimum storage capacity and baseload.

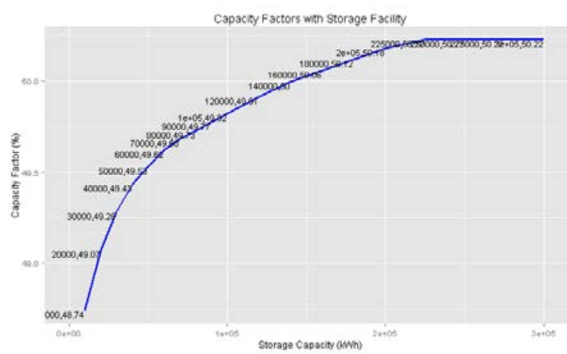
The following graph shows the fraction of curtailment that can be recovered from storage, for various storage capacities.



As can be seen, the efficiency of recovery increases with storage capacity. The rate of increase decreases with increase in storage capacity. Eventually, it plateaus out at 64% (which is the upper limit, as explained earlier). This occurs at about 225MWh of storage, which is not really a realistic capacity to implement.

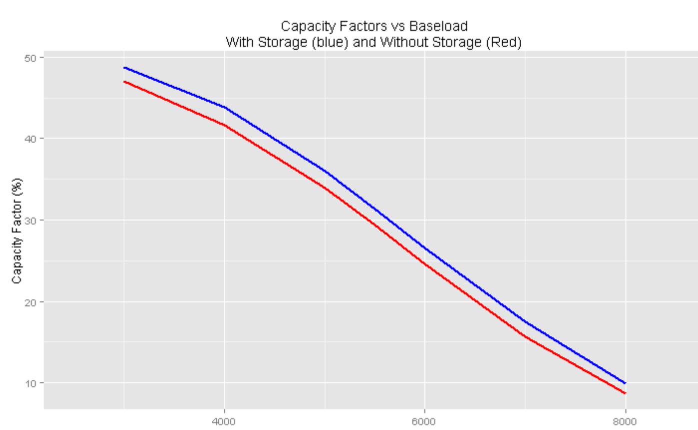
Similarly, the fraction of unmet demand that is met by recovered energy follows a similar trend, as do the capacity factors.





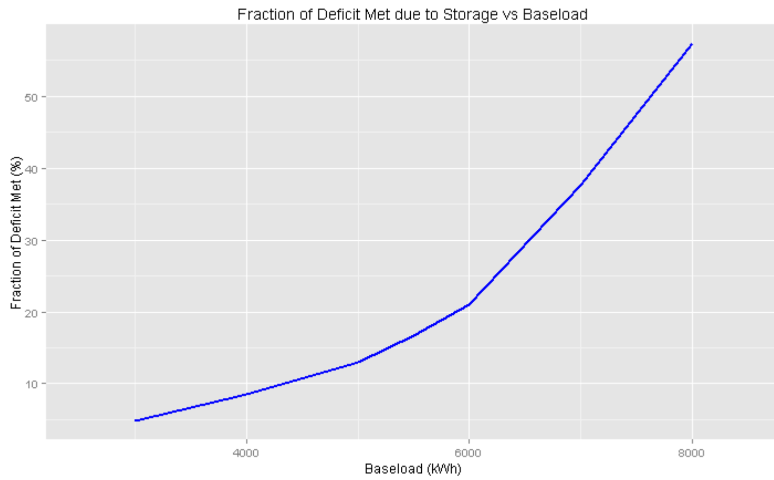
From the plot, it can be seen that about 5% of the unmet demand is now met, for 10-20MWh storage capacity. This must be improved.

The next stage of the analysis is comparing different baseloads for the 10MWh storage scenario.



We find that as the baseload increases, capacity factors plummet due to the increased curtailment.

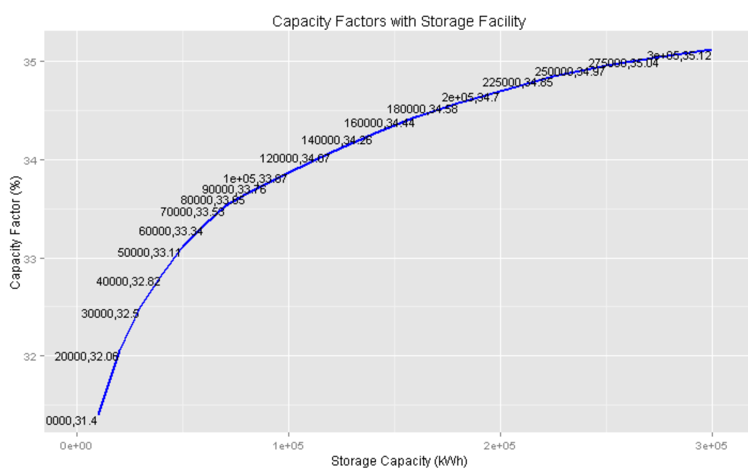
However, there is a positive effect to increases in baseload – a larger fraction of unmet demand can now be met.



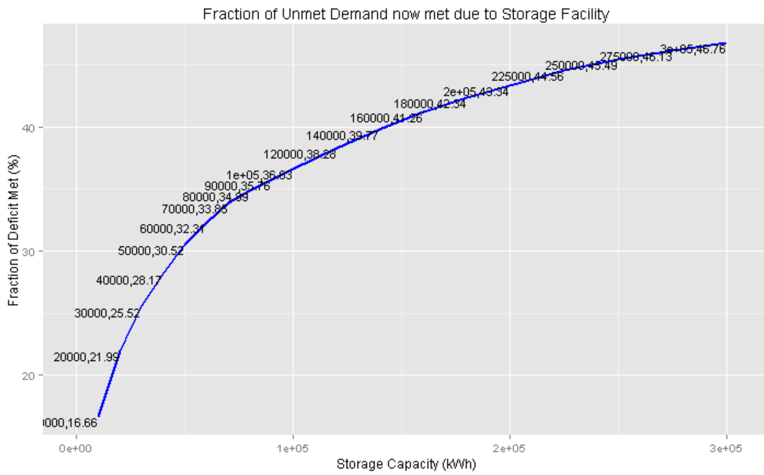
It is important to note that increase in this fraction may be because the absolute value of the unmet demand is decreasing. Therefore, it might be more important to study the absolute value of the remaining unmet demand that must be met by diesel generation.

Also, we must achieve a trade-off between the capacity factor and the fraction of the unmet demand that can be met through storage. We want the baseload to be high enough that a larger fraction of unmet demand is met, but not too much that the capacity factor of wind energy becomes too small – in effect meeting nearly the entire demand by diesel generation, which defeats our purpose.

At this point, we set an expectation for the capacity factor – we want to push the baseload up by as much as possible while achieving a capacity factor of at least 30%. Through many trials, we found this baseload value to be 5500 kWh. For this baseload, the following plot shows variation of capacity factors with storage capacities.



We are achieving our expectation for the capacity factor even in the 10-20MWh storage capacity range, where it varies between 31.4% and 32.06%. Additionally, the fraction of unmet demand met through storage is now increased from 5% (from the 3MW scenario) to the 16.6-22% range, for 10-20MWh storage.



Beyond the 20MWh, additional storage added has lesser and lesser benefit to the capacity factor and unmet demand that can be met, since the slope of the graph continually decreases. Therefore, it does not make much sense to increase the storage capacity beyond this point. We decide now that we are going to choose a storage capacity in the 10-20MWh range.

The benefit of 20MWh storage is that it offers a chance to meet a greater portion of unmet demand through storage (22% as compared to 16.6% with 10MWh). However, we think it is more important to consider the absolute value of the remaining deficit that must be filled by diesel generation.

a. For 10 MWh, 16.5 per cent deficit met. Remaining deficit is 5.36 million kWh
b. For 20 MWh, 22 per cent deficit met. Remaining deficit is 5.02 million kWh

We see that even though a significantly larger share is met, the difference in remaining deficit (to be met by diesel generation) for the two capacities is small. For this reason, we choose the 10MWh, since we do not believe doubling this capacity is worth it.

Therefore, we have chosen our optimum baseload (5.5MW) and storage capacity (10MWh).

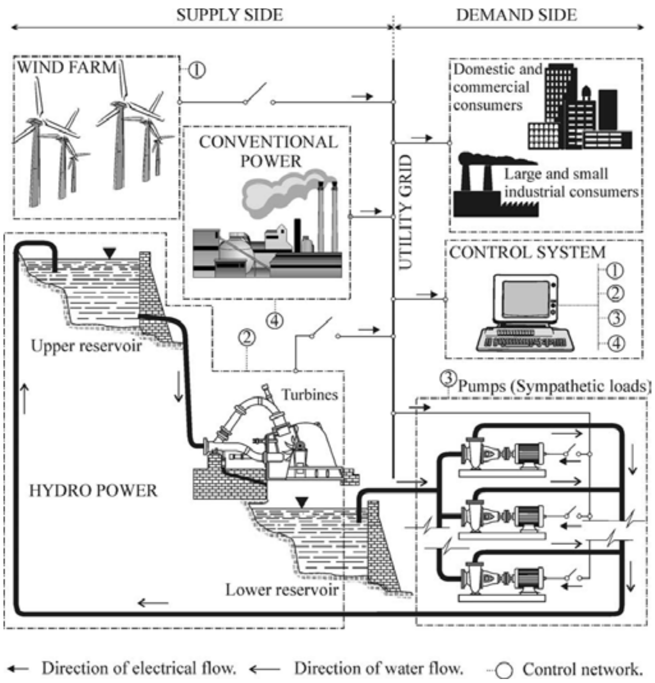
5. ***Finally, perform the same calculations for your proposed storage capacity and set point values. How much additional energy is now recoverable via storage?***

Additional useful wind energy due to storage is 653002.15 kWh. This is 51.01 percent of the curtailment that would have occurred without storage, 1280195.72 kWh

PART 2: Assessment of Energy Storage Options

Pumped Hydropower Storage

1. ***Provide a description of the equipment necessary to drive a pumped hydropower storage system. What components are the most expensive or limiting with respect to sizing? Discuss necessary features for good hydropower storage performance and potential methods of optimizing power and energy density for such systems. Are there any significant drawbacks to using pumped storage compared to other storage methods?***



In a pumped hydropower storage system, energy is stored as gravitational potential energy of water. The excess energy generated by the wind farm is used to pump large volumes of water from a low level reservoir to a reservoir at a higher level, thus increasing the potential energy of the water by virtue of gravity. This potential energy is converted back to electrical energy by releasing the stored water through a height gradient and driving a turbine to generate electricity, which can be fed back into the grid when there is a demand. The setup for this system is illustrated in **Fig. 1**. The various equipment and infrastructural arrangements required in the hydropower storage system are as follows:

a. Water pumps
b. Turbines
c. Control system
d. Lower reservoir
e. Upper reservoir

For large scale storage of energy through hydropower, it is essential to build large reservoirs. The lower level reservoir often needs to have large capacity to accommodate the water released from the higher level reservoir during times of demand. It should not happen that, when there is demand for stored energy, the lower reservoir is full and cannot accommodate water released from the higher level reservoir. Therefore, the cost associated with the construction of reservoirs tends to scale with the size of the system. However, the cost of building a large low level reservoir can be brought down significantly if the site is that of a former open pit mine that already presents a large height gradient. The costs of the pumping system and the turbine can also scale with the overall size of the system.

An optimum height gradient is necessary for optimizing the performance of the pumped hydropower storage system. The definition of "optimum" for the height gradient is a function of power rating of the water pump, which in turn is dependent on the energy capacity of the wind farm. If the high level reservoir is too high for the pump then sufficient amount of water may not be able to be pumped for energy storage. If the height gradient is too low, a large volume of water may be required to be pumped to achieve the required potential energy. Therefore, a suitable height gradient must be chosen that is both suitable for the pump and balances the system with the optimum mass of water.

Though pumped hydropower storage system is a superior solution for large scale storage of energy, it may exhibit a few drawbacks. For instance, constructing the reservoirs may cause environmental damage to the site it is built at. Also, finding an area topographically suitable to build a large water storage reservoir may be difficult.

2. Suppose a location on the island has been located where two reservoirs with a 300-meter height differential can be constructed. For both the 10MWh and the optimum sized capacity from Part 1, how much water would the reservoirs need to be able to hold?

The formula for gravitational potential energy is: ***U = mgh***

where, U = potential energy

m = mass of the water

g = acceleration due to gravity

and h = vertical displacement (height) of the water.

Assuming $g = 9.86\ m/s^2$

Given: h = 300m

and U = 10MWh = 10 x 1000 x 3600 kJ

We have: 10 x 1000 x 3600 x 1000 = m x 9.86 x 300

We get: $m = 12170.38 \times 10^3$ kg

But, m = ρ x V where, ρ = density of water (=1000kg/m^3) and V = volume

Therefore, $12170.38 \times 10^3 = 1000 \times V$

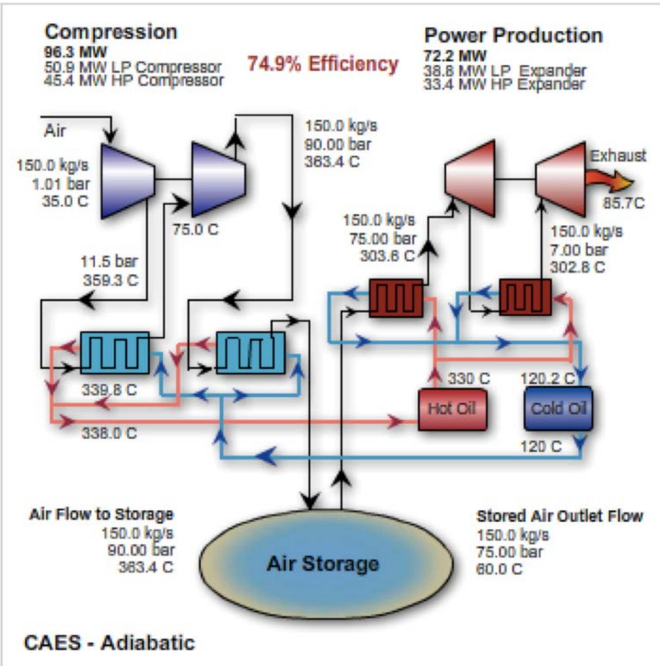
Or, $V = 12170.38\ m^3$

Therefore, for the given conditions, it is recommended to have a water storage capacity of about 12,200 cubic meters.

Underwater Compressed Air Energy Storage

1. ***Provide a brief description of the general structure of a compressed air storage system. What components are the most expensive or limiting with respect to sizing?***

Compressed air energy storage mechanism refers to the technology of storing excess generated electrical energy in the form of compressed air till such time as there is a demand for this energy, at which point the compressed air is made to expand and run a turbine to regenerate electricity. **Figure 2** illustrates the working mechanism of a compressed air energy storage (CAES) system.



The various parts of a UWCAES are as follows:

1. **Compressor:** Compressor motors are run by the excess generated electricity to compress atmospheric air to high pressure into a storage vessel, thus converting electrical energy into stored mechanical energy.

2. **CAES subsystem:** Cable reinforced fabric vessels called Energy Bags store air at high pressure and release them at the time of need. The heat generated during the compression cycle is required to be stored in a thermal reservoir**.** During the expansion cycle the expander allows the air to expand low pressure whilst running a turbine to regenerate electricity, using heat from the reservoir to complete the adiabatic process.
3. **Turbines:** The stored high pressure air is expanded and is made to run wind turbines to regenerate electricity.

4. **Controller:** The whole system is monitored by a control system, like a SCADA, to ensure smooth operations.

The component whose cost scales with size is the Energy Bag. The complexity associated with the construction of the energy bag is directly related to the capacity of the storage system, which is itself dependent on the depth of the Energy Bag. If the Energy Bag is to be anchored at a great depth then the size of the Energy Bag as well as its construction complexity greatly increases. This adds to cost of the overall system.

Since the storage pressure is equal to that of the external hydrostatic pressure, the risk of a violent explosion due to leakage is nonexistent. Care should be taken to ensure environmental protection nonetheless.

2. ***Discuss the features necessary for good compressed air energy storage performance. Compare the overall similarities and differences between compressed air and pumped hydropower storage technologies. Why might one elect to use one system over another? How does the implementation of an underwater air reservoir make it more or less appealing as a storage option in small island nations?***

The features that are necessary to set up a good compressed air energy storage system are as follows:

1. Availability of a good site for the construction of the system, such as a salt cavern or a deep water body, to support the internal storage pressure by means of lithostatic or hydrostatic pressure
2. Availability of consistent renewable energy
3. Must be close to areas of both the generation and the consumption
4. High efficiency values for the turbomachines (compressors and turbines)
5. Patronage from the government and environmental agencies to the project

The similarities between compressed air energy storage (CAES) and pumped hydropower energy storage (PHES) are as follows:

1. Both systems convert excess generated electrical energy into mechanical energy. CAES converts electrical energy into pressure energy by storing compressed air, while PHES converts electrical energy into gravitational potential energy of water.
2. Both mechanisms involve the storage of a fluid in a large reservoir. CAES needs a container or a vessel to store air in high pressure, while PHES requires at least two large reservoirs at different heights to store water.

3. Both systems require the use of turbomachines. CAES requires a compressor to compress atmospheric air into a vessel (thus converting electrical energy into mechanical energy), while PHES uses pumps to pump water from a lower potential to a higher potential. The stored mechanical energy is reconverted back to electricity by releasing the fluid through a turbine that generates electricity.

The differences between the two systems are:

i. The PHES system requires a relatively larger site than CAES and is more likely to cause environmental damage.
ii. CAES employ an adiabatic process in which the ambient temperature of the compressed air plays an important role. Therefore, thermal losses in CAES tends to reduce its efficiency in comparison to PHES.
iii. Maintenance costs of PHES may be higher in comparison to a CAES system of similar capacity because of the degradation caused by water.
iv. The ramp rates of CAES system are more impressive than that of a PHES system.

Small island nations like Cape Verde have abundant natural infrastructural resources to establish a compressed air energy storage system. UWCAES requires a deep water body to construct the system, the depth ranging from 400m to 700m. The surrounding sea may provide a number of possible sites to construct the system. An underwater system may be preferable over an underground system, or any other kind of storage system (like pumped hydropower system) for that matter, as land space is a limited precious resource for a small island. Plus, for a small island like Sao Vicente that relies heavily on tourism for revenue, an UWCAES will not be an "eyesore" as it is hidden under the depths of the ocean.

3. ***Suppose that the lowest acceptable storage pressure of the compressed air system is 200 psi. For both the 10MWh and the optimum sized capacity from Part 1, what mass of compressed air would the reservoirs need to be able to deliver to meet this capacity? At 200 psi, what volume of compressed air would be necessary? Remark on its practicality.***

Given:

Storage pressure, P = 200 psi = 13.789 bar

From the **Table 1** alongside, we can interpolate depth (d) and the adiabatic energy density (u) for the storage system:

d = 153.93m

u = 1.48 kWh/m^3

Therefore, volume required for 10 MWh is: **V = 10 x 1000 / 1.48 = 6756.57 m^3**

Table 1
Energy densities available with underwater CAES.

Depth (m)	Storage pressure (bar)	Isothermal energy density (kWh/m^3)	Adiabatic energy density (kWh/m^3)	Temperature required prior to adiabatic expansion (°C)	Ratio of adiabatic and isothermal energy densities
50	6.04	0.30	0.39	186.33	1.30
100	11.07	0.74	1.05	274.42	1.43
200	21.12	1.78	2.84	386.85	1.59
300	31.18	2.97	5.04	465.32	1.70
400	41.23	4.24	7.55	527.29	1.78
500	51.29	5.59	10.32	579.22	1.85
600	61.34	6.99	13.30	624.31	1.90

1. ***Perform some cursory research and find the energy cost requirements of desalination via reverse osmosis, as well as the population of Sao Vicente. If the entire nation's freshwater supply were to come from reverse osmosis technology and a requirement of 50 liters per day per person for a safe quality of life, how much energy would be required to generate the estimated annual water demand? Given a 3MW baseload generation, if 10MWh of energy could be "stored" in the form of desalinated water, what is the maximum amount of water would that could be retainable at any given point?***

The population of Sao Vicente is 79,374 as of 2010. If 50 liters of water is required person every day, the annual water requirement for the given population is:

Volume of water required, V = (79374 x 50 x 365) liters = 1448575.500 m^3

The specific energy requirements for a desalination process using reverse osmosis varies between 1 kWh/m^3 to 10 kWh/m^3. The specific energy consumption (SEC) when an energy recovery device (ERD), such as Pelton wheel or work exchanger, is used is 3 kWh/m^3 to 5 kWh/m^3. Assuming that this is the case with our setup and SEC = 5 kWh/m^3, we get the net energy required to desalinate seawater for the population of Sao Vicente:

E = 5 x 1448575.500 = 7242.87 MWh
If 10 MWh of energy is available at any given point, we can have 2000 m^3 of desalinated water.

CONCLUSION

Baseload setpoints:

Evening -- **5522 kWh**
Late Night -- **3666 kWh**
Day -- **5443 kWh**

Generation setpoints:

Evening -- **2672 kWh**
Late Night -- **2228 kWh**
Day -- **2313 kWh**

Optimum Storage: **10 MWh**

- For Sao Vicente Island, underwater compressed air energy storage is the best solution, as it is easy to implement in terms of infrastructure already available.
- For a storage capacity of 10 MWh, we need about 6756.57m^3 of compressed air at 200psi of air pressure at a depth of 153.93m below the sea. That works out to about 680 to 700 Energy Bags.

Curtailment: **1.26 million kWh**

Percentage of curtailment recovered: **51%**

Fraction of curtailment available for desalination: **13%**

Amount of water desalinated with excess wind energy: **33285 m^3**

Fraction of potable water demand serviced: **2.4%**

REFERENCES

1. C. Bueno, J.A. Carta, Wind powered pumped hydro storage systems, a means of increasing the penetration of renewable energy in the Canary Islands, Renewable and Sustainable Energy Reviews, Volume 10, Issue 4, August 2006, Pages 312-340, ISSN 1364-0321,

2. Andrew J. Pimm, Seamus D. Garvey, Maxim de Jong, Design and testing of Energy Bags for underwater compressed air energy storage, Energy, Volume 66, 1 March 2014, Pages 496-508, ISSN 0360-5442,

3. Veera Gnaneswar Gude, Energy storage for desalination processes powered by renewable energy and waste heat sources, Applied Energy, Volume 137, 1 January 2015, Pages 877-898, ISSN 0306-2619,

SV2414 and vrp2113 Energy Storage Options in Sao Vicente Note: This RMD does not contain setpoint calculation. Setpoint calculation, along with question 5 of 'Storage Capacity Effects on Capacity Factor' section (which uses setpoints) is included in another RMD following this one.

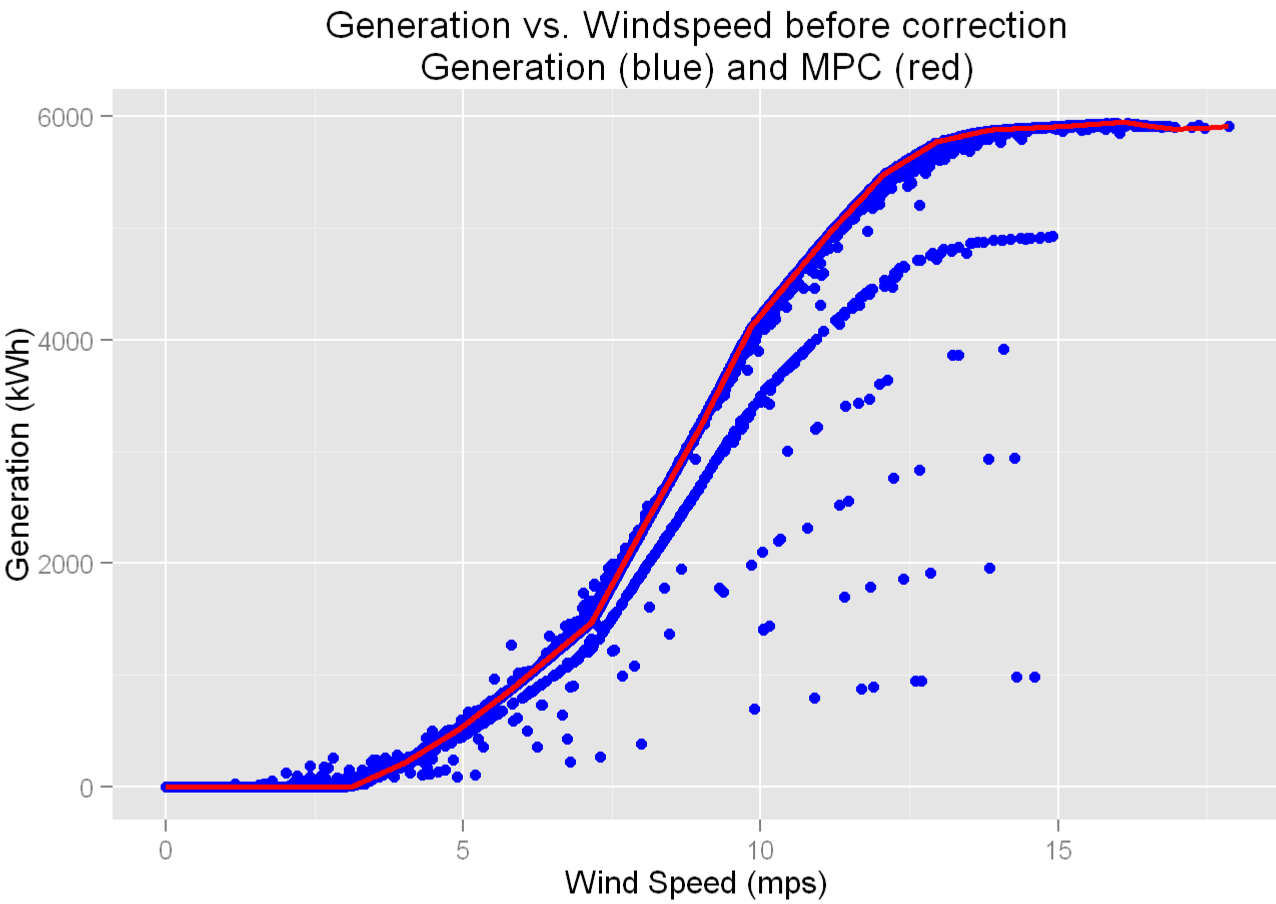
ANALYSIS OF ORIGINAL DISPATCH DATA

Import data required and rename columns for ease.

```
## Loading required package: plyr
## Loading required package: ggplot2
```

Plot to check if imported data adheres to the Manufacturer's Power Curve.

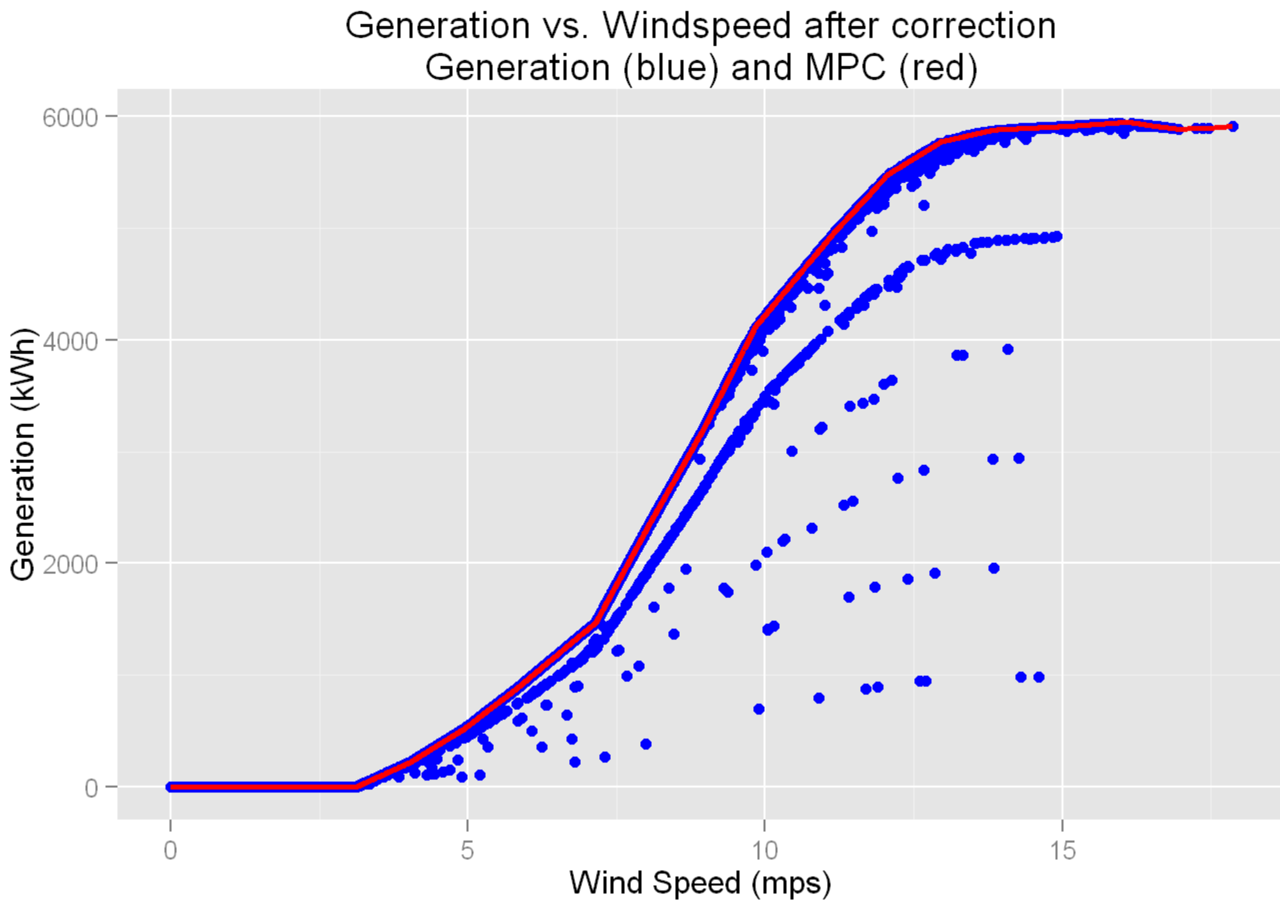
```
#Interpolate for MPC power
interp=splinefun(mpc$windspeed_mps, mpc$power_kW,method = "natural")
#Find equivalent MPC power for the windspeeds we have
wind$mpc_power<-interp(wind$windspeed)*7

#Plot to check data
plot0<-ggplot(wind, aes(x=wind$windspeed))
plot0+geom_point(aes(y=wind$windgen),colour="blue",size=2)+geom_line(aes(y=wind$mpc_power),colour="re
d",size=1)+xlab("Wind Speed (mps)")+ylab("Generation (kWh)")+ggtitle("Generation vs. Windspeed before
 correction\nGeneration (blue) and MPC (red)")
```




```
#Reassign values that are greater than MPC power equivalents to MPC power equivalents
for (j in 1:nrow(wind)){
  if(wind$windgen[j]>wind$mpc_power[j])
    wind$windgen[j]<-wind$mpc_power[j]
}
```

Plot to check if data has been corrected to MPC.

```
#Plot to check if data has been corrected
plot1<-ggplot(wind, aes(x=wind$windspeed))
plot1+geom_point(aes(y=wind$windgen),colour="blue",size=2)+geom_line(aes(y=wind$mpc_power),colour="re
d",size=1)+xlab("Wind Speed (mps)")+ylab("Generation (kWh)")+ggtitle("Generation vs. Windspeed after
correction\nGeneration (blue) and MPC (red)")
```



Organize and clean data.

```
#Convert date to date format
wind$date<-as.Date(wind$date,format="%Y-%m-%d")
#Create new column for datetime using date and hour
wind$datetime=as.POSIXct(wind$date+wind$hour*(1/24)+(1/3), format="%Y-%m-%d %H:%M:%S", origin="2013-0
1-01 00:00:00")

#Convert date and time to datetime format for demand data
dem$data.pt2.date.time<-as.POSIXct(dem$data.pt2.date.time,format="%Y-%m-%d %H:%M:%S")
#Rename columns
names(dem)[3]<-"datetime"
names(dem)[4]<-"demand"

#Remove columns we don'tneed
wind<-wind[-c(1,2,3,7)]
dem<-dem[-c(1,2)]

#Merge generation and demand data
ad<-merge(x = dem,y = wind,by="datetime",all.x=TRUE)

#Check summary of wind speed and generation data
summary(ad$windspeed)
```

```
##    Min. 1st Qu.  Median    Mean 3rd Qu.    Max.    NA's 
##    0.00    7.07    9.02    8.84   11.00   17.90     179 
```

```r
summary(ad$windgen)
```

```
##    Min. 1st Qu.  Median    Mean 3rd Qu.    Max.    NA's 
##      -1    1410    3200    3100    4780    5940     179 
```

```r
#Fill missing generation data
ad$windspeed[is.na(ad$windspeed)]<-summary(wind$windspeed)[4]
ad$del_hourly[is.na(ad$del_hourly)]<-0
for (i in 1:nrow(ad)){
  if(is.na(ad$windgen[i])){
    ad$windgen[i]<-interp(wind$windspeed[i])*7
    }
}

#Convert negative generation values to 0
ad$del_hourly[ad$del_hourly<0]<-0
ad$windgen[ad$windgen<0]<-0

#Check summary of wind speed and generation data after correction
summary(ad$windspeed)
```

```
##    Min. 1st Qu.  Median    Mean 3rd Qu.    Max. 
##    0.00    7.14    8.95    8.84   10.90   17.90 
```

```r
summary(ad$windgen)
```

```
##    Min. 1st Qu.  Median    Mean 3rd Qu.    Max. 
##       0    1400    3190    3100    4780    5950 
```

```r
#Check summary of demand data
summary(ad$demand)
```

```
##    Min. 1st Qu.  Median    Mean 3rd Qu.    Max. 
##       0    6720    7880    7930    9170   11800 
```

```r
#Correct small demand values to mean demand
ad$demand[ad$demand<quantile(ad$demand,0.005)]<-summary(ad$demand)[4]
```

```
#Check summary of demand data after correction
summary(ad$demand)
```

```
##    Min. 1st Qu.  Median    Mean 3rd Qu.    Max.
##    2440    6740    7920    7960    9170   11800
```

1. Calculate the uncurtailed capacity factor of the wind farm over the course of this year in the absence of any energy storage options, as per the turbine power curve and wind speed.

```
#Calculate uncurtailed capacity factor
cf_unc<-sum(ad$windgen)*100/(850*8760*7)
sprintf("Before any baseload is applied, uncurtailed CF is %.2f percent",cf_unc)
```

```
## [1] "Before any baseload is applied, uncurtailed CF is 52.04 percent"
```

2. Calculate the curtailed capacity factor of the wind farm over the course of the year in the absence of energy storage, using dispatched power values. How much energy is lost over the course of the year due to curtailment?

```
#Find wind generation utilized
for (j in 1:nrow(ad)){
  ad$wind_utilized[j]=min(ad$windgen[j],ad$demand[j])
}
#Find curtailment
ad$curtailment=ad$windgen-ad$wind_utilized
ad$deficit=ad$demand-ad$wind_utilized
sprintf("Before any baseload is applied, curtailment is %.2f kWh",sum(ad$curtailment))
```

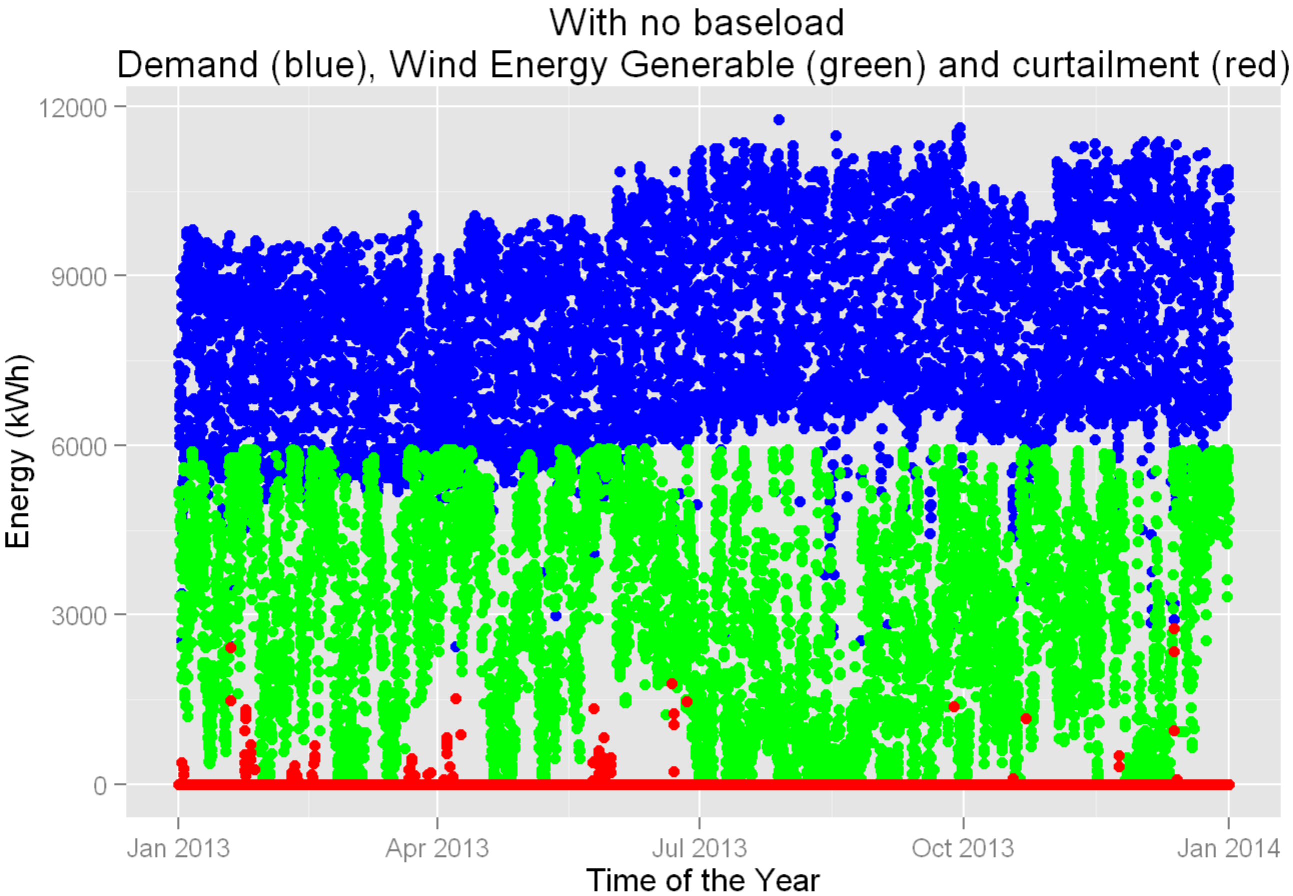
```
## [1] "Before any baseload is applied, curtailment is 52442.29 kWh"
```

```
#Calculate curtailed capacity factor
cf_c<-sum(ad$wind_utilized)*100/(850*8760*7)
sprintf("Before any baseload is applied, curtailed CF is %.2f percent",cf_c)
```

```
## [1] "Before any baseload is applied, curtailed CF is 51.94 percent"
```

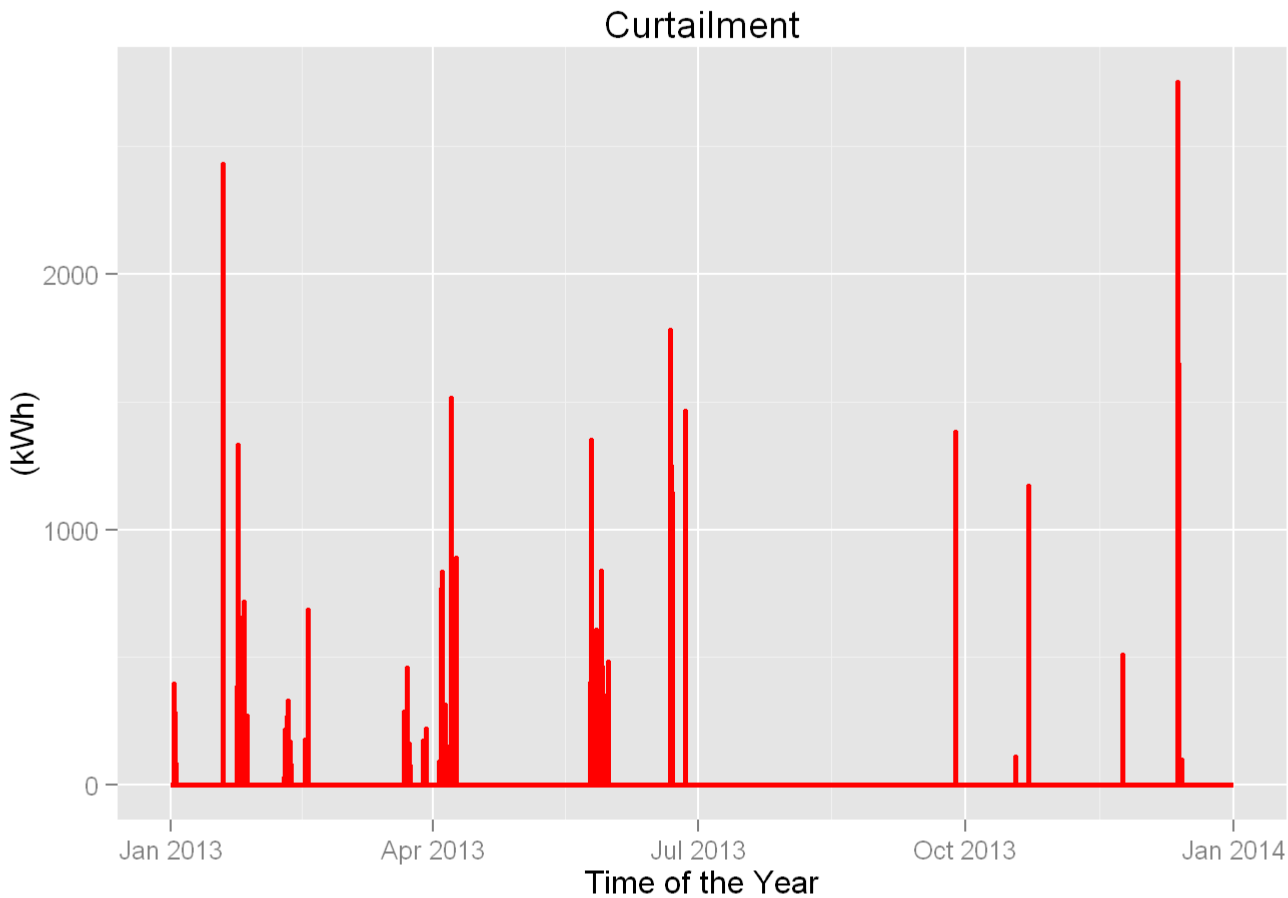
Plot for this scenario:

```
#Plot demand, generation and curtailment across the year
plot2<-ggplot(ad, aes(x=ad$datetime))
plot2+geom_point(aes(y=ad$demand),colour="blue",size=2)+geom_point(aes(y=ad$windgen),colour="green",s
ize=2)+geom_point(aes(y=ad$curtailment),colour="red",size=2)+ylab("Energy (kWh)")+xlab("Time of the Y
ear")+ggtitle("With no baseload \nDemand (blue), Wind Energy Generable (green) and curtailment (red)"
)
```

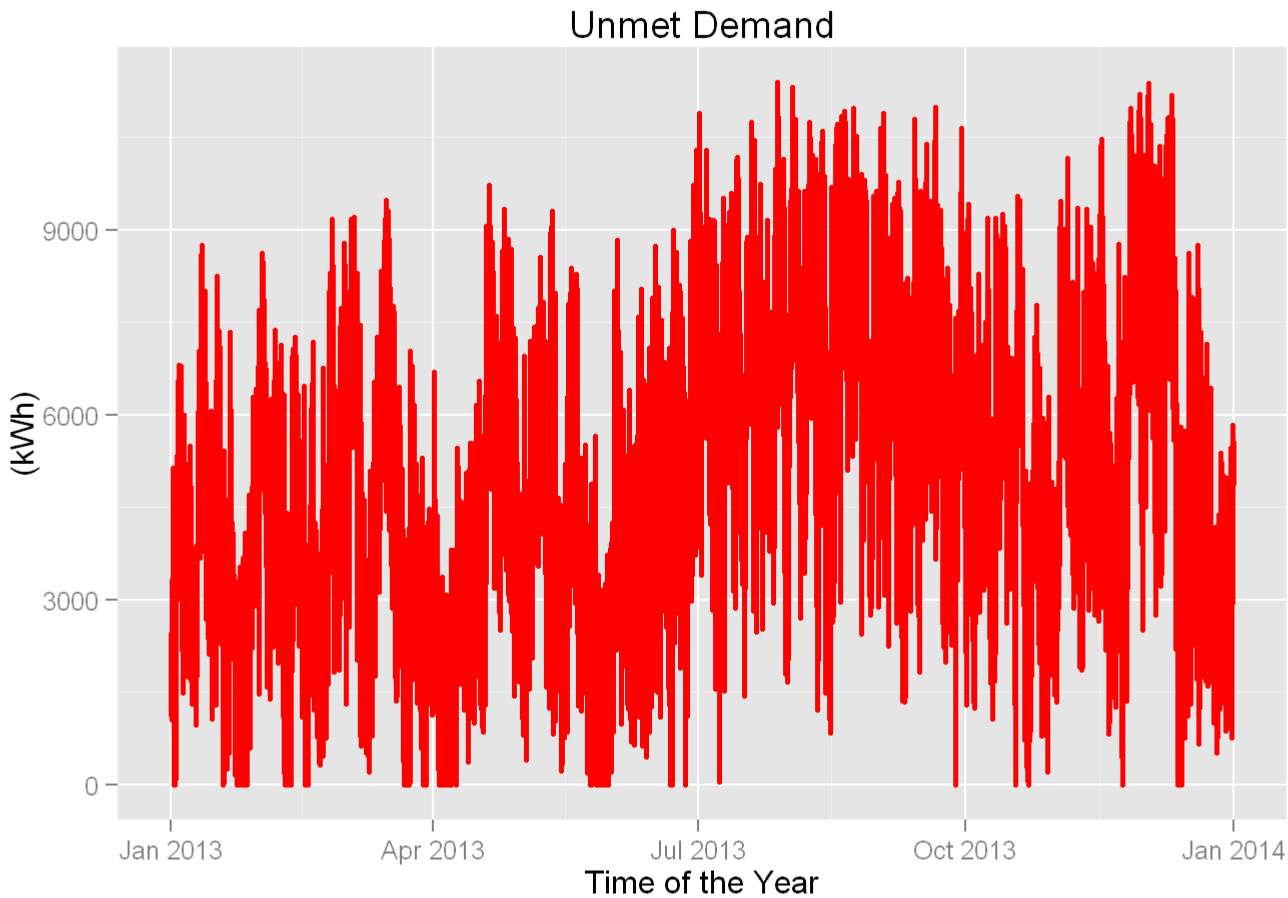


3. What periods of the year have the greatest amount of curtailment over the year? What parts of the year have the highest amount of unmet demand?

```
plot2+geom_line(aes(y=ad$curtailment),colour="red",size=1)+ylab("(kWh)")+xlab("Time of the Year")+ggtitle("Curtailment")
```




```
plot2+geom_line(aes(y=ad$deficit),colour="red",size=1)+ylab("(kWh)")+xlab("Time of the Year")+ggtitle
("Unmet Demand")
```



APPLICATION OF CONSTANT BASELOAD GENERATION

1. Consider the overall range of demand values over the course of the year. What would be a reasonable value for baseload generation? Why? 2. Given this baseload value, calculate the new curtailment and capacity factor of the wind farm.

```
#Find optimum baseload
ad$baseload=5320
ad$totalsupply=ad$baseload+ad$windgen
for (j in 1:nrow(ad)){
    ad$ts_utilized[j]=min(ad$demand[j],ad$totalsupply[j])
  }
ad$ts_curtailment=ad$totalsupply-ad$ts_utilized
ad$ts_deficit=ad$demand-ad$ts_utilized

sprintf("Optimum baseload is found to be %.2f kWh",summary(ad$baseload)[4])
```

```
## [1] "Optimum baseload is found to be 5320.00 kWh"
```

```
sprintf("This is optimum because deficit is %.2f percent of curtailment, and therefore, curtailment c
an completely meet deficit with a large enough storage",100*(sum(ad$ts_deficit)/sum(ad$ts_curtailment
)))
```

```
## [1] "This is optimum because deficit is 64.09 percent of curtailment, and therefore, curtailment c
an completely meet deficit with a large enough storage"
```

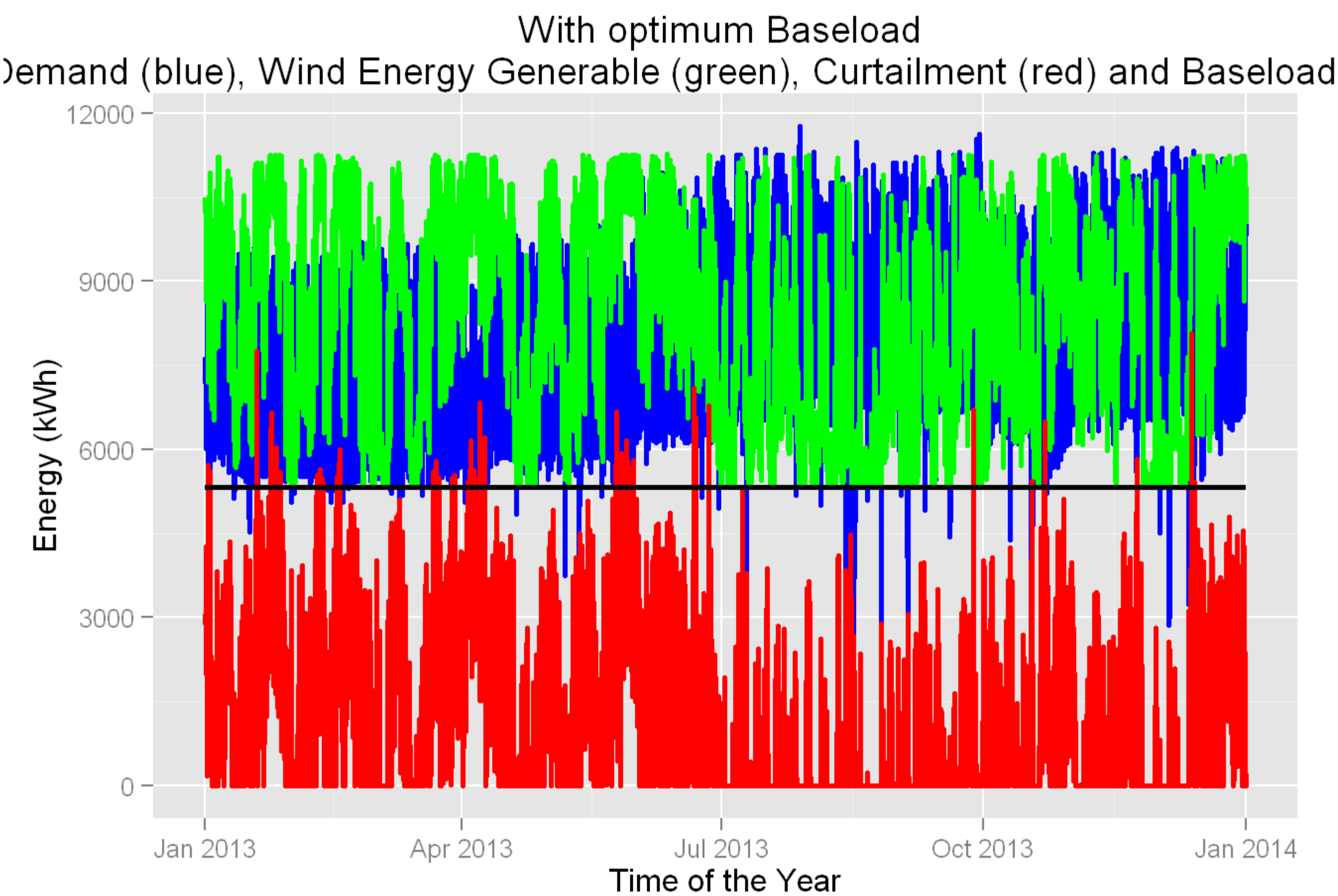
```
sprintf("For optimum baseload, non-baseload energy not met by wind farm over the year is %.2f kWh",su
m(ad$ts_deficit))
```

```
## [1] "For optimum baseload, non-baseload energy not met by wind farm over the year is 7088891.11 kW
h"
```

```
sprintf("For optimum baseload, curtailment over the year is %.2f kWh",sum(ad$ts_curtailment))
```

```
## [1] "For optimum baseload, curtailment over the year is 11061662.99 kWh"
```

```
#Plot to show demand and generation lines for this optimum baseload
plot3<-ggplot(ad, aes(x=ad$datetime))
plot3+geom_line(aes(y=ad$demand),colour="blue",size=1)+geom_line(aes(y=ad$totalsupply),colour="green"
,size=1)+geom_line(aes(y=ad$ts_curtailment),colour="red",size=1)+geom_line(aes(y=ad$baseload),colour=
"black",size=1)+ylab("Energy (kWh)")+xlab("Time of the Year")+ggtitle("With optimum Baseload \nDemand
 (blue), Wind Energy Generable (green), Curtailment (red) and Baseload (black)")
```




```
#Find capacity factor with optimum baseload
sum=0.0
for (i in 1:nrow(ad)){
sum=sum+max(ad$ts_utilized[i]-ad$baseload[i],0.0)
}
cf_c_bl=sum*100/(850*8760*7)
sprintf("For this baseload, curtailed CF is %.2f percent",cf_c_bl)
```

```
## [1] "For this baseload, curtailed CF is 31.04 percent"
```

STORAGE CAPACITY EFFECTS ON CAPACITY FACTOR

1. Perform an energy balance on the system over the entire year, assuming no energy storage. How much non-baseload energy is not met by the wind farm (and must be met by extra diesel energy) over the course of the year? How much energy is lost over the year due to excess generation (i.e. what is the curtailment over the year?)

```
#With 3MW baseload
ad$baseload2=3000.0
ad$totalsupply2=ad$baseload2+ad$windgen
for (j in 1:nrow(ad)){
    ad$ts_utilized2[j]=min(ad$demand[j],ad$totalsupply2[j])
```

```r
  }
ad$ts_curtailment2=ad$totalsupply2-ad$ts_utilized2
ad$ts_deficit2=ad$demand-ad$ts_utilized2
sprintf("New baseload is %.2f kWh",summary(ad$baseload2)[4])
```

```
## [1] "New baseload is 3000.00 kWh"
```

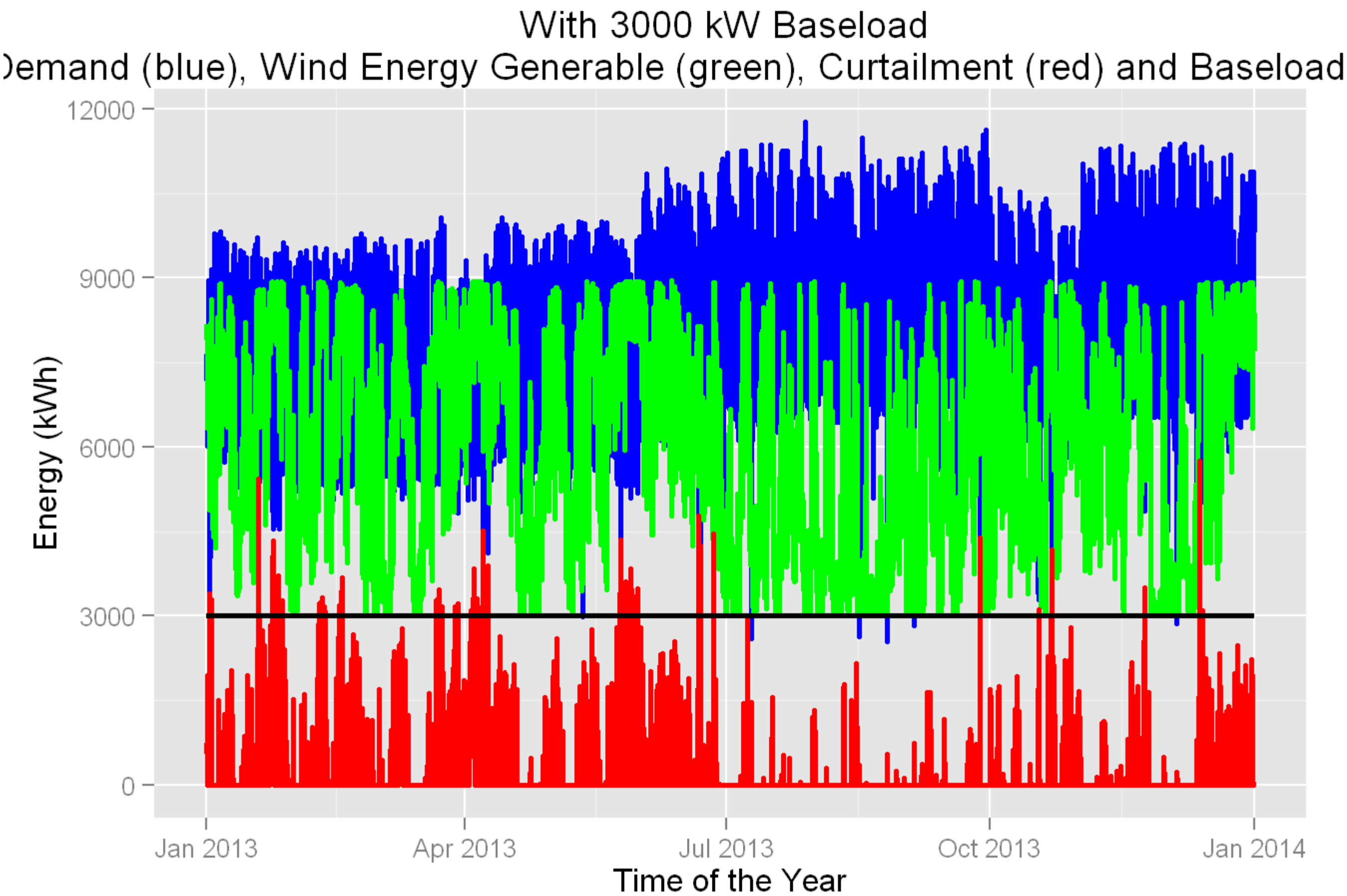
```r
sprintf("For this baseload, non-baseload energy not met by wind farm over the year is %.2fkWh",sum(ad
$ts_deficit2))
```

```
## [1] "For this baseload, non-baseload energy not met by wind farm over the year is 18987679.14kWh"
```

```r
sprintf("For this baseload, curtailment over the year is %.2fkWh",sum(ad$ts_curtailment2))
```

```
## [1] "For this baseload, curtailment over the year is 2637251.01kWh"
```

```r
#Plot to show demand and generation lines for this baseload
plot4<-ggplot(ad, aes(x=ad$datetime))
plot4+geom_line(aes(y=ad$demand),colour="blue",size=1)+geom_line(aes(y=ad$totalsupply2),colour="green
",size=1)+geom_line(aes(y=ad$ts_curtailment2),colour="red",size=1)+geom_line(aes(y=ad$baseload2),colo
ur="black",size=1)+ylab("Energy (kWh)")+xlab("Time of the Year")+ggtitle("With 3000 kW Baseload \nDem
and (blue), Wind Energy Generable (green), Curtailment (red) and Baseload (black)")
```




```
#Find capacity factor
sum2=0.0
for (i in 1:nrow(ad)){
sum2=sum2+max(ad$ts_utilized2[i]-ad$baseload2[i],0.0)
}
cf_c_bl2=sum2*100/(850*8760*7)
sprintf("For this baseload, curtailed CF is %.2f percent",cf_c_bl2)
```

```
## [1] "For this baseload, curtailed CF is 46.99 percent"
```

2. Now, using a simple loop (see the previous projects) and creating a running capacity total over each hour of the year, estimate the amount of recoverable energy possible by implementing this 10MWh storage. How much energy is recovered compared to the amount of non-baseload energy not met by wind over the course of the year? What is the new effective capacity factor of the wind farm? 3. Perform analogous calculations for a variety of different storage capacities for 3MW constant baseload power or the proposed setpoint-defined baseload generation curve. What point would be considered optimum, to deliver the highest fraction of unmet non-baseload capacity with storage discharged energy? Explain your reasoning.

```
#Run 3MW baseload scenario for various storage options
storagecap<-data.frame("Storage_Cap"=c(1,2,3,4,5,6,7,8,9,10,12,14,16,18,20,22.5,25,27.5,30))
storagecap$Storage_Cap<-storagecap$Storage_Cap*10000.0
```

```
for (j in 1:nrow(storagecap)){
  #Calculate state of  storage at each hour
  ad$storage[1]=min(0.8*ad$ts_curtailment2[1],storagecap$Storage_Cap[j])
  for (i in 2:nrow(ad)){
    #with curtailment
    if (ad$ts_deficit2[i]==0){
      ad$storage[i]=min((ad$storage[i-1]+0.8*ad$ts_curtailment2[i]),storagecap$Storage_Cap[j])
      }
    #With deficit
    else if (ad$ts_curtailment2[i]==0){
      ad$storage[i]=max(ad$storage[i-1]-((ad$ts_deficit2[i])/0.8),0.0)
      }
  }

  #Calculate net WE used in each hour
  ad$we_used[1]=max(ad$ts_utilized2[1]-ad$baseload2[1],0.0)
  #Find total wind energy supplied (including from storage) at each hour
  for (i in 2:nrow(ad)){
    if (ad$ts_deficit2[i]==0){
      ad$we_used[i]=max(ad$ts_utilized2[i]-ad$baseload2[i],0.0)
      }
    else if (ad$ts_curtailment2[i]==0){
    ad$we_used[i]=max(ad$ts_utilized2[i]-ad$baseload2[i],0.0)+(ad$storage[i-1]-ad$storage[i])*0.8
    }
  }

  #Print storage capacity
  sprintf("Storage Capacity: %.2f kWh",storagecap$Storage_Cap[j])

  #Print previous useful WE
  sprintf("Without storage, net useful wind energy is %.2f kWh",sum2)

  #Print new useful WE
  sprintf("With storage, net useful wind energy is % .2fkWh",sum(ad$we_used))
  storagecap$WE_useful[j]=sum(ad$we_used)

  #Print additional useful WE
  sprintf("Therefore additional useful wind energy due to storage is %.2f kWh",sum(ad$we_used)-sum2)
  storagecap$benefit[j]=sum(ad$we_used)-sum2

  #Print fraction of previous curtailment saved
  sprintf("This is %.2f percent of the curtailment that would have occured without storage, %.2f kWh"
,(sum(ad$we_used)-sum2)*100/sum(ad$ts_curtailment2),sum(ad$ts_curtailment2))
  storagecap$frac.c.saved[j]=(sum(ad$we_used)-sum2)*100/sum(ad$ts_curtailment2)

  #Print fraction of previous unmet demand now met
```

```
  sprintf("Therefore, %.2f kWh (%.2f percent) of non-baseload energy not met by the wind farm earlier
, %.2f kWh, can be met by adding storage",sum(ad$we_used)-sum2,(sum(ad$we_used)-sum2)*100/sum(ad$ts_d
eficit2),sum(ad$ts_deficit2))
  storagecap$frac.d.met[j]=(sum(ad$we_used)-sum2)*100/sum(ad$ts_deficit2)

  #Print new capacity factor
  cf_c_bl2_st=sum(ad$we_used)*100/(850*8760*7)
  sprintf("Capacity factor with storage is %.2f percent",cf_c_bl2_st)
  storagecap$newCF[j]=cf_c_bl2_st
}

#Print for 10MWh storage capacity scenario
#Print storage capacity
sprintf("Storage Capacity: %.2f kWh",storagecap$Storage_Cap[1])
```

```
## [1] "Storage Capacity: 10000.00 kWh"
```

```
#Print previous useful WE
sprintf("Without storage, net useful wind energy is %.2f kWh",sum2)
```

```
## [1] "Without storage, net useful wind energy is 24490312.86 kWh"
```

```
#Print new useful WE
sprintf("With storage, net useful wind energy is % .2fkWh",storagecap$WE_useful[1])
```

```
## [1] "With storage, net useful wind energy is  25403868.59kWh"
```

```
#Print additional useful WE
sprintf("Therefore additional useful wind energy due to storage is %.2f kWh",storagecap$benefit[1])
```

```
## [1] "Therefore additional useful wind energy due to storage is 913555.73 kWh"
```

```
#Print fraction of previous curtailment saved
sprintf("This is %.2f percent of the curtailment that would have occured without storage.",storagecap
$frac.c.saved[1])
```

```
## [1] "This is 34.64 percent of the curtailment that would have occured without storage."
```

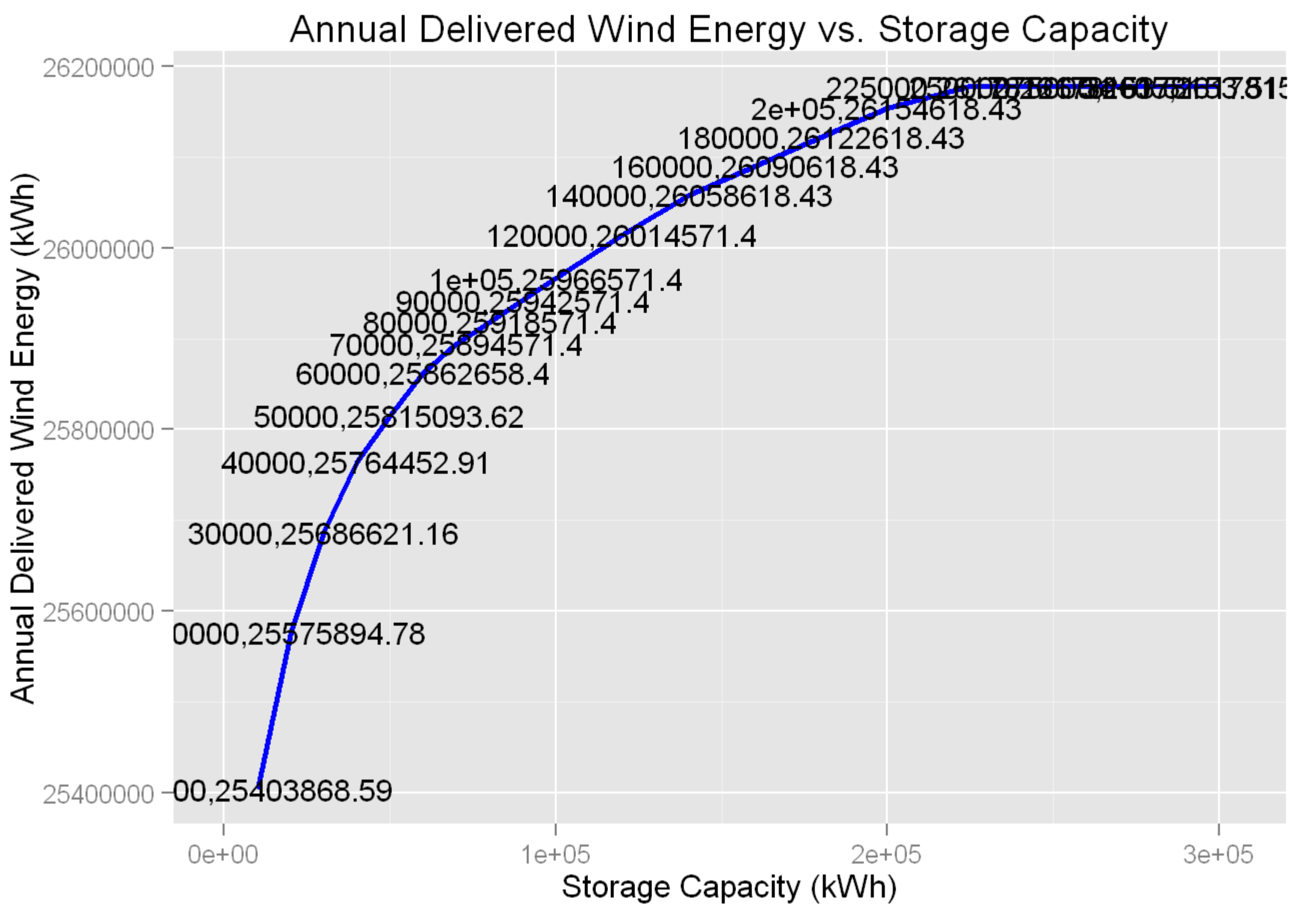
```
#Print fraction of previous unmet demand now met
sprintf("Therefore, %.2f kWh (%.2f percent) of non-baseload energy not met by the wind farm earlier,
%.2f kWh, can be met by adding storage",storagecap$benefit[1],storagecap$frac.d.met[1],(100/4.81)*sto
ragecap$benefit[1])
```

```
## [1] "Therefore, 913555.73 kWh (4.81 percent) of non-baseload energy not met by the wind farm earlier, 18992842.52 kWh, can be met by adding storage"
```

```
#Print new capacity factor
sprintf("Capacity factor with storage is %.2f percent",storagecap$newCF[1])
```

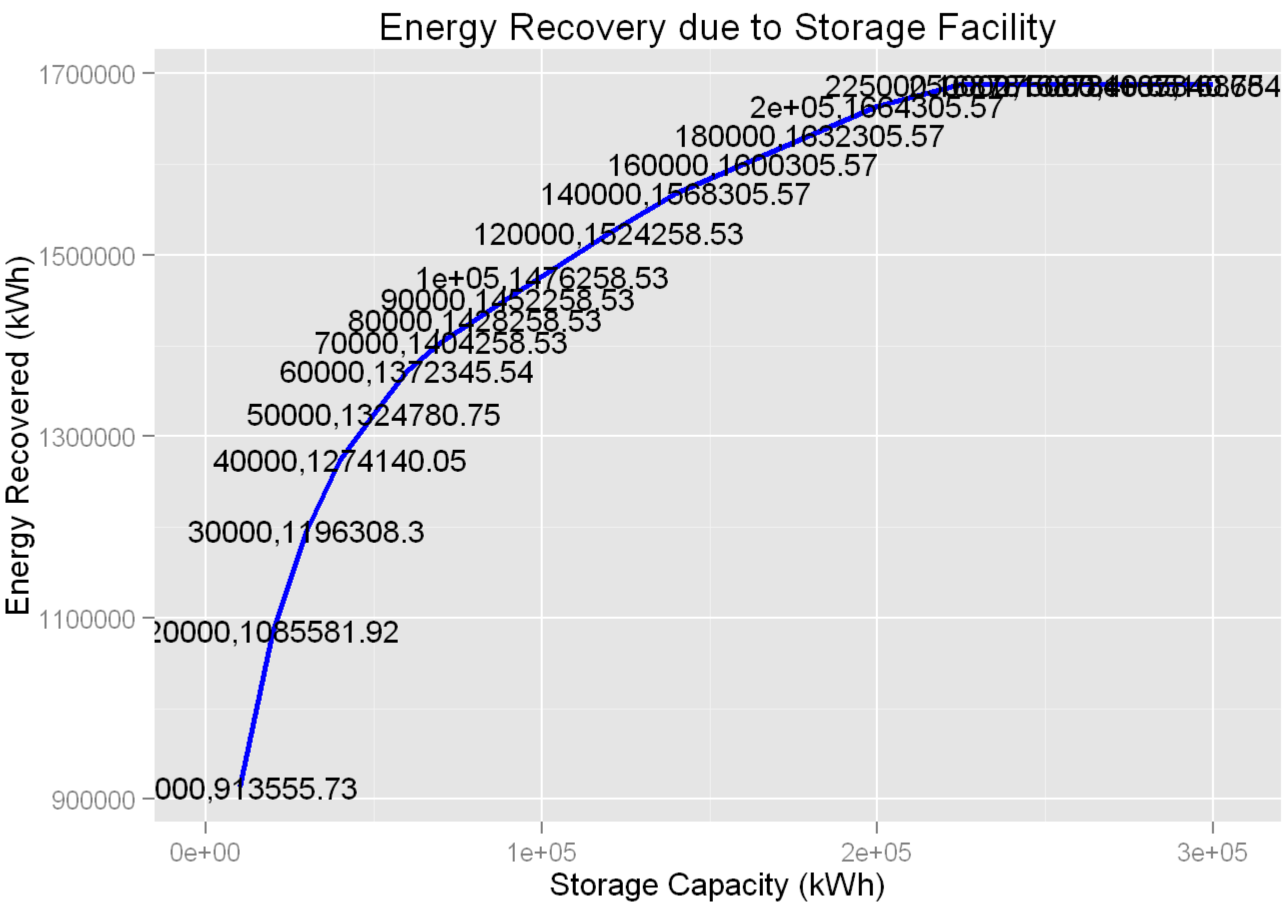
```
## [1] "Capacity factor with storage is 48.74 percent"
```

```
#Plot useful WE for each storage scenario
plot5<-ggplot(storagecap, aes(x=storagecap$Storage_Cap,y=storagecap$WE_useful))
plot5+geom_line(colour="blue",size=1)+geom_text(size=4, label=paste(round(storagecap$Storage_Cap, 2), round(storagecap$WE_useful, 2), sep=","))+xlim(0,5000+storagecap$Storage_Cap[nrow(storagecap)])+ylab("Annual Delivered Wind Energy (kWh)")+xlab("Storage Capacity (kWh)")+ggtitle("Annual Delivered Wind Energy vs. Storage Capacity")
```

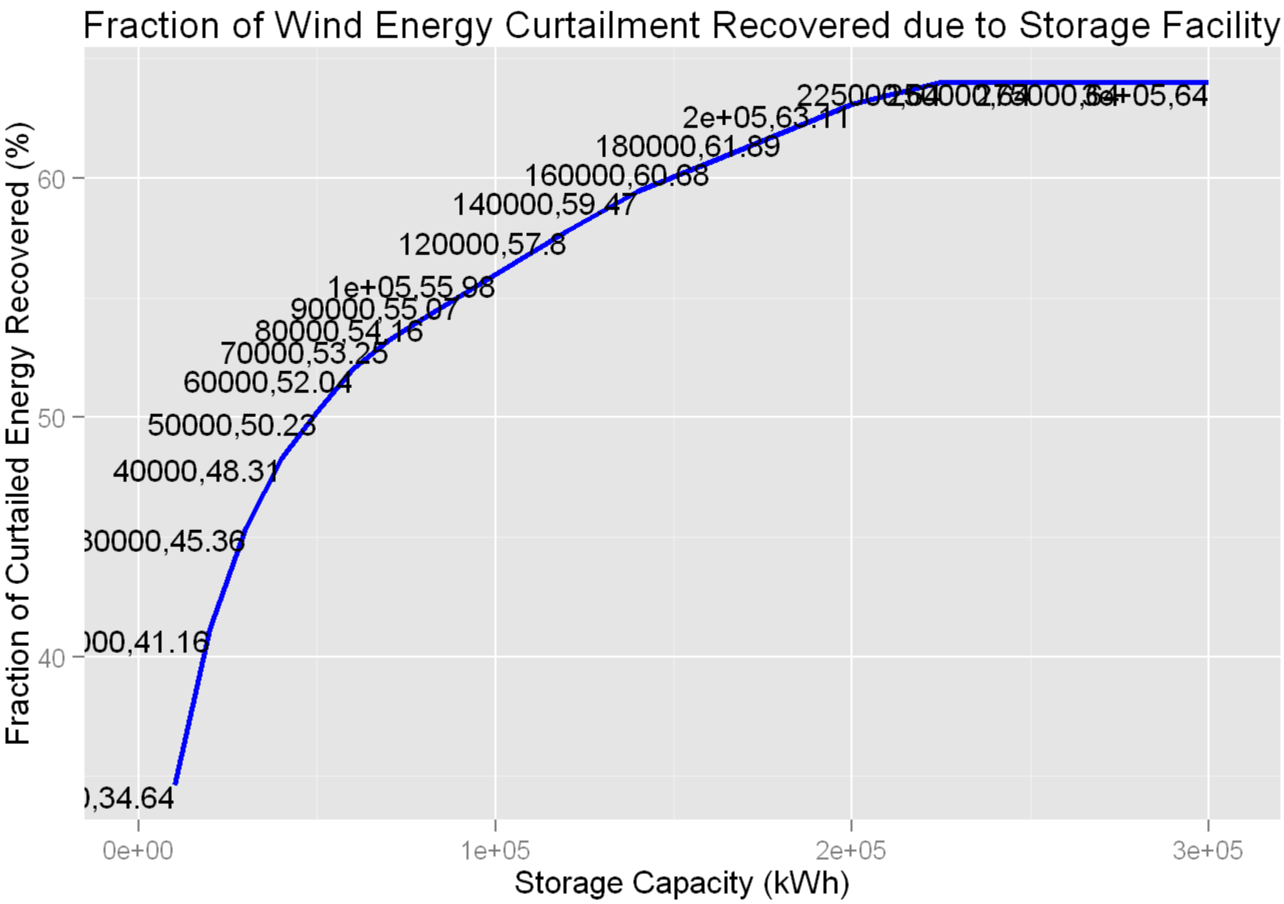



```
#Plot additional useful WE due to storage, for each storage scenario
plot6<-ggplot(storagecap, aes(x=storagecap$Storage_Cap,y=storagecap$benefit))
plot6+geom_line(colour="blue",size=1)+geom_text(size=4, label=paste(round(storagecap$Storage_Cap, 2), round(storagecap$benefit, 2), sep=","))+xlim(0,5000+storagecap$Storage_Cap[nrow(storagecap)])+ylab("Energy Recovered (kWh)")+xlab("Storage Capacity (kWh)")+ggtitle("Energy Recovery due to Storage Facil
```

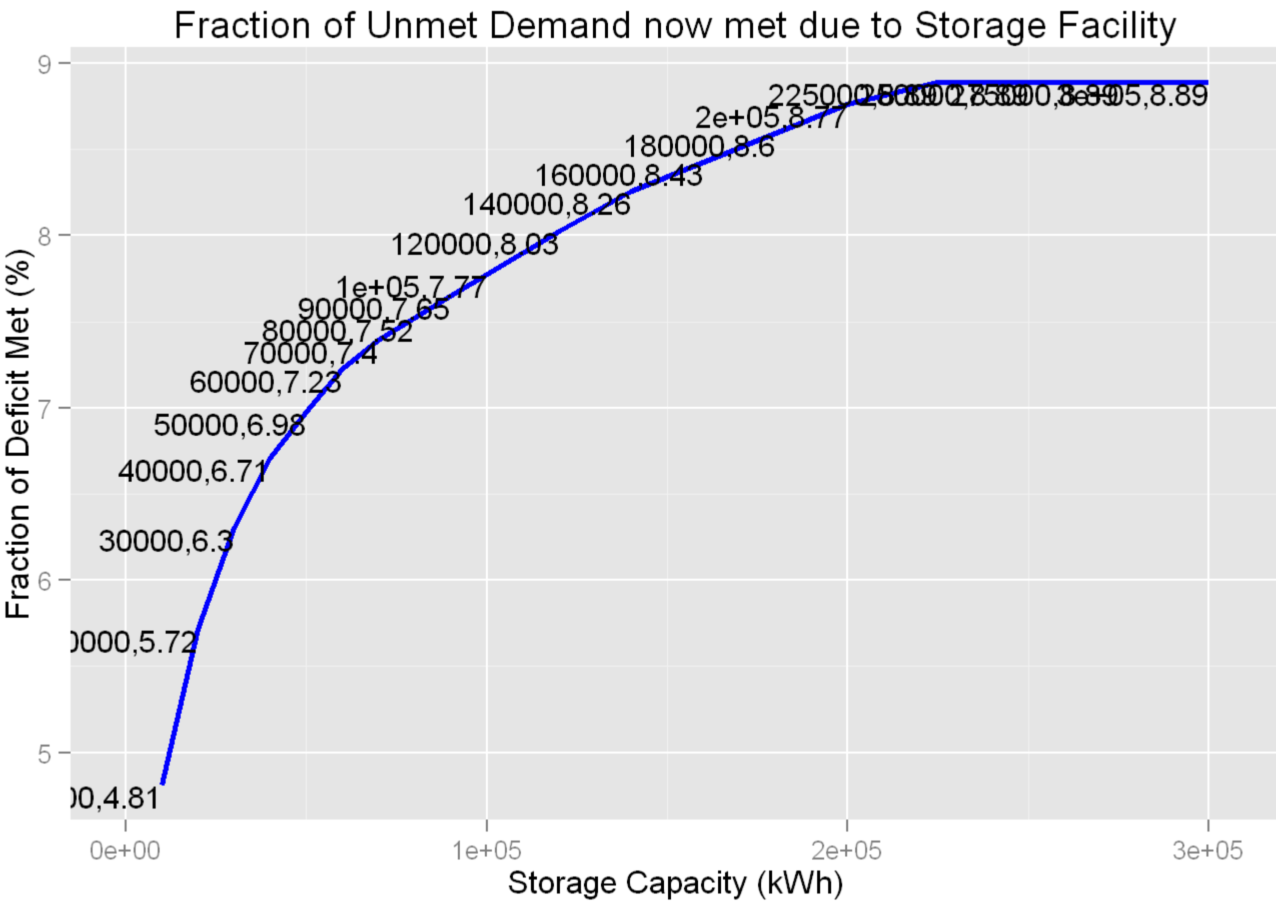
```
ity")
```



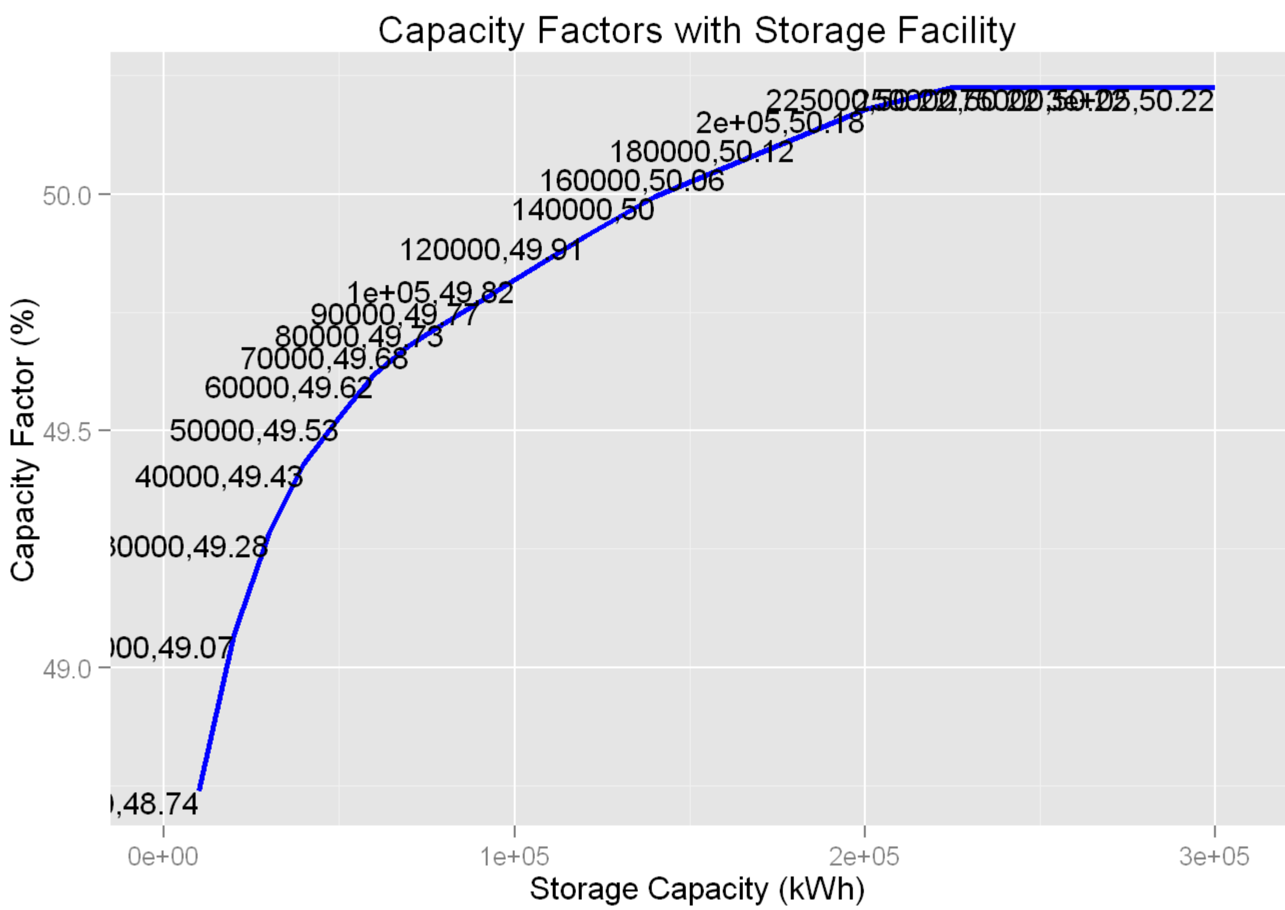

```
#Plot fraction of curtailed energy recovered, for each storage scenario
plot7<-ggplot(storagecap, aes(x=storagecap$Storage_Cap,y=storagecap$frac.c.saved))
plot7+geom_line(colour="blue",size=1)+geom_text(size=4, label=paste(round(storagecap$Storage_Cap, 2),
 round(storagecap$frac.c.saved, 2), sep=","),hjust = 1, vjust = 1)+ylab("Fraction of Curtailed Energy
 Recovered (%)")+xlim(0,5000+storagecap$Storage_Cap[nrow(storagecap)])+xlab("Storage Capacity (kWh)")
+ggtitle("Fraction of Wind Energy Curtailment Recovered due to Storage Facility")
```




```r
#Plot fraction of unmet demand now met, for each storage scenario
plot8<-ggplot(storagecap, aes(x=storagecap$Storage_Cap,y=storagecap$frac.d.met))
plot8+geom_line(colour="blue",size=1)+geom_text(size=4, label=paste(round(storagecap$Storage_Cap, 2),
 round(storagecap$frac.d.met, 2), sep=","),hjust = 1, vjust = 1)+xlim(0,5000+storagecap$Storage_Cap[n
row(storagecap)])+ylab("Fraction of Deficit Met (%)")+xlab("Storage Capacity (kWh)")+ggtitle("Fractio
n of Unmet Demand now met due to Storage Facility")
```




```
#Plot CFs with storage, for each storage scenario
plot9<-ggplot(storagecap, aes(x=storagecap$Storage_Cap,y=storagecap$newCF), label=text)
plot9+geom_line(colour="blue",size=1)+geom_text(size=4, label=paste(round(storagecap$Storage_Cap, 2),
 round(storagecap$newCF, 2), sep=","),hjust = 1, vjust = 1)+ylab("Capacity Factor (%)")+xlab("Storage
 Capacity (kWh)")+xlim(0,5000+storagecap$Storage_Cap[nrow(storagecap)])+ggtitle("Capacity Factors wit
h Storage Facility")
```

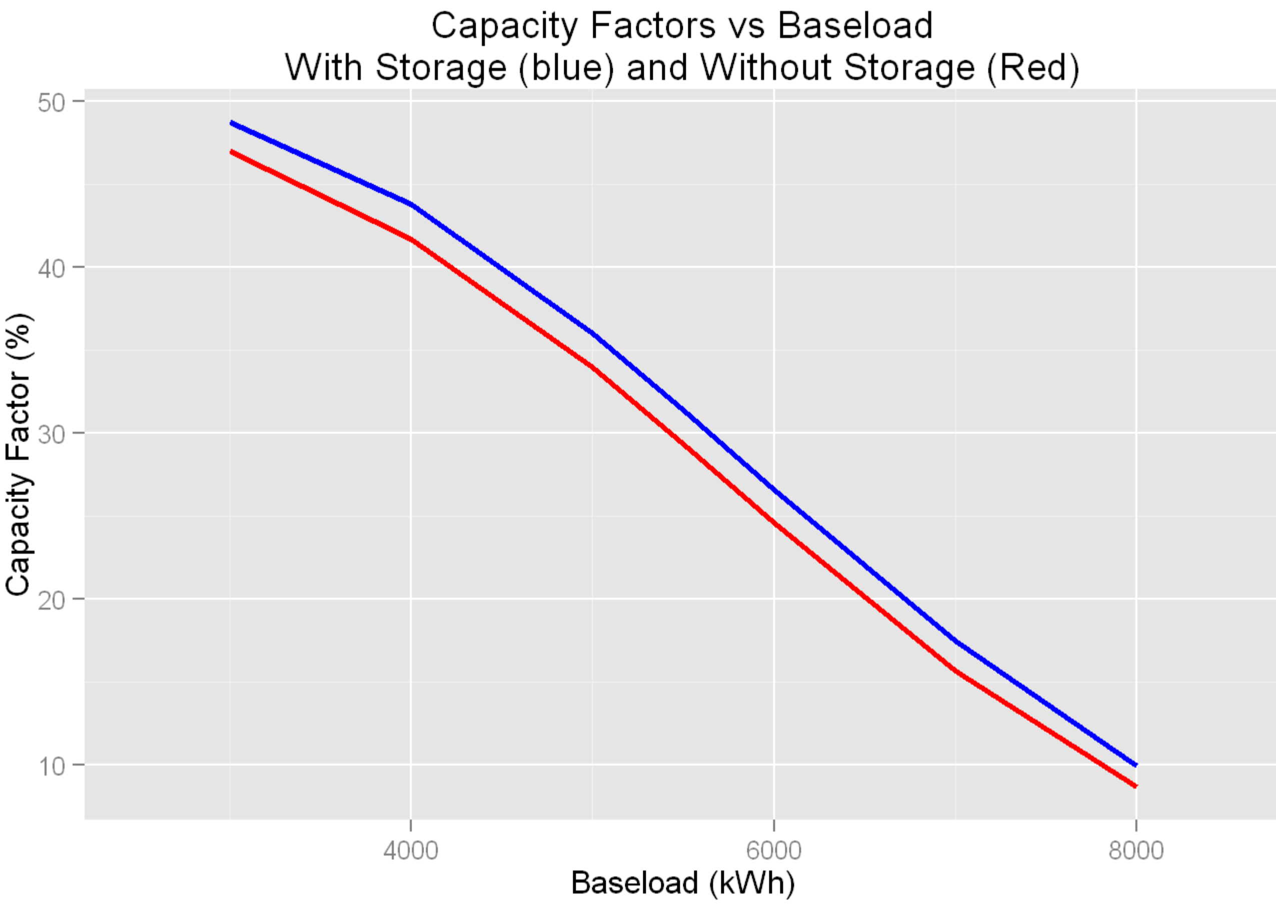


4. Perform analogous calculations for a variety of different baseload power for the 10MWh storage system. What point would be considered optimum, to deliver the highest fraction of unmet non-baseload capacity with storage discharged energy? Explain your reasoning.

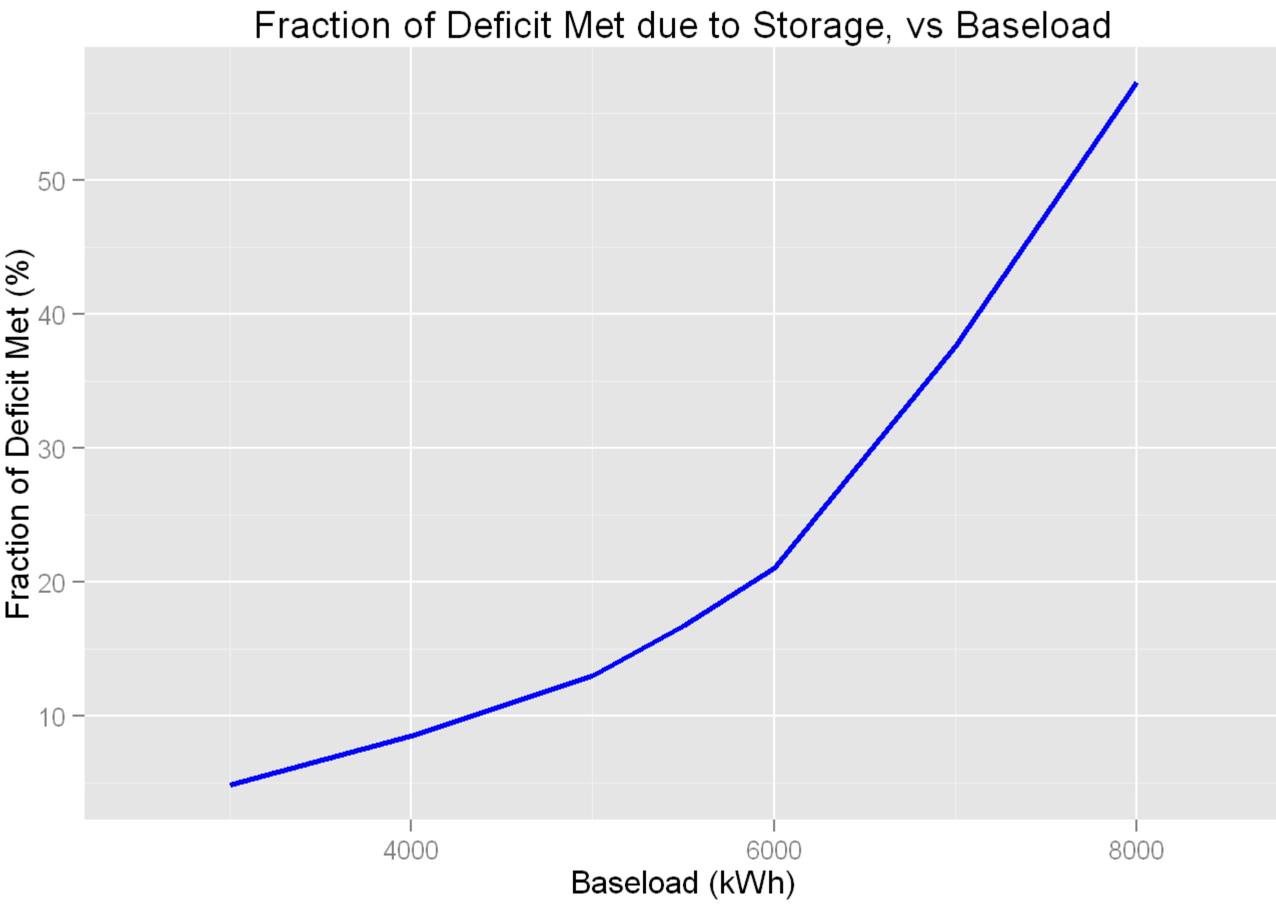
```
#Different baseload scenarios
bl<-data.frame("baseload"=c(30,40,50,55,60,70,80))

for (k in 1:nrow(bl)){
  bl$baseload[k]=bl$baseload[k]*100.0
  ad$baseload3=bl$baseload[k]

  ad$totalsupply3=ad$baseload3+ad$windgen

  for (j in 1:nrow(ad)){
      ad$ts_utilized3[j]=min(ad$demand[j],ad$totalsupply3[j])
    }
  #Calculate curtailment
  ad$ts_curtailment3=ad$totalsupply3-ad$ts_utilized3
  #Calculate deficit
  ad$ts_deficit3=ad$demand-ad$ts_utilized3

  #Print baseload
  sprintf("Baseload is %.2f kWh",summary(ad$baseload3)[4])
```

```
  #Print non-baseload energy not met by windfarm
  sprintf("For this baseload, non-baseload energy not met by wind farm over the year is %.2fkWh",sum(
ad$ts_deficit3))
  bl$deficit[k]=sum(ad$ts_deficit3)

  #Print curtailment
  sprintf("For this baseload, curtailment over the year is %.2fkWh",sum(ad$ts_curtailment3))
  bl$curtailment[k]=sum(ad$ts_curtailment3)

  #Find capacity factor
  sum3=0.0
  for (i in 1:nrow(ad)){
  sum3=sum3+max(ad$ts_utilized3[i]-ad$baseload3[i],0.0)
  }
  cf_c_bl3=sum3*100/(850*8760*7)

  #Print capacity factor
  sprintf("For this baseload, curtailed CF is %.2f percent",cf_c_bl3)
  bl$CFwst[k]=cf_c_bl3

  #Calculate state of  storage at each hour
  ad$storage3[1]=min(0.8*ad$ts_curtailment3[1],10000.0)
  for (i in 2:nrow(ad)){
    #With curtailment
    if (ad$ts_deficit3[i]==0){
      ad$storage3[i]=min((ad$storage3[i-1]+0.8*ad$ts_curtailment3[i]),10000.0)
      }
    #With deficit
    else if (ad$ts_curtailment3[i]==0){
      ad$storage3[i]=max(ad$storage3[i-1]-((ad$ts_deficit3[i])/0.8),0.0)
      }
  }

  #Calculate net WE used in each hour
  ad$we_used3[1]=max(ad$ts_utilized3[1]-ad$baseload3[1],0.0)
  #Find total wind energy supplied (including from storage) at each hour
  for (i in 2:nrow(ad)){
    if (ad$ts_deficit3[i]==0){
      ad$we_used3[i]=max(ad$ts_utilized3[i]-ad$baseload3[i],0.0)
      }
    else if (ad$ts_curtailment3[i]==0){
    ad$we_used3[i]=max(ad$ts_utilized3[i]-ad$baseload3[i],0.0)+(ad$storage3[i-1]-ad$storage3[i])*0.8
    }
  }
```

```
  #Print baseload
  sprintf("Baseload: %.2f kWh",bl$baseload[k])

  #Print previous useful WE
  sprintf("Without storage, net useful wind energy is %.2f kWh",sum3)

  #Print new useful WE
  sprintf("With storage, net useful wind energy is % .2fkWh",sum(ad$we_used3))
  bl$WE_useful[k]=sum(ad$we_used3)

  #Print additional useful WE
  sprintf("Therefore additional useful wind energy due to storage is %.2f kWh",sum(ad$we_used3)-sum3)
  bl$benefit[k]=sum(ad$we_used3)-sum3

  #Print fraction of previous curtailment saved
  sprintf("This is %.2f percent of the curtailment that would have occured without storage, %.2f kWh"
,(sum(ad$we_used3)-sum3)*100/sum(ad$ts_curtailment3),sum(ad$ts_curtailment3))
  bl$frac.c.saved[k]=(sum(ad$we_used3)-sum3)*100/sum(ad$ts_curtailment3)

  #Print fraction of previous unmet demand now met
  sprintf("Therefore, %.2f kWh (%.2f percent) of non-baseload energy not met by the wind farm earlier
, %.2f kWh, can be met by adding storage",sum(ad$we_used3)-sum3,(sum(ad$we_used3)-sum3)*100/sum(ad$ts
_deficit3),sum(ad$ts_deficit3))
  bl$frac.d.met[k]=(sum(ad$we_used3)-sum3)*100/sum(ad$ts_deficit3)

  #Calculate remaining deficit to be met by diesel generation
  bl$rem.deficit[k]=sum(ad$ts_deficit3)-(sum(ad$we_used3)-sum3)

  #Print new capacity factor
  cf_c_bl3_st=sum(ad$we_used3)*100/(850*8760*7)
  sprintf("Capacity factor with storage is %.2f percent",cf_c_bl3_st)
  bl$newCF[k]=cf_c_bl3_st
}

#Plot CFs with storage, for each baseload scenario
plot10<-ggplot(bl, aes(x=bl$baseload))
plot10+geom_line(aes(y=bl$newCF),colour="blue",size=1)+geom_line(aes(y=bl$CFwst),colour="red",size=1)
+ylab("Capacity Factor (%)")+xlab("Baseload (kWh)")+xlim(bl$baseload[1]-500,500+bl$baseload[nrow(bl)]
)+ggtitle("Capacity Factors vs Baseload\nWith Storage (blue) and Without Storage (Red)")
```




```
plot11<-ggplot(bl, aes(x=bl$baseload))
plot11+geom_line(aes(y=bl$frac.d.met),colour="blue",size=1)+ylab("Fraction of Deficit Met (%)")+xlab(
"Baseload (kWh)")+xlim(bl$baseload[1]-500,500+bl$baseload[nrow(bl)])+ggtitle("Fraction of Deficit Met
 due to Storage, vs Baseload")
```



Fraction of Deficit Met due to Storage, vs Baseload
Fraction of Deficit Met (%)
50
40
30
20
10
4000
6000
8000
Baseload (kWh)

SV2414 and vrp2113 Energy Storage Options in Sao Vicente Note: This RMD contains setpoint calculation, along with question 5 of ‘Storage Capacity Effects on Capacity Factor’ section (which uses setpoints).

```
## Loading required package: plyr
## Loading required package: ggplot2
```

REFINING SYSTEM SETPOINTS

1. Propose a reasonable set of setpoints for wind farm generation and baseload generation. How do these values affect the curtailment and capacity factor?

```
#Average demand in the evenings
avgeved=summary(ad$demand[(as.POSIXlt(ad$datetime,format="%Y-%m-%d %H:%M:%S"))$hour>=17 & (as.POSIXlt(ad$datetime,format="%Y-%m-%d %H:%M:%S"))$hour<=21])[4]
#Average demand in the day
avgdayd=summary(ad$demand[(as.POSIXlt(ad$datetime,format="%Y-%m-%d %H:%M:%S"))$hour>=6 & (as.POSIXlt(ad$datetime,format="%Y-%m-%d %H:%M:%S"))$hour<=16])[4]
#Average demand at late nights
avglnd=summary(ad$demand[(as.POSIXlt(ad$datetime,format="%Y-%m-%d %H:%M:%S"))$hour>=22 | (as.POSIXlt(ad$datetime,format="%Y-%m-%d %H:%M:%S"))$hour<=05])[4]

#Average windgen in the evenings
avgevegen=summary(ad$windgen[(as.POSIXlt(ad$datetime,format="%Y-%m-%d %H:%M:%S"))$hour>=17 & (as.POSIXlt(ad$datetime,format="%Y-%m-%d %H:%M:%S"))$hour<=21])[4]
#Average windgen in the day
avgdaygen=summary(ad$windgen[(as.POSIXlt(ad$datetime,format="%Y-%m-%d %H:%M:%S"))$hour>=6 & (as.POSIXlt(ad$datetime,format="%Y-%m-%d %H:%M:%S"))$hour<=16])[4]
#Average windgen at late nights
avglngen=summary(ad$windgen[(as.POSIXlt(ad$datetime,format="%Y-%m-%d %H:%M:%S"))$hour>=22 | (as.POSIXlt(ad$datetime,format="%Y-%m-%d %H:%M:%S"))$hour<=05])[4]

#Average deficit in the evenings, day and late nights
avgevedef=avgeved-avgevegen
avgdaydef=avgdayd-avgdaygen
avglndef=avglnd-avglngen

#Assign setpoints for baseload
for (i in 1:nrow(ad)){
  if((as.POSIXlt(ad$datetime[i],format="%Y-%m-%d %H:%M:%S"))$hour>=17 & (as.POSIXlt(ad$datetime[i],format="%Y-%m-%d %H:%M:%S"))$hour<=21){
    ad$blsp[i]=avgevedef
    }
  if((as.POSIXlt(ad$datetime[i],format="%Y-%m-%d %H:%M:%S"))$hour>=6 & (as.POSIXlt(ad$datetime[i],format="%Y-%m-%d %H:%M:%S"))$hour<=16){
    ad$blsp[i]=avgdaydef
    }
```

```
  if((as.POSIXlt(ad$datetime[i],format="%Y-%m-%d %H:%M:%S"))$hour>=22 | (as.POSIXlt(ad$datetime[i],format="%Y-%m-%d %H:%M:%S"))$hour<=05){
    ad$blsp[i]=avglndef
  }
  #Find gap to be filled above baseload
  ad$gap[i]=max(ad$demand[i]-ad$blsp[i],0.0)
}

#Find average gap to be filled in evenings, days and late nights, and take appropriate fraction
avgevegap=0.76*summary(ad$gap[(as.POSIXlt(ad$datetime,format="%Y-%m-%d %H:%M:%S"))$hour>=17 & (as.POSIXlt(ad$datetime,format="%Y-%m-%d %H:%M:%S"))$hour<=21])[4]
avgdaygap=0.76*summary(ad$gap[(as.POSIXlt(ad$datetime,format="%Y-%m-%d %H:%M:%S"))$hour>=6 & (as.POSIXlt(ad$datetime,format="%Y-%m-%d %H:%M:%S"))$hour<=16])[4]
avglngap=0.76*summary(ad$gap[(as.POSIXlt(ad$datetime,format="%Y-%m-%d %H:%M:%S"))$hour>=22 | (as.POSIXlt(ad$datetime,format="%Y-%m-%d %H:%M:%S"))$hour<=05])[4]

#Calculate setpoints for generation
for (i in 1:nrow(ad)){
   if((as.POSIXlt(ad$datetime[i],format="%Y-%m-%d %H:%M:%S"))$hour>=17 & (as.POSIXlt(ad$datetime[i],format="%Y-%m-%d %H:%M:%S"))$hour<=21){
    ad$gensp[i]=avgevegap
    }
  if((as.POSIXlt(ad$datetime[i],format="%Y-%m-%d %H:%M:%S"))$hour>=6 & (as.POSIXlt(ad$datetime[i],format="%Y-%m-%d %H:%M:%S"))$hour<=16){
    ad$gensp[i]=avgdaygap
    }
  if((as.POSIXlt(ad$datetime[i],format="%Y-%m-%d %H:%M:%S"))$hour>=22 | (as.POSIXlt(ad$datetime[i],format="%Y-%m-%d %H:%M:%S"))$hour<=05){
    ad$gensp[i]=avglngap
  }
  #Update generation values based on the setpoints
  ad$newwindgen[i]=min(ad$windgen[i],ad$gensp[i])
  #Find total supply
  ad$totalsupply[i]=ad$newwindgen[i]+ad$blsp[i]
  #Find total delivered power
  ad$sputilized[i]=min(ad$demand[i],ad$totalsupply[i])
}

#Calculate curtailment
ad$spcurtailment=ad$totalsupply-ad$sputilized
#Calculate deficit
ad$spdeficit=ad$demand-ad$sputilized

#Print curtailment
sprintf("The total curtailment over the year, using setpoints, is %.2f kWh",sum(ad$spcurtailment))
```

```
## [1] "The total curtailment over the year, using setpoints, is 1282269.17 kWh"
```

```
#Calculate curtailed capacity factor
sum=0.0
for (i in 1:nrow(ad)){
sum=sum+max(ad$sputilized[i]-ad$blsp[i],0.0)
}
cf_c_sp=sum*100/(850*8760*7)
sprintf("Using setpoints for baseload and wind generation, curtailed CF is %.2f percent",cf_c_sp)
```

```
## [1] "Using setpoints for baseload and wind generation, curtailed CF is 28.92 percent"
```

STORAGE CAPACITY EFFECTS ON CAPACITY FACTOR

5. Finally, perform the same calculations for your proposed storage capacity and set point values. How much additional energy is now recoverable via storage?

```
#Calculate state of  storage at each hour
ad$storage[1]=min(0.8*ad$spcurtailment[1],10000.0)
for (i in 2:nrow(ad)){
  if (ad$spdeficit[i]==0){
    ad$storage[i]=min((ad$storage[i-1]+0.8*ad$spcurtailment[i]),10000.0)
    }
  #With deficit
  else if (ad$spcurtailment[i]==0){
    ad$storage[i]=max(ad$storage[i-1]-((ad$spdeficit[i])/0.8),0.0)
    }
}

#Calculate net WE used in each hour
ad$we_used[1]=max(ad$sputilized[1]-ad$blsp[1],0.0)
#Find total wind energy supplied (including from storage) at each hour
for (i in 2:nrow(ad)){
  if (ad$spdeficit[i]==0){
    ad$we_used[i]=max(ad$sputilized[i]-ad$blsp[i],0.0)
    }
  else if (ad$spcurtailment[i]==0){
  ad$we_used[i]=max(ad$sputilized[i]-ad$blsp[i],0.0)+(ad$storage[i-1]-ad$storage[i])*0.8
  }
}



#Print previous useful WE
sprintf("Without storage, net useful wind energy is %.2f kWh",sum)
```

```
## [1] "Without storage, net useful wind energy is 15075644.35 kWh"
```

```
#Print new useful WE
sprintf("With storage, net useful wind energy is % .2fkWh",sum(ad$we_used))
```

```
## [1] "With storage, net useful wind energy is  15729264.50kWh"
```

```
#Print additional useful WE
sprintf("Therefore additional useful wind energy recoverable from storage is %.2f kWh",sum(ad$we_used
)-sum)
```

```
## [1] "Therefore additional useful wind energy recoverable from storage is 653620.15 kWh"
```

```
#Print fraction of previous curtailment saved
sprintf("This is %.2f percent of the curtailment that would have occured without storage, %.2f kWh",(
sum(ad$we_used)-sum)*100/sum(ad$spcurtailment),sum(ad$spcurtailment))
```

```
## [1] "This is 50.97 percent of the curtailment that would have occured without storage, 1282269.17
kWh"
```

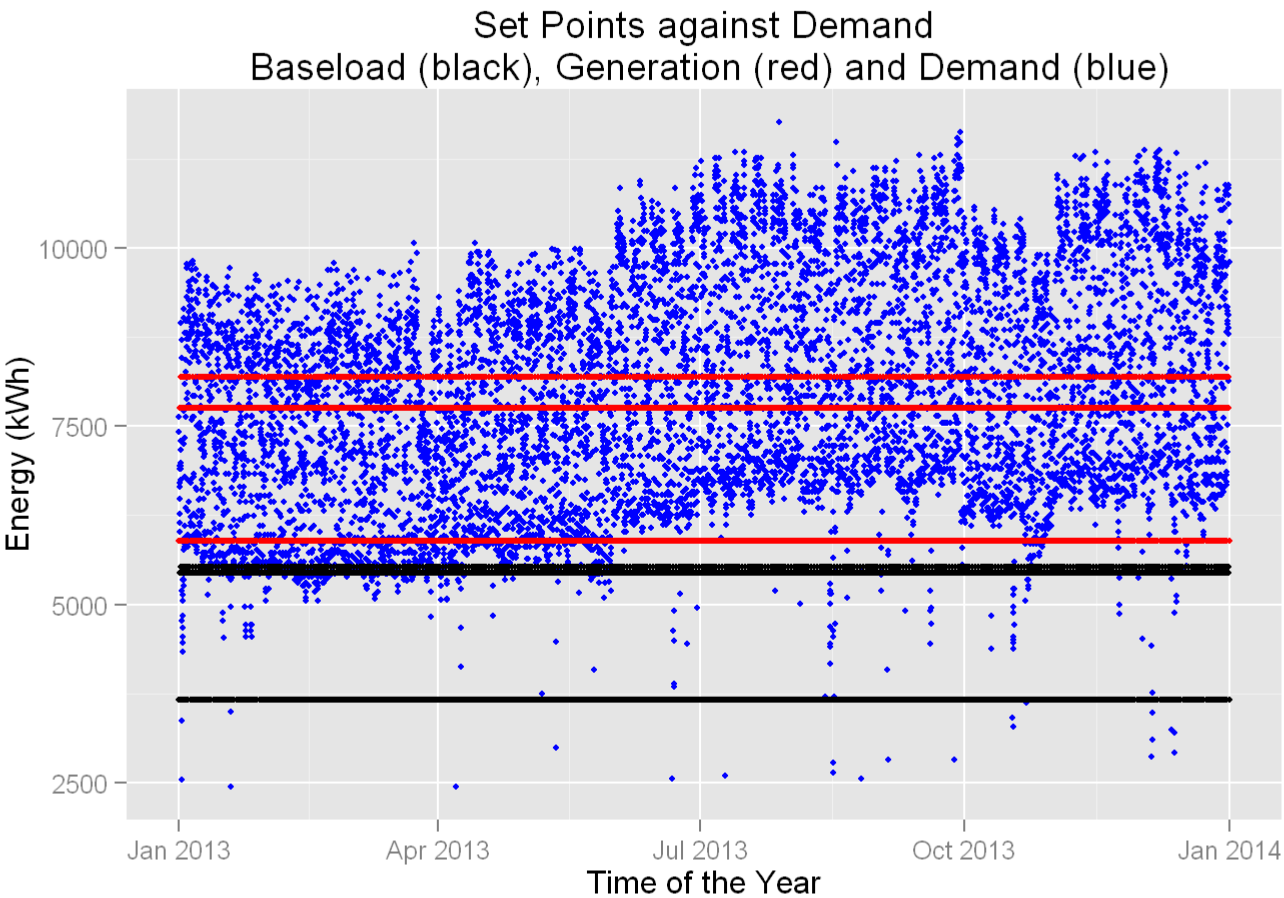
```
#Print fraction of previous unmet demand now met
sprintf("Therefore, %.2f kWh (%.2f percent) of non-baseload energy not met by the wind farm earlier,
%.2f kWh, can be met by adding storage",sum(ad$we_used)-sum,(sum(ad$we_used)-sum)*100/sum(ad$spdefici
t),sum(ad$spdeficit))
```

```
## [1] "Therefore, 653620.15 kWh (5.39 percent) of non-baseload energy not met by the wind farm earli
er, 12135497.65 kWh, can be met by adding storage"
```

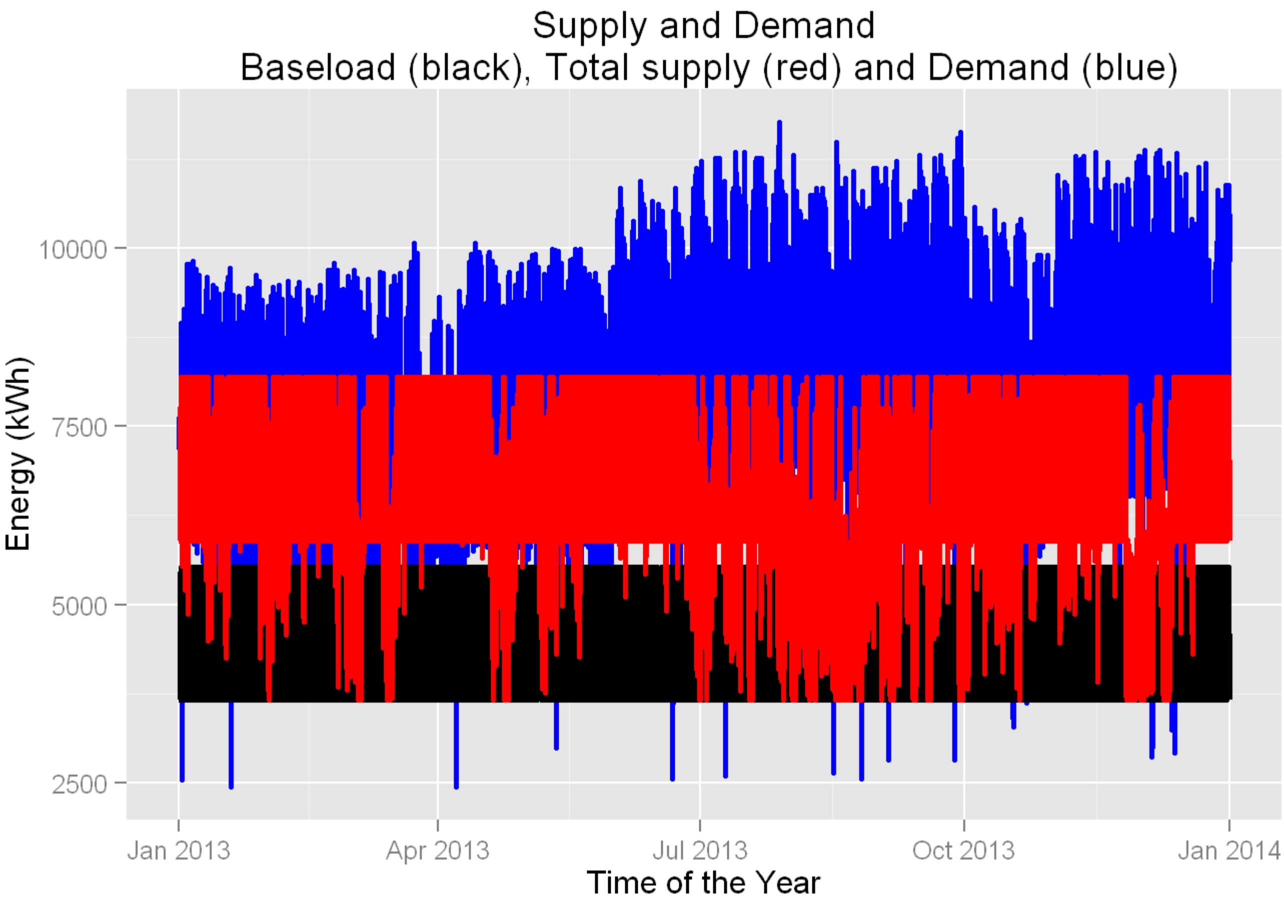
```
#Print new capacity factor
cf_c_bl_st_sp=sum(ad$we_used)*100/(850*8760*7)
sprintf("Capacity factor with storage is %.2f percent",cf_c_bl_st_sp)
```

```
## [1] "Capacity factor with storage is 30.18 percent"
```

```
plot3<-ggplot(ad, aes(x=ad$datetime))
plot3+geom_point(aes(y=ad$demand),colour="blue",size=1)+geom_point(aes(y=ad$blsp),colour="black",size
=1)+geom_point(aes(y=ad$blsp+ad$gensp),colour="red",size=1)+ylab("Energy (kWh)")+xlab("Time of the Ye
ar")+ggtitle("Set Points against Demand\n Baseload (black), Generation (red) and Demand (blue)")
```




```
plot4<-ggplot(ad, aes(x=ad$datetime))
plot4+geom_line(aes(y=ad$demand),colour="blue",size=1)+geom_line(aes(y=ad$blsp),colour="black",size=1
)+geom_line(aes(y=ad$totalsupply),colour="red",size=1)+ylab("Energy (kWh)")+xlab("Time of the Year")+
ggtitle("Supply and Demand\n Baseload (black), Total supply (red) and Demand (blue)")
```



Supply and Demand
Baseload (black), Total supply (red) and Demand (blue)
Energy (kWh)
10000
7500
5000
2500
Jan 2013
Apr 2013
Jul 2013
Oct 2013
Jan 2014
Time of the Year