Energy Conversion and Management xxx (2010) xxx–xxx

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

# Autonomous dual-mode CAES systems for maximum wind energy contribution in remote island networks

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ARTICLE INFO

*Article history:*
Received 27 October 2008
Received in revised form 28 July 2009
Accepted 14 March 2010
Available online xxxx

*Keywords:*
Compressed air energy storage
Wind energy recovery
Gas turbine
Natural gas
Crete island

ABSTRACT

Wind parks operating in autonomous island networks with limited capacity of wind energy absorption are faced with considerable energy curtailments. To encounter the existing situation, the concept of wind energy storage suggests an alternative worth investigating. On the other hand, the expansion of natural gas networks in big islands, where remarkable wind potential may be met as well, questions the future of wind energy. To recover wind energy rejections and benefit from the introduction of natural gas, the adoption of wind–compressed air energy storage (Wind–CAES) systems is currently investigated. More specifically, the proposed solution examines the operation of a dual-mode CAES configuration in collaboration with private wind parks operating on the island of Crete. The system operation is configured so that guaranteed amounts of energy may be delivered to the local network on a daily basis, during certain peak demand hours. Based on a simulation algorithm for the dual-mode CAES system, configurations ensuring maximum recovery of wind energy curtailments may be obtained, while the proposed solution considerably reduces fuel consumption, otherwise required to operate conventional gas turbine plants.

## 1. Introduction

Considerable exploitation of wind energy in autonomous island networks is often hindered by the fact that such electrical systems usually depend on oil based-power generation [1,2] and also present serious grid limitations [3,4]. More specifically, intermittent wind energy production integrated in a weak electrical grid relying on diesel/heavy oil units may result to appreciable wind energy curtailments [5], especially in cases of excellent wind potential [6]. At the same time, expansion of the natural gas (NG) market in island areas as well [7] comprises a critical factor for the future of wind energy. Acknowledging the possibility of policy decisions supporting the implementation of sweeping NG electricity generation plans, attention should be given in order to secure the future of wind energy in these areas. Besides, to achieve sufficient penetration of renewable energy sources (RES) and satisfy the targets set at international level [8,9], maximum exploitation of wind energy in priority areas of excellent wind potential, such as windy island sites, is prerequisite. To deal with the situation encountered, against the alternatives of grid reinforcement and island interconnection [10], the solution of wind energy storage is currently examined. More precisely, application of the appropriate energy storage [11] may improve the performance of operating wind farms since greater levels of wind energy penetration may be achieved through the recovery of rejected wind energy [5,12–14]. Given also the high production cost of the oil-based electricity generation [1], opportunities appearing for testing the feasibility of such RES-storage configurations [15,16] should not be neglected.

In this context, a bulk energy storage technology that may both recover considerable amounts of wind energy curtailments and benefit from the introduction of NG is currently studied. Compressed air energy storage (CAES) comprises a relatively old storage concept [17,18], actual applications of which are however limited. CAES systems are usually examined on the basis of large scale (even at the national level) grid-connected applications [19], used to supplement base load power stations through load levelling [17–21]. Trade-off between upgrading transmission lines and installing CAES for the support of wind farms is a common subject in the specific field [22,23] while feasibility of the CAES solution has been studied in both spot and regulating power markets [24]. Furthermore, modification of the typical CAES cycle may be encountered in certain studies [25,26], while recently, coupling of CAES with photovoltaic plants has also been examined [27].

Novelty of the specific study lies on the examination of a relatively small scale dual-mode CAES configuration, used to support the operation of already existing wind farms in a representative autonomous island network of the Greek territory. Dual-mode means that the system shall be able to shift its operation to the respective Brayton/Joule cycle while adjustment to the grid and market conditions of electricity generation in autonomous island

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doi:10.1016/j.enconman.2010.03.008

Please cite this article in press as: Zafirakis D, Kaldellis JK. Autonomous dual-mode CAES systems for maximum wind energy contribution in remote island networks. Energy Convers Manage (2010), doi:10.1016/j.enconman.2010.03.008

## Nomenclature

| | |
|---|---|
| $C_{pA}$ | specific heat capacity of air (J/kg/K) |
| $C_{pR}$ | specific heat capacity of combustion chamber gases (J/kg/K) |
| $DOD_{MAX}$ | maximum depth of discharge |
| $E_{AIR\text{-}CAES}$ | wind energy stored in the form of compressed air (MW h) |
| $E_{AIR\text{-}CAES}^{MAX}$ | maximum exploitation of wind energy stores (MW h) |
| $E_{cr\text{-}rej}$ | wind energy curtailments rejected due to the limited power of the compressor (MW h) |
| $E_g$ | daily guaranteed energy amounts provided by the dual-mode CAES system (MW h) |
| $E_G$ | energy production of the dual-mode CAES system (MW h) |
| $E_{NG}$ | fuel consumption energy content (MW h) |
| $E_{NG\text{-}CAES}$ | fuel consumption energy content only for the CAES cycle (MW h) |
| $E_{NG\text{-}GT}$ | fuel consumption energy content only for the Brayton/Joule cycle (MW h) |
| $E_{REJ}$ | wind energy curtailments rejected by the energy storage system (MW h) |
| $E_{sch\text{-}rej}$ | wind energy curtailments rejected due to the energy production schedule (MW h) |
| $E_{ss}$ | energy capacity of the storage cavern/tank (MW h) |
| $E_{ssmin}$ | minimum energy storage capacity for the satisfaction of daily energy requirements (MW h) |
| $E_{stor}$ | energy storage level of cavern/tank (MW h) |
| $E_{stor\text{-}exist}$ | energy stores already existing in the cavern/tank, previous to the examined period (MW h) |
| $E_{stor\text{-}left}$ | energy stores remaining in the cavern/tank at the end of the period examined (MW h) |
| $E_{stor\text{-}rej}$ | wind energy curtailments rejected due to the storage cavern/tank being full (MW h) |
| $E_{WH}$ | waste heat energy losses (MW h) |
| $E_{wrej}$ | wind energy curtailments (MW h) |
| $h_o$ | energy autonomy period or period of energy production (h) |
| $H_u$ | natural gas specific calorific value (kJ/kg) |
| $\dot{m}_A$ | air mass flow rate (kg/s) |
| $m_a$ | mass of air for stoichiometric combustion (kg/kg$_{NG}$) |
| $M_A$ | air mass storage level of cavern/tank (kg) |
| $\dot{m}_A^*$ | required air mass flow rate to achieve guaranteed energy production (kg/s) |
| $\dot{m}_f$ | mass flow rate of natural gas during the CAES cycle operation (kg/s) |
| $\dot{m}_f'$ | mass flow rate of natural gas during the Brayton/Joule cycle operation (kg/s) |
| $N_c$ | power available for air compression (MW) |
| $N_{cr}$ | rated power of the compressor (MW) |
| $N_{cr}^*$ | rated power of the compressor ensuring maximum wind energy exploitation (MW) |
| $N_{crmin}$ | minimum rated power of the compressor to allow the Brayton/Joule cycle operation (MW) |
| $N_{ex}$ | guaranteed output power of the dual-mode CAES system (MW) |
| $N_{ex\text{-}max}$ | maximum selected guaranteed output power of the dual-mode CAES system (MW) |
| $N_{exo}$ | start-up value for the guaranteed output power of the dual-mode CAES system (MW) |
| $N_{gen}$ | electrical generator rated power (MW) |
| $N_M$ | motor rated power (MW) |
| $N_{TO}$ | gas turbine rated power (MW) |
| $N_{to\text{-}stor}$ | power led to storage caver/tank via the compressor (MW) |
| $N_{wp}$ | installed power capacity of wind park(s) (MW) |
| $N_{wrej}$ | hourly wind power curtailments (MW) |
| $P_A$ | cavern/tank storage pressure (Pa) |
| $P_{amb}$ | atmospheric pressure (Pa) |
| $P_{t1}$ | total air pressure at the compressor inlet (Pa) |
| $P_{t2}$ | total air pressure at the compressor outlet (Pa) |
| $R_g$ | air constant (J/kg/K) |
| $T_A$ | cavern/tank storage temperature (K) |
| $T_{amb}$ | ambient temperature (K) |
| $T_{t1}$ | total air temperature at the compressor inlet (K) |
| $T_{t2}$ | total air temperature at the compressor outlet (K) |
| $T_{t3}$ | total air temperature at the preheater outlet or combustion chamber inlet (K) |
| $T_{t4}$ | total air temperature at the gas turbine inlet or combustion chamber outlet (K) |
| $T_{t5}$ | total air temperature at the gas turbine outlet (K) |
| $T_{tmax}$ | maximum temperature of operation for the gas turbine (K) |
| $V_A$ | air volume storage level of cavern/tank ($m^3$) |
| $V_{max}$ | maximum level of air volume in the storage cavern/tank ($m^3$) |
| $V_{min}$ | minimum level of air volume in the storage cavern/tank ($m^3$) |
| $V_{ss}$ | storage volume of the cavern/tank ($m^3$) |
| $V_{ssmin}$ | minimum storage volume able to at least satisfy daily energy requirements ($m^3$) |

*Greek letters*

| | |
|---|---|
| $\gamma$ | adiabatic coefficient |
| $\Delta E_{ss}$ | energy storage capacity increase step (MW h) |
| $\delta m$ | air mass losses from the storage cavern/tank (kg) |
| $\delta \dot{m}_f$ | fuel savings achieved by the CAES cycle operation (kg/s) |
| $\delta N_{cr}$ | compressor rated power increase step (MW) |
| $\delta N_{ex}$ | guaranteed output power increase step (MW) |
| $\delta P$ | pressure losses from the compressor outlet to the storage cavern/tank inlet (bar) |
| $\Delta t$ | time step (h) |
| $\delta N$ | power deficit covered by the operation of the Brayton/Joule cycle (MW) |
| $\delta \mathrm{T}$ | variation levels of the storage cavern/tank temperature (K) |
| $\eta_{gen}$ | electrical generator efficiency |
| $\eta_{GT\text{-}tot}$ | round-trip efficiency of the Brayton/Joule cycle operation |
| $\eta_{isc}$ | isentropic efficiency of the compressor |
| $\eta_{isT}$ | isentropic efficiency of the gas turbine |
| $\eta_M$ | motor efficiency |
| $\eta_{mc}$ | mechanical efficiency of the compressor |
| $\eta_{mT}$ | mechanical efficiency of the gas turbine |
| $\eta_w$ | preheater efficiency |
| $\lambda_a$ | air ratio |
| $\Pi_c$ | compressor pressure ratio |
| $\Pi_T$ | gas turbine pressure ratio |
| $\rho_A$ | air density (kg/$m^3$) |

*Abbreviations*

| | |
|---|---|
| AFC | annual fuel consumption |
| BOS | balance of system |
| CAES | compressed air energy storage |
| DMCAES | dual-mode compressed air energy storage |
| LNG | liquefied natural gas |
| NG | natural gas |
| PHS | pumped hydro storage |
| RES | renewable energy sources |
| WER | wind energy recovery |

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networks of the Greek territory implies that regulation and pricing are much dependent on the operation of oil units. Seeking to improve the economic performance of operating wind farms, CAES shall be used for peak shaving on the basis of daily guaranteed energy production during peak demand periods (i.e. when costly gas turbines enter the system). Furthermore by considering small scale CAES, the employment of a storage tank in the absence of an appropriate underground cavern is also possible, thus eliminating any siting issues. Based on the above attributes, CAES is currently viewed as a system that may equally well serve medium to small scale applications (tens of MWs), obtain stand-alone characteristics (due to its dual-mode operation) and sufficient siting flexibility. Overall, replacement of costly oil-based peak power units used up to date in island regions and maximum recovery of wind energy curtailments through the application of a sizing algorithm comprise the system main purposes.

## 2. Description of the compressed air energy storage (CAES) technology

In a typical CAES system, off-peak power is absorbed either from the grid or other electricity generation source (wind parks in particular) and is used to pressurize air into an underground cavern via a compressor and possibly an air cooling system that decreases the absorbed air temperature [28]. During periods of increased energy demand, the amount of air necessary to operate the gas turbine is released from the storage, while electricity is then generated from the directly connected electric generator. Prior to energy production, the air released from the cavern is first preheated in the recuperator (an alternator exploiting the waste heat of the gas turbine), while before being expanded in the gas turbine, the amount of preheated air is mixed with the required amount of fuel (NG) in the combustion chamber. The main benefit deriving from the operation of a CAES system lies on the fact that the stages of compression and generation are separated from one another. Consequently, what seems to be as much as 60–70% (rough estimations) of fuel consumption for the compressor to be driven in a typical Brayton/Joule cycle, is not the case for a CAES system. Actually, in a CAES system the entire power generated by the gas turbine is available to cover the electricity consumption via the electrical generator. Nevertheless, fuel consumption is still required (in the range of 4500 kJ per output kW h [29]), this preventing the unconditional acceptance of such systems. In an effort to disengage CAES from the NG factor, biofuel may be used instead [25], while another interesting approach, where no fuel is used and an air turbine is employed, is the so called "advanced adiabatic CAES" [26]. Furthermore, as the losses recognized are not appreciated as important, the storage period is considerable, while when compared with conventional and combined cycle units, CAES exhibits very fast ramp rates (two to three times faster than conventional units [30]).

On the other hand, CAES systems, like pumped hydro storage (PHS), demand favourable sites and geological formations, suitable for underground storage. The storage media most commonly used are the rock caverns, the salt caverns, the porous media reservoirs made by aquifers and the buried pipes for small subsurface CAES units [31], while an air storage tank may also be an option. What is important to consider is that since the capital cost of the installation can present a great variation, the feasibility of such systems is largely dependent on the storage media used. In this context, a constructed rock cavern appears to be the most cost demanding media while the aquifer storage is the least expensive solution [31]. Although identified by siting considerations, CAES is thought to be the only reliable alternative for PHS in terms of energy storage capacity [32,33], this revealing the ability of the system to exploit energy rejections of several wind parks. Besides, due to the fact that fuel consumption is remarkably reduced and the ramp rates are faster, the flexibility of the system to serve either base load applications [25,34,35] or satisfy peak demand [27] is also illustrated.

Finally, one should also consider the fact that the technology of gas turbines – incorporated in a CAES system – is both granted as established and offers the opportunity for further research and development. In this context, one may encounter various applications and concepts [28] in order to improve the performance of similar systems, potentially used in CAES configurations as well.

Appreciating the CAES benefits and considering similar wind energy projects being underway [36] as well as the results of previous research studies (principally regarding Wind-PHS schemes in the area of the Aegean Sea [13,14]), the idea of adopting such a system in autonomous island networks gains interest. Taking also into account the energy plans concerning the introduction of natural gas in certain island networks, e.g. Canary islands and Crete [7,37], and the local wind power potential that in many cases is not yet exploited, the implementation of the CAES concept is further supported.

In particular, the rationale of selecting CAES derives from certain limitations of other candidate technologies, these including PHS, certain battery systems, and hydrogen storage along with fuel cells, mainly due to their ability of bulk storage capacity. As already mentioned, PHS is site dependent and is usually considered for larger scale applications (at the levels of GW h) while it appears to be more costly (both energy and power costs) than CAES. Certain battery systems, such as Na–S or flow batteries could also be used in terms of energy storage capacity, nevertheless, service period, cycling ability and costs are the main factors excluding the specific technologies. On the other hand, hydrogen storage and fuel cells are determined by considerably low efficiency, moderate cycling ability and very high volume energy density, hindering their application in larger scale projects. Although CAES is also limited by certain attributes, such as siting issues and dependence on NG supplies, small scale systems currently adopted offer siting flexibility while the introduction of NG in certain island regions under examination is a sound stimulus for the investigation of the CAES solution.

## 3. Proposed dual-mode Wind–CAES energy solution

Based on typical hourly distributions of load demand on a daily basis (i.e. peak demand during noon and night times) and considering the ability of the CAES technology to provide bulk energy storage, the supply of guaranteed amounts of energy by the system to the local island network during periods of peak load demand [38] is currently investigated. Shifting to the gas turbine cycle (dual mode operation) on the other hand ensures autonomy from the local grid during the charging stage, thus an immediate benefit accrues, i.e. instead of using off-peak power to charge the system in case that excess wind energy is not sufficient to cover guaranteed energy amounts, NG already available for the CAES operation is used to run the Brayton/Joule cycle. More specifically, in times that the energy stores (i.e. wind energy curtailments in the form of compressed air) are not sufficient, the gas turbine is coupled with the compressor via the use of a clutch and the required guaranteed energy is generated on the basis of the gas turbine cycle operation (Brayton/Joule cycle). Disengagement from the electricity grid during charging may prove beneficial during price negotiations with the local administrator (usually configuring the selling price of guaranteed energy on the basis of long term contracts) whereas profitability or not in the first place depends on the cost difference between off-peak power and NG. Besides, stand-alone attributes and increased levels of reliability given to the system (since

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back-up charging power is only dependent on the NG reserves available) should be considered. Note however that shifting to the gas turbine mode entails greater levels of fuel consumption and zero exploitation of wind energy curtailments during these periods of time, thus minimizing the contribution of the gas turbine cycle is imperative.

In this context, the concept under examination, Fig. 1, suggests the collaboration of one or more existing wind parks with a dual-mode CAES system that may exploit the excess/rejected energy produced by the former due to the incapability of the local autonomous island network to absorb the entire wind energy production during off-peak periods. Actually, the main components of the proposed solution include the following:

- One or more existing wind parks of “$N_{\text{wp}}$” rated power, responsible for an annual wind energy curtailment potential “$E_{\text{wrej}} = \sum_{t=1}^{8760} N_{\text{wrej}}(t) \cdot \Delta t$”, with “$N_{\text{wrej}}(t)$” being the hourly (e.g. $\Delta t = 1$ h) wind energy rejection.
- A compressor of “$N_{\text{cr}}$” rated power, driven by a motor (“$N_{\text{M}}$, $\eta_{\text{M}}$”), used to either pressurize air into a storage cavern/tank by exploiting the wind energy surplus or allow the operation of the Brayton/Joule cycle.
- A gas turbine, “$N_{\text{TO}}$” being its rated power, operating either coupled with the compressor (Brayton/Joule cycle) or based on the amounts of compressed air inside the cavern/tank (CAES cycle) and an electrical generator “$N_{\text{gen}}$, $\eta_{\text{gen}}$” coupled with the gas turbine.
- An air storage cavern/tank of a given volume and useful energy capacity, “$V_{\text{ss}}$” and “$E_{\text{ss}}$” respectively, able to at least satisfy the hourly guaranteed energy requirements “$N_{\text{ex}} = N_{\text{TO}} \cdot \eta_{\text{gen}}$” for “$h_{\text{o}}$” hours of energy generation per day (“$V_{\text{ssmin}}$” and “$E_{\text{ssmin}}$” respectively).
- The balance of the system components (BOS), including a recuperator used to preheat the air released by the cavern/tank before entering the combustion chamber, a combustion chamber used to heat up the mixture of compressed air and natural gas, a NG storage tank in order to meet the fuel requirements of the installation, etc.

## 4. Simulation of the proposed solution operation

To determine the size of main components for the dual-mode CAES system in collaboration with wind parks, simulation of the proposed solution operation is used, while the sizing criterion currently adopted requires that maximum recovery of wind energy rejections is achieved by the operation of the CAES unit.

In this context, the two governing parameters of the system used during the sizing procedure are the rated power of the compressor “$N_{\text{cr}}$” and the hourly guaranteed amount of energy “$N_{\text{ex}}$” (MW h/h) or equivalently the daily amounts of guaranteed energy “$E_{\text{g}} = N_{\text{ex}} \cdot h_{\text{o}}$”. To confront similar problems, a numerical algorithm, dual-mode CAES-II (DMCAES-II) is devised (Fig. 2). The developed numerical code is used to carry out the necessary parametrical analysis on an hourly basis. More precisely, for each pair of “$N_{\text{cr}}$” and “$N_{\text{ex}}$” the algorithm is executed for the time period selected (currently a year’s time) with emphasis laid on obtaining maximum exploitation of the wind energy surplus (i.e. when “$N_{\text{cr}} = N^{*}_{\text{cr}}$”). If this is not achieved, the compressor size is increased and the calculation is performed again, up to the case that the maximum wind energy surplus exploitation condition is fulfilled. Next, another amount of hourly guaranteed energy “$N_{\text{ex}}$” is selected and the calculations are repeated. In this way, the simulation of the Wind–CAES configuration is possible and the generation of valid energy related results is ensured. Note, that in order to result to the configuration of the DMCAES-II algorithm, a computational framework (see also Appendix A), based on the use of principal thermodynamic formulas, considers both the distinct stages of the CAES system operation, i.e. the compression stage, the storage stage and the combustion–expansion stage, and the operation of the classic Brayton/Joule cycle mode.

Besides, in order to simulate the dual-mode CAES operation the following steps, also configuring the sequence of steps for the DMCAES-II algorithm, should be considered. Hence, to obtain CAES configurations ensuring maximum wind energy recovery one must:

- Provide all the necessary inputs (see also Table 1) in order to start the calculations, these including the start-up value for the guaranteed energy per hour “$N_{\text{exo}}$” along with the corresponding range maximum value “$N_{\text{ex-max}}$” and the calculation step “$\delta N_{\text{ex}}$”. Both the time step “$\Delta t$” and the energy generation hours “$h_{\text{o}}$”, along with any values of parameters necessary (values of parameters and coefficients determining the operation of the system during the compression, combustion and expansion stages, see also Appendix A and Table 1), are also required.
- Estimate, in relation to the guaranteed energy per hour “$N_{\text{ex}}$” to be delivered by the gas turbine, the initial, minimum acceptable power of the compressor “$N_{\text{crmin}}$” in order to allow the classic

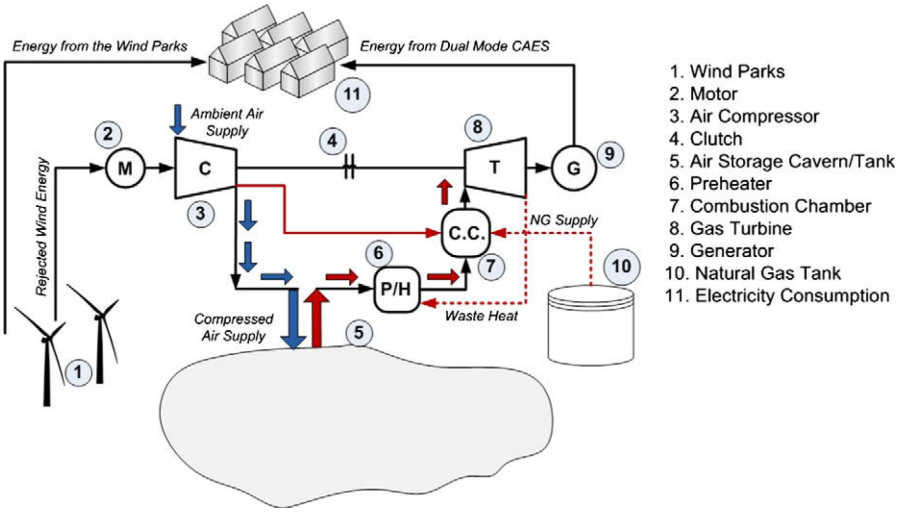

**Fig. 1.** Dual-mode Wind–CAES solution.

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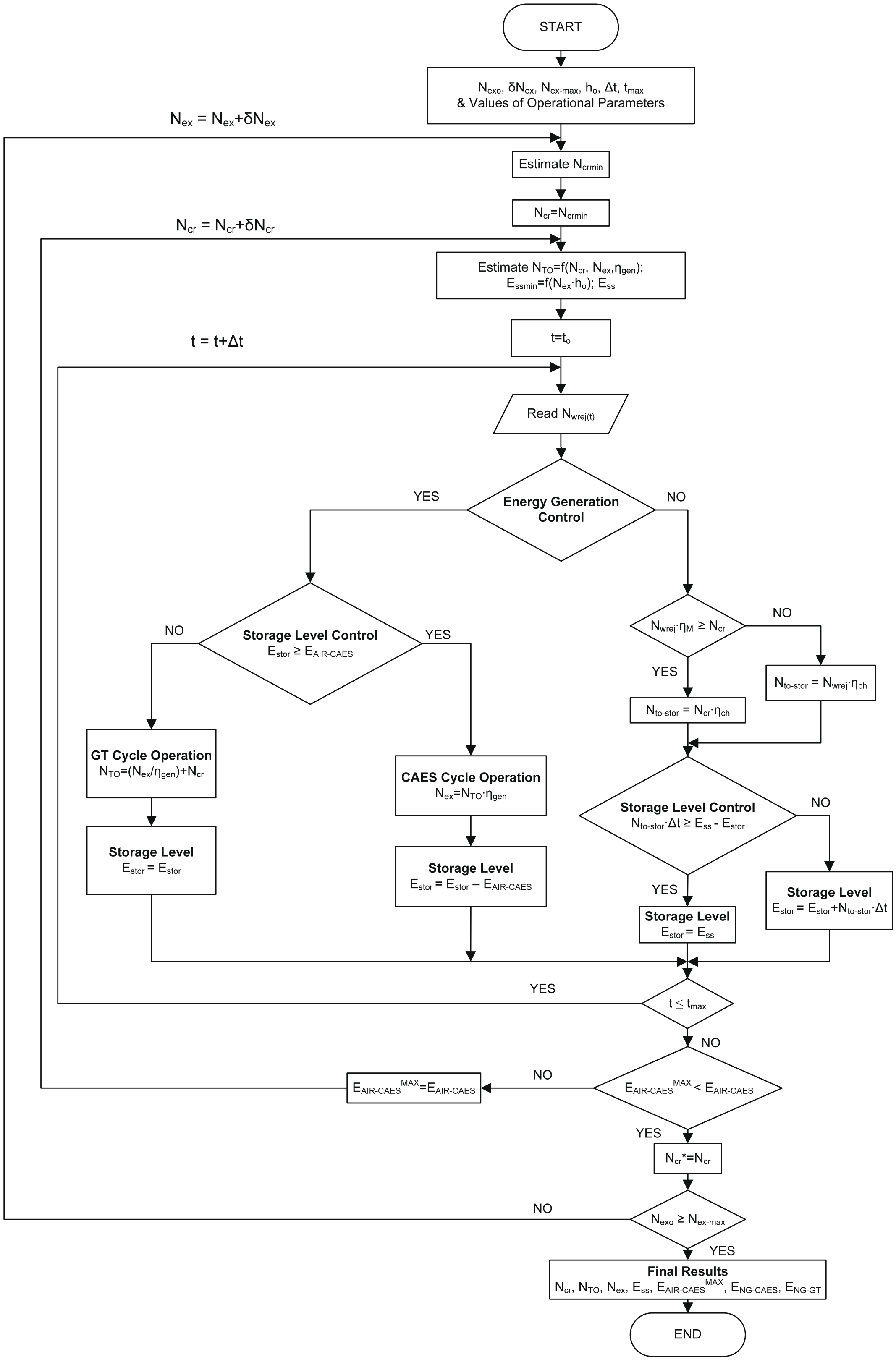

**Fig. 2.** The DMCAES-II algorithm.

cycle to operate, i.e. estimate the necessary air mass flow rate “$\dot{m}_A$”. For this purpose, the values of parameters and coefficients determining the operation of the compression, combustion and expansion stages are also considered (Table 1).

- Determine the nominal power of the gas turbine “$N_{TO}$” considering that it should both deliver the amounts of energy required and allow full-load operation of the compressor during the Brayton/Joule cycle mode.

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**Table 1**
Assigned values for the DMCAES-II algorithm input parameters.

| Parameter | Assigned value |
|---|---|
| Compressor isentropic efficiency “$\eta_{isc}$” | 0.85 |
| Gas turbine isentropic efficiency “$\eta_{isT}$” | 0.88 |
| Compressor mechanical efficiency “$\eta_{mc}$” | 0.99 |
| Gas turbine mechanical efficiency “$\eta_{mc}$” | 0.99 |
| Motor efficiency “$\eta_M$” | 0.98 |
| Preheater efficiency “$\eta_w$” | 0.5 |
| Electrical generator efficiency “$\eta_{gen}$” | 0.98 |
| Maximum depth of discharge “$\mathrm{DOD}_{MAX}$” | 0.7 |
| Storage temperature “$T_A$” (K) | 288 |
| Storage pressure “$P_A$” (bars) | 50 |
| Compressor pressure ratio “$\Pi_c$” | 50 |
| Atmospheric pressure “$P_{amb}$” (bars) | 1 |
| Ambient temperature “$T_{amb}$” (K) | 298 |
| Specific heat capacity of air “$C_{pA}$” (J/kg/K) | 1004.5 |
| Specific heat capacity of gases “$C_{pR}$” (J/kg/K) | 1105 |
| Air ratio “$\lambda_a$” | 4 |
| Mass of air “$m_a$” for stoichiometric combustion (kg/kg$_{NG}$) | 15 |
| Gas turbine maximum temperature of operation “$T_{tmax}$” (K) | 1473 |
| Air constant «$R_g$» (J/kg/K) | 287 |
| Calorific value of natural gas “$H_u$” (kJ/kg) | 47,000 |

- Estimate the minimum acceptable energy capacity “$E_{ssmin}$” of the storage cavern/tank, able to at least satisfy the energy generation requirements on a daily basis “$E_g$” through the CAES mode operation and determine the final energy storage capacity “$E_{ss}$” (considering a step by step increase of capacity “$\Delta E_{ss}$” additional to the minimum permitted value).
- Read the annual data of wind energy curtailments “$E_{wrej}$”, provided by the investigated wind parks' recordings, on an hourly basis “$N_{wrej}(t)$”.
- Check the time schedule and decide whether the hourly wind energy available “$N_{wrej}(t)$” should be rejected by the system (during the energy generation hours) or led to storage (during the rest of the day period).
- If the energy generation schedule permits wind energy storage, compare the hourly wind energy curtailment “$N_{wrej}(t)$” with the nominal power of the compressor “$N_{cr} = N_{crmin}$” and determine the hourly energy “$N_{to\text{-}stor}$” led to storage via the compressor.
- Check the energy storage level “$E_{stor}$” and decide whether additional compressed air may be stored or rejected due to the cavern/tank being full. Determine also the new energy storage level.
- If the energy generation time schedule calls for the generation of energy by the system, check if the energy storage level “$E_{stor}$” is adequate in order to provide the desired energy amounts “$E_{AIR\text{-}CAES}$” (or desired air mass flow “$\dot{m}_A^*$”) for the production of agreed energy “$E_g$”. If this is possible, the system operates on CAES mode, otherwise the gas turbine is coupled with the compressor and the Brayton/Joule cycle mode is activated. Determine also the new energy storage level.
- Check whether maximum exploitation of wind energy curtailments “$E_{AIR\text{-}CAES}^{MAX}$” has been achieved for the given values of energy storage capacity “$E_{ss}$”, hourly guaranteed energy delivered to the local grid “$N_{ex}$” and compressor's nominal power “$N_{cr}$”. If the condition is not fulfilled, the nominal power of the compressor is gradually increased by “$\delta N_{cr}$” and the calculations are repeated, up to the point that maximum exploitation “$\mathrm{E}_{AIR\text{-}CAES} = E_{AIR\text{-}CAES}^{MAX}$” is eventually achieved, i.e. when “$N_{cr} = N_{cr}^*$”.
- Increase the guaranteed energy amount “$N_{exo}$” per hour by “$\delta N_{ex}$”, and repeat the calculations up to the point that “$N_{ex} = N_{ex\text{-}max}$”.
- Determine the final, nominal power of the compressor “$N_{cr}$” and the gas turbine “$N_{TO}$” along with the energy storage capacity “$E_{ss}$”, the fuel consumption during both the CAES “$E_{NG\text{-}CAES}$” and the classic cycle “$E_{NG\text{-}GT}$” operation as well as the maximum wind energy exploitation achieved “$E_{AIR\text{-}CAES}^{MAX}$” for the scenario of “$N_{ex}$” each time examined.

## 5. Case study: private wind parks on the island of Crete

### 5.1. The energy system of Crete

The developed sizing methodology is accordingly applied on a representative island network, i.e. the island of Crete, where the compatibility of the CAES system with the energy patterns of the island is reflected by the forthcoming introduction of NG and the gradual stagnation of wind power investments [39].

Regarding the main features of the Crete electricity network, one should consider a constant increase of electrical energy consumption and peak load demand, described by mean annual increase rates in the levels of 6–7% during the last 20 years [40]. Additionally, according to the latest official data [40], one may encounter 791.2 MW of thermal power plants and 148.4 MW of wind power. On the other hand, both the hydropower and the photovoltaic stations operating on the island correspond to a remarkably low capacity of approximately 1.3 MW. Considering the annual increase rate attached to the peak load demand (at the levels of 650 MW during 2007) and the forthcoming retirement of certain units, arguments regarding urgent reinforcement of the existing electricity capacity, should be taken into account.

What is also interesting to discuss is the corresponding electricity generation fuel mix [40]. As already implied, the greatest part of the island electricity generation is attributed to diesel and heavy oil units that are responsible for considerable environmental impact and high electricity production cost due to the required fuel consumption. In fact, the production cost of gas turbines, mainly serving as peak power units, even reaches 196€/MW h (2007 values) [40]. On the other hand, the annual participation of wind parks operating on the island reaches 393 GW h, equal to 15% of the total electricity generation. Note also that that the local onshore wind energy potential still remains unexploited [41], while local wind parks are faced with significant financial losses [42] due to the fact that considerable wind energy rejection is caused by the local network limitations [5]. Meanwhile, according to the most recent announcements concerning the energy system of Crete [37], a call for the installation of 500 MW comprised by two combined cycle power plants, 250 MW each, operating on natural gas (an LNG terminal will be constructed in the area of Korakia) questions the future of wind energy on the island. Although acknowledging the benefits from using NG instead of oil, attention must be paid on the former required imports [43], as well as on the possible abandonment of the RES prospect.

Considering the forthcoming advancements in the energy status of the island and taking into account the concept of wind energy storage, the adoption of an alternative electricity supply scheme, compatible with the future electricity production pattern is recommended. More specifically, the adoption of compressed air energy storage systems that take advantage of both wind energy rejections and NG is thought to comprise a solution that is worth investigating. At this point, it is critical to note that according to the results of a public survey [44], the majority of Cretans strongly favour wind power applications (90% of acceptability encountered) and thus similar public attitude may be expected for projects called to secure wind energy.

### 5.2. Case study specifications

Regarding the specific case study, the problem to be solved investigates the production of agreed amounts of energy “$E_g$” by the Wind–CAES configuration, on a daily basis, during peak

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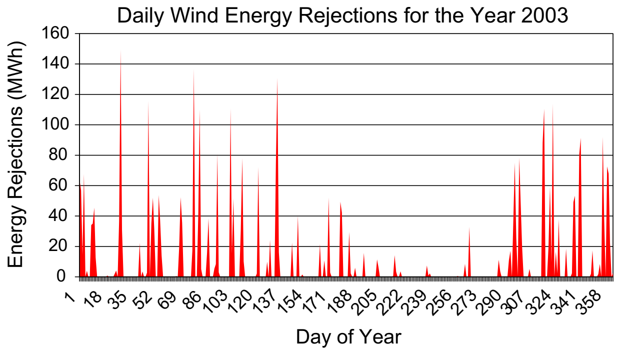

**Fig. 3.** Annual profile of daily wind energy rejections from three private wind parks.

demand periods, i.e. from 12:00 to 15:00, when expensive and outmoded gas turbines are set in operation. For this purpose, the available wind energy surplus from three private wind parks operating in the Sitia region (rated power 25 MW) is presently used (Fig. 3). As one may see, a significant rejection of wind energy is encountered, even reaching 150 MW h on a daily basis. Further, although a lack of wind energy rejections during the summer period is evident, the configuration currently investigated will ensure agreed amounts of energy during the whole year by shifting to the gas turbine cycle operation. In this context, the possibility of excluding the summer period from the guaranteed energy agreement may also be investigated. Additionally, for the solution of the problem the following should also be considered:

- If analyzing the wind energy rejections potential (Fig. 4) one should recommend the use of a compressor power not higher than 10–12 MW (in terms of capital cost only). However, the final power of the compressor is always determined by the "$N_{cr} = \max\{N_{crmin}; N^*_{cr}\}$" condition (see also Appendix A).
- The amount of electricity to be delivered on a daily basis to the local grid, "$E_g = N_{ex} \cdot h_o$", is currently selected to vary between 3 MW h and 30 MW h, i.e. 1 MW × 3 h up to 10 MW × 3 h. Note that remarkably higher contribution (up to 50 MW) is expected in case that the analysis also includes the entire available wind power of the island (~150 MW).
- The rated power of the gas turbine "$N_{TO}$" is called to both provide the amounts of energy guaranteed per hour "$N_{ex}$" during the CAES operation, and satisfy both the agreed energy and the compressor operation during the gas turbine cycle mode, i.e. "$N_{TO} = \frac{N_{ex}}{\eta_{gen}} + N_{cr}$".
- If not considering an already existing cavern of a given capacity, the minimum storage volume "$V_{ssmin}$ " is decided by the daily energy provision requirements "$E_g = N_{ex} \cdot h_o$".

## 6. Application results

Accordingly, the application of the DMCAES-II algorithm for the specific case study leads to the generation of results presented in the following figures. Two distinct cases are primarily examined: a moderate storage capacity ("$E_{ss}$ = 15 MW h") with the respective agreed energy amounts "$E_g$" ranging from 3 MW h/day to 15 MW h/day and a larger storage capacity case ("$E_{ss}$ = 30 MW h") with the corresponding energy generation ranging from 3 MW h/day to 30 MW h/day.

For the evaluation of configurations ensuring maximum wind energy recovery the parameters of wind energy recovery, annual fuel consumption and CAES cycle participation will be currently investigated, with the latter definition given in the following:

- Wind energy recovery: The energy share of available wind energy rejections converted into agreed energy via the CAES cycle operation during a year's period.
- Annual fuel consumption: The total fuel consumption of the installation considering both the CAES operation and the shifts to the classic thermodynamic cycle during a year's period.
- CAES cycle participation: The energy share of the CAES cycle in the annual generation of agreed energy amounts.

### *6.1. CAES only operation*

In order to illustrate the performance of the CAES-only solution (not considering dual mode operation) and also interpret the methodology steps followed by the DMCAES-II algorithm, certain results regarding the operation of the CAES system alone will also be presented. In this context, in Fig. 5 one may obtain the wind energy recovery achieved for the moderate storage case, using a fixed storage capacity that is equal to the minimum required for the 15 MW h/day case ("$E_{ss}$ = 15 MW h"). As one may see, wind energy recovery increases with the increase of the compressor's nominal power "$N_{cr}$" and maximizes when the power of the compressor exceeds 4 MW (area of maximum wind energy recovery configurations for the DMCAES-II algorithm, provided that the power of the compressor allows the operation of the classic cycle $N_{cr} \geqslant N_{crmin}$). In fact, wind energy recovery is found to even reach 30% for higher values of agreed energy "$E_g$", since a fair exploitation of the energy storage in combination with the generation of appreciable energy amounts (e.g. 15 MW h/day) is encountered. Contrariwise, exploitation of wind energy rejections does not exceed 17% for the 3 MW h/day case.

Following, the respective annual fuel savings (resulting from the comparison with the annual fuel consumption of the typical gas turbine cycle, currently given for zero compressor power)

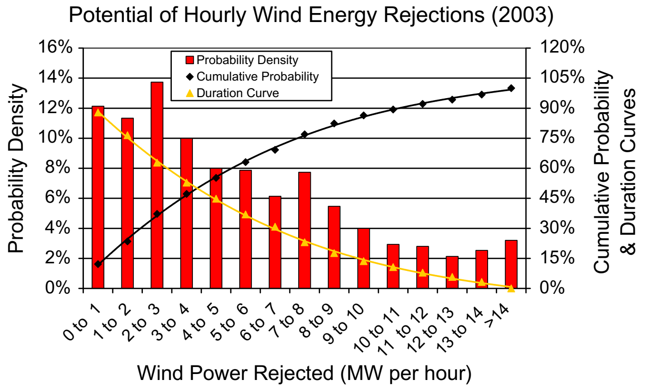

**Fig. 4.** Evaluation of the wind energy rejections' potential.

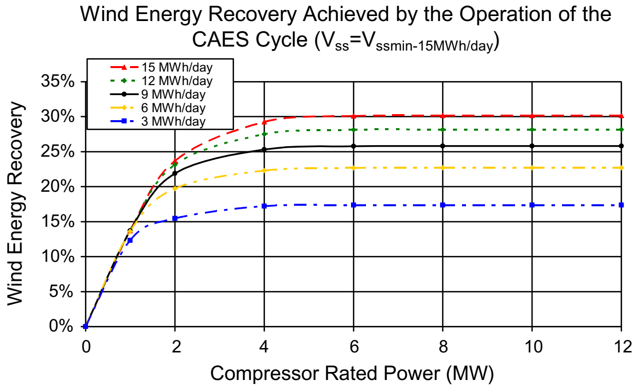

**Fig. 5.** Wind energy recovery achieved by the CAES operation (15 MW h case).

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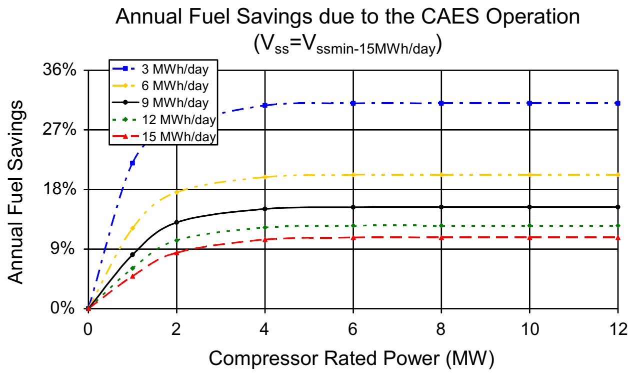

**Fig. 6.** Annual fuel savings achieved by the CAES operation (15 MW h case).

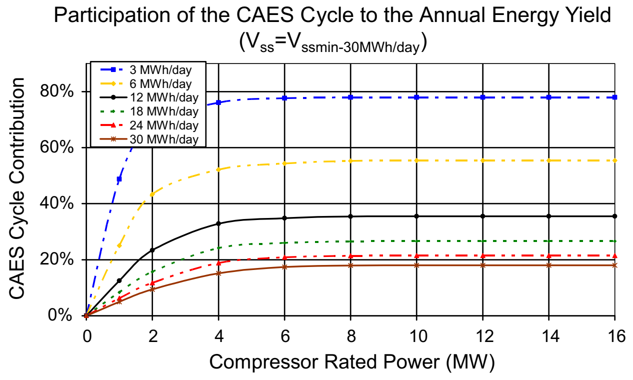

**Fig. 7.** Participation of the CAES in the annual energy yield of the system (30 MW h case).

may be obtained from Fig. 6. As it may be noted, higher levels of fuel savings, even 30%, are encountered when both the compressor power increases and the energy storage capacity "$E_{ss}$" becomes significantly higher than the corresponding minimum "$E_{ssmin}$" (e.g. in the cases of 3 MW h/day and 6 MW h/day one could use minimum useful storage capacities "$E_{ssmin}$" of 3 MW h and 6 MW h instead of the 15 MW h currently examined). In fact, if selecting minimum storage capacity, e.g. for the 3 MW h/day case, the respective annual fuel savings are calculated to drop to 14%, considerably less than the respective 30% for the 15 MW h storage capacity.

Subsequently, one should also present the participation of the CAES cycle. Regardless if the dual-mode operation is currently adopted, it should again be noted that the remaining energy deficit (energy share not covered by the CAES cycle) may also be covered by using off-peak power in order to sufficiently charge the storage cavern/tank, this however jeopardizing any autonomy benefits (in relation to the interaction with the local network). From the results obtained for the 30 MW h capacity case (Fig. 7), one may observe strong variation among the agreed energy cases examined. For the "tighter" storage cases, i.e. when the daily agreed amounts of energy "$E_g$" approach or reach the energy storage capacity "$E_{ss}$" of the cavern/tank (e.g. 30 MW h/day and 30 MW h), the contribution of the CAES cycle minimizes. On the other hand, if a "looser" storage case is examined, i.e. 3 MW h/day and 30 MW h, the CAES cycle is responsible for the production of 78% of the annual energy yield of the installation.

### *6.2. Maximum wind energy recovery dual-mode CAES configurations*

After the presentation of the CAES-only results, in Figs. 8 and 9 one may obtain the results concerning dual-mode CAES configurations, able to ensure maximum wind energy exploitation. Note that each of the specific configurations not only ensures maximum wind energy recovery but also allows the operation of the typical gas turbine cycle for the energy storage capacity "$E_{ss}$" and agreed energy "$E_g$" each time examined. Besides, as already implied, the parameters of energy storage capacity "$E_{ss}$" and agreed energy "$E_g$" are critical for the system evaluation. In this context, the influence of the energy storage capacity "$E_{ss}$" variation on the wind energy recovery is demonstrated in Fig. 8. As one may conclude considerable amounts of wind energy, otherwise not absorbed by the CAES system, may be exploited due to the selection of a larger storage unit. The most illustrative example regards the 3 MW h/day (1 MW × 3 h) case, where the use of 30 MW h useful energy storage "$E_{ss}$" implies 13% greater exploitation of wind energy than the respective achieved by the minimum useful storage capacity "$E_{ssmin}$" of 3 MW h (from 8% to 21%) ensuring the coverage of one day's agreed energy requirements. Besides, one cannot neglect the fact that for greater guaranteed energy cases, e.g. 12 MW h/day (4 MW × 3 h), the additional exploitation of storage (30 MW h) reaches a plus of 14%. Besides, by including the option of infinite energy storage capacity as well, the upper limit of wind energy recovery is determined. Infinite capacity solution reaches a maximum of 29% for the 3 MW h/day case while exceeds 70% for the 12 MW h/day case. To further exploit wind energy curtailments, the increase of agreed daily energy amounts "$E_g$" is required.

Accordingly, although in the reverse order, similar are the results concerning the annual fuel consumption variation (Fig. 9). "Looser" energy storage, e.g. 30 MW h of storage capacity, implies minimum fuel consumption while "tighter" storage cases (minimum storage capacity volume) suggest less considerable fuel

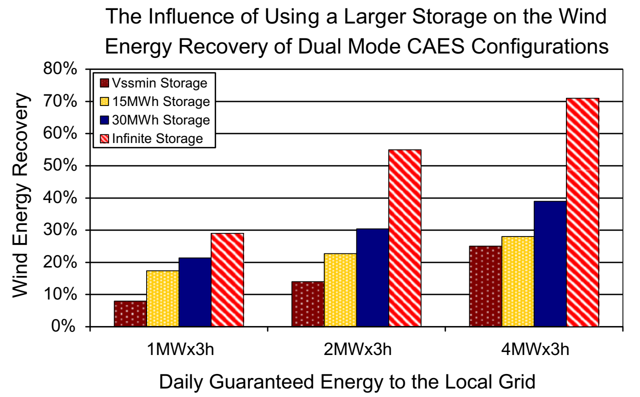

**Fig. 8.** Maximum wind energy recovery of dual-mode CAES configurations on the basis of energy storage capacity variation.

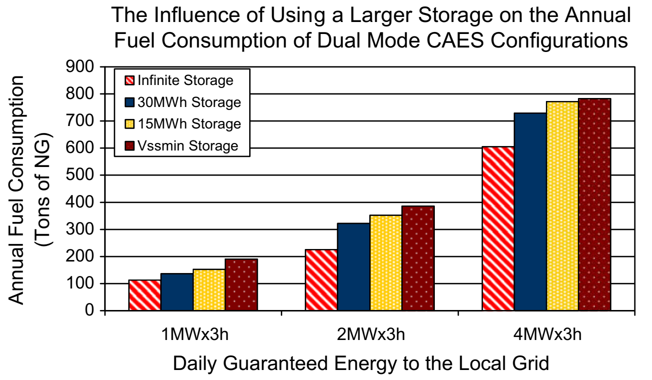

**Fig. 9.** Annual fuel consumption of dual-mode CAES configurations ensuring maximum wind energy recovery on the basis of energy storage capacity variation.

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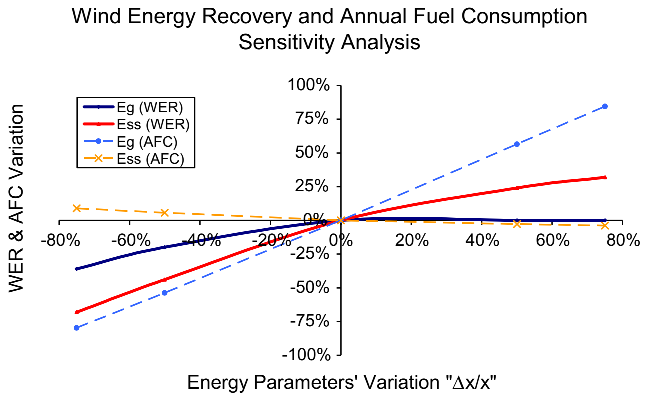

**Fig. 10.** Influence of the energy storage capacity and agreed energy parameters' variation on wind energy recovery and annual fuel consumption.

savings due to more shifts to the classic cycle. On the other hand it is impressive to see that even infinite storage does not allow remarkable fuel savings unless considerable agreed energy "$E_g$" is examined (from 783 tons to 605 tons for the 4 MW × 3 h case). In this context, one should take into account that greater levels of wind energy recovery were recorded for analogous levels of agreed energy "$E_g$", while fuel consumption – although not as high as the respective of the classic cycle – is still required for the CAES operation. In fact the heat ratio of the CAES system currently examined is estimated at 1.34 kW $h_{th}$/kW $h_{out}$ with the respective of the gas turbine cycle calculated at 2.63 kW $h_{th}$/kW $h_{out}$ (see also Table 1).

Finally, to better interpret the performance of configurations under the variation of energy storage capacity "$E_{ss}$" and agreed amounts of energy "$E_g$", the results of a sensitivity analysis regarding the case of a 4 MW × 3 h and 12 MW h combination, are given in Fig. 10, while the relative variation range selected ("$\Delta x/x$") is common for both variables, i.e. ±75%. In relation to the annual fuel consumption (AFC) – as already implied – minimum is the influence of the energy storage capacity "$E_{ss}$" variation. If reducing the storage capacity of the employed cavern/tank, more shifts to the classic cycle are required and the fuel consumption marginally increases (+9%) while even if employing an almost double storage capacity ("$1.75 \times E_{ssmin}$"), the increase of fuel savings is inconsiderable. On the other hand, if deciding to either increase or decrease the energy delivered to the local grid for a fixed energy storage capacity "$E_{ss} = E_{ssmin}$", the AFC presents analogous, quire remarkable variation.

Regarding the parameter of wind energy recovery (WER), by reducing the energy storage capacity "$E_{ss}$", i.e. going to extremely "tight" storage cases, remarkable reduction of WER even reaches −68%. Although an increase of WER is encountered when going to "looser" storage cases, the influence is not as strong (+32%). Similarly, if reducing the agreed amounts of energy "$E_g$" for a fixed energy storage capacity "$E_{ss} = E_{ssmin}$", i.e. going again to "looser" storage cases, the reduction of WER exceeds 35% due to both the moderate exploitation of a larger than the minimum storage and the fact that less energy is eventually provided to the grid. Finally, as it may be expected, allowing the agreed amounts of energy "$E_g$" to increase further than the initial "tight" scenario, i.e. 12 MW h/day and 12 MW h, entails zero variation of WER, since the system is unable to provide greater amounts of energy on a daily basis, due to the fact that the energy storage capacity "$E_{ss}$" has already been exploited.

### 6.3. The concept of dual-mode CAES in perspective

Closing, an attempt is made to correlate the research findings with the results of other relative work. Due to the novelty and destination of the system under investigation however, a straightforward comparison, especially concerning the problem critical parameters, i.e. wind energy recovery, fuel consumption and CAES cycle contribution is either not easily obtained or is not attainable. On the other hand, by examining certain attributes of the CAES cycle alone such as the heat ratio, places results in close proximity with the results of other works (1.34 kW $h_{th}$/KW $h_{out}$ against 1.17–1.4 kW $h_{th}$/kW $h_{out}$ in [24,25,27,34,35]). At the same time it is interesting to see that a similar study concerned with the application of an analogous scale Wind-PHS system in the island of Crete [5], under the pattern of guaranteed energy amounts as well, argues that the recovery of wind energy curtailments may range between 40% and 60% (values identical to the ones potentially achieved by the CAES configuration). Furthermore, based on the results of an economic evaluation for the proposed system undertaken by the authors [45], the life cycle energy production cost of certain optimum size configurations may both beat the respective cost of peak power units on the island of Crete and also compete with the other main storage alternative, namely PHS [38]. Besides, the results of the research regarding Crete may be related to other island areas as well (Aegean, Canary, etc.), hence providing a rough evaluation regarding the adoption of the system to a much broader extent. For instance, several scattered islands, favored by excellent wind energy potential are located in the Aegean Sea, at the east side of the Greek mainland. To obtain maximum participation of wind energy in the local fuel mix, currently not exceeding 10% on average, energy storage is required. Assuming an expansion of the NG network within the Aegean Sea, opportunities for examining various Wind–CAES concepts (such as seasonal storage) may arise as well, while extremely high production costs attributed to the operation of oil based units (especially in small scale islands) further support the proposed solution.

## 7. Conclusions

Acknowledging the need for the support of wind energy in autonomous island networks, the concept of wind energy storage should be investigated. Considering also the expansion of natural gas networks (LNG shipments) to island regions as well, compressed air energy storage is currently proposed for the recovery of wind energy rejections. Deciding that the system should provide agreed amounts of energy during peak demand and high electricity production cost periods, an alternative mode of the CAES operation is examined, i.e. a dual-mode CAES configuration.

In this context, a simulation algorithm has been developed for the dual-mode CAES, providing the dimensions of similar systems based on the criterion of maximum wind energy recovery. The developed algorithm is then applied on the island of Crete, based on the annual profile of wind energy curtailments from three wind parks of 25 MW rated power. From the results obtained, both remarkable wind energy recovery (even at the levels of 50% for larger systems) and considerable fuel savings were achieved by the CAES operation. Furthermore, special attention was given to the impact caused by the variation of the two parameters identified as critical, i.e. the amounts of agreed energy and the energy storage capacity. According to the sensitivity analysis results, the variation of agreed energy provided to the local grid during peak load demand periods, strongly affects the annual fuel consumption while the respective of the storage capacity has considerable influence on the recovery of wind energy.

Adopting the dual-mode CAES operation, the agreed energy condition is satisfied on the basis of NG consumption. Although the gas turbine of the system has to be oversized in order to ensure both the gas turbine cycle and the generation of agreed energy amounts, the system appreciates full autonomy in relation to the local network (i.e. no amounts of off-peak power is used to charge the storage) and is only based on the consumption of natural gas, already required for the operation of the CAES-only cycle. Besides, according to the results of an economic evaluation undertaken by the authors, certain dual-mode CAES configurations may beat the electricity production cost of existing peak power units and thus prove to be feasible for the island of Crete.

## Appendix A

In order to proceed to the sizing of the storage system, the governing equations configuring the operation of the various CAES components are presented. Both the CAES and the Brayton/Joule cycle modes are studied in terms of a thermodynamic analysis [46–48], while to facilitate the presentation of equations, the CAES operation will be divided in its main stages, i.e. the compression stage, the storage stage and the combustion–expansion stage. A short analysis of the storage cavern sizing as well as of the system energy balance, are also provided.

### A.1. CAES operation

#### A.1.1. Compression stage

The power each time available for the compression of air "$N_c$" derives from the hourly wind energy rejection "$N_{wrej}$" and the employed motor efficiency "$\eta_M$" (Eq. (A-1)).

$$N_c = \eta_M \cdot N_{wrej} \tag{A-1}$$

Next, the mass flow rate of air "$\dot{m}_A$" pressurized inside the storage cavern is given by Eq. (A-2), where "$\eta_{isc}$" and "$\eta_{mc}$" are the isentropic and mechanical efficiencies of the compressor respectively, "$T_{t1}$" is the total temperature of air (currently treated as an ideal gas) entering the compressor (usually equal to the ambient air temperature, "$T_{t1} = T_{amb}$"), "$\Pi_c$" is the compressor pressure ratio, "$C_{pA}$" is the specific heat capacity of air and "$\gamma$" is the adiabatic coefficient.

$$\dot{m}_A = \frac{N_c \cdot \eta_{isc} \cdot \eta_{mc}}{C_{pA} \cdot T_{t1} \cdot \left( \Pi_c^{\frac{\gamma-1}{\gamma}} 1 \right)} \tag{A-2}$$

If properly analyzing the annual hourly wind energy rejection's profile, one may select an appropriate range of compressor power that suggests maximum exploitation of wind energy (see also Fig. 4). However, the final selection of the compressor's rated power is directly related to the fulfillment of the following condition:

$$N_{cr} = \max\{N_{crmin}\ ; N_{cr}^*\} \tag{A-3}$$

where "$N_{crmin}$" is the compressor rated power corresponding to the requirements of technical specifications and features for the gas turbine-compressor set operation and "$N_{cr}^*$" is the rated power of the compressor ensuring maximum wind energy exploitation (see also the DMCAES-II algorithm). Having selected the nominal power of the compressor "$N_{cr}$", the exploitation of wind energy during the stage of compression, is given. If the amount of wind energy available is greater than the nominal power of the compressor, i.e.

$$N_c = \eta_M \cdot N_{wrej} > N_{cr} \tag{A-4}$$

then the mass flow rate of air to be delivered to storage is:

$$\dot{m}_A = \frac{N_{cr} \cdot \eta_{isc} \cdot \eta_{mc}}{C_{pA} \cdot T_{t1} \cdot \left( \Pi_c^{\frac{\gamma-1}{\gamma}} - 1 \right)} \tag{A-5}$$

otherwise the mass flow rate of air pressurized is given by Eq. (A-2), while the air total temperature at the end of the compression stage "$T_{t2}$" is given by Eq. (A-6):

$$T_{t2} = T_{amb} \cdot \left[ 1 + \frac{1}{\eta_{isc}} \cdot \left( \Pi_c^{\frac{\gamma-1}{\gamma}} - 1 \right) \right] \tag{A-6}$$

#### A.1.2. Energy storage stage

After being compressed, the ambient air is stored inside the storage cavern. The cavern storage level is decided by Eq. (A-7), where "$M_A(t)$" represents the mass of air inside the storage at a given time "$t$", "$M_A(t-1)$" is the storage level during the previous hour (an hourly time step is to be considered), "$\dot{m}_A \cdot \delta t$" is the mass entering the cavern and "$\delta m$" stands for any mass losses present.

$$M_A(t) = M_A(t-1) + \dot{m}_A \cdot \delta t - \delta m \tag{A-7}$$

The respective pressure level is decided by the pressure ratio of the compressor "$\Pi_c$" utilized as well as the existence of any pressure losses "$\delta P$" from the compressor outlet up to the storage cavern inlet, see Eq. (A-8).

$$P_A = P_{t2} - \delta P = \Pi_c \cdot P_{t1} - \delta P = \Pi_c \cdot P_{amb} - \delta P \tag{A-8}$$

where "$P_{t2}$" is the total pressure at the exit of the compressor and "$P_{t1}$" is the pressure of air in the entry of the compressor, usually taken slightly less than the ambient air pressure "$P_{amb}$".

Similarly, the air temperature inside the cavern may vary at a given variation level "$\pm\delta T$", depending on the heat transfer characteristics of the cavern walls and the underground temperature levels (see Eq. (A-9)).

$$T_A = T_{amb} \pm \delta T \tag{A-9}$$

Finally, the storage level may vary in terms of storage volume "$V_A(t)$" between a minimum permitted value of discharge "$V_{min}$", dictated by the corresponding maximum depth of discharge, and a maximum "$V_{max}$", decided by the selected volume of the cavern "$V_{ss}$" (see Eq. (A-10)).

$$V_{min} \leqslant V_A(t) = \frac{M_A(t)}{\rho_A} \leqslant V_{max} = V_{ss} \tag{A-10}$$

where "$\rho_A$" is the density of air inside the cavern, determined by the corresponding values of air pressure "$P_A$" and air temperature "$T_A$", as well as by the air constant "$R_g$", equal to 287 J/kg K (see Eq. (A-11)).

$$\rho_A = \frac{P_A}{R_g \cdot T_A} \tag{A-11}$$

#### A.1.3. Combustion–expansion stage

From the equation of energy balance for the combustion chamber one may obtain the temperature of gases entering the gas turbine "$T_{t4}$" (see Eq. (A-12)), not allowed to exceed the maximum temperature of operation "$T_{tmax}$" ascribed to the gas turbine specifications.

$$T_{t4} = \frac{C_{pA}}{C_{pR}} \cdot \frac{\lambda_a \cdot m_a}{(\lambda_a \cdot m_a + 1)} \cdot T_{t3} + \frac{H_u}{(\lambda_a \cdot m_a + 1) \cdot C_{pR}} \leqslant T_{t\,max} \tag{A-12}$$

where "$C_{pR}$" is the specific heat capacity of gases, "$T_{t3}$" is the air temperature after the preheater, "$H_u$" is the calorific value of natural gas, "$\lambda_a$" is the air ratio and "$m_a$" is the mass of air used for stoichiometric combustion of 1 kg of NG. Besides, in order to estimate the temperature of air leaving the preheater "$T_{t3}$", one may use Eq. (A-13), resulting from the determination of the preheater's efficiency, i.e.

$$T_{t3} = T_A + \eta_w \cdot (T_{t5} - T_A) \tag{A-13}$$

where "$\eta_w$" is the preheater's efficiency, "$T_{t5}$" is the temperature of the waste heat air stream leaving the gas turbine and "$T_A$" is the temperature of air taken from the storage.

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Next, to determine the temperature of the waste heat air stream "$T_{t5}$", the isentropic efficiency of the expansion stage "$\eta_{isT}$" as well as the expansion ratio "$\Pi_T$" ($\Pi_T \approx 0.95\Pi_c$) should be used, see also Eq. (A-14).

$$T_{t5} = T_{t4} \cdot \left[1 - \eta_{isT} \cdot \left(1 - \frac{1}{\Pi_T^{\frac{\gamma-1}{\gamma}}}\right)\right] \tag{A-14}$$

Finally, the power each time delivered to the local grid "$N_{ex}$" may be estimated by Eq. (A-15), considering both the power generation provided by the gas turbine employed "$N_{TO}$" and the efficiency of the electrical generator "$\eta_{gen}$" used to produce electricity.

$$\begin{aligned} N_{ex} &= \eta_{gen} \cdot N_{TO} \\ &= \eta_{gen} \cdot (\lambda_a \cdot m_a + 1) \cdot \dot{m}_f \cdot C_{pR} \cdot (T_{t4} - T_{t5}) \cdot \eta_{mT} \end{aligned} \tag{A-15}$$

or

$$N_{ex} = \eta_{gen} \cdot (\lambda_a \cdot m_a + 1) \cdot \dot{m}_f \cdot C_{pR} \cdot T_{t4} \left(1 - \frac{1}{\Pi_T^{\frac{\gamma-1}{\gamma}}}\right) \cdot \eta_{isT} \cdot \eta_{mT} \tag{A-16}$$

where "$\dot{m}_f$" is the mass flow rate of NG and "$\eta_{mT}$" is the mechanical efficiency of the gas turbine in operation. Note finally that the mass flow rate of NG "$\dot{m}_f$" is directly related to the corresponding mass flow rate of air "$\dot{m}_A$", see also Eq. (A-17).

$$\dot{m}_f = \frac{\dot{m}_A}{\lambda_a \cdot m_\alpha} \tag{A-17}$$

### A.1.4. Sizing of the cavern/tank

As already implied, the minimum volume of the storage cavern/tank "$V_{ssmin}$ " is directly related to both the maximum depth of discharge "$DOD_{MAX}$" and the minimum useful energy storage capacity "$E_{ssmin} = E_g = N_{ex} \cdot h_o$".

$$V_{ssmin} = f(N_{ex} \cdot h_o; DOD_{MAX}) \leqslant V_{ss} \tag{A-18}$$

For the minimum storage size "$V_{ssmin}$ " to be estimated, the mass flow rate of air "$\dot{m}_A^*$" required to provide the desired energy generation output "$N_{ex}$" is used in Eq. (A-19) (see also Eqs. (A-16) and (A-17)),

$$V_{ssmin} = \frac{\dot{m}_A^* \cdot h_o \cdot T_A \cdot R_g}{P_A \cdot DOD_{MAX}} \tag{A-19}$$

while the final size of the storage cavern/tank "$V_{ss}$" takes into account the useful energy storage capacity of the system "$E_{ss} = N_{ex} \cdot h_o + \Delta E_{ss}$" (see Eq. (A-20)), where "$\Delta E_{ss}$"represents any additional – to the minimum – energy capacity in order to further exploit the amounts of wind energy rejections "$E_{wrej}$".

$$V_{ss} = f(E_{ss}; DOD_{MAX}) \tag{A-20}$$

## A.2. Gas turbine cycle operation

Alternatively, when the amount of air inside the cavern/tank is not adequate to satisfy the commitment of guaranteed energy per hour being equal to "$N_{ex} = \eta_{gen} \cdot N_{TO}$ ("$N_{TO}$" being the rated power of the gas turbine), or equivalently when "$\dot{m}_A = \lambda_a \cdot m_a \cdot \dot{m}_f < \dot{m}_A^*$", the power deficit "$\delta N$" is covered by the operation of the typical gas turbine cycle (i.e. the gas turbine is coupled to the compressor) under the condition of energy production described by Eq. (A-21).

$$N_{TO} = \frac{\delta N}{\eta_{gen}} + N_{cr} \tag{A-21}$$

where "$\delta N$" may vary in the range "$0 \leqslant \delta N \leqslant N_{ex}$". Besides, the gas turbine output power "$N_{TO}$" may also be expressed by Eq. (A-22).

$$N_{TO} = \eta_{GT\text{-}tot} \cdot \dot{m}_f' \cdot H_u \tag{A-22}$$

where "$\eta_{GT\text{-}tot}$" is the round-trip efficiency of the gas turbine cycle operation [46–47] and "$\dot{m}_f'$" is the corresponding mass flow rate of NG. Overall, the benefit of using the CAES cycle may be expressed on the basis of fuel gain "$\delta\dot{m}_f$", see Eq. (A-23).

$$\delta\dot{m}_f = \dot{m}_f' - \dot{m}_f \tag{A-23}$$

## A.3. Energy balance of the system

In the following, a brief analysis of the system wind energy balance is realized. As already seen, the system may operate under two possible ways, i.e. either via the CAES cycle, or via the typical gas turbine cycle. Regarding the first mode of operation and the balance of the storage cavern/tank in particular, the following is valid for a given period of time:

$$\begin{aligned} E_{wrej} = {} & E_{AIR\text{-}CAES} + E_{cr\text{-}rej} + E_{sch\text{-}rej} + E_{stor\text{-}rej} + E_{stor\text{-}left} \\ & - E_{stor\text{-}exist} \end{aligned} \tag{A-24}$$

More specifically, the amount of wind energy curtailments "$E_{wrej}$", being afterwards driven to storage, is either stored "$E_{AIR\text{-}CAES}$" or rejected due to:

1. The size of the compressor leading to the analogous rejection of wind energy curtailments "$E_{cr\text{-}rej}$", see also Eq. (A-4).
2. The energy generation schedule: it is assumed that during the hours that guaranteed energy is provided to the grid, no charging of the storage cavern/tank takes place, hence allowing the compressors to avoid full-time operation and implying an energy rejection "$E_{sch\text{-}rej}$".
3. The useful storage capacity: if the storage cavern/tank is full, i.e. if the instantaneous storage level is equal to the useful storage capacity "$E_{stor} = E_{ss}$" or "$V_A(t) = V_{max} = V_{ss}$", then any further compressed air energy storage "$N_{to\text{-}stor} \cdot \Delta t$" is bounded and the respective amounts of wind energy curtailments "$E_{stor\text{-}rej}$" are rejected.
4. The possibility of stored energy "$E_{stor\text{-}left}$" remaining unexploited inside the cavern/tank at the end of the given time period examined.

Any case given, the possibility of stored energy "$E_{stor\text{-}exist}$" already existing inside the cavern/tank at the start of the given time period examined should also be taken into account.

Finally, if considering the dual-mode of the system for a given period of time, also accounting for the required amount of energy, the overall energy balance is given by Eq. (A-25).

$$E_{wrej} + E_{NG} = E_G + E_{REJ} + E_{WH} \tag{A-25}$$

where "$E_{NG}$" is the total amount of NG used for both the CAES "$E_{NG\text{-}CAES}$" and the gas turbine cycle "$E_{NG\text{-}GT}$" operation, "$E_G$" is the total energy production, "$E_{REJ}$" is the sum of rejected energy previously analyzed and "$E_{WH}$" is the system loss, mainly including waste heat deriving from the gas turbine operation.

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Please cite this article in press as: Zafirakis D, Kaldellis JK. Autonomous dual-mode CAES systems for maximum wind energy contribution in remote island networks. Energy Convers Manage (2010), doi:10.1016/j.enconman.2010.03.008

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Please cite this article in press as: Zafirakis D, Kaldellis JK. Autonomous dual-mode CAES systems for maximum wind energy contribution in remote island networks. Energy Convers Manage (2010), doi:10.1016/j.enconman.2010.03.008