المواصفات الفنية لأوراق العمل المقدمة

Potentialities of CAES (Compressed Air Energy Storage) and V2G (Vehicle to Grid) in the Electricity Market Optimization and in the Integration of Renewable Resources

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***Abstract**: One of the major challenges of an electric system is to match a fluctuating power demand. This problem becomes more and more complex thanks to the growing recourse to renewable sources, which are unpredictable and intermittent in nature, largely depending upon local site and unpredictable weather conditions. By coupling suitable storage systems with power plants, based on conventional or renewable sources, significant benefits in terms of flexibility in matching a fluctuating power demand can be achieved.*

Among storage systems, Compressed Air Energy Storage (CAES) and Pumped Hydroelectric Storage (PHS) seem today the only storage technologies that offer sufficiently low storage-specific capital costs suitable for use in conjunction with large plants. In CAES, particularly suitable for dry and flat regions, 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.

Interesting perspectives are also offered by the Vehicle to Grid (V2G) technology. In this approach, plug-in electric, hybrid or fuel cell vehicles, when parked, can both absorb energy from the grid (Plug-In Vehicles) or also give energy to it. V2G may therefore provide a means by which to utilise the spare power capacity available in each parked vehicle and avoid the need to maintain the excess conventional electricity generation capacity currently required to provide regulation, peak power and spinning reserves. V2G technologies represent therefore a paradigm shift in how the energy and mobility markets are related.

After an overview on the potentialities and the problems of these storage systems, the results obtained by the authors in the study of a hybrid power plant consisting of a wind farm coupled with CAES are presented. A Matlab/Simulink model has been developed and successfully validated starting from the operating data of the McIntosh CAES Plant in Alabama. Time-series neural network-based wind speed forecasting are employed to determine the optimal daily operation strategy for the storage system. 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 energy market prices. Substantial savings in operational costs can be achieved, up to 60%, leading to a simple pay back as low as 4-5 years. When compared to grid-generated electricity, the proposed hybrid power plant would produce up to 60% fewer emissions per MW of generated electricity.

***Key Words:** Compressed Air Energy Storage (CAES), Wind Energy, Renewable Energy, Storage, Vehicle to Grid (V2G), Plug-in Hybrid Electric Vehicles (PHEVs),Energy Market, Emissions*

1. Introduction

There is increasing effort toward the use of green technology that helps reduce pollution, and allows higher penetration of renewable energy sources in the energy market. The evidence for climate change and public awareness of energy saving issues are becoming stronger each year. Most scientists who study global climate agree that the effects are real.

Although we burn fossil fuels as though they are limitless, they are in fact finite. In the context of several thousand years of human history, our last 100 years of exponentially growing energy consumption is notable. For example, most assessments of "Estimated Ultimately Recoverable" oil are around 2000 billion barrels, meaning that 2000 billion barrels is all the oil that can ever be recovered.

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 renewable energy sources 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 favorable 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_2 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_2 emissions and it may have a significant role to play in a carbon-constrained world.

In a renewable energy-driven scenario, a key factor would be the employment of alternative fueled vehicles, such as PHEV (plug-in hybrid electric vehicles), BEV (battery electric vehicles) and FCHEV (fuel cell hybrid electric vehicles). As discussed in the next sections, PHEVs are receiving a great deal of interest. Recent improvements in lithium batteries technology are making PHEVs a viable solution to reduce cost, petroleum consumption and emissions in the transportation sector.

PHEVs aim at bridging the gap between pure electric vehicles (EVs) and conventional vehicles using a hybrid electric powertrain. The distinguishing feature of a PHEV is the ability of the vehicle to receive/give energy from/to the electrical grid.

2. Storage Systems

Electric utility storage field has enormous potential, but rapid deployment of storage devices is held back by concerns over technology risk and financial complexity. Wide-scale energy storage might change the face of the transmission grid and make wind and solar power more compelling economically.

In this scenario, utilities store electricity produced during off-peak times or made from renewable sources. Then, when demand for electricity peaks in the middle of the day, they could draw from the stored-up charge. This would reduce the cost of peak demand electricity by making off-peak energy available for use during peak demand without having to provide excess generation capacity that would not be used most of the day.

It is well known that major limitations of wind power systems include their low power density and intermittent nature. The performance of such systems strongly depend upon the local site and unpredictable weather conditions; these factors tend to increase the unit cost of the power obtained from wind power systems, limiting their deployment and the benefits due to the reduced exploitation of fossil resources.

The recourse to storage systems for wind energy could provide the necessary flexibility for smoothing the use of wind power. In this way, possibilities for market penetration can be improved.

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, going from residential (10 kW) to electric utility scale (100+MW).

In the following a brief overview of available energy storage systems is given.

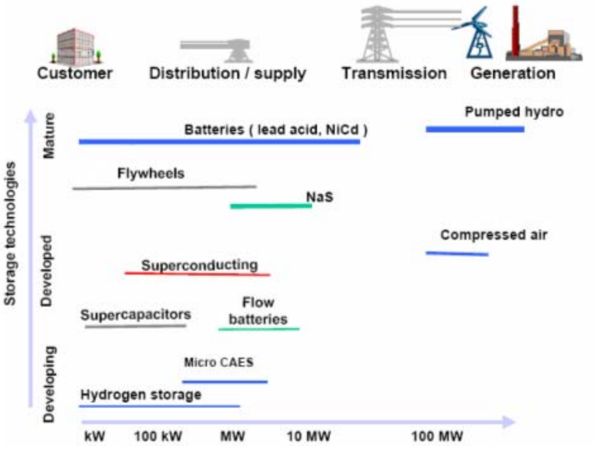

Fig. 1: Technical capability and commercial availability of energy storage types.

2.1 Pumped Hydroelectric

Pumped hydroelectric has been in use since 1929, making it the oldest of the central station energy storage technologies. In fact, until 1970 it was the only commercially available storage option for generation applications. Conventional pumped hydro facilities consist of two large reservoirs, one is located at base level and the other is situated at a higher elevation. Water is pumped to the upper reservoir where it can be stored as potential energy. Upon demand, water is released back into the lower reservoir, passing through hydraulic turbines that generate electrical power. The barriers to increased use of this storage technology include high construction costs and long lead times as well as the geographic, geologic and environmental constraints associated with reservoir design. For these reasons, an increasing attention has being paid in recent times to CAES, that could represent a feasible solution, particularly in flat areas.

2.2 Compressed Air Energy Storage

Compressed Air Energy Storage (CAES) plants use off-peak energy to compress and store air in an air-tight underground storage cavern. Upon demand, stored air is released from the cavern, heated and expanded through a combustion turbine to create electrical energy. 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, geological surveys have been done in the USA [8] and 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 energy storage (Fig. 2) [9]. Besides geological characteristics it should be noted that some sites may involve more installation problems and higher investment cost. For further discussions on possible CAES sites see [9],[10], [11].

Pumped hydroelectric storage (PHS) and CAES provide alternative means for utility-scale power storage (Fig. 3). 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. PHS is suited to regions having elevation differences whereas CAES require a large cavern.

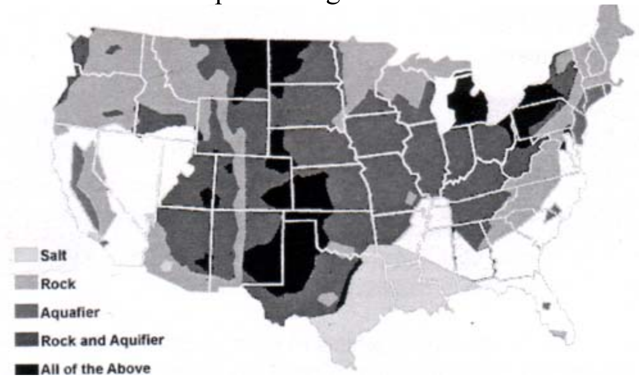

Fig. 2 - Geologic formations potentially suitable for compressed-air energy storage.

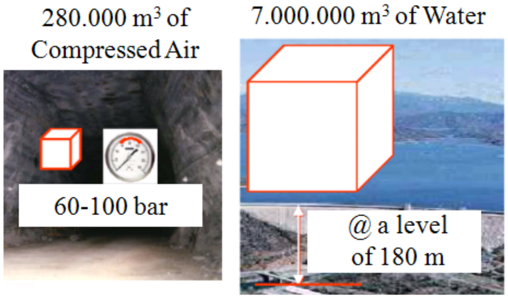

Fig. 3 - CAES vs. Pumped Hydro, required storage volume to generate 300 MW (12 hours storing, 12 hours generating).

2.3 Batteries

In recent years, much of the focus in the development of electric energy storage technology has stressed battery storage devices. There is currently a wide variety of batteries available commercially and many more in the design phase. In a chemical battery, charging causes reactions in electrochemical compounds to store energy from a generator in a chemical form. Upon demand, reverse chemical reactions cause electricity to flow out of the battery. The first commercially available battery was the flooded lead-acid battery, which was used for fixed, centralized applications. The valve-regulated lead-acid (VRLA) battery is the latest commercially available option. The VRLA battery is low-maintenance, spill- and leak-proof, and relatively compact. Zinc/bromine is a newer battery storage technology that has not yet reached the commercial market. Other lithium-based batteries are under development. Batteries are manufactured in a wide variety of capacities ranging from less than 100 watts to modular configurations of several megawatts. As a result, batteries can be used for various utility applications in the areas of generation, T&D (Transmission and Distribution), and customer service.

In 2006, American Electric Power installed the first megawatt-class NAS battery system to be used on a U.S. distribution system. That installation, on a substation near Charleston, W.Va., operated by AEP utility unit Appalachian Power, delayed the need for upgrades to the substation. A similar, but much smaller, NAS-based system installed in 2002 at an AEP office park in Gahanna, Ohio, was the first U.S. demonstration of the NAS technology. The six megawatts added to AEP's system during this deployment is a step toward the company's goal of having 1,000 megawatts of advanced storage capacity on its system in the next decade.

2.4 Flywheels

Flywheels are currently being used for a number of non-utility related applications.

Recently, however, researchers have begun to explore utility energy storage applications. A flywheel storage device consists of a flywheel that spins at a very high velocity and an integrated electrical apparatus that can operate either as a motor to turn the flywheel and store energy or as a generator to produce electrical power on demand using the energy stored in the flywheel.

2.5 Superconducting Magnetic Energy Storage (SMES)

A SMES system stores energy in the magnetic field created by the flow of direct current in a coil of superconducting material. To maintain the coil in its superconducting state, it is immersed in liquid helium contained in a vacuum-insulated cryostat. The energy output of a SMES system is much less dependent on the discharge rate than batteries. SMES systems also have a high cycle life and, as a result, are suitable for applications that require constant, full cycling and a continuous mode of operation.

2.6 Advanced Electrochemical Capacitors

Advanced Electrochemical Capacitors: (also known as ultracapacitors or supercapacitors) are in the earliest stages of development as an energy storage technology for electric utility applications. An electrochemical capacitor has components related to both a battery and a capacitor. Consequently, cell voltage is limited to a few volts. Specifically, the charge is stored by ions as in a battery. But, as in a conventional capacitor, no chemical reaction takes place in energy delivery. An electrochemical capacitor consists of two oppositely charged electrodes, a separator, electrolyte and current collectors.

2.7 Hydrogen Energy Storage

Hydrogen energy storage is still in the developmental stages as well, but may be an integral component of any post-fossil energy market. The hydrogen can be stored in a gas, liquid, metal hydride, or carbon-based form, which is then released through a chemical reaction to power a fuel cell or used as fuel in an internal combustion engine. Such storage systems can be used for both stationary and vehicle applications. However, there are no current commercial applications of hydrogen storage systems due to cost considerations.

2.8 Plug-in Hybrid Electric Vehicles

PHEVs could provide services to the electricity sector (vehicle to- grid or V2G services). These benefits might include peak load shifting, smoothing variable generation from wind and other renewables, and providing distributed grid-connected storage as a reserve against unexpected outages. Hybrid electric vehicles, battery electric vehicles, and plug-in hybrid electric vehicles (PHEVs) rely on batteries located in the vehicle to store energy. Thus, the main differences between PHEVs and stationary batteries are: i) PHEVs are not continuously available to the grid, ii) PHEVs can generate electricity by mean of on-board generators, i.e. internal combustion engines, fuel cells or other APUs (auxiliary power units). Furthermore, driving needs have to be taken into account before charging/discharging the on-board battery.

3. CAES Research activities: State of Art

Several papers have been recently published on CAES systems, analyzing different aspects of such plants.

A comparison of different operation strategies for a given CAES plant is presented by Lund et al [32].

Two practical strategies were compared with the optimal strategy, identified by the previous knowledge of future spot market prices, and it is shown that with these strategies the CAES plant can be expected to earn 80-90 per cent of the optimal earnings.

A comparative analysis of CAES, Gas Turbines and HPS has been performed by Najjar and Zaamout [30], evidencing the advantages of CAES systems, particularly for the dry regions.

A comparison between gas turbines and compressed air energy storage as competitors for supplemental generation has been performed by Greenblatt et al [31]. It has been shown that the wind+CAES system has the lowest dispatch cost of the alternatives considered (lower even than for coal power plants) above a GHG emissions price of $35/tC equiv., with good prospects for realizing a higher capacity factor and a lower total cost of energy than all the competing technologies over a wide range of effective fuel costs.

Based on life cycle assessment, a study on three different storage technologies (PHS, CAES and advanced battery energy storage (BES) using vanadium and sodium polysulphide electrolytes) has been also performed [28]. The results have shown that CAES has significantly lower net GHG emissions than PHS or BES when coupled with fossil generation, while GHG emissions from PHS when coupled with nuclear and renewable energy systems are lower than those from BES or CAES.

In order to characterize the mechanical and hydrological properties of the rock mass for the purpose of maintaining the stability and air tightness of the CAES caverns, hydro-geological models have been also developed, and the procedure for the geotechnical evaluation of sedimentary rock that surrounded the CAES cavern proposed [34].

Studies on closed form approximate analytical solutions for the pressure variations in porous media reservoirs for CAES have also been performed [33]. The model predicts well pressure variations and the radius of the active region around the well, in order to yield improved CAES plant designs.

4. Plug-in Hybrid Electric Vehicles (PHEVs)

A Plug-in hybrid vehicle is a hybrid vehicle with ability to charge from the grid (Fig. 4).

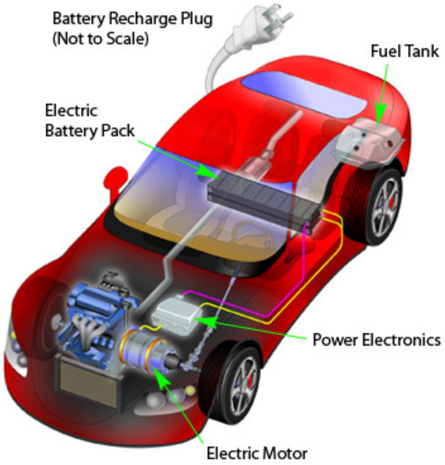

Fig. 4: PHEV schematics.

The battery is discharged while driving and then it is recharged from the grid when the vehicle is parked. The ability of recharging allows the vehicle to be run in pure electric mode. A hybrid typically has All Electric Range (AER) of 2-5 miles while a PHEV can provide AER from 10 to 60 miles, with standard values being 20, 40, 60. The external charging ability also allows to use battery (and electric motor) more frequently and share more power with the engine. Thus, the engine is used at its best operating region for more time as compared to hybrid vehicle. Therefore, the PHEV can provide better fuel economy.

Plug-in hybrid vehicle architecture is exactly same as a hybrid vehicle consisting of a electric drive, and engine except the size of engine is smaller, and motor and battery are bigger. Use of larger battery also allows reducing the engine size and giving more flexibility for tuning the engine in its best operating region. Apart from the power train requirements, a PHEV requires charging unit for the battery and interface for the grid.

PHEVs have gained interest over the past decade due to their high fuel economy, convenient low-cost recharging capabilities and reduced use of petroleum. Plugging-in can also improve the reliability and power quality of the electric grid and to ameliorate utility emissions, thus connecting the automotive sector to the electric power sector.

BEVs and PHEVs benefit from an existing infrastructure that could directly use renewable energy: they do not require major energy supply infrastructure developments. Additional substantial public benefits include: more rapid introduction of zero- or near-zero- tailpipe emissions vehicles (Fig. 5); increased reliability of the electric system; lowered transportation cost (per vehicle mile) and lower cost per kWh for residential and commercial electricity; driver for higher penetration of renewable electricity.

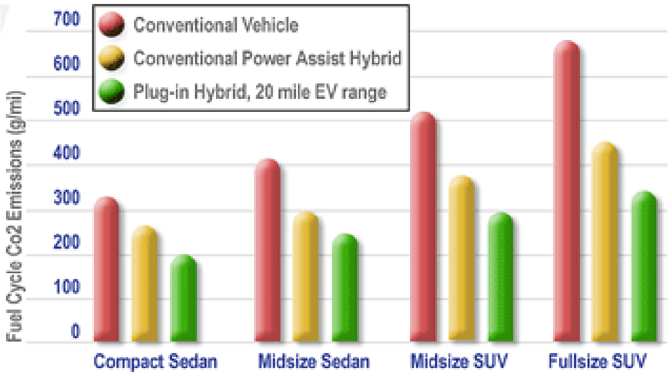

Fig. 5 - CO_2 emissions. Source – EPRI.

5. PHEV and Vehicle to Grid (V2G) Opportunities

The basic concept of vehicle-to-grid power is that the vehicles provide power to the grid while parked. Therefore, the vehicle should be able to generate electricity on board and therefore it has to be a electric vehicle, fuel cell vehicle, or a plug-in hybrid. The V2G capable vehicle must have three required elements [35]: (1) a connection to the grid for electrical energy flow, (2) control or logical connection necessary for communication with the grid operator, and (3) controls and metering on-board the vehicle. The electric energy is stored in the battery while charging and is supplied back to the grid when performing V2G services.

The on board power electronics can be used to supply or absorb active and reactive power from the grid and it has fast response time. Thus, PHEVs can be used for peak power, and also can be used to perform ancillary services [35].

When a vehicle is connected to the grid it can charge its batteries or perform the V2G operations. If the vehicle controller decides to perform any of these operations locally, without any external signal, then it is dangerous for grid stability. Therefore it is necessary to provide a central control to all the vehicles. Each vehicle is equipped with a communication interface, either a wireless link, internet connection etc. This interface provides the commands to the vehicle and also it sends signals back to ISO. The signals may include power availability in the vehicle battery, power usage history, power absorbed from and supplied to the grid etc. The power usage may provide revenue to the vehicle owner. For example if a vehicle operates and spinning reserve, then it would be paid just far remain connected, if a vehicle performs a regulatory service, then it might receive a high rate for supplying the electricity. Thus, V2G can provide monetary benefits to the PHEV owner.

Use of PHEV for V2G can provide benefits to vehicle owner and the power utility company apart from the reduced tailpipe emissions and increased mileage. Statistical analysis suggest that the use of PHEV to supply energy to the grid is beneficial when the number of vehicle connected to the grid is large [36].

One of the fundamental properties of electricity markets is the lack of cost-effective storage. Without storage, meeting peak demand requires underutilized investment in generators and transmission lines. Because of the costs of meeting peak demand, the difference between daily peak and off-peak costs can vary greatly throughout the year. A plausible conjecture is that V2G, that relies on dual purpose batteries where the initial capital cost of the battery is not assigned to the off-vehicle electricity use because the battery was purchased for driving, will be more economic for grid support than batteries whose capital cost must be amortized for grid use.

With vehicle batteries, if load shifting or peak shaving is not economical the only wasted expenditure is the cost of the controllers and converters, some of which will likely be installed in any case to enable off-peak charging (although additional electronics would be required for V2G). This possibility, along with quick battery reaction times, has made V2G applications to stabilize or slow fluctuations from intermittent sources (such as wind or solar) a subject of research interest [35], [36], [37], [38], [39]. V2G has the potential to diminish the need for rapid ramping of following generators to match variable power sources. Rapidly ramping generators may not be the lowest cost generators, and ramping can lead to increases in pollution.

V2G services could be sold in an organized market as ancillary services (spinning reserve and regulation), as energy sales to the grid (running the meter backwards), or their value could be captured as avoided grid electricity purchases (running the meter slower).

Another important aspect is related to the petroleum displacement, thus the effects on CO2 emissions.

The effect of PHEVs on emissions from power plants shows mixed results and they vary with electricity regions. Analysis show that the emissions depend on the power generation technology used in the region called as ‘generation mix’. If most of the energy is supplied through coal fire plants then the benefits for emissions of using V2G are negligible, even sometimes they worsen. PHEV charging tends to increase the generation that leads to increased pollution and it is not compensated by V2G services. In contrast, if a region is using less coal fire generators then the benefits are substantial. In US majority of generation is from coal fire plants therefore the benefits are small. Various studies are performed to predict the developments in generation technology, use of wind/solar power generators. These predictions are used to study the effect of PHEV and V2G on power sector. The results from simulations at year 2030 or 2050 show reduced emissions. Fig. 6:6 shows the projection of one such study. For more detailed results refer to [40], [41], [42]. The studies on emissions show different conclusions for different gases: emissions of some gases reduce while the other gases increase although this highly depends on the generation mix of a particular region [40].

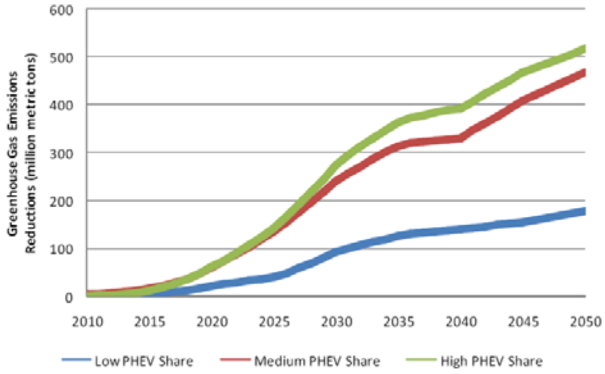

Fig. 6: Effect of PHEV on total emissions: Long term scenario [40].

6. CAES/WIND Opportunities

6.1 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. 7. 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.

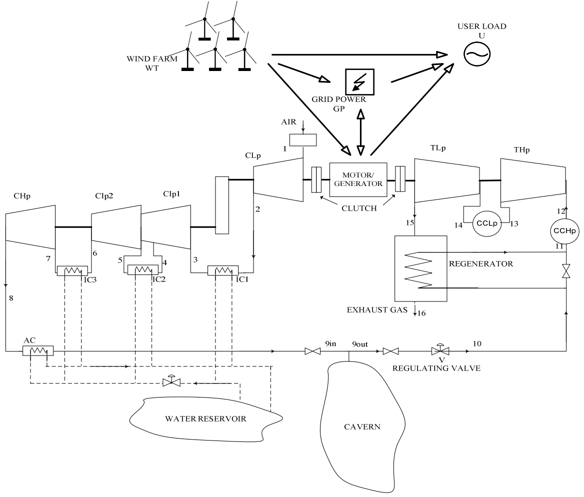

Fig. 7: Power Plant schematic.

A detailed description of the adopted model is given in [18],[19] ; 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.

It is worth noting that the model has been validated on data obtained during one of the author’s visit (May 2006) to the AEC McIntosh CAES Plant. 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_2 emissions has an average value of about 6%. To summarize, the presented model shows very good agreement with the real operating data and can be used with confidence to analyze different scenarios [15].

6. 2 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.

However, with increasing penetration of wind power, accurate forecasting could 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 is one of the most difficult meteorological parameters to forecast. 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 [16] 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.

Based on prediction performances and computational time, a proper combination of a NAR model (without any eXogenus 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. A complete description of this algorithm is outside the scope of this paper; please refer to [18] [19] for further details. Results show that the proposed forecasting model is suitable for implementation in an energy management strategy based on wind speed forecasting.

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. Modeling assumptions for the economic analysis are given in [13][14].

6.2.1. MANAGEMENT STRATEGY

A main drawback of a 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. 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 [13], [14].

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 [12]. 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 [12]. 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.

If the energy provided by wind turbines and the net load are known only in real time, CAES managing strategy can result in non optimal operation in terms of cost and energy savings and emissions. Moreover, user demand might not be satisfied during some periods. Knowing the incoming wind power several hours in advance helps in estimating the net load for the current day and thus determining the best management strategy by model-based optimization techniques.

6.2.2. STORAGE

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 ~50 MW) are partly driven by the wind farm and partly (if necessary) by electricity provided by the power grid.

6.2.3. GENERATION

For each day, the following procedure (based on Eqs. 1-4) is used to provide an effective approach to system management:

$$E_{sto}(\text{per week}) = \int_{off-peak\ hours} P_{sto}(t)dt \qquad (1)$$

$$\bar{E}_{gen}(\text{per day}) = \frac{1}{5}\eta_{gen}\cdot E_{sto}(\text{per week}) \qquad (2)$$

$$\bar{E}_{gen,strategy}(\text{per day}) = \int_{\text{peak hours}} P_{gen}(t)\cdot EMI(t)dt \qquad (3)$$

$$Savings = \text{f}\left(P_{gen}(t), P_{sto}(t), EMI(t)\right) \qquad (4)$$

As a function of the compressor power and of the peak-hours a day, Eq. 1 estimates the stored energy per week. Eq. 2 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). This average value can be compared with the value obtained by Eq.3, by applying the management strategy based on wind speed forecasting.

EMI(t) is introduced in Eq. 3 to estimate the daily generated energy by using the management strategy. In this equation, P_{gen} represents the net electric load (above the energy provided by wind turbines) estimated by the wind speed forecasting.

VARIABLES

EMI=[0;1] – gas turbines off-on sampled every hour

PE=[L, M, H, HH] - price of electricity, low, medium, high, super high

PR=[F, M, L] - power request, full, medium, low

MAIN RULES

EMI=0 if

- wind energy is enough to satisfy the user load
- CAES is in storage mode
- PR=L
- PR=M AND (PE=L OR PE=M)

Then:

T1=time 0 of the prediction horizon (7am)

T2= final time of the prediction horizon (9pm)

EMI(t) affects the daily cost of the hybrid power plant:

$$\sum_{T1}^{T2} EMI(T) * PE(T) * PR(T) * T = DailyCost$$

where T represents a 1hour interval.

The optimal time trajectory is found by maximization of the savings using non-linear constrained optimization techniques. Suitable constraints account for i) the difference between initial and final temperature and pressure in the cavern, ii) the pressure in the cavern between 40 and 80 bar, iii) the water temperature in the recuperator greater than 273.15 K, iv) the difference between initial and final values for mass and temperature in the recuperator. A detailed description is available in previous papers [11].

Summarizing, the proposed strategy aims to (i) satisfy the user giving priority to peak hours, (ii) use all the stored energy available for the current day.

6.3 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 the following. The reference scenario used to evaluate economic and environmental performance is the *conventional solution* (load is satisfied only by power from the national grid). A comprehensive analysis is shown in [43]. Sample results are shown in the following. 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. 8 shows the most significant performance indexes normalized with respect to the case with no wind turbines.

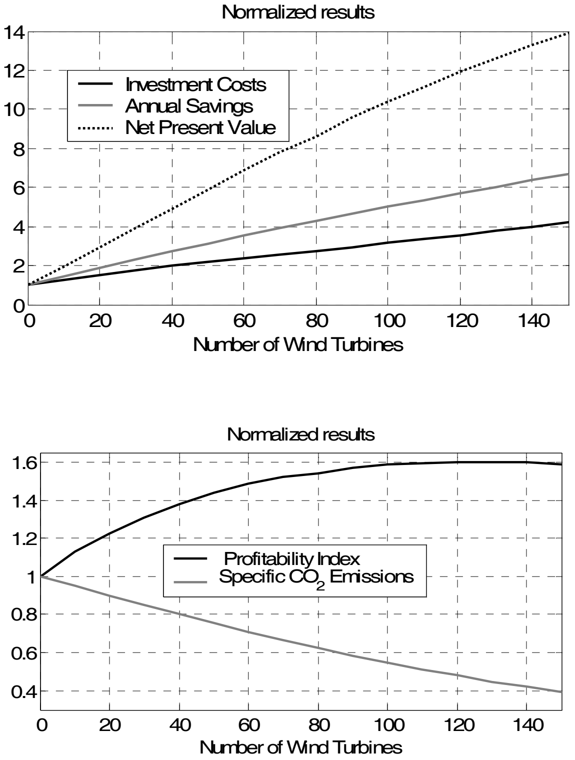

Fig. 8: Normalized investment costs, annual savings and NPV, specific CO_2 emissions and profitability index.

As can be observed in the above 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.

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_2 emissions are reduced up to about 40% of the reference case.

6.3.1 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, and the management of CAES storage/generation is achieved following 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. 9). 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.

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 noting 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.

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.

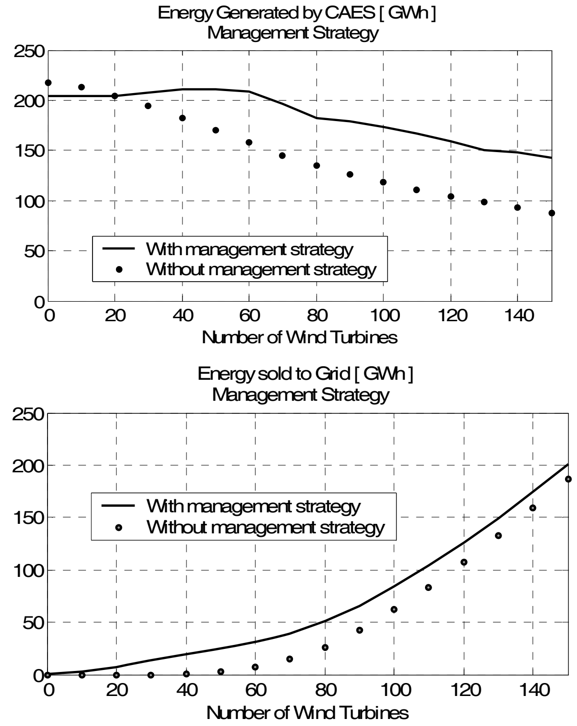

Fig. 9: Effects of the management strategy on energy generated by the CAES system and on energy sold to the grid.

6.3.2 CLOSURE

The results obtained on a case study, dealing with the storage of wind energy by means of compressed air on a electric utility scale (100 MW), and using a management strategy based on wind speed forecasting, show that significant benefits can be achieved by such systems, in terms of operational costs and CO_2 emissions.

The proposed plant 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. Using system management based on predicted wind speed data, annual savings for the proposed power plant increase by 18% (no wind turbines) to 3% (140 wind turbines) leading to a further reduction of operational costs up to 5 % for the analyzed scenarios.

7. Conclusions

The paper gives an overview on the potentialities and the problems of storage systems, showing a case study of a hybrid power plant consisting of a wind farm coupled with CAES are presented. A Matlab/Simulink model has been developed and successfully validated starting from the operating data of the McIntosh CAES Plant in Alabama. Time-series neural network-based wind speed forecasting are employed to determine the optimal daily operation strategy for the storage system. A detailed economic analysis has been discussed, considering both investment operating costs.

Results show that Compressed Air Energy Storage is an important alternative to mitigate the impact of intermittent generation by wind turbine, making wind power dispatchable on demand.

Interesting perspectives are also offered by the Vehicle to Grid (V2G) technology.

However, the control of the vehicle to grid interconnection is more complex problem as it includes the interconnection with the power system. Power system has its own control problems, and the controller, continuously manages the generation to supply the demand. The grid control has many generators to choose from, and so the controller selects the best option that minimizes the cost of generation and distribution. Apart from the managing the demand-generation many tasks are required for the grid stability. When PHEVs are connected to the grid they can act in different modes, a load while charging, or perform any other services required for the grid. But if the vehicle controllers decide to choose these modes locally, this might destroy the stability of the entire grid. Therefore, it is strongly necessary to have some central control over the vehicle to grid interface. Even if the vehicles are designed only to charge from the grid it can be harmful to the grid. The vehicle acts as load to the grid, and if large number of vehicles are charging at a time when power demand is already high (afternoon peak), then this demand may increase the maximum capacity of the grid. Therefore it is necessary to control the charging. The solution to this problem is having some communication interface between vehicle and power system. This is clearly an open debate and detailed analyses and studies are needed, able to determine value propositions, benefits and barriers of PHEVs as a function of energy market, generation mix, regulations and customers' needs.

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