Performance Improvement of Wind Power Generation System by Using Compressed Air Energy Storage on a Seasonal Basis

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ABSTRACT

Renewable energy isn't completely reliable for generating specific amounts of power at all times. Due to the fluctuations in the wind's behavior, energy storage technologies must be considered. There are many energy storage methods, such as pump hydro, flywheel, battery, compressed air energy storage, and so on. Among the various storage methods, CAES was chosen due to its lower environmental impacts. In this study, the power mismatch between the wind generation and the load was first considered and observed to improve the performance of the system with CAES according to the three seasons. The research was analyzed for daily energy demand and supply. This paper describes the simulation of this plant by using Simulink tools in MATLAB programmed. The simulation results for three seasons show that the charging process absorbs 40% of the excess wind energy into the storage tank of 2838.79 m^3. Finally, it was observed that if the air is expanded from 30 to 10 bars with the production of 3000 kWh of storage energy in the CAES, the power mismatch is nearly zero or very small, which can supply nearly 70% of the demand requirement. Therefore, the CAES could be efficient for the installation of wind turbines in Myanmar, and the proposed system indicates successful operation under certain weather conditions and site surveys.

INTRODUCTION

Wind is the atmospheric air at any velocity or movement. The wind speed rotates the wind turbines to run as generators for electricity distribution. Wind energy also has the unpredictable problem. Since wind has a natural, or destructive, blow, its power output is not constant at all times. With the current rapid industrial development in the world, energy shortages have become one of the biggest issues for many countries [1].

Since wind is not a reliable renewable energy source, it also has a variable power output. In order to generate the reliable power output, the energy storage technologies must be implemented [2]. During high wind speeds, the surplus wind energy is squandered. During low wind speeds, there is a lack or shortage of wind power output to supply the consumer. So, energy storage technologies must be installed at wind farms in order to adjust the load requirement during the variable wind speeds.

Four storage technologies to solve the wind output fluctuation are the pumped hydro, the CAES, the flywheel, and the battery [3]. Whereas pumped hydro storage provides long term storage capacity at high power levels, it is highly dependent upon the geographic location. Flywheels provide short term storage capacity at high power levels. Batteries have low power capacities, high maintenance costs, and short lifetimes. CAES can provide long term storage capacity at high power levels. Table 1 shows a comparison of storage system methods [4, 5]. The storage time, the discharge time, the lifetime, the sizing, and the efficiency of the various energy storage methods are compared.

Table 1. Comparison of storage system methods [4, 5]

Energy Storage System	Storage Time	Discharge time	Max cycles or lifetime	Sizing (kW)	Efficiency
Pumped hydro	To years	4 h– 16 h	10–50 years	5,000-2,700,000	70 – 85%
CAES	**Hours-months**	**1-6 h 2 h–30 h**	**10–40 years**	**1-300000**	**40 70%**
Lead-acid battery	4-25 months	1 min – 8 h	6–40 years	1-10,000	80 – 90%
Fly wheel	From days to months	secs-mins	20,000 – 100,000	2-2,000	70 – 95%

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2. WIND ENERGY RESOURCES

The wind has no impact on any atmospheric emissions, like power plants which consume fossil fuel and so emit a series of gasses with greenhouse emissions when producing electricity. The wind turbine construction can be very tall, and the land below can still be used, especially in the agricultural areas. Since wind has a natural, or destructive, blow, its power output is not constant at all times. With the current rapid industrial development in the world, energy shortages have become one of the biggest issues for many countries. The opportunity for excess energy is that it can be kept available to supply enough during peak loads by using CAES, batteries, pump hydro storages, and so on [6].

3. BASIC OPERATION OF THE CAES SYSTEM

This is a method in which the atmospheric air is compressed and stored within a sealed enclosure during off-peak electricity. CAES can maintain a stable and constant power output at fluctuating wind speeds and high demand for electricity [7]. As explained in Fig. 1, the desired power demand is pulled from the wind power generation during strong wind speeds. And the exceeding amount of wind power output is for storing, via compressor, in an underground tank or above ground tank. When the consumers need more power, the stored energy from excess wind is expanded to run the turbine-generator.

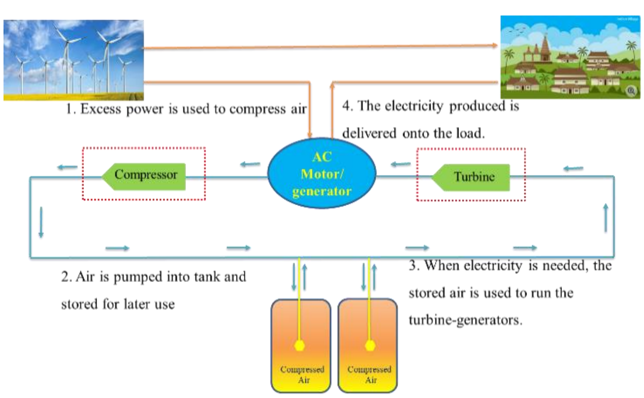


Fig. 1. CAES system operation.

4. EQUATION OF THE WIND+CAES SYSTEM

4.1. Equation of the wind energy system

The power output (P_{wind}) from each wind turbine is calculated as follows [8]- [10]:

$$P_{wind} = ½ \rho AV^3 C_p N_g N_b \quad (1)$$

where,

ρ = the air's density
A = the swept area by rotors
V = the wind speed or velocity
C_p = the power coefficient of a wind turbine
Ng = turbine-generator efficiency
N_b = gearbox efficiency

4.2. Equation for integrated CAES

The individual components of the CAES section coupled with wind power generation are studied using a Matlab/Simulink model. The power mismatch is calculated by the following equation:

$$P_d = P_{wind} - P_{load} \quad (2)$$

If P_d is positive, there's power sufficiency and excess, so that the compressor is in charging operation. When P_d is negative, there is a deficiency for the required power supply, so the turbine is in a discharging mood [11]. CAES sizing is a key issue that influences the consumer's benefits. As the CAES sizing is increased, the tank size may increase, and the installation of the system may require more expense unexpectedly. If the system is based on the annual minimum demand requirement, it does not cover the actual demand load. Based on the annual average requirement, the CAES size can be reduced, and the installation of the system may be more effective. Therefore, the optimal size should be considered based on the annual average requirement by using the equations in Fig. 2.

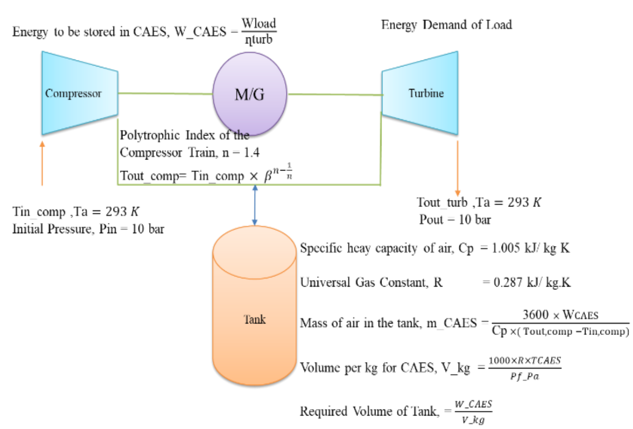


Fig. 2. Equations for the CAES system

5. CASE STUDY AREA

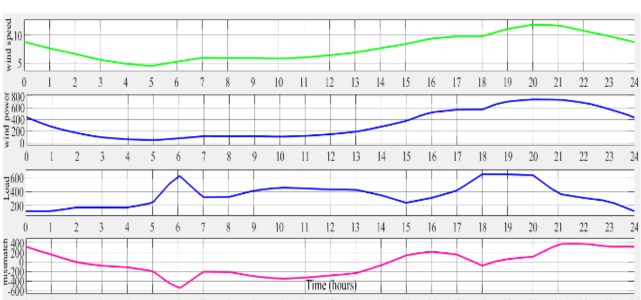
The provision of an electricity supply to the rural areas is still difficult and costly, and extension of the main grid over difficult terrain is not generally economic for small power demand. Hence, to solve the urgent electrification problem of rural consumers spread throughout Myanmar, the government is trying to promote renewable energy system especially in rural areas.

For the study of wind power generation integrated with the CAES system, a field study and data survey are carried out in A-Lae-Pone Village, Saitoktaya Township, Magwe Region, Myanmar.

The selected village is located at latitude 20°24'29"N and longitude 94°18'13"E. A-Lae-Pone village has 351 households and more than 1500 residents. Fig. 3 shows the location of the selected area for the rural electrification study.

On summer days, the wind velocity is low in the early morning and high in the early night. The lowest wind speed is 4.44 m/sec at 5:15 AM, and the highest wind speed is 11.92 m/sec at 8:00 PM. According to the simulation results, the maximum wind power output is 744 kW at 8:00 PM and the minimum is 48 kW at 5:15 AM.

Fig. 3. A-Lae- Pone village map.



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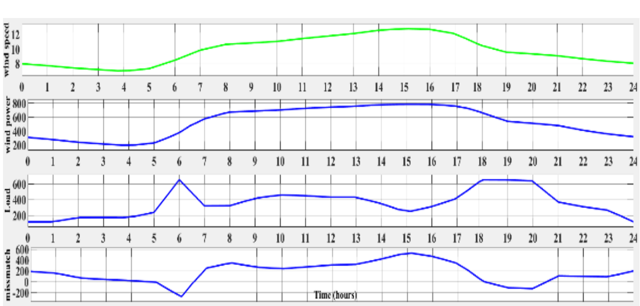

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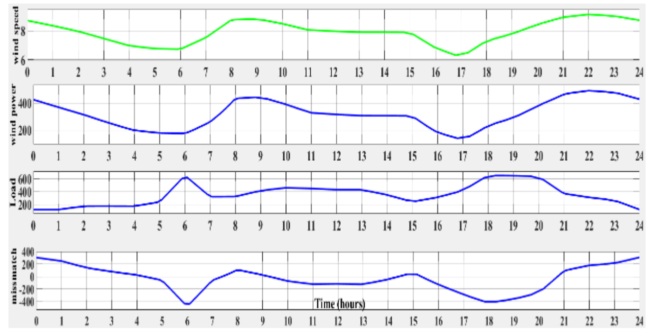

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Fig. 4. Comparison of wind speed, wind turbine output, load demand, and power mismatches for (a) summer, (b) rainy, and (c) winter.

On rainy days, the maximum wind power output is 780 kW at 8:00 PM and the minimum is 195 kW at 4:00 AM. In comparison to the summer, the wind turbine output increases as the wind speed increases. The peak load is 652.3 kW at 6:00 PM, and the lowest load demand is 118.5 kW at 12:00 AM. Based on the above values, the power mismatch is calculated as +528 kW maximum at 3:15 PM and -271.2 kW minimum at 6:00 AM.

In the winter, the range is between 6.17 m/sec at 5:00 AM and 9.14 m/sec at 10:00 PM, which is the smallest among the three seasons.

6. DESIGN PROCEDURE FOR THE SYSTEM

For design consideration of the wind+CAES system, first the annual weather conditions are collected from NASA, while the annual load demand profile is estimated from site visits and surveys. Wind power output can be calculated by using equation (1). And then, the comparison between the wind power generation and the load demand can be calculated by using equation (2). From these results, if the surplus energy is available, charging process is on, the compressor will be energized to store the energy. If so, optimal sizing for the compressor and storage tank will be designed for the charging process. If the available wind power output is not enough to meet the required load demand due to the low wind speed, the discharge process is on, and the stored energy from the tank will energize the turbine to run the generator for the electricity distribution [12].

In the modeling of the CAES integrated wind generation system, the main system components are load demand, wind energy generation, CAES power command, and the CAES system. The single stage of CAES is expressed by the

$$C_pT_1[(\frac{P_1}{P_{in}})^{\frac{n-1}{n}} - 1]$$ [13, 14].

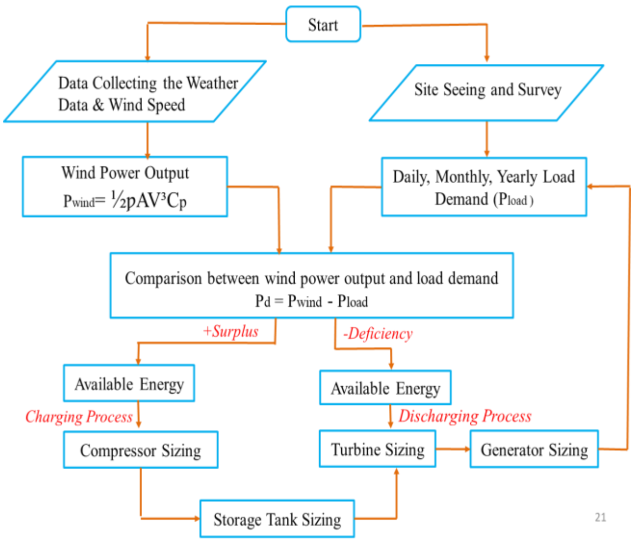


Fig. 5. Procedure for the wind+CAES system.

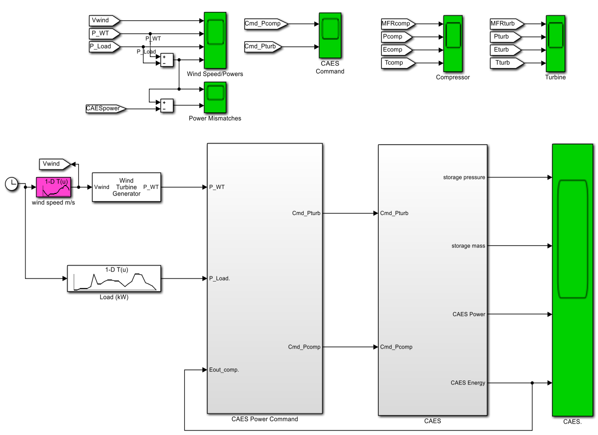


Fig. 6. Simulation model with main system components: load demand, wind energy generation, CAES power command, and the CAES system.

7. RESULT AND DISCUSSION

7.1 Compressor model

The compressor is operated based on CAES's compressor command [15]. Although the compressor operation is based on the CAES command, there are some additional limitations for actual operation, such as:

i. Minimum power limit of the compressor (100 kW)

ii. Energy Limit of CAES tank (2.8062×10^3 kWh)

iii. Maximum pressure limit of the CAES tank (30.00 bars)

Based on the CAES command and following the above limitations, the compressor operates as shown in the second display of Fig. 8. As the compressor operates, this energy is about 1817.2 kWh for a typical summer day. In the 4th display in Fig. 8 (a), the compression time to store is about 7.12 hours in summer.

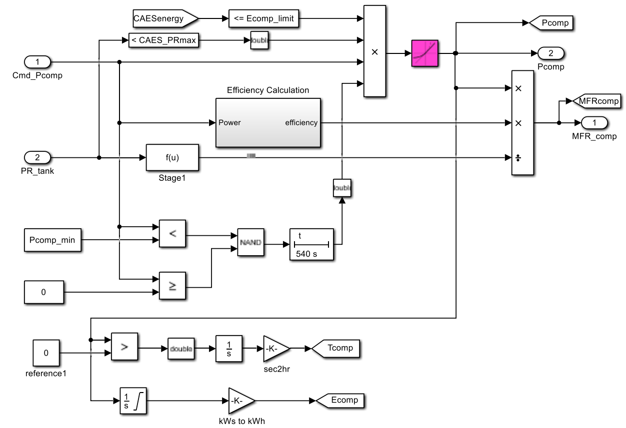
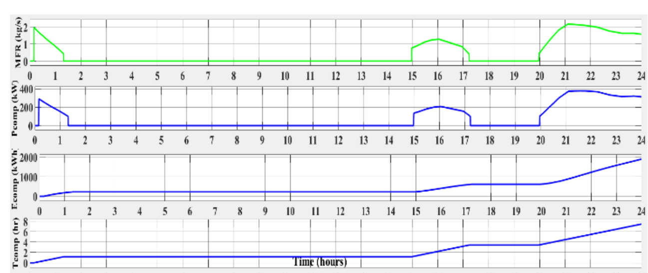


Fig. 7. Compressor model

During the rainy season, the compressor is mostly used late at night and during the day. Total energy is about 3000 kWh, which is much higher than summer energy (1800 kWh). The compressor consumes approximately 2903.7 kWh of energy. The 4th display in the figure is the total storage time of the compressor, which is about 9.67 hours on a rainy day.

In winter, compressor output power is smaller compared to other seasons. The compressor uses about 1000 kWh energy on a typical winter day. (In summer, it is 1817.2 kWh, and in the rainy season, it is about 2903.7 kWh.) The 4th display in figure is the storage time, it is about 5 hours in the winter day while it is about 7.12 hours in the remaining seasons.



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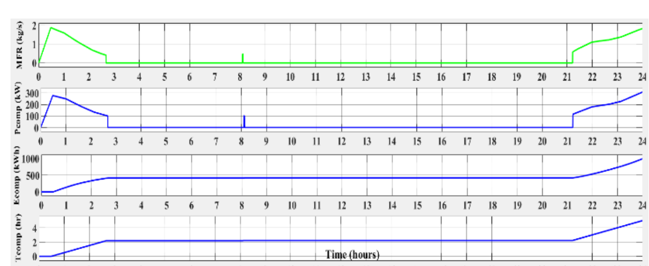

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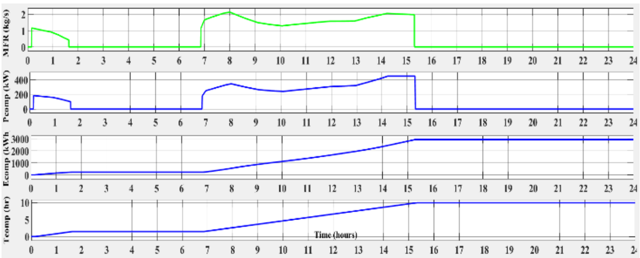

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Fig. 8. Simulation result of compressor in (a) summer, (b) rainy, and (c) winter.

7.2 Turbine model

The turbine is also operated based on CAES's turbine command [15]. The turbine operation is also based on CAES command, and limitation conditions as follows:

i. Minimum pressure of the CAES tank (10 bars)

ii. Maximum pressure of the CAES tank (30 bars)

iii. Minimum power of a turbine (50 kW).

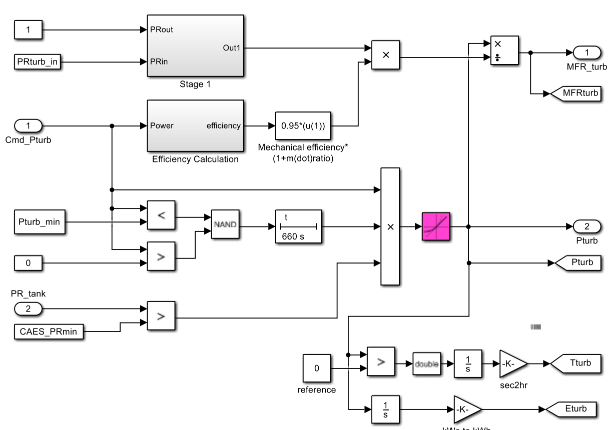
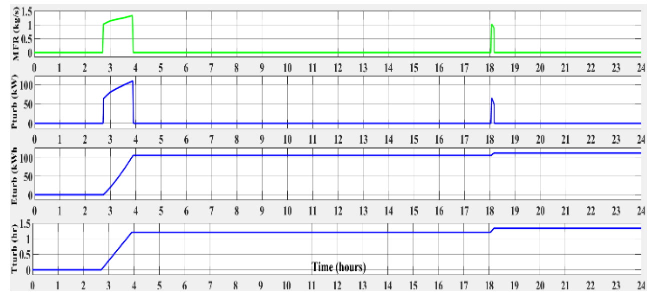


Fig. 9. Turbine model.

Based on the CAES command and following the above limitations, the total supply of energy from the turbine is about 69.00 kWh. The 4th display in Fig. 10 is the turbine expansion time, and according to the simulation result, it is about 0.905 hours in summer. In the rainy season, the turbine operates only between 5:00 a.m. and 6:00 a.m. The total supply of energy from the turbine is about 99.5 kWh, and the turbine operating time is about 0.605 hours on a rainy day. In winter, the turbine operates only in the early morning. But turbine output power is higher compared to other seasons due to low wind speed and high load demand. The total supply of energy from the turbine is about 310 kWh for a typical winter day. The fourth display in the figure is for turbine expansion, it is about 1.1 hours in a winter day. (It is about 0.905 hr in the summer and 0.609 hr in the winter.)



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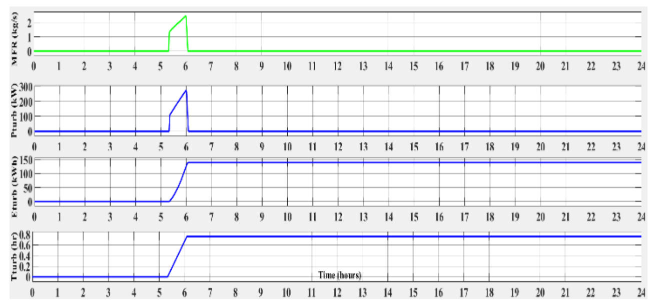

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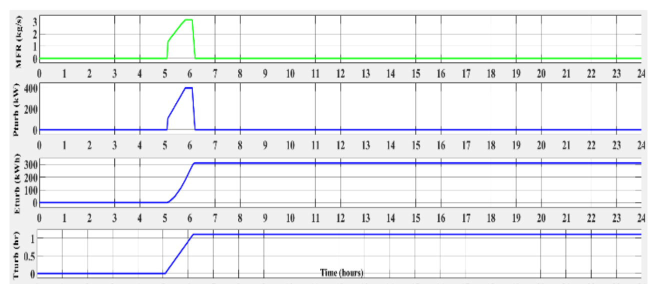

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Fig. 10. Simulation result of a turbine in three seasons.

7.3. Storage tank model

In this model, the storage cavern is considered the aboveground tank.

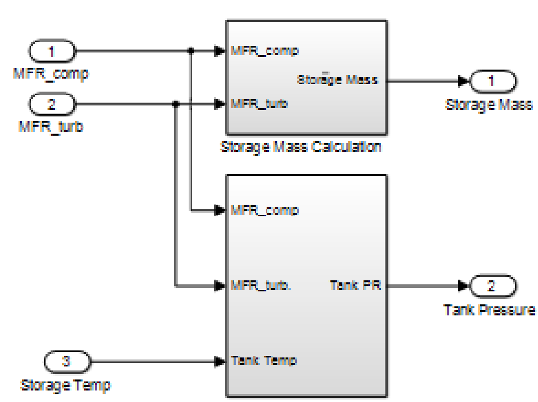
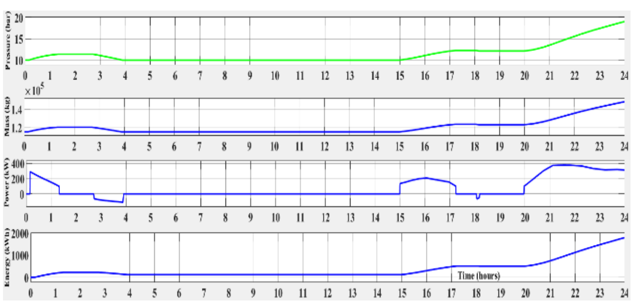


Fig. 11. Storage tank model

In the summer of Fig. 12, CAES was charged at its maximum from 0 to 4 hours when the wind power generation was greater than the consumer load, which is a maximum of 380 kW. This storage amount was later used for the maximum deficiency power mismatch of 100 kW. The analysis with CAES showed an absolute compression of about 19 bars and a maximum energy capacity of 1750 kWh. And the CAES was fully charged with its maximum air mass of 148500 kg.

In rainy weather, CAES was charged late at night and during daytime hours. This surplus amount of energy was later used to meet the maximum deficiency demand of 242 kW. The analysis with CAES was done at 24 bars and a maximum energy capacity of 2800 kWh. The CAES tank was fully charged at an air mass of 167000 kg.

In the winter, CAES is charged at night, which is not significant compared to other seasons. This energy was stored at 400 kW. CAES was initially fully charged to about 13.25 bars and a maximum energy capacity of 685 kWh. The simulation results during winter show a maximum air mass of 127250 kg to fully charge the CAES storage.



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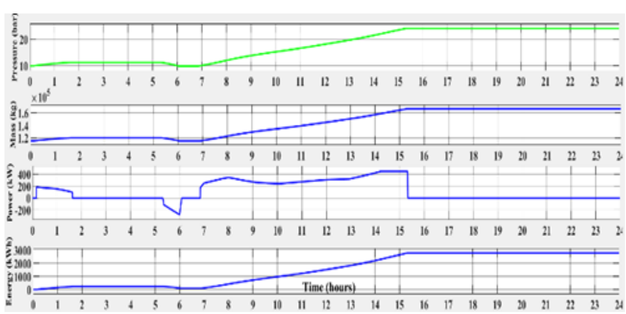

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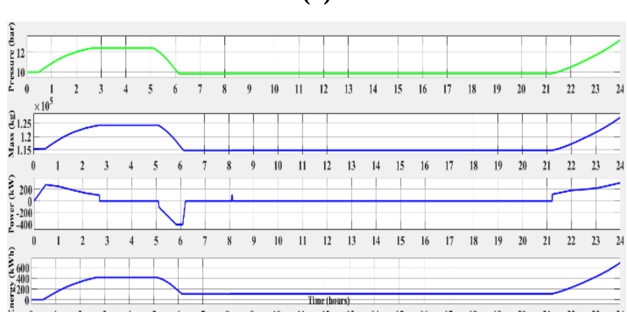

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Fig. 12. Simulation result of CAES in three seasons.

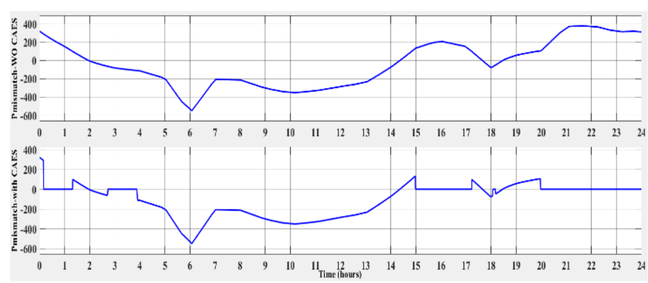
7.4. The difference between Without CAES and With CAES

Fig. 13 shows the difference in power mismatches between without CAES and with CAES in three seasons.

In summer with CAES, the power mismatch is nearly zero or very small for the 0:00-3:30 hour and the 15:00-24:00 hour. Between 3:30 and 15:00, the difference is large because the load power demand is high and the WTG power output is small.

In a rainy day with CAES, between 15:30 and 18:00, the positive power mismatch is large as the load power demand is small and WTG power output is high. Between 18:00 and 21:00, the negative power mismatch is large as the load power demand is high and the WTG power output is small. Therefore, CAES can reduce the power mismatch to some extent and supply the required load power demand at low wind speed conditions.

In the winter, the mismatch is large compared to the rainy season. With CAES, the power mismatch is nearly zero or extremely small for 0:30-2:30 hours and 21:30-24:00 hours. Between 15:00 and 21:00, the negative power mismatch is large as the load power demand is high and the WTG power output is small. Compared to without CAES, the power difference is reduced due to the stored energy in the tank at high wind speeds.



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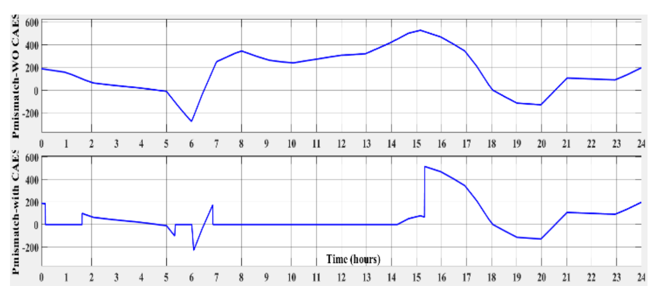

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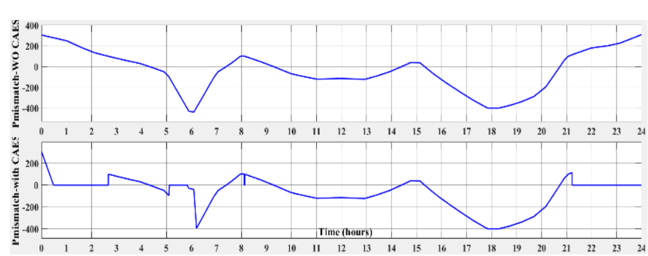

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Fig. 13. Simulation result of the difference between being CAES and not being CAES during three seasons.

8. CONCLUSION

In this research, effective usage of the storage system on a seasonal basis is presented. For this research, the detailed research area is carried out at A-Lae-Pone village, Sidoktaya township, Magwe division. The daily consumer load demand is obtained from site visits and surveys, and the available wind speeds for three different seasons are based on NASA. In this paper, a 650 kW wind turbine with an integrated CAES has been modeled and simulated in order to optimize the system design parameters. Based on these data, the detail design calculations, the modeling, and the simulations for the CAES system are done using Matlab/Simulink software. This result shows that the CAES could play the main role in reducing the electricity outage due to the required volume of the tank size of 2838.79 m^3 and the energy to be stored in the tank of 3000 kWh during three seasons. It has been shown that CAES may solve as an efficient energy storage technique for the problem of intermittent wind energy in Myanmar. For further research, the cost comparison should be done by comparing with other storage systems.

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