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Wind energy and natural gas-based energy storage to promote energy security and lower emissions in island regions

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HIGHLIGHTS

- The prospect of wind energy and natural gas introduction in islands is considered.
- We propose a combined dual mode Wind–CAES scheme to support clean energy production.
- Development of an appropriate sizing algorithm is undertaken.
- The proposed scheme is evaluated for different wind potential case studies.
- Benefits accrue concerning energy security, CO_2 emissions and economic performance.

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ABSTRACT

Usually, isolated and remote areas, like islands, meet their electricity needs using oil-fired power generators. When available, natural gas can potentially substitute oil. Moreover, the high-quality wind energy potential found in many of these areas cannot be used extensively. Main reason is the operation of small-scale, weak electricity grids which cannot cope with wind energy intermittency. To compensate for that, we examine the combination of wind energy and energy storage. For the latter we focus on the technology of compressed air energy storage (CAES), which is suitable for scalable applications. To ensure the highest level of demand satisfaction, while avoiding system oversizing, we recommend a novel Wind–CAES system that allows switch from the CAES to the Brayton cycle when the stored energy is inadequate to meet demand. We develop a new algorithm for the sizing of such configurations, and use it on a case study that includes a typical, medium-scale Aegean Sea island in combination with three representative wind regimes. The results demonstrate that even in areas with relatively low-quality wind potential there are significant improvements in fuel use reduction, CO_2 emissions and strengthening of energy supply security, while for island regions with higher-quality wind potential, the proposed solution also becomes cost-effective in comparison to other alternatives.

1. Introduction

Increased interest is recently noted in promoting distributed generation (DG) [1]. Renewable energy sources (RES) are called to play a critical role in the transition from centralized power generation to DG patterns. At the same time, there are several regions internationally that are not connected to an electricity grid (e.g. non-interconnected island regions); thus they rely on stand-alone energy production systems, such as autonomous, oil-fired power stations [2]. Since these regions operate small electricity networks which lack interconnections, they are exposed to supply side vulnerabilities. These relate to either direct electricity links or supply of primary fuels (such as oil commonly used on islands). Moreover, many of these regions benefit from RES potential of medium to high quality that encourages installation of wind and solar energy systems. Although such technologies are nowadays considered established, they require back-up power because of their variable power generation (e.g. due to stochastic nature of wind speed).

In this context, there are various energy storage technologies [3–5], either mature or emerging, that may interact with the primary RES energy source and achieve high levels of energy autonomy, largely reducing or even eliminating the contribution of thermal power generation. Among the various energy storage technologies, grown interest is recently noted in compressed air energy storage (CAES) systems [6–8], normally used in energy management applications. Operation of such systems is based on the exploitation of waste, surplus (e.g. wind energy curtailments)

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or off-peak, low-price energy [9]. Using this energy, air is compressed inside either an underground cavern or a high pressure tank. When an incentive to sell energy (i.e. during peak hours) or an energy deficit (i.e. when demand is high and RES energy production is not sufficient) appears, high pressure air is drawn from the cavern/tank and is mixed with natural gas to produce high enthalpy gases, then used to operate a gas turbine for power generation. It is noteworthy that during this cycle, CAES achieves operation under a considerably lower heat rate [9] if compared with the respective conventional gas turbine cycle; therefore it ensures proportional fuel savings.

Acknowledging the benefits arising from CAES operation and the fact that CAES can serve small–medium size applications [10], this study investigates an integrated Wind–CAES scheme used to serve demand of remote communities. Plans about the introduction of natural gas in island areas [11,12], as a substitute of oil, could also facilitate the operation of CAES configurations and lead to cleaner and more efficient energy production patterns. To ensure 100% energy autonomy without the need to oversize system components, a novel Wind–CAES system is proposed. It allows switching from the CAES to the Brayton cycle when stored energy is not adequate to satisfy demand [13,14]. A new algorithm is developed for the sizing of such configurations. For demonstration purposes we use the case study of a typical, medium-scale island of the Aegean Sea in combination with three representative wind regimes. Accordingly, the recommended solution is evaluated in terms of economic performance, CO_2 emissions' reduction and contribution to energy security improvements.

Following the introduction section, description of a typical CAES system is given in Section 2, with the proposed dual-mode, wind-based energy system analysed in Section 3. The analytical model is presented in Section 4 and the description of the examined case study along with application results are provided in Sections 5 and 6 respectively. Finally, the conclusions of this research are discussed in Section 7.

2. Description of the CAES system

In a typical CAES system, off-peak or excess power is used to compress air into an underground cavern (pressures reaching 80 bars [9]). During times of peak demand, the required amount of air is released from the cavern, burned with natural gas and then supplied in the form of gases to a gas turbine, where expansion takes place as in the typical Brayton/Joule cycle. This also suggests the main benefit of a CAES system, i.e. the fact that the stages of compression and generation are separated from one another. Consequently, ~2/3 of fuel consumption for the compressor in a typical Brayton/Joule cycle is not used in the CAES cycle. As a result, in a CAES system, the entire power of the gas turbine is available to cover demand. In this context, during a complete cycle, 1 kWh of output electricity requires approximately 0.75 kWh of input electricity for the compressor and 4500 kJ of fuel during combustion [15]. This amount of fuel raises controversy over the unconditional acceptance of such systems, presenting a negative (even if limited) impact in terms of energy autonomy and emissions when compared with other energy storage solutions. Alternative approaches suggest the use of biofuel [16], or fuel-free systems such "Advanced Adiabatic CAES" [17,18]. Nevertheless, the specific concepts are still in development stage; thus they are not currently considered mature enough to substantially support increased contribution of wind energy production in remote communities.

The requirement for geological formations that can facilitate underground storage is one more disadvantage of CAES. The storage media most commonly used include rock caverns, salt caverns and porous media reservoirs or even buried pipes for small subsurface CAES units [19]. The use of high pressure tanks could equally well serve for the storage of compressed air, especially in small–medium size applications. Furthermore, since storage losses identified in CAES are not significant, the storage period can be very long. Moreover, CAES demonstrates fast ramp rates (2–3 times faster than conventional units) and low fuel consumption-CO_2 emissions (compared to both simple and combined cycle units). Finally, flexibility of CAES systems to serve as both base load plants [20] and peak following units [8] strongly supports collaboration with wind farms [21,22], requiring both sufficient energy storage capacity and adequate system flexibility in order to better adjust to the inelastic load demand and compensate for sudden wind power losses.

3. Description of the dual-mode CAES system

Any type of power generation system that relies on wind energy would require oversizing in order to achieve high level of demand satisfaction. This is owed to the stochastic nature of wind energy. In order to avoid expensive, oversized Wind–CAES configurations, an alternative system is proposed. More precisely, to counterbalance the need for extreme wind power and energy storage capacity so as to achieve 100% energy demand satisfaction for a given isolated area, a dual-mode CAES plant is adopted. It is configured to switch its operation from the CAES mode to the traditional gas turbine cycle with the addition of a second compression system and the help of a clutch that allows connection between the gas turbine and the compressor. In detail, the proposed system (see also Fig. 1) comprises of the following components:

- A wind farm that includes a number of wind turbines with total capacity "N_{WP}".
- A CAES motor of rated power "N_m", used to exploit any wind energy surplus and feed the compressor under an efficiency of "η_m".
- A multi-stage compressor, used in the CAES cycle to compress ambient air into the air cavern/tank, under a given pressure ratio "r_c". Similar to the motor, the compressor power "$N_{cr\text{-}CAES}$" is determined in relation to the maximum wind energy surplus appearing, i.e. "$N_w - N_d$", taking also into account any energy losses induced by the motor. "N_W" represents the mean hourly wind farm power output and "N_d" the mean hourly load demand.
- A second compression system, operated in the case of the dual-mode cycle execution, i.e. when energy deficit appears and the combined Wind–CAES system is not able to cover it. Its rated power is "$N_{cr\text{-}dual}$" and its pressure ratio is "r'_c".
- A storage cavern or tank of maximum storage volume "V_{ss}" and maximum depth of discharge "DOD_L", determined by the ratio of $[(r_c - r_t) \cdot r_c^{-1}]$, where "$r_t$" is the pressure ratio of the gas turbine employed.
- A combustion chamber, where the required amount of compressed air and natural gas are mixed together for the production of gases that will operate the gas turbine under a maximum permitted temperature of "T_{cc}".
- A natural gas tank, used for the storage of fuel, with the latter being determined by the respective calorific value (CV) "H_u".
- A gas turbine of power output "$N_{gt\text{-}f}$", determined after considering the maximum appearing deficit in the case of both the CAES "N_{def}" and the dual-mode "N'_{def}" cycle, that is connected to an electrical generator responsible for the delivery of electrical energy to the demand side.

The main variables taken into account are the wind farm capacity and storage volume, while detailed wind speed and ambient temperature–pressure data alongside hourly electricity load is