

# OPTIMAL MANAGEMENT OF A WIND/CAES POWER PLANT BY MEANS OF NEURAL NETWORK WIND SPEED FORECAST

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## ABSTRACT

Some of the major limitations of renewable energy sources are represented by their low power density and intermittent nature, largely depending upon local site and unpredictable weather conditions. These problems concur to increase the unit costs of wind power, so limiting their diffusion. By coupling storage systems with a wind farm, some of the major limitations of wind power, such as a low power density and an unpredictable nature, can be overcome. Furthermore, the use of time-series neural network-based prediction models aims at reducing the stochastic uncertainty of wind power.

A Matlab/Simulink model of a hybrid power plant consisting of a wind farm coupled with Compressed Air Energy Storage (CAES) is presented.

In CAES energy is stored as compressed air in a reservoir during off-peak periods, while it is used on demand during peak periods to generate power with a turbo-generator system. Such plants can offer significant benefits in terms of flexibility in matching a fluctuating power demand, particularly when coupled with renewable sources.

The model employs ANN-based wind speed forecasting to determine the optimal daily operation strategy for the storage system. As shown in the paper, the knowledge of the expected available energy is a key factor to optimize the management strategies of the proposed hybrid power plant.

A detailed economic analysis has been carried out: investment and maintenance costs are estimated based on literature data, while operational costs and revenues are calculated according to the Italian energy market prices.

## INTRODUCTION

Worldwide demand for energy is rapidly growing, threatening price stability and causing concerns over the security of supply. Thus, it looks clear that a strong deployment of renewable energy is needed, but several factors (costs, regulations, incentives) should be taken into account in a rapidly changing energy environment.

Sun, wind, tides and waves cannot be controlled to provide directly either continuous base-load power or peak-load power when it is needed. In practical terms such renewables are therefore limited to about 20% of the capacity of an electricity grid, and cannot directly be applied as economic substitutes for coal or nuclear power, however important they may become in particular areas with favourable conditions. Nevertheless, such technologies will to some extent contribute to the world's energy future, even if they are unsuitable for carrying the main burden of supply. Some of the major limitations of renewable energy sources are represented by their low power density and intermittent nature, largely depending upon local site and unpredictable weather conditions [1]. These features tend to increase the unit costs of the energy obtained by renewable sources, so limiting their diffusion and benefits [2].

A way to overcome these limitations may be the simultaneous utilization of two or more energy resources within a Hybrid Power Plant (HPP). In this case, the recourse to multiple energy sources, either renewable or traditional, can effectively mitigate the effects of their variability. Furthermore, significant climate change mitigation aimed at stabilizing atmospheric concentrations of CO<sub>2</sub> will require a radical shift to a decarbonised energy supply. Among renewable sources, wind energy has lately become very promising: wind power is currently one of the least expensive ways to produce electricity without CO<sub>2</sub> emissions and it may have a significant role to play in a carbon-constrained world.

## STORAGE SYSTEMS

Energy storage devices with the ability to store large amounts of energy for several hours could provide the necessary flexibility for smoothing the use of wind power. In this way, possibilities for market penetration can be improved. Moreover, for potential wind farm sites remote from a strong electrical connection point, energy storage could provide an alternative to grid support. There is a growing research interest in using energy storage to increase the value of intermittent energy sources in electricity markets [3], [4], [5],[6]. Fig. 1 shows the technical capability and commerce availability of these storage types [7].

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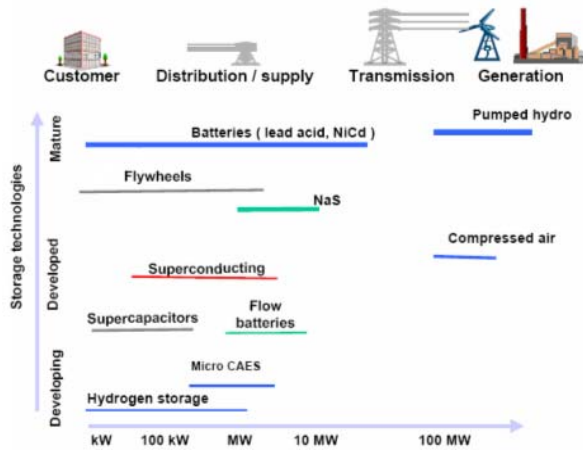


Fig. 1: Technical capability and commercial availability of energy storage types.

Pumped hydroelectric storage (PHS) and CAES provide alternative means for utility-scale power storage, as shown in Table 1. The selection of one over the other depends on several factors, including geological features locally. Compressed air energy storage and pumped hydro are the only storage technologies that offer sufficiently low storage-specific capital costs suitable for use in conjunction with large wind farms.

Table 1: CAES vs. Pumped hydroelectric.

Technology	Pro's	Con's
Compressed Air Energy Storage (CAES)	<ul style="list-style-type: none"> <li>- High capacity</li> <li>- Lower storage cost</li> <li>- Fast start-up</li> <li>- Turbine power entirely available</li> </ul>	<ul style="list-style-type: none"> <li>- Natural caverns required for large power plants</li> </ul>
Pumped Hydroelectric Storage (PHS)	<ul style="list-style-type: none"> <li>- Mature technology</li> <li>- Very high capacity</li> </ul>	<ul style="list-style-type: none"> <li>- Higher capital cost</li> <li>- Not suitable in flat regions</li> </ul>

#### COMPRESSED AIR ENERGY STORAGE

While the concept of compressed air energy storage is more than 30 years old, only two such plants exist: in Germany and the USA. Yet, a study conducted by California EPRI (Electric Power Research Institute) has estimated that more than 75 percent of the United States has geological characteristics to accommodate underground compressed air storage [8]. Similar studies might be expected in Europe but this needs to be documented.

The first commercial scale CAES plant in the world is the 290MW plant in Huntorf, Germany, operated by Nordwest Deutsche Kraftwerke (NDK) since 1978. The Huntorf plant, with salt caverns (2 caverns for a total volume of about 310,000 m<sup>3</sup>), runs on a daily cycle in which it charges the air storage for 8 hours and provides generation for up to 4 hours. The Alabama Electric Co-operative Inc. in McIntosh, Alabama, USA built the second commercial scale CAES plant [9], with a cavern capacity of about 560,000 m<sup>3</sup> and 110 MW of power generation. The plant is constructed in connection with a 100 MW coal plant and acts as a regulating capacity between the coal plant's capacity and the electricity demand. The coal plant always runs at its maximum efficiency, providing maximum power: during off-peak hours the surplus energy (exceeding the user demand) is sent to the CAES and used to compress air in the cavern. During peak hours, when the coal plant is not able to completely fulfill the electrical load, the compressed air is released and used to produce electricity by gas turbines.

The Iowa Association of Municipal Utilities is considering the installation of a combined compressed air energy storage and wind energy generating facility as part of the future electric supply for Iowa, USA. The plant will consist of a 75 MW wind farm and a 200-260 MW CAES facility. If it is built, construction costs would be \$215 million.

Table 2: Huntorf and McIntosh CAES technical data.

Technical Data	290 MW CAES in Huntorf, Germany	110 MW CAES in McIntosh, Alabama, USA
Power	290 MW @ 50 HZ	110 MW @ 60 HZ
Air Storage for	1160 MWh = 4hrs@ 290 MW	2640 MWh = 24hrs @ 110 MW
Cavern Volume	310.000 m <sup>3</sup> (2 caverns)	560.000 m <sup>3</sup>
Turbines Mass Flow Rate	416 kg/s	154 kg/s
Compressors Mass Flow Rate	104 kg/s	96 kg/s

A main drawback of an overall system combining two or more energy sources with an appropriate storage system is the significant increase of investment costs, due to larger plant complexity. For CAES, a significant contribution to the cost is the construction of the underground cavern. Therefore, careful plant design and investment analysis is required. Furthermore, the presence of two or more energy sources, the intrinsic variability and uncertainty related to renewable energy availability, the need to adopt suitable strategies to manage the energy storage system in presence of an unknown future energy demand depict a very complex scenario and make the analysis of these plants a very difficult task. To face this problem, complex model based methodologies are needed in order to determine the best plant structure and its optimal operation and scheduling, as a function of plant location and power demand [10], [11].

#### WHY WIND SPEED FORECASTING?

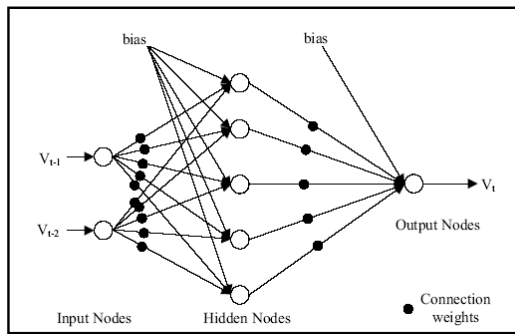
From the point of view of system operators and wind power traders, forecasting of wind speed and power is of fundamental importance. In the deregulated electricity market, power generators may be penalized if their actual generation in a given time span is too far below or above the generation level contracted. Political support systems may broaden the tolerance margins specifically for wind power plants, before penalties are induced. However, with increasing penetration of wind power, accurate forecasting will increase the economical and ecological value of wind power considerably. Furthermore, knowledge of the future incoming energy can be a powerful means for planning the daily operating strategy of the storage system.

#### WIND CHARACTERISTICS AND ANN APPROACH

Wind is one of the most difficult meteorological parameters to forecast. This is a result of the complex interactions between large-scale forcing mechanisms such as pressure and temperature differences, the rotation of the earth, and local characteristics at the earth's surface.

Prediction of wind power is important for efficient load management and operation of the wind power systems. According to the literature, a wind turbine power forecast should be based on a wind speed forecast rather than directly on power time series [12] and this has also been adopted in the present work. Time series of wind speed  $V(t)$  are transformed into a power series using manufacturers' curves.

Artificial Neural Networks (ANNs) provide an alternative way to tackle complex and not well-defined problems. ANNs can learn from examples, are error tolerant (they are able to handle noisy and incomplete data) and are able to perform with nonlinear problems. ANNs, once trained, can return prediction and generalization at high speed. ANNs have been used in many applications in controls, robotics, pattern recognition, forecasting, medicine, power systems, manufacturing, optimization, signal processing and social-psychological sciences. To set up an ANN system, requires data that represents the history and performance of the real system and a suitable selection of a neural network model.



A neural network basically consists of interconnected neurons. Each neuron or node is an independent computational unit which works as the following equation

$$y = F \left[ \sum (x_1 w_1 + x_2 w_2 + x_3 w_3 + \dots) + \beta \right] \quad (1)$$

where  $y$  is the output from neuron;  $x_1, x_2, x_3, \dots$  are the input values;  $w_1, w_2, w_3, \dots$  are the connection weights;  $\beta$  is the bias value; 'F' is the transfer function, typically a sigmoid function

Fig. 2: Typical ANN logical scheme.

#### THE FORECASTING MODEL

For the purpose of this analysis a proper combination of a NAR model (without any eXogenous parameters) and a NOE model was implemented. A 30 input ( $n_i$ ) NAR was selected for this study: one layer with 20 hidden nodes ( $n_h$ ), and a fifty epochs training phase with early stopping to reduce the overtraining problem.

The time series employed consists of the wind speed data for the year 2002 acquired at the Weather Station *ID 226* in Turi (BA), Italy, adapted to the hub height by means of the Wind Shear Formula [13]. The data, sampled each 10 minutes, are shown in Fig. 3. The first objective has been to examine and minimize the prediction error at different forecast time horizons. First of all, the given series, sampled each 10 minutes (S1) has been reduced to a hourly (S2) and daily mean values series (S3), to instruct 3 NARs (NAR\_S1, NAR\_S2, NAR\_S3). Thus, the instructed NARs have been tested to evaluate the error changing as a function of the data sampling; in all cases, the input to the NAR is composed by the past 30 values of wind speed and the output is the 31<sup>st</sup> value (1 step ahead), so that the data

sampling represents the time horizon. Table 3 shows the average error, the RMS error and the percentage error of prediction on test data.

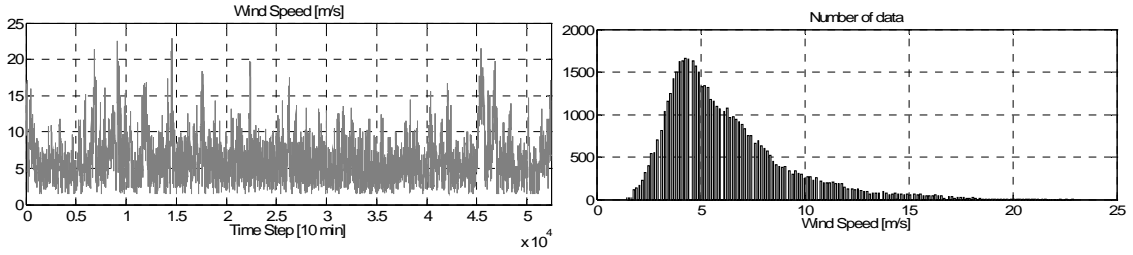


Fig. 3: Time series data and histogram.

Table 3: NARs series performance.

<i>NAR</i>	<i>Average error on test data [m/s]</i>	<i>RMS error on test [m/s]</i>	<i>% Error on test data</i>
<i>S1</i>	0.7334	1.0013	10.78
<i>S2</i>	1.0510	1.4144	15.48
<i>S3</i>	1.904	2.8663	31.87

The switch from NAR to NOE computation mode is performed as shown in the following (Fig. 4). The first prediction ' $y(t+1)$ ' is evaluated in NAR mode. At the second step, ' $y(t+1)$ ' is added as feedback to the input vector, thus allowing evaluation of the second prediction ' $y(t+2)$ ' in the NOE mode. This step is repeated until completion of the requested prediction horizon.

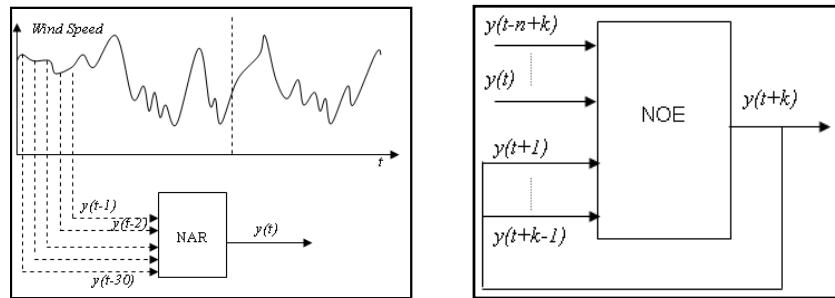


Fig. 4: Employed neural network logical scheme.

The mathematical formalization of the procedure described above yields the following relationships, where ' $n$ ' are the inputs and ' $k$ ' is the time horizon:

$$\text{NAR: } y(t+1) = F[y(t), \dots, y(t-n+1)] \quad (3)$$

$$\text{NOE: } y(t+k) = F[y(t+k-1), \dots, y(t+1), y(t), \dots, y(t-n+k)] \quad (4)$$

A NOE neural network (Neural Output Error model structure), that predicts the next ' $k$ ' values has been considered. The last 30 values of wind speed just measured are given as input to obtain:

- ♦ the next 31<sup>st</sup> value in a NAR mode
- ♦ the 32<sup>nd</sup> value from the NOE. For this second step the last 29 measured values and the last predicted value (by NAR) are used to get the next value, and so on, until the chosen forecast horizon ' $k$ ' is reached.

The forecasting model has been tested for different time horizons  $k$ ; Table 4 shows a summary of the prediction performance of the ANN NOE\_S2 (adopted for the management strategy) for different time horizons (3, 6, 12 and 18 hours). A test set with  $k=14$  (value assumed in this study) is shown in Fig. 5.

Table 4: NOE\_S2 - Performance as function of forecasting time horizon.

NOE_S2	Average error on test data [m/s]	RMS error test [m/s]	% Error on test data
$k=3$	1.1968	1.6035	17.67
$k=6$	1.3098	1.7606	19.37
$k=12$	1.5291	1.9770	22.51
$k=18$	1.6706	2.1821	24.54

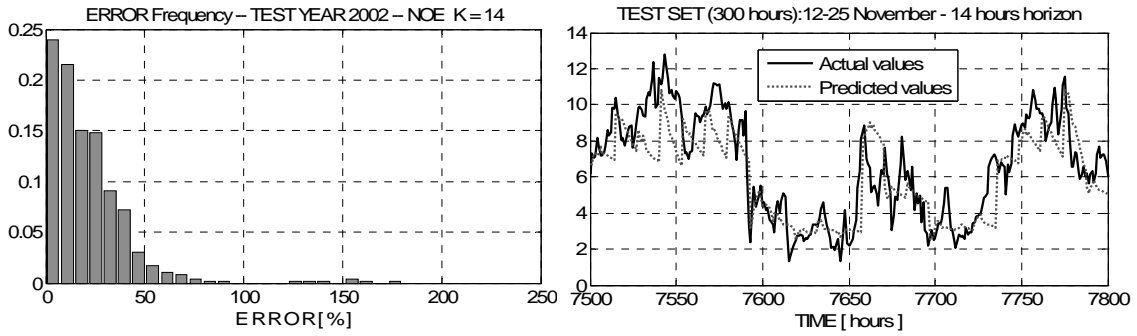


Fig. 5: NOE\_S2 k=14 (time horizon – 14 hours), error frequency and sample results.

Based on prediction performances and computational time, the proposed forecasting model appears to be suitable for implementation in an energy management strategy based on wind speed forecasting.

#### MATLAB/SIMULINK MODEL

For this study, a mathematical model of a hybrid power plant has been developed, consisting of a wind farm coupled with CAES storage. The schematic of the hybrid power plant considered is presented in Fig. 6.

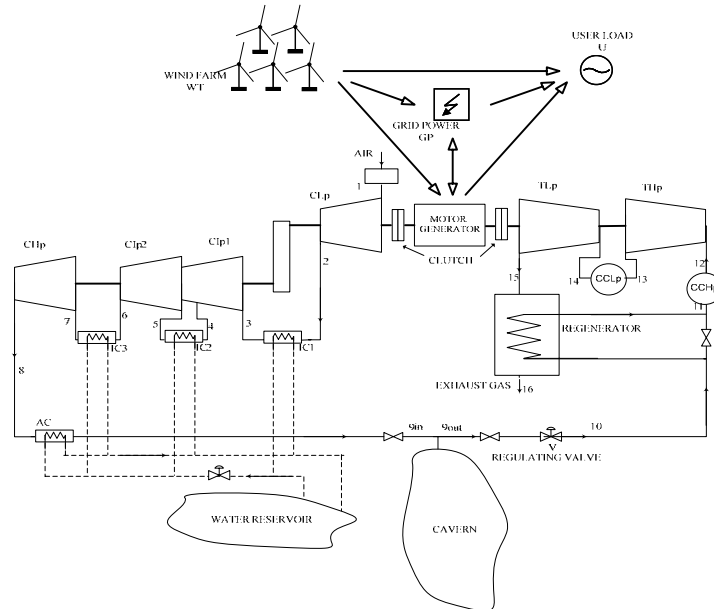


Fig. 6: Power Plant schematic.

Electricity from the wind turbines (WT) and/or from grid power (GP) powers an electric motor (M) that drives a four-stage air compressor. When air is extracted from the cavern, it is preheated in the regenerator (R), utilizing the heat at the discharge of the low pressure turbine (TLp). The air is then mixed with fuel, burned in the high pressure combustor (CCHp) and expanded in the high pressure turbine (THp). A second (low pressure) combustor (CCLp) is then used before the second expansion in the low pressure turbine (TLp). The residual heat of the discharge gas is used to pre-heat the air before the high pressure combustor in the regenerator (R).

Different operating modes can be considered in this plant. Energy from the wind turbines (WT) can be provided to the motor (M), to the grid power (GP) or directly to the user (U). Grid power (GP) can be supplied to the user (U) or to CAES, while the electricity generated from CAES can be only provided to the user (U). Consequently, the regulating valve (V) manages the corresponding charge or discharge processes. A detailed description of the adopted model is given in [14],[15] ; basic assumptions include:

- Wind-generated power is used primarily to satisfy the load.
- Surplus power either can be delivered to the compressors or sold to the grid.
- The power required by a load, above that provided by wind turbines, can be provided by CAES and/or by the grid.

The wind turbine adopted in this study is the GE 1.5sle (1.5 MW of rated capacity) [16]. Cut-in, rated and cut-out speed are 3.5, 12 and 25 m/s, respectively.

A three-body compressor train has been considered with three intercoolers and an aftercooler. According to McIntosh Power Plant operating data, the design compression ratios are:

- Low pressure:  $\beta_{LP} = 3.8$
- Intermediate pressure:  $\beta_{IP,1} = 2.6$  and  $\beta_{IP,2} = 2.4$
- High pressure:  $\beta_{HP} = 3.2$

Variable and unpredictable incoming wind power and very low off-peak power rates preclude using only wind power for driving compressors. Accordingly, to maintain operating conditions close to the design conditions, the compressors (total consumption  $\sim 50$  MW) are partly driven by the wind farm and partly (if necessary) by electricity provided by the power grid.

A conventional “un-compensated” constant volume cavern has been considered, with a volume of  $560,000 \text{ m}^3$ . Air pressure ( $P$ ) and temperature ( $T$ ) during charging and discharging processes can be computed by combining conservation of mass and energy together with the ideal gas model for air. Due to the large capacity of the cavern and the relatively short residence time, heat losses are ignored. Due to the characteristics of the expander train and to the geological and structural properties of the cavern, the maximum allowable pressure is 75 bar and the minimum allowable pressure is 48.3 bar [9].

The powertrain consists of an High Pressure (HP) and Low Pressure (LP) expander arranged in series. Thus, a two-stage expander has been considered (total production  $\sim 110$  MW), with two combustion chambers and a regenerator. The turbines’ design conditions adopted in the model are summarized in Table 5, while the off-design operation required to follow the user electric load has been estimated by an improved Flügel formula [17]. The assumed combustion temperatures are, 810 K at the inlet to the high-pressure expander and 1145 K at the inlet to the low-pressure expander [9]. Furthermore, constant rotating speed has been assumed.

Table 5: Gas turbines operating data [9]

$p_{inlet}$ [bar]	$p_{outlet}$ [bar]	$T_{inlet}$ [K]	$\eta$ [%]
<i>High Pressure Turbine</i>			
42.7	15.1	810	79
<i>Low Pressure Turbine</i>			
15	1	1145	82
$\dot{m}_T = 154$ [kg/s]			

For the assumed electric load, a typical variable load for Italy has been employed. The data (a sampling of which are shown in Fig. 7: have the same distribution and characteristics of the Italian national consumption and a maximum value of around 125 MW [18].

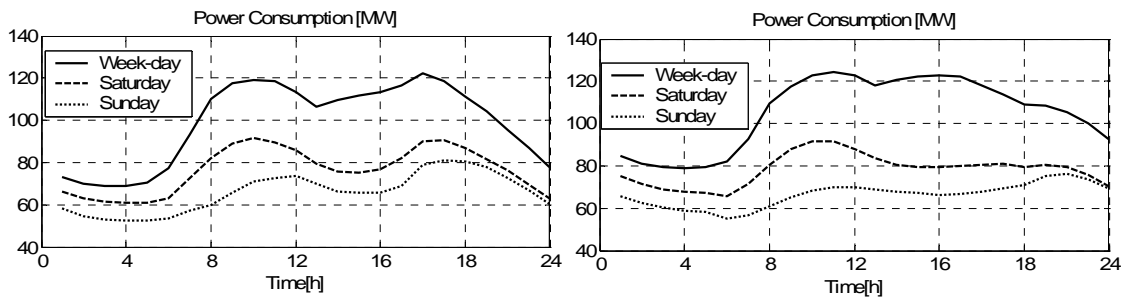


Fig. 7: Typical winter (January) and summer electric load (July).

## ECONOMIC MODEL

Owing to economies of scale in production, the capital cost for wind turbines, in €/kW, decreases as the number of wind turbines increases, ranging from about 1250 €/kW for a single turbine to about 750 €/kW for a 150 wind turbines farm. The capital costs of CAES can be simply obtained by considering power-specific and storage-specific contributions. The former is the cost to generate electricity with a storage technology, and the latter is the cost to develop a storage system. Their values are 130 €/kW and 120 €/kW, respectively [19]. In addition, the cost to develop an underground reservoir storage has to be estimated: for a solution-mined salt cavern an investment cost of 0.75 €/kWh has been assumed [19]. The balance of plant includes other subsystems required for operation of the plant (electrical, mechanical, hydraulic and miscellaneous systems); this cost is estimated as 130 €/kW [19]. Long-distance electricity transmission will be a critical component in the development of large-scale wind farms. Its cost depends on transmission capacity and on distance between power plant and grid/user. The cost has been estimated as 270 €/kW (for a transmission distance of 1000 km) [19]. The economic model evaluates the annual maintenance and operational costs due to the electrical energy and the methane purchased from the respective providers, according to the Italian energy market; the model also considers the possible revenues due to the sale of surplus electricity.

The economic feasibility of the investment is evaluated by means of Simple Pay-Back (SPB), Net Present Value (NPV) and Profitability Index (PI), defined as the ratio between present value of annual savings and investment costs. In this model a time horizon of 10 years and a capital charge rate of 10% have been assumed.

## CAES MANAGEMENT

CAES operation can be at any desired power level from 10 MW to 110 MW. The compressors and turbo expanders are sized such that one hour of operation at 100 MW requires about 1.6 hours of compression to maintain the mass balance in the air-storage cavern [9]. Typically during the week the plant operating cycle may involve one or two daily power generation periods of up to 10 hours/day with overnight compression cycles of 10 hours/day. On weekends, the plant is operated in compression up to 30 additional hours to restore the cavern to full pressure. The cavern is sized to provide a maximum of 2600 MWh of uninterrupted power generation [9].

The proposed CAES plant requires approximately 0.75 kWh of off-peak electrical energy (for storage charging) and 1.37 kWh of thermal energy per kWh of peak energy produced (design operations). For off-design power production, a decrease in component efficiency produces an increase in the required off-peak electric and thermal energy.

Without predicting the incoming wind energy, the net load above the energy provided by wind turbines, would be known only in real time. Thus, the only way to manage CAES storage/generation would be to follow the net load for a pre-fixed number of hours; the operation of CAES would be function of the load, of the wind power generation and the energy prices. Because wind speed is variable and not predictable, plant management can be a problem. Mainly, user demand might not be satisfied during some periods. So, forecasting the wind contribution is a key factor proper system management.

Knowing the incoming wind power several hours in advance helps in estimating the net load for the current day and thus determining the management strategy. For each day, before the HPP simulation is performed, the following procedure (based on Eqs. 5-8) is used to provide an effective approach to system management:

$$E_{sto} \text{ (per week)} = \int_{\text{off-peak hours}} P_{sto}(t) dt \quad (5)$$

$$E_{gen} \text{ (per day)} = \frac{1}{5} \eta_{gen} \cdot E_{sto} \text{ (per week)} \quad (6)$$

$$E_{gen} \text{ (per day)} = \int_{\text{peak hours}} P_{gen}(t) \cdot EMI(t) dt \quad (7)$$

$$\text{Savings} = f(P_{gen}(t), P_{sto}(t), EMI(t)) \quad (8)$$

As a function of the compressor mechanical consumption and of the peak-hours a day, Eq. 5 estimates the stored energy per week. Eq. 6 gives an estimate of the energy that can be generated per day, uniformly distributing the stored energy over the week and taking into account the generation efficiency (estimated through previous simulations).  $EMI(t)$  is introduced in Eq. 7 to estimate the daily generated energy. In this equation,  $P_{gen}$  represents the net electric load (above the energy provided by wind turbines) estimated by the wind speed forecasting.  $EMI(t)$  affects the daily savings of the hybrid power plant and its values are found by maximizing Eq. 8. Summarizing, the proposed strategy aims to:

- ♦ Satisfy the user giving priority to peak hours
- ♦ Use all the stored energy available for the current day

## MODEL ACCURACY

In this section, some operating data obtained during the author's visit (May 2006) to the AEC McIntosh CAES Plant, are presented and compared with the output of the mathematical model.

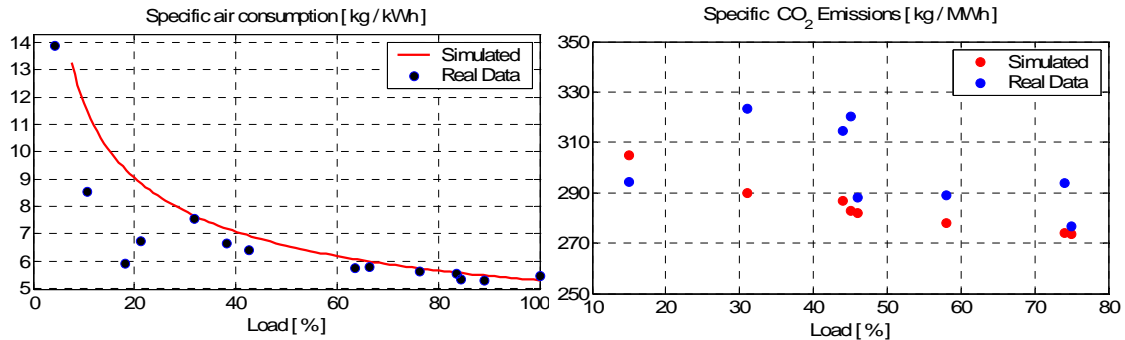


Fig. 8: Real vs. Simulated data – specific air consumption and specific CO<sub>2</sub> emissions.

In the estimation of the specific air consumption a negligible error is achieved for load greater than 30%. Furthermore, the percentage error in the estimation of specific CO<sub>2</sub> emissions ranges from 1.20% to 11.67%, with an average value of about 6%. To summarize, the presented model shows very good agreement with the real operating data of the AEC McIntosh CAES Plant. Thus it can be used with confidence to analyze different scenarios.

## RESULTS

A parametric analysis has been carried out in order to evaluate power plant performance as function of installed wind power. The analysis considers wind farm sizes from 0 to 150 turbines (0 to 225 MW of installed power), with and without the CAES plant. Sample results are shown in Table 6. The reference scenario used to evaluate economic and environmental performance is the *conventional solution* (load is satisfied only by power from the national grid).

Table 6: HPP Performance indexes.

# Turbines	Investment [M€]	Savings [M€]	SPB [years]	NPV [M€]	PI [I]	Spec CO <sub>2</sub> [kg/MWh]
0	52.9	9.63	5.5	21.0	1.36	437.6
20	85.2	18.16	4.7	55.3	1.65	394.4
50	120.9	30.14	4.0	112.3	1.93	332.3
80	153.3	41.05	3.7	164.1	2.07	272.4
110	186.3	51.58	3.6	212.6	2.14	222.0
140	220.9	61.43	3.6	253.5	2.15	180.9

In order to point out the benefits due to the presence of a wind farm as an additional energy source for a CAES facility, Fig. 9 show the most significant performance indexes normalized with respect to the case with no wind turbines. As can be observed in the following figures, benefits due to the wind farm are substantial. All of the proposed solutions show a positive and satisfactory net present value. Savings and NPV increase with the number of turbines up to about 6 and up to about 14 times the reference case, respectively.

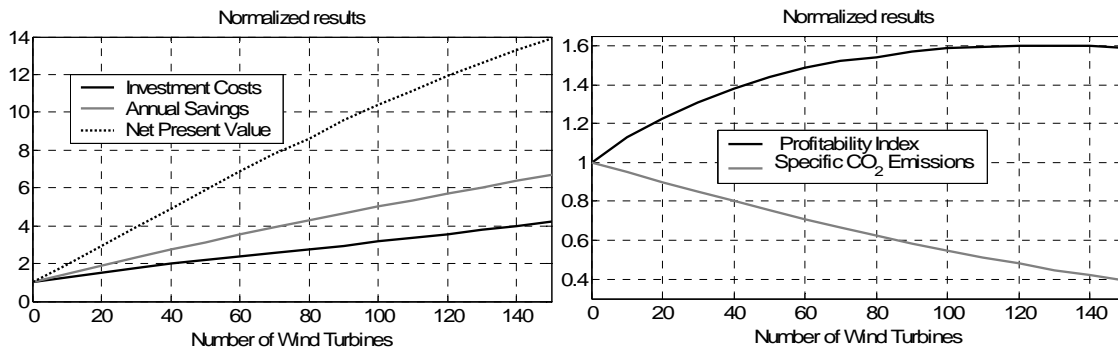


Fig. 9: Normalized investment costs, annual savings and NPV, specific CO<sub>2</sub> emissions and profitability index.

Even though the *NPV* always shows a positive trend, it is also worth analyzing the *PI*, which indicates how efficiently the investment capital is used. In fact, the *PI* trend suggests that more than about 100-110 wind turbines should not be installed because the maximum gain (+60%) is achieved for these values and further increase in the wind farm size would result in no *PI* benefits. As expected, one of the key aspects of coupling a wind farm with a CAES is the environmental impact: CO<sub>2</sub> emissions are reduced up to about 40% of the reference case.

#### EFFECTS OF MANAGEMENT STRATEGY

In order to consider the benefits achievable by means of the proposed management strategy, a similar parametric analysis has been conducted, without using the forecasted wind data. In this case, the net load is known only in real time. Thus, the only way to manage CAES storage/generation is to follow the net load for a predetermined number of hours. The duration of CAES generation is a function of the load, the wind farm size, and the energy prices.

Observe that the proposed management strategy does not change the amount of energy purchased from the grid, but increases both the energy generated by CAES and the energy sold to the grid (Fig. 10). This means that by applying proper management the input energy (provided by the wind farm and supplied by the grid) is used differently. Thus, a more efficient use of the storage system is achieved.

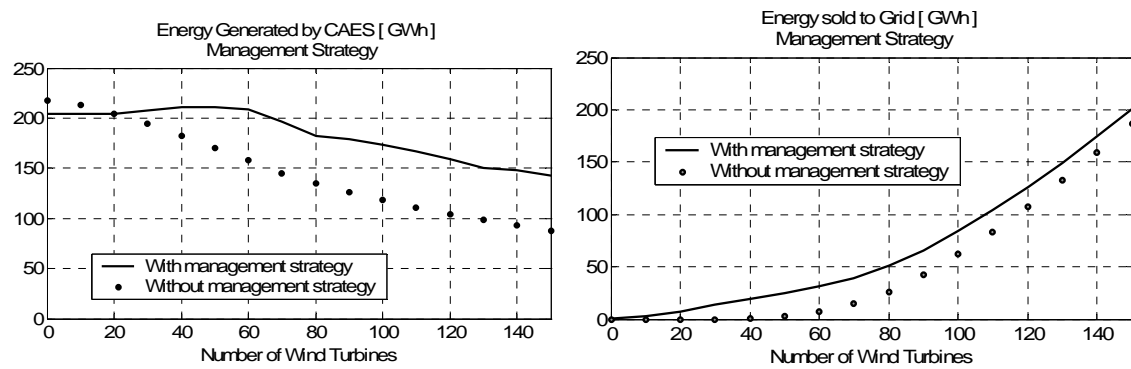


Fig. 10: Effects of the management strategy on energy generated by the CAES system and on energy sold to the grid.

As shown in Table 7 the benefits on annual savings range from about 5-11% for up to 80 wind turbines and approach a minimum value of about 3% for very large wind plant sizes. Thus, the proposed management strategy increases annual savings, but with an advantage that decreases with wind farm size. This result can be easily explained by noticing that the larger the size of the wind farm, the less energy is required by gas turbines. For a high number of wind turbines (lower net load), in fact, CAES can generate even for 12-14 hours a day, thus avoiding possible management problems previously described.

Table 7: Economic analysis of HPP solution with and without wind speed forecasting.

# Turbines	Investment [M€]	Savings [M€] without management strategy	Savings [M€] with management strategy	$\Delta$ Savings [%]	<i>PI</i> [ / ] without forecasting	<i>PI</i> [ / ] with forecasting
20	85.23	16.47	18.16	10.25	1.50	1.65
50	120.86	27.92	30.14	7.96	1.79	1.93
80	153.27	39.14	41.05	6.16	1.98	2.07
110	186.25	49.56	51.58	4.09	2.06	2.14
140	220.89	59.57	61.43	3.13	2.08	2.15

In summary, it can be stated that a proper management strategy leads to a more efficient utilization of storage system, resulting in better economic indexes.

#### CONCLUSIONS

The model presented evaluates the energetic, economic and environmental aspects of a CAES coupled with a wind farm. Besides benefits in terms of operational costs and CO<sub>2</sub> emissions due to the proposed HPP, the results show further economic advantages achievable with proper system management based on predicted wind speed data. Summarizing, the key findings of this work can be identified as follows:

- the presented model shows very good agreement with the operating data of the McIntosh CAES Plant;

- the proposed Hybrid Power Plant shows substantial benefits in terms of operational costs and CO<sub>2</sub> emissions;
- economic advantages are achievable with proper system management based on predicted wind speed data;
- results show that the design of all plant components (wind turbine, compressor, reservoir and turbine) strictly depends on the time distribution of incoming energy, electric load and economics.

Compressed Air Energy Storage is an important alternative to mitigate the impact of intermittent generation by wind turbine, making wind power dispatchable on demand. It is more efficient than other electricity generating systems when running at partial load, and can operate at as little as 10% of total generating capacity. A CAES/Wind power plant combines three proven technologies: wind turbines for lower energy costs and clean energy, underground reservoir storage for flexibility and reliability, and CAES for efficiency. Substantial savings in operational costs can be achieved, up to 60%, leading to a simple pay back as low as 4-5 years. Compared to grid-generated electricity, the proposed hybrid power plant would produce up to 60% fewer emissions per MW of generated electricity.

## REFERENCES

- [1] El Wakil M. M., 1984, *Power Plant Technology*, McGraw Hill.
- [2] Ackermann T., Söder L., 2002, *An Overview of Wind Energy Status*, Renewable and Sustainable Energy Reviews, 6 (2002) 67–128.
- [3] Energy Storage Council, 2002, *Energy Storage, the Missing Link in the Electricity Value Chain*, ESC (Energy Storage Council) White Paper, May 2002.
- [4] Elmegaard B., Szameitat N., Brix W., 2005, *Compressed Air Energy Storage (CAES) - Possibilities In Denmark*, Proc. of ECOS 2005, 18<sup>th</sup> International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems, Trondheim, Norway, June 20-22, 2005.
- [5] Korpaasa M., Holena A. T., Hildrumb R., 2003, *Operation and Sizing of Energy Storage for Wind Power Plants in a Market System*, Electrical Power and Energy Systems, 25 (2003) 599–606.
- [6] Cavallo A. J., 2000, *Compressed Air Energy Storage for High Wind Power Penetration Markets*, Proc. of Wind Energy for the 21<sup>st</sup> Century Conference, Kassel, Germany.
- [7] DTI, 2004, *Status of Electrical Energy Storage Systems*, Report DTI (Department of Trade & Industry).
- [8] EPRI-DOE, 2003, *EPRI-DOE Handbook of Energy Storage for Transmission and Distribution Applications*, Washington, DC: Report 1001834.
- [9] Holden P., Moen D., De Corso M., Howard J., 2000, *Alabama Electric Cooperative Compressed Air Energy Storage (CAES) Plant Improvements*, Proc. Of ASME Turbo Expo 2000, May 8-11, 2000, Munich Germany, 2000.
- [10] Arsie I., Marano V., Nappi G., Rizzo G., 2005, *A Model of a Hybrid Power Plant with Wind Turbines and Compressed Air Energy Storage*, Proc. of ASME Power Conference, Chicago, Illinois (USA), April 5-7, 2005.
- [11] Arsie I., Marano V., Rizzo G., 2005, *Thermo-Economical Analysis of a Wind Power Plant with Compressed Air Energy Storage*, Proc. of 60<sup>th</sup> ATI Congress, Roma (Italy), September 13-15, 2005.
- [12] Beyer H. G., Degner T., Hausmann J., Hoffmann M., Rujan P., 1994, *Short term prediction of wind speed and power output of a wind turbine with neural net networks*, Proc. of EWEC '94 (European Wind Energy Conference), Thessaloniki, Greece, 1994.
- [13] Mathew S., 2006, *Wind Energy: Fundamentals, Resource Analysis and Economics*, Springer.
- [14] Arsie I., Marano V., Rizzo G., Savino G., Moran M., 2006, *Energy and Economic Evaluation of A Hybrid CAES/Wind Power Plant with Neural Network-Based Wind Speed Forecasting*, Proc. of ECOS 2006, 19th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems, Aghia Pelagia, Crete (Greece), July 12-14, 2006.
- [15] Arsie I., Marano V., Rizzo G., Savino G., Moran M., 2006, *Use of Wind Forecast for the Management of a Hybrid Power Plant with Wind Turbines and Compressed Air Energy Storage*, Proc. of 61st ATI Congress, Perugia (Italy), September 12-15, 2006.
- [16] [www.gepower.com/prod\\_serv/products/wind\\_turbines/en/15mw/specs.htm](http://www.gepower.com/prod_serv/products/wind_turbines/en/15mw/specs.htm)
- [17] Zhang N., Cai R., 2002, *Analytical Solutions and Typical Characteristics of Part-Load Performances of Single Shaft Gas Turbine and its Cogeneration*, Energy Conversion and Management, 43, Issue: 9-12, June - August, 2002, pp. 1323-1337.
- [18] [www.grtn.it](http://www.grtn.it)
- [19] Greenblatt J. B., Succar S., Denkenberger D. C., Williams R. H., 2004, "Toward Optimization of a Wind/Compressed Air Energy Storage (CAES) Power System", Proc. of ASME Power 04 Conference, Baltimore, MD, 30 March – 1 April 2004.