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Application of dynamic programming to the optimal management of a hybrid power plant with wind turbines, photovoltaic panels and compressed air energy storage

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A model for thermo-economic analysis and optimization of a hybrid power plant consisting of compressed air energy storage (CAES) coupled with a wind farm and a photovoltaic plant is presented. This kind of plant is aiming to overcome some of the major limitations of renewable energy sources, represented by their low power density and intermittent nature, largely depending upon local site and unpredictable weather conditions.

In CAES, energy is stored in the form of 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, characterized by high and often unpredictable variability.

A mathematical model, validated in a previous study over the CAES plant in Alabama, US, is coupled with a dynamic programming algorithm to achieve the optimal management of the plant, in order to minimize operational costs while satisfying constraints related to the operation of reservoir, compressors and turbines, also considering their off-design performance. The potential benefits of such plant in terms of energy consumption and CO_2 emission are analyzed and discussed, for different configurations and scenarios.

1. Introduction

Worldwide demand for energy is rapidly growing, threatening price stability and causing concerns over the security of supply. Moreover, there are serious worries about global warming and climate changes due to the increase of greenhouse effect caused by combustion of fossil fuels. Significant climate change mitigation aimed at stabilizing atmospheric concentrations of CO_2 will require a radical shift to a decarbonized energy supply. Thus, it looks clear that a strong deployment of renewable energy is needed [1], but several factors (costs, regulations, incentives) should be taken into account in a rapidly changing energy environment.

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 [2]. Sun, wind and waves cannot be controlled to provide directly either continuous base-load power or peak-load power when it is needed. These features tend to increase the unit cost of the energy obtained by renewable sources, so limiting their diffusion and benefits [3].

Some ways to overcome these limitations may be the recourse to energy storage systems and/or 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.

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 [4]. Moreover, in recent years, a significant development in photovoltaic has also occurred, with a continuous decrease of costs and improvement of conversion efficiencies [5,6].

CAES plants use off-peak energy to compress and store air in a reservoir, usually 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.

CAES is not a novel concept [7–9]: a compressed air storage system with an underground cavern was patented back in 1948, and the first CAES plant with 290 MW capacity has been operating in

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Nomenclature

Greek symbols

β	pressure ratio, /
η	efficiency, /
ρ	air density, kg/m^3

Latin symbols

A	swept area of wind turbine, m^2
C_P	specific heat at constant pressure, kJ/kg K
H_i	lower heating value, kJ/m^3
k	specific heat ratio, /
m	mass, kg
p	pressure, Pa
P	mechanical power, kW
R	gas constant, kJ/kg K
T	temperature, K
v	wind speed, m/s
V	reservoir volume, m^3

Subscripts

C	compressor
cv	cavern
in	inlet
out	outlet
T	turbine
WT	wind turbine

Huntorf, Germany, since 1978. A further 110 MW CAES plant has also been operating in McIntosh, Alabama, since 1991.

CAES is one of the few energy storage technologies suitable for long duration (tens of hours) and large power applications (utility scale), at relatively low cost, as evidenced by the data on capital costs reported in Table 1.

The other practical feasible alternative, the Pumped Hydroelectric Storage (PHS), has a greater degree of field experience, but can be applied only where reservoirs at different elevations are available. Moreover, there are growing environmental impact issues associated to the installation of large PHS plants, which have a greater surface footprint with respect to CAES plants. CAES, instead, can use a broad range of solutions for air storage, such as reservoirs, surface piping and underground geologic formation such as solution mined salt, saline aquifer, abandoned mine, or mined hard rock. Underground solutions are usually preferred for large-scale applications, being more cost effective. Several studies have evidenced a good coincidence of zones with high wind potential and geological structures suitable for CAES, both in USA (Fig. 1) and in Europe (Fig. 2). CAES appears therefore particularly suitable to balance the variability of wind power.

With regard to energy storage systems, an increasing attention has been paid to compressed air energy storage (CAES) [10,11], for large-scale grid applications.

Ibrahim et al. [12] focused on the integration of wind–diesel hybrid systems (WDS) with CAES. This article compares the available technical alternatives to supercharge the diesel used in high penetration wind–diesel system with compressed air storage (WDCAS), in order to identify the one that optimizes its cost and performances. Their proposed design, that requires the repowering of existing facilities, leads to heightened diesel power output, increased engine lifetime and efficiency and to the reduction of fuel consumption and GHG emissions, in addition to savings on maintenance and replacement cost. Despite their case study deals with low average wind speed, remarkable savings may be obtained through the use of compressed air. However, their analysis is only energy-based and does not consider the energy cost based on the investment cost and the purchase of new equipment (wind turbines, CAES equipment, etc.).

Madlener and Latz [13] model the economic feasibility of compressed air energy storage (CAES) to improve wind power integration by means of a profit-maximizing algorithm; their model considers three different variants of systems: (1) a conventional wind park without CAES; (2) a wind park with conventional centralized CAES in diabatic or adiabatic use; and (3) a wind park with integrated CAES in diabatic or adiabatic use. Capital and O&M costs are based on literature data, while they use real data on available wind power to the grid, spot market prices, and the price of minute reserve. They conclude that at present conditions on the minute reserve market, no CAES power plant is economically feasible. However, as soon as hourly contracts can be concluded on the minute reserve market, such as is possible on the spot market, CAES becomes attractive for smoothing fluctuations caused by wind energy feed-in.

Elmegaard et al. [14] and Salgi and Lund [15] discuss the opportunities for CAES plants in regions with high penetration of wind power into the energy market. Specifically, these works are focused on energy-balance effects of adding CAES to the Western Danish energy-system, where about 20% of energy (annual electricity demand in Denmark is about 36 TW h) is supplied by wind turbines. In particular, [15] show that even with an unlimited CAES plant capacity, excess wind power production is not eliminated because of the high percentage of CHP production. The optimal wind-power penetration for maximum CAES operation is found to be around 55%. The minimum storage size for CAES to fully eliminate condensing power plants operation in the optimized system is over 500 GW h, which corresponds to a cavern volume of around 234 Mm^3. at an average pressure of 60 bar. Such a storage size would be technically and economically unfeasible.

Similarly to our approach, Raju and Khaitan [16] propose an accurate dynamic simulation model, validated using data from the Huntorf CAES plant. They focus more on the heat transfer coefficient between the cavern walls and the air inside the cavern, which is accurately modeled based on the real tests data obtained from the Huntorf plant trial tests. By incorporating accurate heat transfer model, the cavern behavior can be accurately simulated, and their results suggest that the isothermal and adiabatic models inadequately describe the behavior of the cavern.

Table 1
Capital costs for energy storage options [10].

Technology	Capital cost: capacity ($/kW)	Capital cost: energy ($/kW h)	Hours of storage	Total capital cost ($/kW)
CAES (300 MW)	580	1.75	40	650
Pumped hydroelectric (1000 MW)	600	37.5	10	975
Sodium sulfur battery (10 MW)	1720–1860	180–210	6–9	3100–3400
Vanadium redox battery (10 MW)	2410–2550	240–340	5–8	4300–4500