Analysis of compressed air energy storage for large-scale wind energy in Suez, Egypt

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Abstract

Renewable energy systems are considered essential green energy technologies that could replace a considerable proportion of the current fossil fuel-based electricity generation systems; hence the interest in these technologies is on the rise. However, due to the intermittence nature of most of the renewable energy sources, in particular wind and solar, there are major concerns with the large integration of these technologies in many of the current grid systems. This paper presents a parametric analysis of sizing a large-scale energy storage system that may help to stabilize energy supply based on large-scale grid integration in Suez area in Egypt. The system is based on a Compressed Air Energy Storage, which has the ability to accommodate a large volume of energy from large-scale wind energy integration to the Suez electricity grid system. The paper analyses the characteristics of Suez grid system and the expected wind generation, based on the current integration projections. The results show how compressed air energy storage could add value to the installation of large-scale wind farms in the Suez area in Egypt and indicate the technical ability and successful operation of the proposed system under certain circumstances of the Suez weather conditions.

Keywords: compressed air energy storage; CAES; large-scale wind energy integration; Egypt

1 INTRODUCTION

Energy demand is increasing worldwide on yearly basis and has almost doubled over the last 30 years, and it is expected to grow steadily over the next few years [1]. The increase in energy demand is mostly due to the growing global population and urbanization, which are continuously growing as well. The increase in energy demand requires an increase in energy production to meet the additional demand. Thus, more investment in power generation plants and infrastructure is needed to meet the needs. However, there exists large untapped potential in renewable energy resources, which are not only unlimited but could also help to meet the increase in demand and to alleviate environmental risks including greenhouse gas effect.

On the other hand, most of renewable energy sources are intermittent and may cause a considerable variation in electricity production, especially in the case of solar and wind energy. These pose both technical and economic challenges when these energy systems are integrated on a large-scale. Wind energy technology poses even bigger problems when it comes to intermittency as the output variation is annual, seasonal, diurnal and hourly; so innovative solutions are needed to accommodate the wind intermittency effect on the grid. There are several different technologies which are currently under research to minimize the effect of intermittency and the probable mismatch of their output and the demand [2, 3]. One of the areas under exploration is the energy storage systems. When large-scale renewable energy systems such as wind energy are considered, the most common options are large-scale storage systems which are either Compressed Air Energy Storage (CAES) or Pumped hydro. The pumped-hydro storage is a well-established technology with many systems all over the world. These have high storage capacity which makes them suitable for wind energy applications; however, their main disadvantages are the high capital cost and possible water loss through evaporation. Additionally, a suitable location must be found for incorporating these systems, which have to include a difference in heights between two reservoirs that is necessary for pumped-hydro system operation. The CAES systems are the focus of this paper, and they are more suitable as they have large storage capacity and have relatively shorter starting time [4, 5]. On the other hand, CAES systems have some
drawbacks which include the inevitable use of natural gas for heating up the air for the expansion stage and also have lower efficiency compared with Pumped Hydro. When the wind power is higher than the load demand meaning that the supply is higher than the demand, the air is compressed using the compressors (charging period of the CAES unit); the air is stored in an underground air reservoir with minimal heat loss. When the wind power is low to meet the demand, the compressed air is released from the underground air reservoir to power the gas turbines and generate electricity which is fed back to the grid (CAES unit is in discharging mode) to meet the demand.

2 CAES UNIT DESCRIPTION

CAES consists of several components which are quite similar to those of a gas turbine system. The main components include compressors, underground air reservoir, turbines, combustion chambers, heat exchangers and sometimes additional thermal stores. The operation of the system can be divided into two main operation modes, compression and expansion. When the air is compressed during the charging phase, the air under high pressure gets hot, and therefore intercooling is usually used between the different stages of compression to reduce the air temperatures for the next compressor, and finally to the underground air store. In doing so, the work done by the compressors is reduced by intercooling. There are two types of CAES system. Firstly, a diabatic system which does not employ a thermal energy store as shown in Figure 1a. Hence, it does not store extra thermal energy which could be used to pre-heat the air for improved turbine efficiency. These systems have a low overall efficiency. A diabatic system usually uses gas combustion in order to boost the temperature of the air for expansion process. An adiabatic system has a separate heat storage arrangement that is used to store the thermal energy taken during the compression process and this is used to pre-heat the air before entering the combustion chambers. Also, the use of the heat taken from the compression stage helps to reduce the amount of heat needed for the turbine inlet air flow and hence reduction in the fuel use in the gas combustion. In practice, systems may strive towards an adiabatic system with the setup shown in Figure 1b; however, some heat has to be added before the air is allowed into the turbines. The design and implementation of such a system poses many difficulties; however, the isentropic efficiency is expected to reach around 70% for an adiabatic system with no fuel consumption [6, 7].

Several researches had been carried out for CAES systems in order to increase the system efficiency. Each component in the system has been studied to optimize the performance under the expected operating conditions. One research has looked at the economics behind different energy storage options for grid connected wind generation applications [8]. A number of CAES systems are examined economically on both small and large scale using studies and data from existing plants [8]. The feasibility of creating an adiabatic CAES system in the so-called AA-CAES Project (Advanced Adiabatic Compressed Air Energy Storage), such that no additional heating is required other than the thermal energy storage (TES) has been investigated. The research also showed that the higher the level of wind penetration to the grid, the higher the economic benefits of adiabatic CAES will be [9]. For the AA-CAES, the TES was simulated under different conditions and the effect of these on the overall heat utilization was assessed [10]. A number of research papers have been also produced which modelled CAES systems with similar setup [11, 12]. Research has been done using modelling and comparing the results with the existing Huntorf system (1st implemented CAES system in Germany) for validation [11]. The effect of different parameters on the isentropic efficiency of the system was researched and modelled by Hartman et al [12]. The research shows that a realistic estimation of efficiency between 52% and 62% is possible using adiabatic CAES system.

3 EGYPT CASE STUDY

3.1 Overall energy situation
Electricity supply in North Africa, especially in Egypt, is a major issue as the power supply systems are struggling to meet the load on a daily basis and power cuts, for example, have become a

![Figure 1. (a) A diabatic system; (b) an adiabatic system [6].](https://example.com/figure1.png)
routine practice in the Egyptian grid. The electrical energy load in Egypt increases annually as shown in Figure 2 from 2007 to 2011 [13]. The peak demand has increased by 26% from 2007 to 2011 with an annual increase of 6.5%. Therefore, based on the average rate of energy increase in the recent 5 years, it is expected that the electrical energy load will increase by 58.5% by 2020 compared with 2011 numbers.

The variation in the energy load pattern in a summer day in Egypt is shown in Figure 3 [13]. A very similar pattern takes place in winter but with lower load and lower peak load.

The application of renewable energy technology in Egypt is very limited despite the large untapped resource for such energy sources, especially solar and wind energy. Currently, there are plans to increase the renewable energy supply in Egypt immensely in the next decade to cover 20% of the total electricity supply. Of this 20% energy share, 12% is expected to be supplied by wind energy. This means that the installed wind energy capacity will increase from 780 MW to 7.2 GW by 2020 [13]. Wind energy is widely available in Egypt and is particularly high in Suez area. The wind map for Egypt is shown in Figure 4 [14]. Therefore, it is expected that this massive increase in wind energy supply will cause large levels of penetration into the grid and the issue of energy storage becomes essential in order to minimize the effect of wind intermittency on the stability of the fragile Egyptian grid [15].

3.2 Wind electrical supply in Suez area

There are three planned projects in the Suez area totalling 580 MW of installed capacity [15]:

1. 180 MW farm financed by the Spanish Government;
2. 200 MW farm implemented by MASDER;
3. 200 MW farm implemented in cooperation with German Development Bank (KFW), French Development Agency (AFD) and the European Investment Bank.

It is therefore important to analyse the feasibility of implementing CAES systems in Egypt in order to accommodate the proposed wind farms to be installed in the Suez Area of the Egyptian grid system. A model is developed using MATLAB software to simulate the effects of implementing the suggested CAES system on the overall electrical output from the wind farms planned in the Suez area. The model also looks at the implications of this on the overall electrical supply to the load, how this could benefit the Egyptian grid and minimise the concerns of high levels of wind penetration.

The geology of the Suez area close to the site of wind farms is formed of basement rocks [16]. This geology is suitable for excavation and hence creating an underground air reservoir (cavern) is possible. This type of geology is less favourable economically compared with molten salt, for example, as rocks excavation could cost around $30/kWh compared with $1/kWh for salt caverns. However, several studies have been conducted on the possibility of operation of CAES in underground rock caverns in terms of air tightness and stability; and most of these have shown that this geology type would be suitable as an underground cavern for operation of CAES, with a possibility of operation under shallow depth for pressure between 50 and 80 bars [17].

According to ref. [18], the cost of initial installation for a 300 MW CAES is around $135 M for a salt dome cavern which rises up to around $190 M for the rock caverns ($30/kWh of excavation) where initial costs include acquisition, space and installation costs. Fixed O&M (operation and maintenance) costs of $40 M is estimated which includes projected annual costs for parts and labour, plus property taxes and insurance [18]. Therefore, the total fixed cost of CAES system for a 300 MW plant could be estimated at $230M for rock caverns [18]. The running cost which includes the price of fuels, for example, are quite variable and depends on the amount of fuel used and the corresponding fuel price. The benefit-to-cost ratio is dependent on the prices of electricity in the CAES location for peak and off-peak times; but it is reported that this could get as high as 3.6 [18]. This shows that CAES systems could be very beneficial for wind load-levelling if an appropriate geology of underground reservoir is available which is true for the Gulf of Suez.

![Figure 2. Yearly peak electrical energy load in Egypt.](image)

![Figure 3. Variation in the energy load in June 2009.](image)
The current work focuses mainly on the technical aspects of Compressed Air Energy Storage.

4 MATHEMATICAL MODELLING OF THE CAES SYSTEM

The main components which are modelled include the power supply from wind turbines, the CAES compressors, turbines, heat exchangers, underground air reservoir and combustion chambers.

4.1 Available power to the CAES

The power output \( P_{\text{wind}} \) from each wind turbine can be estimated using the following equation:

\[
P_{\text{wind}} = \frac{1}{2} \rho A C_p U^3
\]

where \( \rho \) is the density of air, \( A \) is the swept area by the rotors, \( C_p \) is the power coefficient of the turbines and \( U \) is the wind speed.

The difference between the supply and the demand is calculated by following equation:

\[
P_d = P_{\text{wind}} - P_{\text{load}}
\]

4.2 Modelling of the compressed air energy storage

4.2.1 Sizing and arrangement of compressors

The excess wind power is used to operate the compressors when there is excess in the supply. The equations governing each...
compression stage are given by [12]:
\[
\frac{P_2}{P_1}^{(y-1)/\left(\eta_c \times y\right)} = \frac{T_2}{T_1}
\]
(3)

where \(\eta_c\) is the polytropic efficiency of the compressors, \(y = 1.4\) is the adiabatic index, \(P_1\) and \(T_1\) are the pressure and temperature of air before the compression, respectively, \(P_2\) and \(T_2\) are the pressure and temperature of air after the compression, respectively.

The value of the polytropic efficiency is dependent on the capacity of the total output power used. The compressors are sized using multiple parallel chains with compressors in series to cater for high powers coming for a more realistic setup. In order to cater for the entire range, the power ratio of each parallel chain is split such that the power halves each time, for example:

- 2:1 for two parallel chains
- 4:2:1 for three parallel chains
- 8:4:2:1 for four parallel chains etc.

This means that for two parallel chains, the compressors could cater for 1/3 times the maximum power input to them. For three parallel chains, 1/7 times of the maximum output and for the four parallel chains, 1/15 times of the maximum output. For example, in the Matlab simulation presented later, the four parallel chains configuration is used which allows the lowest compressor power catering, 1/15 of the maximum power input to the compressors. From performance point of view, the higher the number of chains the better the performance, because different compressors will be catering for higher ranges of power, hence compressors will be working close to their rated values and hence at a higher efficiency. However, from an economic point of view, higher number of parallel chains means higher number of compressors and therefore higher cost. The number of chains is determined by the desired lowest output. This method also ensures that the mass flow rate entering each parallel chain is limited. A number of turbines are used in parallel at different stages of expansion in order to supply high power outputs in the same manner as that of the compressors. Figure 5 shows the arrangement of the simulated system where multiple parallel chains are used for both the compressor and turbine side. Figure 5 shows the configuration of the CAES system with the different elements in the system.

### 4.2.2 Heat exchangers in compression side

In this heat exchanger, air flows from the compressors to the underground air storage while heat transfer fluid flows from the TES extracting the heat from the air and back into the TES. For a single stage of heat exchangers on the compressor sides, equations (4) and (5) provide the respective air and heat transfer fluid stream outlet temperatures:

\[
T_2 = T_1 - \varepsilon \times (T_1 - T_{x0})
\]
(4)
\[
T_{x1} = T_{x0} + \frac{\varepsilon \times \dot{m}_c \times C_{p_{\text{air}}} \times (T_1 - T_{x0})}{\dot{m}_{\text{f}} \times C_{\text{fluid}}}
\]
(5)

where \(T_1\) and \(T_{x0}\) are the inlet temperatures of the air stream and the heat transfer fluid stream, respectively. \(T_2\) and \(T_{x1}\) are the outlet temperatures of the air stream and the heat transfer fluid stream, respectively. \(\varepsilon\) is the effectiveness of heat exchangers.

### 4.2.3 Sizing of the underground air storage cavern

In the underground air storage (cavern), when air under high pressure is added to cavern, the internal energy inside the cavern increases and vice versa when the air is taken out in the expansion stage. The rate of change of the internal energy in the cavern is given by

\[
d\left(\frac{M_{\text{total}}(t)U}{dt}\right) = \dot{m}_c H_c - \dot{m}_{\text{t}} H_T - h A_{\text{cav}} (T_{\text{cav}} - T_{\text{wall}})
\]
(6)

Terms 1 and 2 in the right-hand side are the change in enthalpy due to the flow in and out of the cavern. \(M_{\text{total}}(t)\) is the instantaneous total mass of air in the cavern at a given time which varies with the incoming air flow from the compressors or outgoing air flow to the turbines. The last term is the heat losses to the surroundings where \(h\) is the heat transfer coefficient between the cavern wall and the air.

For an ideal gas:

\[
U = H - \frac{P}{\rho}
\]
(7)

Solving equation (6) as done by Raju and Khaitan [11] will result in

\[
\rho(t) C_p \frac{dT}{dt} + \frac{\dot{m}_c C_p (T_{\text{cav}} - T_{\text{inlet}})}{V_{\text{cav}}} - \frac{dP}{dt} + h_{\text{eff}} (T_{\text{cav}} - T_{\text{wall}}) = 0
\]
(8)

Equation (8) describes the overall heat transfer balance based on the volume of the cavern. \(h_{\text{eff}}\) is the effective heat transfer coefficient and is expressed as a function of air flow rates in and out of the cavern [11, 12]. \(dP/dt\) represents the variation in pressure with time during the system operation. \(\rho(t)\) is the compressed air density as a function of time; the density of air changes with time as the mass of air in the cavern changes.

Using the ideal gas law

\[
PV = nRT
\]
(9)

Equation (8) is solved in order to estimate the new cavern temperature and hence the new cavern pressure. \(M_{\text{total}}\) changes according to the air flow rates into the cavern. \(T_{\text{cav}}\) is also changing during the operation of the system and denotes the overall
cavern temperature. Therefore, the pressure variation during the operation of the cavern is calculated using the instantaneous values of the temperature and mass of air in the cavern. Taking the molecular weight of air as 0.029 kg:

\[
P_{\text{cav}} = \frac{M_{\text{total}} \times R \times T_{\text{cav}}}{0.029 \times V_{\text{cav}}}
\]

where \(M_{\text{total}}\) is the mass of air in the cavern, \(R\) is the universal gas constant, \(T_{\text{cav}}\) is the air temperature in the cavern and \(V_{\text{cav}}\) is the volume of the cavern.

4.2.4 Sizing of the turbines (power generation part)
The output from the system is due to the work over the turbines and this is dependent on the enthalpy flow of the stream of air through the turbine and is given by

\[
\dot{H} = n \tau C_{p,\text{air}} T_{\text{air}}
\]

where \(C_{p,\text{air}}\) is taken as 1005 J/kg K. The polytropic equation for expansion process is given by

\[
\left(\frac{P_3}{P_4}\right)^{\frac{\gamma (\gamma - 1)}{\gamma}} = \frac{T_3}{T_4}
\]

where \(\eta_p = 0.85\) [19], and is the polytropic efficiency of the turbine; \(\gamma = 1.4\) is the adiabatic index; \(P_3\) and \(T_3\) are the pressure and temperature before expansion in the turbine, respectively; \(P_4\) and \(T_4\) are the pressure and temperature after expansion in the turbine, respectively.

4.2.5 Sizing of the TES
The proposed design for the TES medium is using sensible heat storage in the form of a concrete block. Embedded copper pipes are installed in the concrete storage. The number of embedded pipes is determined by sizing the concrete storage in a way to provide uniform temperature distribution. Concrete is chosen due to its reliability and low relative cost. The concrete storage was sized to be able to intake most of the heat from the compression stage and re-use the heat for the air discharged from the cavern before entering the turbine. The concrete storage is divided into 50 equal sections in order to take into account the temperature gradient across it. Finite difference method is used to calculate the temperatures for each section at each time step. The following equations are used for calculation of the thermal resistance for each section for every time step of the simulation. Conductive heat resistance for each section is given by:

\[
R_{\text{cond}} = \frac{\ln(r_0/r_i)}{k_c \times 2 \times \pi i \times L_{\eta}}
\]

where \(r_i\) is the radius of the pipe, \(r_0\) is half the distance of the...
gap between the pipes, \( k_c \) is the thermal conductivity of the concrete and \( L_p \) is the pipe length.

The Reynolds number is calculated for each time step. Since the fluid temperature is changing every second; and the fluid speed, density and viscosity are also changing with temperature. Hence the Re number is also changing with temperature and hence with time.

\[
\frac{d\, Re}{dt} = \frac{D \times \left(\frac{v_{\text{fluid}}}{dt}\right) \times \left(\frac{d\rho}{dt}\right)}{d\mu/dt}
\]

where \( D \) is the pipe diameter, \( v_{\text{fluid}} \) is the fluid velocity, \( \rho \) is the fluid density, \( \mu \) is the fluid viscosity.

Using the Reynolds number, the fluid Nusselt number is calculated based on the fluid flow whether it is turbulent or laminar. The convective heat transfer is calculated using following equation:

\[
H(t) = \frac{\text{Nusselt}(t) \times K(t)}{\text{Pipe diameter}}
\]

The total resistance is then given by

\[
R_{\text{total}} = \frac{1}{H(t) \times A_p} + \frac{\ln(r_o/r_i)}{k_c \times 2 \times \pi \times L_p}
\]

where \( H \) is the convective heat transfer related to the heat transfer fluid.

From equations (13)–(16), the heat transfer between the fluid and the thermal storage is calculated for every section at each time step.

### 4.2.6 Sizing of the heat exchangers and combustion chambers (turbine side)

These heat exchangers are similar to the ones in the compressors side. In this case the air flows from the air cavern and gains heat before entering the turbine by using the heat in the thermal storage. The temperature of the air stream discharged from the cavern after the heat exchange with the heat transfer fluid is calculated using the following equation:

\[
T_{\text{cav1}} = T_{\text{cav}} - \varepsilon \times (T_{\text{cav}} - T_{x13})
\]

The temperature of the outlet of the heat transfer fluid after the heat exchange with air stream discharged from the cavern is calculated using

\[
T_{x14} = T_{x13} + \frac{\varepsilon \times m_{\text{cav}} \times C_{\text{pall}} \times (T_{\text{cav}} - T_{x13})}{m_{\text{cav}} \times C_{\text{pfluid}}}
\]

where \( T_{\text{cav}} \) and \( T_{x13} \) are the inlet temperatures of the air stream and the heat transfer fluid stream, respectively. \( T_{\text{cav1}} \) and \( T_{x14} \) are the outlet temperatures of the air stream and the heat transfer fluid stream, respectively.

The air from the cavern gains thermal energy from the thermal store and then passes through the gas combustion chamber where its temperature is increased to the required inlet temperature of the turbines. The equation for the energy requirement from the combustion chamber, \( Q_{\text{Combustion}} \), is then

\[
Q_{\text{Combustion}} = \dot{m}_{\text{cav}} \times C_{p_{\text{air}}} \times (T_{\text{turbine}} - T_{\text{cav1}}) / \eta_{c.c.}
\]

where \( \eta_{c.c.} \) is the combustion chambers efficiency and \( T_{\text{turbine}} \) is the turbine inlet temperature.

After leaving the CAES, the air splits into separate channels to the different power turbine trains, where the mass flow splits by the power ratio between these turbines as shown later in Figure 12. After the first stage of expansion, all air streams are heated back to the required inlet turbine temperatures, using gas burning or combustion chambers.

### 4.3 Description of the analytical model

The sizing and operation models of the CAES are developed and implemented using an advanced high-level technical computing language and interactive environment of Matlab R2012. Based on the mathematical formulations presented in the previous sections, a set of governing equations are established leading to the development of a transient model to predict the CAES system thermal and electrical performance with various input and output parameters. First, an analytical model was developed to provide the wind speeds of the location used in the study and the load variation of the case study. Using these inputs, the number of hours of surplus power and system deficiency are estimated and then the time for charging and discharging of the CAES are deduced. In addition, the available surplus power and the deficiency in power supply are calculated. This information is used to size all the components of the energy supply system, which include the compressors rating (flow rates handled, maximum pressure ratios and the number of parallel and series chains used to supply the required power), the turbines rating, cavern volume size, TES volume and size of the heat exchangers using some of the equations described in the previous sections. After the sizing stage is completed, the operation stage starts following a transient simulation. For each time step the equations in the previous sections are solved in Matlab and the values of the varying parameters of the system are calculated. These parameters include temperature variation in the charging and discharging modes, pressure of air in the cavern, mass flow rates of air in both modes, temperature of heat transfer fluid, temperature of the TES and power output of the CAES and the efficiency of the system. Figure 6 shows a snapshot taken for the Simulink used to perform some parts of the operational modelling.

Several assumptions are made in order to run the simulations. The maximum allowable pressure and minimum allowable pressure in the cavern are based on the geology and are estimated at 75 bars and 45 bars, respectively, which are based on previous studies of CAES systems for similar geologies of the Suez area [17].

Heat exchangers effectiveness is assumed at 85%. Temperature of the cavern wall is assumed to be 303 K.
The concrete used in the simulation was of thermal conductivity 1.4 W/m K, specific heat capacity of 971 J/kg K and density of 2400 kg/m³ [20]. Figure 7 shows the flow chart of the modelling process with its various stages. The heat transfer fluid chosen for this simulation is mineral oil. The mineral oil has good thermal characteristics and temperature range (up to 330°C) which makes it a good medium of heat transfer between the air stream and the thermal storage.

Figures 8–16 present the results of the Matlab simulation and predictions of the overall CAES system performance.

5 RESULTS AND DISCUSSION

5.1 Wind power estimation
As mentioned earlier, the planned projects in Suez, Egypt, with installed capacity of 580 MW, is simulated as a single wind farm with 193 V90–3 MW Vestas wind turbines of 3 MW each. This wind turbine is chosen based on the compatibility of the turbine characteristics with the weather data at the location. Table 1 shows the number of turbines and characteristics of the chosen wind turbines. The power curve for the chosen turbine is shown in Figure 8. Wind speed data are collected from a location in Suez Area. Using the proposed farms of Suez Egypt as a case study, the model is run and the results for this case study are presented. The collected data for 3 summer days are presented in Figure 9. These data are used to size the various components of the CAES system.

As mentioned in Section 3, the electrical load demand in Egypt is expected to increase by 1.58 times compared with the current demand. Since the wind energy supply in Egypt is expected to reach 12% of the total electrical supply in 2020 and the proposed wind farms in Suez would be 8% of the total wind supply. Therefore, the Suez wind farms will represent ~1% of the total electricity supply in Egypt. An estimate of 1% of the expected 1.58 times increase in load demand in Egypt is taken as an estimate of the load supply in the modelling of the case study.

Figure 9 shows Suez weather climate and wind speeds for a month in the summer. These data are used as input to the Matlab model and are used to predict the wind energy potential at this location. Based on the obtained results, it is shown that the wind potential in this location is relatively high; varying between 6 and 16 m/s under summer climate conditions. Another point to be observed is the daily variation in the wind speed over the 3-day period of data. The wind is highest during the midday throughout the monitoring period.

5.2 System components design
After sizing the CAES system components, the numerical simulation model was used to predict the operational behaviour of the system under real conditions. The input parameters of the load demand and the wind speeds data of the Suez location are used to calculate the percentage of load demand, the wind power expected from the proposed plants and the excess/deficiency in the power supply which are plotted in Figure 10. The positive values indicate that the wind energy supply is higher than the load demand, whereas the negative values show that the wind supply is lower than the load. Thus, according to Figure 10, the air compression process starts when the excess/deficiency power values are positive which lasted for ~18 h during the first compression stage, and then the expansion started when the excess/deficiency power values are negative and this has lasted for ~14 h during the first expansion stage. The charging
Figure 7. Flowchart of the simulation model.
and discharging periods are of course always varying due to the variation of the supply and demand.

5.2.1 Compressors sizing
The compressors are divided into several parallel chains. The number of chains is determined by the desired lowest output following the parallel chains method explained in Section 4.2 which in this case was selected as four parallel chains of compressors to allow catering for relatively low power, 1/15 of the maximum power available for the compressors. During the sizing of the system using MATLAB, it was found that for the data of wind and load demand for Suez (Figure 10), the maximum compressor power calculated from the highest surplus is 259 MW. Since this system uses four parallel chains, therefore the minimum power that this design can cater for is given by

\[
\frac{259}{8 + 4 + 2 + 1} = 17.3 \text{ MW}
\]

Figure 11 shows the compressors chains with the maximum power in each chain.

5.2.2 Cavern sizing
The sizing of the volume of the cavern is performed using statistical analysis. The air cavern is sized based on a certain output power being maintained for a certain length of time. The sizes of these are gauged statistically using the standard deviations of both the expansion power and number of consecutive hours of expansion which is calculated from the program using the historical data (excess and deficiency values calculated from wind and load demand data). The volume of the cavern to meet the above conditions is calculated as

\[
1248 \times 10^6 \text{ m}^3 \text{ (Table 2)}
\]
from the turbines which is the lowest value in the excess/deficiency curve is $\approx 331$ MW leading to four parallel chains with the maximum power output expected from each chain as shown in Figure 12.

5.2.4 TES sizing

The TES sizing was performed employing an optimization method to find the optimum size and number of pipes inside the concrete block which should maximize the overall efficiency of the system which is determined based on the amount of output power produced and the amount of heat needed from the combustion chambers. The sizing of the concrete thermal storage was done by calculating the concrete capacity needed for the number of consecutive hours the compressors are expected to operate. A total concrete volume of $24,000 \text{ m}^3$ is required for storing the heat energy from the compressors in this study (Table 3).

5.3 System operation results

In this section the operational results for the main parameters in the CAES system are discussed. Figure 13 displays the pressure variation in the air in the cavern during 3 days of the system operation. These are the results of the Matlab simulation with the variation in the pressure which are calculated and plotted against the time. As shown, the pressure increases when there is a surplus of power reaching the maximum pressure after around 16 h, and then the compressors are stopped. The pressure never reaches the minimum allowable pressure, i.e. 45 bars, indicating that there is adequate air to meet all the demand during the discharge period.

Figure 14 illustrates the temperature variation in the air in the cavern which follows a pattern quite similar to the pressure variation in the cavern. The temperature increases during
compression stage and decreases during expansion process. However, when the CAES operation stops after around 16 h, the temperature of air in the cavern does not stay constant. Since the wall temperature is at 303 K, some heat is lost to the surrounding ground as the temperature of air in the cavern is higher than that of the cavern wall temperature. Therefore, there is a slight decrease in temperature of air in the cavern until the expansion starts and hence the cavern air temperature starts to drop further as a result of air discharge.

Figure 15 shows the variation of temperature in the concrete block energy storage during 3 days of operation period. The energy in the TES is important to pre-heat the discharged air from the cavern before entering the combustion chamber for further heat addition and then expansion through the turbine.

As shown in Figure 15, the temperature in the concrete block increases from ~200°C (473 K) to reach a maximum of 318°C (591 K) for the volume of concrete chosen in this system. It can be observed that the combustion chambers is used almost all the time during the discharge mode in order to supply the extra heat required for the air before entering the turbine. Since the highest temperature reached by the concrete block during the operation is ~600 K and the turbine inlet is set at 800 K then at least 209 K is required at the expansion stage using the combustion chamber.

Figure 16 shows the heat added by the combustion chambers to the air during the expansion process. It is obvious that the heat added by the combustion chambers varies with time according to the heat available to the thermal storage. The required energy from the combustion chamber is always zero during the compression time.

6. CONCLUSIONS

CAES is a large-scale energy storage technology which could be a highly effective to reduce the effect of the intermittency of grid-integrated wind farms; as well as to solve the variable output problem associated with wind farms. A MATLAB model was developed to size and simulate the operation of the CAES system to illustrate the potential of the system in Suez Egypt. This allowed examination of the results regarding the operation and behaviour of the air storage cavern, as well as the effect on the overall net power delivered to the load.

The model has shown the potential of adding a CAES system to an installed wind farm. The results show that the CAES system is able to store and supply the load at the time where wind power is lower than the load demand. Therefore, CAES could play a large role in reducing the wind intermittency dilemma that may face Egyptian grid due to the expected increase in wind power generation to 7.2 GW, i.e. supplying 12% of the Egyptian power demand. The model simulation was based on load-levelling principle, however, for future modelling; modifications could be applied to examine the economic perspective as well, by supplying the electricity load at the times when it is most economic depending on electricity prices. Based on the results obtained from the case study considered, it has shown that CAES has a large potential as an efficient and environmentally friendly large-scale energy storage technique in Egypt and may solve the problem of wind energy intermittence and provide technical, economic and social positive impacts.
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