Large-scale energy storage and dynamic performance of the autonomous power system in Crete Island: A review of the literature

Yiannis A. Katsigiannis, Emmanuel S. Karapidakis, Antonios G. Tsikalakis, and Anastasia Katsamaki

***Abstract*—**The autonomous power system of Crete Island is the largest autonomous power system in Greece, accounting for around 5% of total energy demand. The Cretan power system is of particular interest, not only because of its high renewable energy sources (RES) potential, but also due to its specific operating characteristics, including the absence of interconnection, the large number of small capacity conventional plants existence, and its high electricity production costs. Apart from the already apparent and expected benefits of high RES penetration, a variety of parameters that include variation of RES, loss of conventional units, added errors, and complexity in the operating system's conditions due to increased number of RES plants may also cause significant issues in its stability. Moreover, the technical constraints that are added due to RES technologies operation may lead to a reduction of their absorbed energy by the system, reducing therefore the benefits from their commitment. One way to achieve high penetration from renewable energy is the installation of large scale energy storage units, such as pumped hydro storage (PHS) systems. However, in any case it is essential to maintain the desired dynamic stability and economic operation of the system. This can be only implemented with the design and development of an advanced and intelligent real time power management system. The scope of this paper is to provide the necessary review and evaluation of related literature in these subjects.

***Keywords*—**Autonomous power systems, dynamic performance, energy storage, power system monitoring, renewable energy sources.

I. INTRODUCTION

THE Greek power system consists of the mainland interconnected system, which consumes the largest portion of total electricity demand (≈90%), and a large number of autonomous power systems, with the vast majority of them located in the Aegean Archipelago islands [1]. In most of these systems, the cost of electricity production is much higher than in interconnected systems due to the high operating costs of their thermal generating units, mainly diesel and gas turbines, and the import and transportation costs of the fuel used.

The majority of these autonomous islands present significant wind and solar potential, which make ideal the exploitation of these renewable energy sources (RES) by using technologies such as wind turbines and photovoltaics (PVs), and significant progress has been made till now. These technologies, when installed properly, may provide significant benefits to the system [2]. Unfortunately, technical constraints that are added due to RES technologies operation may lead to a reduction of their absorbed energy by the system, reducing therefore the benefits from their commitment. More specifically, in such systems, contrary to interconnected ones, mismatches in generation and load and/or unstable system frequency control might lead to system failures much easier. Increased share of intermittent RES, may be economically attractive [3] but unless special precautions are made, dynamic security of the whole system may deteriorate [4].

Energy storage may be an interesting solution to alleviate technical barriers for increasing intermittent RES penetration. One of the main disadvantages of energy storage is its high initial cost. However, when sized properly, energy storage can provide an economically viable solution, especially in the cases of autonomous power systems that present high operating costs. Under these circumstances, the combination of desired dynamic stability and economic operation of the system can be only implemented with the design and development of an advanced and intelligent real time power management system.

This paper is related to the autonomous power system of Crete Island, and presents a literature review and evaluation of the following fields: (a) proposed large-scale energy storage applications, and (b) system monitoring tools and dynamic performance simulation results. The Cretan power system is by far the largest autonomous power system in Greece (≈5% of total electricity demand), that presents a significant penetration of RES technologies (more than 20% of energy shares in 2012).

II. DESCRIPTION OF CRETAN POWER SYSTEM

Crete is the largest Greek island with approximately 8500 km^2 and the fifth in Mediterranean Sea with more than

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600,000 inhabitants, tripling in summer period. It is also the largest isolated system in Greece [5]. Additionally, considerable annual increase of electricity demand, up to 7%, had been noted during the period 2000-2008 (see Fig. 1). As a result, the annual energy consumption during 2008 achieved 2.8TWh, compared to the modest 280GWh of year 1975. However, during the last years (2008-2011), electricity consumption has remained steady between 2.8 and 2.65TWh. Fig. 1 shows the demand for the last 12 years as allocated to end-uses [6].

Electricity generation system is based mainly on oil-fired thermal power units. A large number of conventional units with different technology and response characteristics (steam turbines, diesel generators, gas turbines, and one combined cycle unit) in three power plants with total capacity of 813MW have been installed as described in Table I.

Table I Installed capacity (in MW) per unit type and power station

Power station	Steam	Diesel	Gas	CC	Total
Linoperamata	106	44	115	-	265
Chania	0	0	216	132	348
Atherinolakos	102	98	-	-	200
Total Capacity	208	142	331	132	813

The steam and diesel units mainly supply the base-load. The gas turbines normally supply the daily peak load or the load that cannot be supplied by the other units in outage conditions. These units have a high running cost that increases significantly the average cost of the electricity being supplied. In Fig. 2, a map of the Cretan power system is provided, which includes the main power stations and the 150kV transmission network.

On the island, in many locations average wind speed is higher than 8.5m/sec. Moreover, Crete presents one of the highest solar potentials in whole Europe. These characteristics make Crete ideal for the installation of wind and solar technologies. As a result, there exist more than 20 wind farms installed with rated power of 183MW, with half of them at the Sitia region, on the eastern part of the island. Additionally, more than 1000 small PV parks (mainly of 80kW each) and 1800 roof PVs have been installed, reaching a total of 94MW (July 2013). Moreover, large solar thermal plants of around 40MW are expected be installed on the east side of the island by 2016.

Table II also presents the percentage of annual energy production in 2012 for all installed units of the island (conventional and renewables). RES penetration was 20.5%, already surpassing the Greek national target of 20% for the year 2020. It should be also noted that since 2000, Crete steadily meets more than 10% of the demand by RES.

Table II Characteristics of Crete Island's electricity units

Technology	Fuel	Annual electricity production in 2012
Steam turbines	Mazout	36.6%
Diesel generators	Mazout	23.6%
Gas turbines	Diesel	3.6%
Combined cycle (CC)	Diesel	15.7%
Wind turbines	-	15.8%
PVs	-	4.7%

Also, it is worth to mention that there is an interconnection plan between the Cretan power system and the main Greek power system, as well as an interconnection plan between Crete, Cyprus and Israel [7]-[9]. Should these plans implemented, the renewable energy penetration in the island is expected to be increased significantly (already there are 1000MW of authorized wind parks) and may make Crete an exporter of RES electricity.

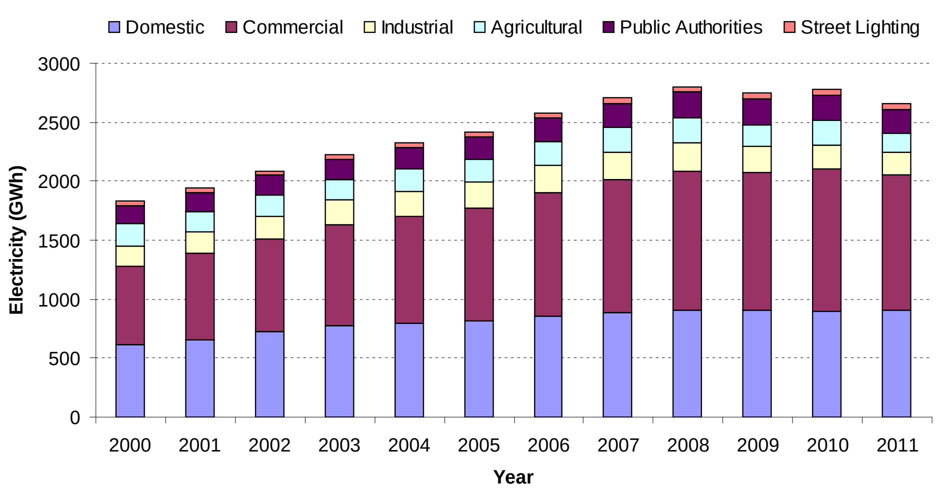


Fig. 1 Cretan electricity consumption per category of use [6]

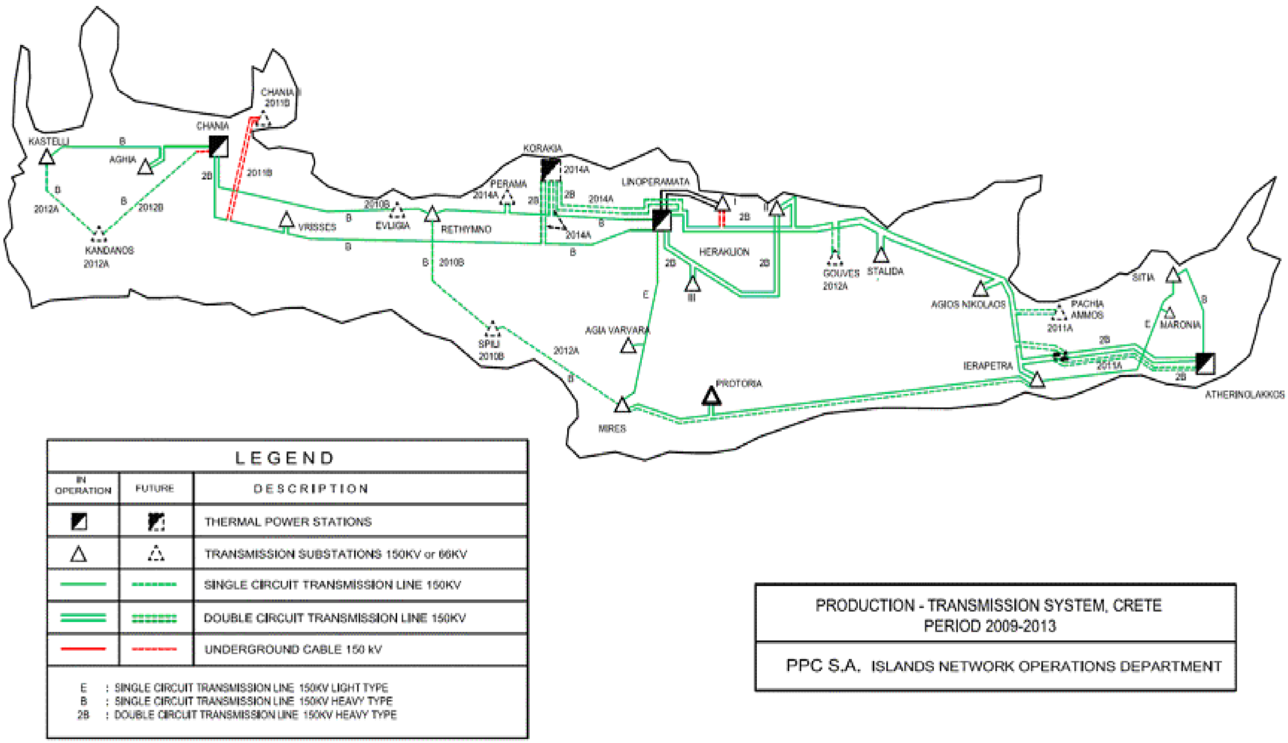


Fig. 2 Cretan power system map

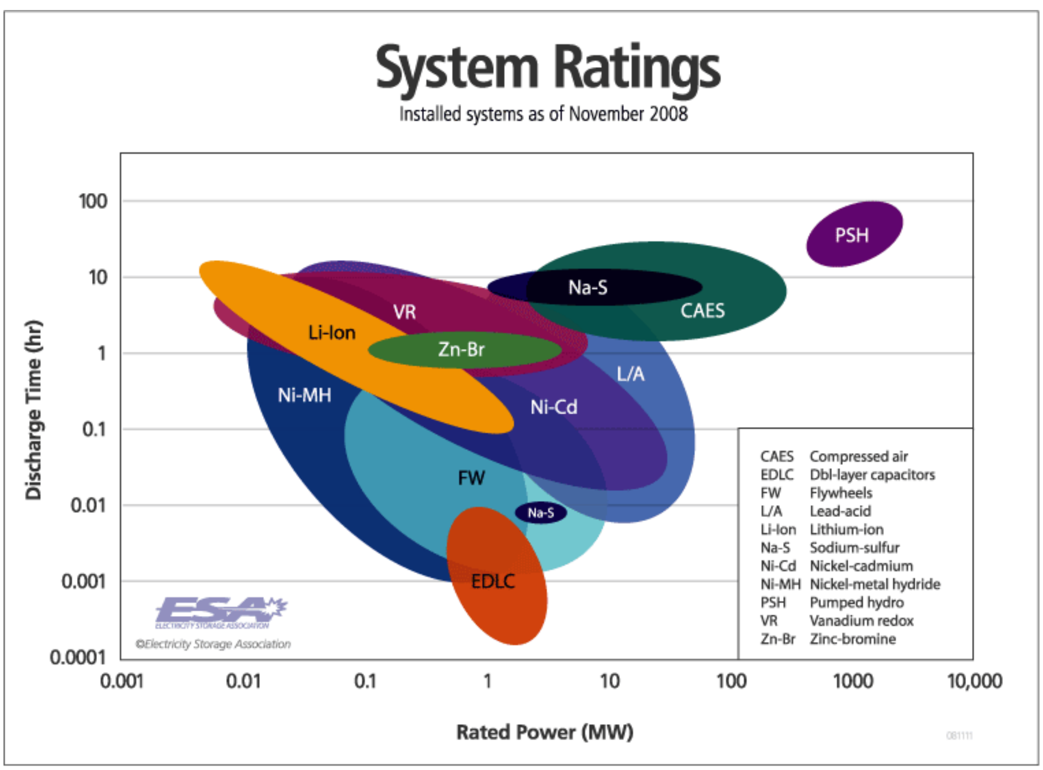


Fig. 3 Energy storage systems ratings [12]

III. Energy Storage Systems

One of the most promising applications of energy storage is co-operation with RES for the operation of such systems [10]. The intermittent nature of RES and the low correlation between load consumption and their productions makes energy storage an interesting solution to investigate as a means of alleviating technical barriers for increasing RES penetration.

Energy storage is faced with two coexisting challenges: 1) to improve the operation of already existing conventional centralized power networks, and 2) to signal the shift to the era of RES-based and distributed electricity generation. A number of available technologies is covering a broad range of applications, including pumped hydro storage (PHS) systems, compressed air energy storage (CAES) systems, fuel cells and hydrogen storage, flywheels, supercapacitors, superconducting magnetic energy storage and various battery systems [11].

Some expected benefits from electricity storage applications include:

- Improved asset utilization and efficiency
- Increased penetration of renewable generation
- Enhanced reliability, availability and power quality
- Peak load management
- Flexibility in meeting customer demand

Regarding large-scale stationary applications, energy storage systems can be divided in three major functional categories [12]:

- *Power quality*: In these applications, stored energy is only applied for seconds or less, to assure continuity of quality power [13].
- *Bridging power*: In these applications, stored energy is used for seconds to minutes to assure continuity of service when switching from one source of energy generation to another.
- *Energy management*: In these applications, stored energy is used to decouple the timing of generation and consumption of electric energy. A typical application is load leveling, which involves the charging of storage when energy cost is low and utilization as needed. This would also enable consumers to be grid-independent for many hours.

Fig. 3 shows the energy storage systems ratings, in terms of discharge time and rated power.

IV. Proposed Energy Storage Applications for Crete Island

A. General

Regarding medium and large-scale autonomous power systems with significant penetration in renewable energy technologies, the most suitable, mature and used storage technologies are PHS systems and batteries [14]. Considering, however, the absence of large-scale energy storage in such systems, the electrical networks manager need to define an instantaneous upper wind energy penetration limit λ in order to protect the local grid stability, in case of simultaneous change in intermittent production and demand [15].

The definition of λ is based on an on-line analysis of the local electrical network taking into account both static and dynamic security criteria. In most cases, a typical value of λ is equal to 30%, although in some circumstances higher values can be safely used, e.g. 40%. This value may change according to the type of the committed units of the power system [16].

Based on this concept, Kaldellis et al. [17] propose a numerical algorithm that estimates the maximum wind energy penetration in a given autonomous electrical network. Details of the algorithm are also included in [18]. The used calculation method estimates the maximum instantaneous wind energy contribution on the basis of the information provided by the system operator, concerning the corresponding load demand and the operational status of the existing thermal power stations. The algorithm is applied in the Cretan power system, and the authors conclude that the local electrical utility often imposes more strict barriers to wind energy penetration than the proposed model. As a result, wind energy investor loses increase significantly (25,000€/MW of installed power).

However, the excellent potential of Crete Island in intermitted RES (wind and solar), combined with the relatively low correlation between peak load consumption and intermitted renewable energy production, make the utilization of large-scale energy storage systems a very interesting solution in order to increase significantly RES penetration. The majority of the proposed energy storage systems refer to PHS, whereas applications of CAES and large-scale battery systems have been proposed as well.

B. Pumped Hydro Storage (PHS) Systems

A study related to the wind power injection in the autonomous power system of Crete is described in [19], and is based on the data for years 2004 and 2007. The adopted methodology takes into account the wind power penetration probability, restricted by the thermal generators technical minima and the maximum allowed wind power instant penetration percentage over the instant power demand, as well as the wind power production probability. The results of this work show that for a maximum wind power instant penetration percentage of 30% of the power demand, the total installed wind power should not exceed the 40% of the mean annual power demand in order to ensure an annual wind energy rejection percentage less than 10%. Apart from Crete, the above analysis was applied to the island of Rhodes (second largest autonomous power system in Greece). According to the authors, this methodology can be applied to any medium or large size isolated power system, if its power production is based on thermal power plants, the power demand exhibits intensive seasonal variations and is uncorrelated to the wind data, the mean annual power demand is higher than 10MW, and it presents high wind potential.

The above mentioned analysis is extended in [20] by introducing PHS systems in the two studied isolated power systems, in order to minimize the electricity production cost and to maximize the wind energy penetration. Energy is stored to the PHS systems when wind energy is rejected, and the conventional thermal generators that burn cheap heavy fuel oil do not operate at the most efficient operating point. Regarding Crete, the results show that the introduction of a PHS system yields to almost 10% annual electricity production cost reduction, and nullifies the annual wind energy rejection. Moreover, this solution proves to be economically viable if the electricity cost is greater than 0.15€/kWh, whereas it can be proved economically feasible for costs of electricity between 0.05€/kWh and 0.15€/kWh. The analysis refers to results of year 2004. However, the worldwide trend of both increased fossil fuels and taxes prices is expected to make this investment today even more attractive.

Reference [21] adds to the previous study the concept of improved dynamic security. More specifically, the installation of PHS units improves considerably the dynamic security of the studied isolated power systems, due to the existence of (fast-response) hydro turbines. As a result, the necessity for spinning reserve from thermal generators is restricted. According to this study, the wind power penetration for the island of Crete can reach 80% if the hydro turbines of the PHS system are kept synchronized, whereas in the opposite case the penetration is slightly less than 75%. Moreover, the existence of geothermal or biomass potential may help minimize further of the electricity production of the conventional thermal power plants. The economic results for Crete are proved better in comparison to lower scale isolated power systems that are also considered.

The concept of installing PHS systems in the power system of Crete for maximizing wind energy contribution and improving grid stability is also examined in [22]. The significant amount of wind energy rejection in Crete corresponds to an annual financial loss of income of 30,000€/MW of wind power installed (data from the end of year 2005 are used). The proposed PHS system(s) consist of a number of water reservoirs (two minimum) at different elevations. The required volume for the entire water reservoirs is less than 700,000m^3 (2×350,000m^3 for upper and lower reservoirs) at 280m height-difference, in order to manage the wind energy surplus of the existing wind farms (90MW rated power at that period). The expected marginal wind-hydro electricity production cost is 0.175€/kWh, a favorably comparable value with the operational cost of the existing thermal power units, since it is clearly less than the operational cost of the Cretan power system's gas turbines.

In [23], a numerical methodology is applied in Crete Island for the optimum sizing of the various components of a PHS system, adopting a simple operating policy, where the pumps consume excess wind energy and the hydro turbines provide firm power over an agreed time interval every day. The applied methodology is focused in the calculation of the design parameters of the PHS system, which include the turbine size, the size and the number of the pumps, the penstock diameter and thickness, and the reservoirs' capacity, whereas some critical financial parameters are also considered. Data of the year 2002 are used to estimate the corresponding values of year 2006. The results show that a feasible design could recover 40-60% of the rejected energy, while the optimum reservoir capacity ranges between 50,000 and 70,000m^3 and the water pipe diameter between DN800 and DN850. The financial prospects of the investment become more attractive for higher installed power of the water turbine.

In [24], an operating policy is introduced for hybrid wind-hydro power stations operating in autonomous island grids (including Crete) with significant wind power penetration. The proposed methodology is directly correlated to the existing legal framework in Greece (Law 3468/2006), and utilizes a logistic model with wind and load time series as inputs, to simulate the annual operation of the system. Two configurations of PHS systems are compared: single-penstock and double-penstock. The results indicate that PHS systems can increase substantially wind energy penetration and provide firm capacity to the systems, substituting expensive peak units. Moreover, under the current pricing framework, PHS systems constitute attractive investments, especially the double-penstock alternative. For the island of Crete, such a project presents internal rate of return (IRR) of over 25%, net present value (NPV) of approximately 1,500,000€/MW, and generating cost of less than 0.15€/kWh.

Although wind energy may reduce the cost in autonomous power systems, considering the current expensive electricity production cost [25], the increased wind penetration in such a system without storage could reduce the electricity production cost only up to a maximum of 7% [26]. In [26], the prospects of a combined wind-PHS system that provides peak demand supply are examined in three Greek islands of different size and characteristics (including Crete), in order to decrease the electricity production cost, and increase the renewable energy supply and the renewable capacity credit (which is related to the substitution of conventional power installed capacity). For the simulation, the design parameters of the whole plant (PHS system and wind farm) are considered as known. The methodology calculates the annual energy amounts and derives electricity production cost. The results show that in Crete the investments seem to be feasible, since the required price is competitive to the electricity production cost and the fuel cost of the system before the PHS system integration.

The analysis of the previous study is extended in [27], as the effect of wind energy on the reliability of autonomous power systems is analyzed. The proposed methodology is applied in three Greek islands (including Crete), in order to assess the concept of substitution of conventional power plants with wind energy (with or without PHS systems), in terms of wind capacity credit. In case of a PHS system existence, the evaluation is implemented through the improvement of the reliability of the system with reference to the required installed capacity. The reliability performance of the system is measured in terms of Loss of Load Probability index (LOLP), and Loss of Energy Expectation index (LOEE). The results show that the capacity credit of wind farms without considering PHS is relatively limited, and is depended on the wind potential and on the current reliability of the system. More specifically, wind capacity credit increases with the wind potential and decreases in power systems that are already reliable. Additionally, the analysis proves that the wind capacity credit is improved considerably through the PHS system integration, providing substitution of significant capacity of conventional power plants and establishing a reliable design for the whole power system.

In [28], the concept of feed-in tariffs (FITs) for various energy storage technologies is discussed, along with a proposal for their application in more appropriate regions. Regarding Crete, based on data that are provided in [29], the FIT for a wind-PHS system would be 269€/MWh, by assuming hydroturbine's peak demand supply equal to 50%, which contributes to the 43% of total energy. One additional interesting conclusion is that by assuming that the discount rate in the design of FIT is equal to 5% and the payback period is set to 20 years, the resulting FIT value decreases more than 40%.

The effect of PHS systems in greenhouse gases reduction on the Cretan power system is studied in [30] and [31]. The analysis in this studies covers the period from 2009 to 2020, and two scenarios are considered: in the first scenario, a 20% RES energy penetration in year 2020 is assumed, whereas in the second scenario the final RES energy penetration is increased to 50% through the installation of PHS systems. Both scenarios include the installation of two natural gas units of 250MW each in years 2014 and 2017, respectively. The results show that substantial RES production till 2020 is technically feasible, and provides benefits in the forms of carbon emission reductions, energy adequacy and dependency. More specifically, by assuming 3% annual increase of energy demand during the whole period, the consideration of 20% RES energy penetration in year 2020 (first scenario) results almost constant CO_2 equivalent emissions for the whole examined period. On the other hand, in the second scenario, the high penetration of renewable energy technologies (50% by 2020) overcomes the increase in annual energy demand, so the final CO_2 equivalent emissions are almost 40% lower, compared to the first scenario.

A comparison of different solution methods for the unit commitment problem is performed in [32]. Moreover, this study aims to examine the need for installing a PHS unit. The objective of the unit commitment problem is to schedule the generation units of a power system in order to serve the load demand at the minimum operating cost, while meeting all plant and system constraints [33]. The considered system has similar characteristics with the autonomous power system of Crete. More specifically, it contains five thermal units (one steam turbine, one combined cycle unit, one diesel unit and two gas turbines) and a PHS unit, whereas no renewable power units are included. The analysis is performed for a 48 hour interval, and three methods are applied and compared for the solution of the unit commitment problem: (a) the priority list method, which is a popular heuristic method that is applied until now in the Cretan power system (see also Section II), (b) the gradient method, which is a mathematical-based method, and (c) a genetic algorithm. The considered constraints include generation output limits, load balance, spinning reserve, volume limits of a PHS system reservoir, begin/end level constraint of storage reservoir, and hydro turbine and pump operating constraints. The results show that the genetic algorithms provide much better results that are based on an improved thermal unit commitment. Moreover, this study concludes that the need for an installation of PHS system in a thermal units based power system is doubtful, whereas the benefits of such a system installation in the case of significant renewable power penetration has to further investigated.

C. Compressed Air Energy Storage (CAES) Systems

The announcement in 2007 by the Power Public Corporation (PPC) that two combined cycle power plants, 250MW each, are planned to be installed in the island of Crete [34], led Zafirakis et al. [35] and [36] to propose the concept of a small-scale CAES system implementation, in order to recover wind energy curtailments and benefit from the introduction of natural gas. For the proposed CAES system, a dual mode operation is proposed, i.e. the CAES system is able to shift its operation to the typical gas turbine cycle as well, and will be based only on the consumption of natural gas, already required for the operation of the CAES-only cycle. More specifically, in times that the energy stored (i.e. the energy provided by the available wind energy curtailments) is not sufficient, the gas turbine will be coupled with the compressor via the use of a clutch and the required guaranteed energy will be generated on the basis of the classic cycle operation (Brayton/Joule cycle). It has to be noted, however, that when shifting to the classic cycle mode greater levels of fuel consumption and zero exploitation of wind energy curtailments are expected. Fig. 4 shows that configuration of the proposed dual mode CAES system.

The proposed small-scale CAES system uses wind energy surplus from three private wind parks (a total of 25MW operating in the area of Sitia, in eastern Crete), and is used for peak shaving on the basis of daily guaranteed energy production during peak demand periods, when costly gas turbines enter the system. Moreover, the small scale of the system makes possible the employment of a storage tank in the absence of an appropriate underground cavern, thus eliminating any sitting issues, like the T-CAES proposed in [37]. The obtained results show that the life cycle energy production cost of the optimum size configurations may beat the respective cost of peak power units on the island of Crete (estimated as 250€/MWh), and also compete with the alternative of a PHS system installation.

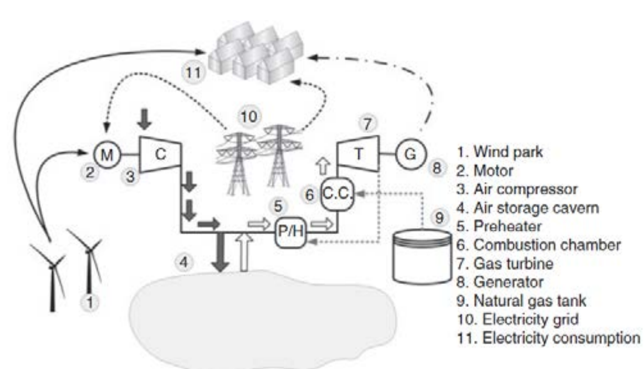


Fig. 4 Dual-mode CAES configuration [36]

D. Battery Systems

Reference [38] proposes a methodology for the optimal design and economic evaluation of a lead-acid battery energy storage system that increases wind energy penetration in isolated electric grids by using the rejected energy of the wind farms. This energy is released back to the electric grid during the peak load-demand hours, thus enabling the reduction of the thermal power stations peak contribution. According to the authors, the main advantage of the proposed battery energy storage system, compared to the solution of PHS, is the minimal requirements for civil engineering works, resulting in lower installation cost. Additionally, it can be implemented in a shorter time interval, it does not influence the environmental topography of the installation area, it can be easily transferred to another installation area and its operation does not depend on extra natural resources, such as water, which is frequently unavailable in remote islands.

The proposed methodology has been applied in Crete Island. The maximization of the economic benefit function is implemented using genetic algorithms. Although the expected lifetime of the lead-acid batteries is significantly shorter compared to PHS, the authors conclude that the installation of the proposed system will be economically viable (for both the investor and the local electric network operator) even in the case that the electric energy selling price is equal to 0.13€/kWh, the ratio of the imported energy cost to the battery energy storage system electric energy selling price lies in the interval (0.2 … 0.4), the subsidization rate is 50%, and the battery bank operational lifetime is 5 years.

V. Dynamic Performance and System Monitoring

The successful operation of a power system depends largely on its ability to provide reliable and uninterrupted service to the loads [39]. As a result, security is a major concern, since mismatches in generation and load might lead to system failures. In practical, this means that both voltage and frequency must be held within close tolerances so that the consumer's equipment may operate satisfactorily [40]. When an unbalance between the system generation and load occurs, a new steady-state operating condition is established. The system behavior during the transient period needed for adjustment to the new operating condition is called the dynamic system performance.

Dynamic security represents a very significant parameter in power system operation, as it has been accounted for by assuring sufficient reserve capacity in the system, so that it can withstand various disturbances. Wind turbines and PVs, by being non-dispatchable, have different operational characteristics than conventional power units. Thus, high levels of their penetration (such as in the case of Cretan power system) create issues of grid control. A key component in a power system that presents the above characteristics is a strong software support that will help to overcome some difficulties that inevitably accompany all the non-dispatchable renewable energy technologies [41].

This section is divided into two parts. In the first part, a review of the proposed software tools and methodologies for on-line dynamic security assessment in Cretan power system operation is presented. The second part examines the effect of non-dispatchable renewable energy technologies and large scale energy storage in Cretan system's dynamic performance.

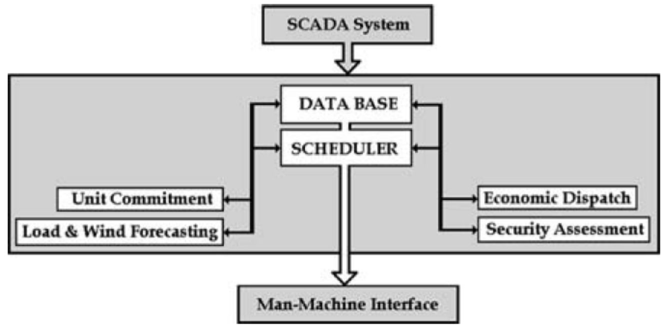


Fig. 5 Main functions and procedures of energy management systems

A. Tools and Methodologies for On-line Dynamic Security Assessment

In modern energy environment, the use of enhanced operation management and monitoring programs is judged necessary. One of the main control centre's tools that are used for this purpose is energy management systems, which are divided into two categories [42]:

- Real-time planning and operation tools
- Short-term planning and system operation tools, which are operating off-line

Regardless of their category, the main modules that are related to energy management systems are (see also Fig. 5):

- *Load and wind power forecasting*: It can be implemented via time series methods, regression based methods, and computational intelligence based methods [43]
- *Unit commitment*
- *Economic dispatch*
- *Dynamic security assessment*: It can be implemented via conventional mathematic methods, and expert systems and computational intelligence based methods

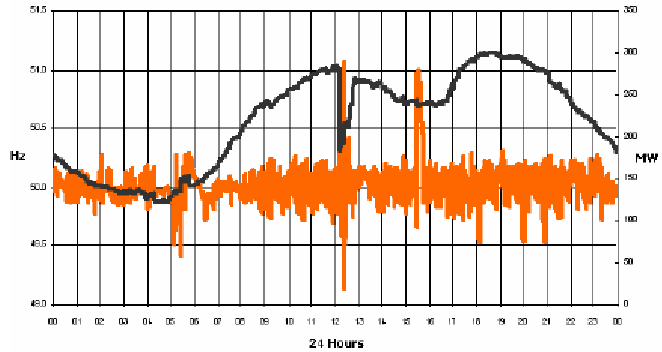
The application of such a system is presented in [4], which utilizes decision trees for on-line preventive dynamic security for the autonomous power system of Crete. Decision trees have the hierarchical form of a tree structured upside down, and they are a nonparametric learning technique able to produce classifiers about a given problem in order to deduce information for new unobserved cases [44]. One of the main advantages of decision trees is their fast execution time, which is required for on-line classification. This characteristic makes the method suitable for on-line control of larger systems. In the proposed study, the construction of a decision tree is based on a knowledge base consisting of a large number of operating points covering all possible states of the power system under study, in order to ensure its representativity.

The adopted methodology is implemented as follows: Economic dispatch is performed without dynamic security constraints, whereas the generator power setpoints are subsequently used as inputs in the decision tree structure, in order to estimate the security of the proposed operating state. If the state is secure, the units' set points are displayed to the operator. In the opposite case, an alternative dispatch solution in the neighborhood of the previous solution is sought. In case no secure operating point is found, a new unit commitment is applied. It should be noted that the above problem is in general non-convex, and the proposed algorithm does not necessarily lead to optimal solutions from an economic point of view, however, it provides secure operating points. Moreover, this technique provides the flexibility of displaying the cost of each proposed solution weighted against the cost of load shedding; therefore it forms the basis for valuable decision-making aid.

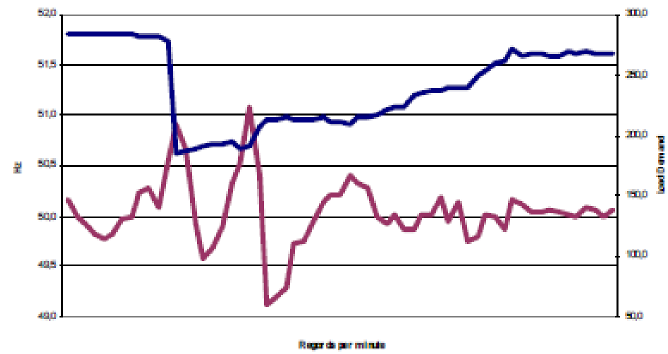
The analysis of the previous study is extended in [45]. In this study, three machine learning techniques for on-line dynamic security assessment of the autonomous power system of Crete are presented and compared: decision trees, artificial neural networks, and entropy networks, which are a hybrid neural network approach [46]. More specifically, decision trees are first developed and applied in order to identify the most important system parameters for the given problem, because of their effectiveness to extract interpretable rules from very large bodies of simulated examples. These operating rules were taken in account for the determination of the input variables for the artificial neural networks, which provide a slightly better performance at similarly fast computational time, however, at the expense of results interpretability. Finally, entropy networks were applied aiming at combining the attractive features of two techniques, namely the simplicity and transparency of decision trees and the information accuracy of multi layer perceptrons. The comparison between decision trees and entropy networks shows that both techniques are able to provide an operator with an on-line classification of the system security, but decision trees exhibit high interpretability and fast computational time, whereas entropy networks maintain these qualities and provide improved performance.

B. Effect of Increased Renewable Penetration and Energy Storage

In case of significant non-dispatchable renewable power penetration (mainly from wind turbines) in isolated power systems, dynamic simulation studies are the first step in determining the level of penetration. Analytical studies are required in order to derive security rules and guidelines for the optimal operation of the system. Simulations of a power system dynamic performance mainly cover voltage and frequency calculations under several abnormal operating conditions, start-up or sudden disconnection of wind generation, wind fluctuations and short circuits on the transmission and distribution network. One of the main characteristics in such systems is the frequency oscillations, which may easily trigger the under-frequency protection relays of the wind parks, thus causing further imbalance in the system. Fig. 6 depicts a real situation when short circuit occurred at 12:10 p.m. leading the frequency to drop till 49Hz, in spite of the fast load shedding [47].



(a)



(b)

Fig. 6 (a) Frequency fluctuations and load disconnection on the autonomous power system of Crete, (b) zoom at short circuit occurrence

The impact of high wind power penetration (up to 40%) on the dynamic stability of the Cretan autonomous power system is studied in [48]. The most considerable disturbances that were investigated are the short circuit, the sudden disconnection of conventional power units and wind parks, and the strong wind velocity fluctuations. The performed simulations show that the deviations of the power system voltage and frequency remain acceptable under most examined perturbations. However, the situation depends on the scheduling of the power units (in order to provide sufficiently fast response) and the amount of allocated spinning reserve.

Reference [21] examines, among others, the effect of PHS systems installation on the dynamic security of the Cretan power system, under wind power penetration that can reach 80%. It is concluded that the dynamic security may be ensured if some of the PHS hydro turbines are synchronized. This may be achieved even if at a certain time the wind power production is higher than the power demand, hence no hydro turbines power is produced. In that case, the hydro turbines may be kept synchronized if necessary (low power demand, intensive weather conditions) by consuming a low percentage of the wind power surplus, instead of storing it in the PHS upper reservoir, or waste it, in case it can't be stored (low pumps power or full upper reservoir). This may lead to an increase of the required installed wind power.

The application of probabilistic neural networks on dynamic security assessment of the Cretan power systems is addressed in [49]. In this work, two distinct operating situations of the system with different distributions are identified: 1) the system is considered at its current configuration (that corresponds to year 2002), and 2) the system is considered at its future operation after the installation of a PHS plant. For each situation, a training set of 6552 operating points is used. Each operating point has with its own corresponding status (secure/insecure) that depends on voltage level. At each learning step, the success rate is calculated with two ways: 1) from the number of samples that were successfully classified in all previous n steps, and 2) from the number of samples that were successfully classified in the last 500 steps, which is considered as a more objective index. The results show that the adopted method is capable of adapting its security structures even to drastic changes of the system configuration, as the success rate exceeds 90%. The main advantage of probabilistic neural networks is that they can deal with the changes in the structure of the power system without the need of completely retraining, which makes them ideal for on-line learning.

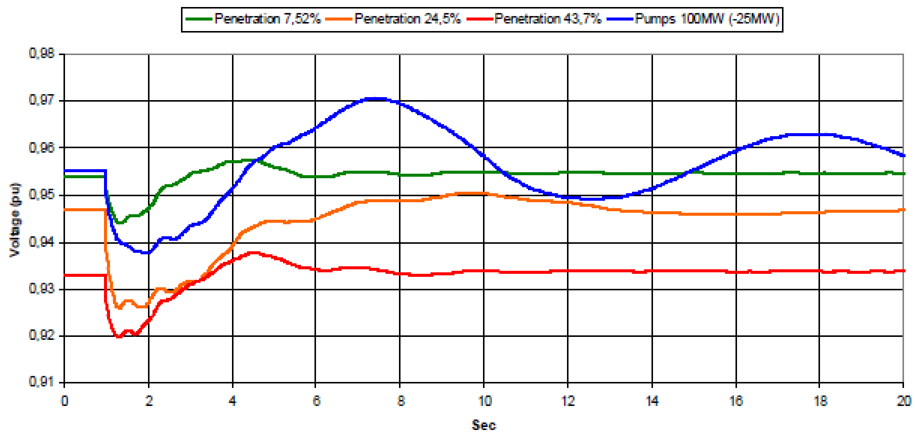


Fig. 7 Voltage variations for four different scenarios of Cretan power system [50]

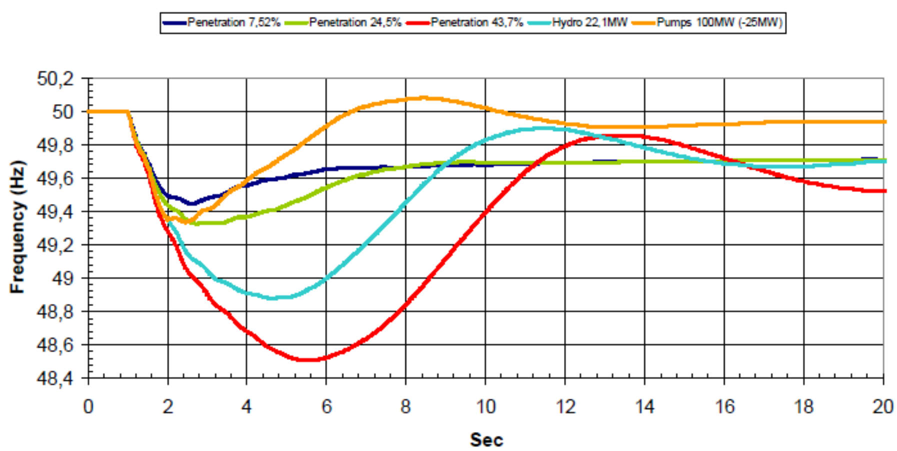


Fig. 8 Frequency fluctuations for five different scenarios of Cretan power system [50]

In [50], the impact of high wind power and PVs penetration, as well as PHS units installation, on the dynamic behavior of the Cretan power system is examined, under a large number of alternative scenarios. The investigated disturbances are the short circuit, the sudden disconnection of conventional power units and wind parks, and the strong wind velocity fluctuations. The simulation of the transient analysis is implemented via PowerWorld Simulator and MATLAB. From the study of the system, it is concluded that its operation with a high level of renewable penetration can maintain a high level of security, if adequate spinning reserve of the conventional units or energy storage units are available.

More specifically, Fig. 7 shows voltage variations for four different scenarios: (a) 7.5% wind penetration, (b) 24.5% wind penetration, (c) 43.7% wind penetration, and (d) installation of 100MW PHS units. The voltage profile follows an opposite trend from the wind power variations, in contrast with frequency variations. In case of normal wind power fluctuation, when the wind parks are not suddenly disconnected and spinning reserve is sufficient, the Cretan power system remains satisfactorily stable.

Moreover, Fig. 8 shows the frequency fluctuations for five alternative scenarios: (a) 7.5% renewable penetration, (b) 24.5% renewable penetration, (c) 43.7% renewable penetration, (d) PHS units operate as hydro generators in their technical minimum, and (e) PHS units operate as pumps that consume exclusively wind energy. The nominal power for PHS units is considered equal to 100MW. As it can be seen from Fig. 8, the frequency behavior (and consequently the dynamic performance) of Cretan power system are clearly improved by the operation of PHS system, especially in the fifth scenario where the use of controlled load shedding enforce significant system stability.

VI. Conclusion

The above review shows that PHS systems seem to be a mature solution for increasing RES penetration on the island of Crete. The economic viability of such a project is shown in a variety of studies, under the condition of storage system's proper sizing. This viability is also proved by the fact that two PHS systems have been already authorized to be constructed in the near future, in the areas of Malia [51] and Fragma Potamon [52]. The former case is about a Power station of 90.1MW of wind power and 100MW of guaranteed hydro capacity with wind parks across the island and one pump-storage facility. The expected investment cost is in the order of 320 million €. The latter is a group of 3 wind parks with 81MW capacity, hydro power station of 50MW and a group of 3 pumps with rating power of 36MW each. The down reservoir has been already built.

Moreover, this review shows that for the autonomous power system of Crete, a crucial step for the successful combination of increased RES technologies penetration and PHS systems installation is the implementation and reliable operation of an advanced software, based on expert systems, that will contribute to the maximum possible integration of RES technologies and the overall improvement of system's power quality.

References

[1] N.D. Hatziargyriou, A. Tsikalakis, and A. Androutsos, "Status of distributed generation in the Greek islands", in *Proc. 2006 IEEE PES General Meeting*, Montreal, Canada, 2006.

[2] K.A. Papadogiannis, E.S. Karapidakis, and N.D. Hatziargyriou, "Cost allocation of losses in autonomous power systems with high penetration of RES," *WSEAS Transactions on Power Systems*, vol. 4, iss. 6, pp. 210-220, 2009.

[3] A.Tsikalakis, N. Hatziargyriou, K. Papadogiannis, A. Gigantidou, J. Stefanakis, and E. Thalassinakis, "Financial contribution of wind power on the island system of Crete", in *Proc. RES for Islands Conference*, Crete, pp. 21-31, 2003.

[4] E.S. Karapidakis and N.D. Hatziargyriou, "Online preventive dynamic security of isolated power systems using decision trees," *IEEE Transactions on Power Systems*, vol. 17, no. 2, pp. 297-304, 2002.

[5] J. Syllignakis, C. Adamakis, and T.M. Papazoglou, "Development of a digital data base for power system of Crete, for displaying system's data on geographical maps, using GIS and web tools," in *Proc. 5th International Conference on Heat Transfer, Thermal Engineering and Environment (IASME/WSEAS)*, Athens, Greece, pp 68-72, 2007.

[6] http://www.statistics.gr/portal/page/portal/ESYE

[7] http://www.iene.gr/articlefiles/final%20draft_5.11.2012.pdf (in Greek)

[8] A. Antoniou, N. Theodorou, A. Tsikalakis, K. Kalaitzakis, and G. Stavrakakis, "Impact of the Euro-Asia interconnector project on the economic operation of Crete and Cyprus power systems", in *Proc. 2nd International Conference on Power Options for East Mediterranean Regions (POEM 2013)*, Cyprus, 2013.

[9] http://www.euroasia-interconnector.com/Index.aspx

[10] A. Ter-Gazarian, "Energy storage for power systems," IEE, London, UK, 1994.

[11] J.K. Kaldellis (Editor), "Stand-alone and hybrid wind energy systems – Technology, energy storage and applications," CRC Press, UK, 2010.

[12] http://www.electricitystorage.org/technology/tech_archive/technology_comparisons

[13] S. Swaminathan, R.K. Sen, "Review of power quality applications of energy storage systems," Sandia National Laboratories, Report no. SAND98-1513, 1998. Available: http://www.prod.sandia.gov/cgi-bin/techlib/access-control.pl/1998/981513.pdf

[14] http://www.storiesproject.eu/

[15] A.G. Tsikalakis, N.D. Hatziargyriou, Y.A. Katsigiannis, P.S. Georgilakis, "Impact of wind power forecasting error bias on the economic operation of autonomous power systems", *Wind Energy*, vol. 12, iss. 4, pp. 315-331, 2009.

[16] http://www.rae.gr/old/K2/Consult_KDMN/Code_MDN.pdf (in Greek)

[17] J.K. Kaldellis, K.A. Kavadias, and A.E. Filios, "A new computational algorithm for the calculation of maximum wind energy penetration in autonomous electrical generation systems," *Applied Energy*, vol. 86, pp. 1011-1023, 2009.

[18] J.K. Kaldellis, K.A. Kavadias, A.E. Filios, and S. Garofallakis, "Income loss due to wind energy rejected by the Crete island electrical network – the present situation," *Applied Energy*, vol. 79, pp. 127-144, 2004.

[19] D.A. Katsaprakakis, N. Papadakis, D.G. Christakis, and A. Zervos, "On the wind power rejection in the Islands of Crete and Rhodes," *Wind Energy*, vol. 10, pp. 415-434, 2007.

[20] D.A. Katsaprakakis, D.G. Christakis, A. Zervos, D. Papantonis, and S. Voutsinas, "Pumped storage systems introduction in isolated power production systems," *Renewable Energy*, vol. 33, pp. 467-490, 2008.

[21] D.A. Katsaprakakis and D.G. Christakis "Maximisation of R.E.S. penetration in Greek insular isolated power systems with the introduction of pumped storage systems," in *Proc. European Wind Energy Conference and Exhibition (EWEC 2009)*, Marseille, France, 2009.

[22] J.K. Kaldellis, K.A. Kavadias, D.E. Papantonis, and G.S. Stavrakakis, "Maximizing wind generated electricity with Hydro Storage: Case study Crete," *Wind Engineering*, vol. 30, no. 1, pp. 73-92, 2006.

[23] J.S. Anagnostopoulos and D.E. Papantonis, "Simulation and size optimization of a pumped–storage power plant for the recovery of wind-farms rejected energy", *Renewable Energy*, vol. 33, pp. 1685-1694, 2008.

[24] S. Papaefthimiou, E. Karamanou, S. Papathanassiou, and M. Papadopoulos, "Operating policies for wind-pumped storage hybrid power stations in island grids," *IET Renewable Power Generation*, vol. 3, iss. 3, pp. 293-307, 2009.

[25] G. Caralis and A. Zervos, "Analysis of wind power penetration in autonomous Greek islands," *Wind Engineering*, vol. 31, no. 6, pp. 487-502, 2007.

[26] G. Caralis and A. Zervos, "Analysis of the combined use of wind and pumped storage systems in autonomous Greek islands," *IET Renewable Power Generation*, vol. 1, iss. 1, pp. 49-60, 2007.

[27] G. Caralis and A. Zervos, "Value of wind energy on the reliability of autonomous power systems," *IET Renewable Power Generation*, vol. 4, iss. 2, pp. 186-197, 2010.

[28] G. Krajacic, N. Duic, A. Tsikalakis, M. Zoulias, G. Caralis, E. Panteri, and M. da Graca Carvalho, "Feed-in tariffs for promotion of energy storage technologies," *Energy Policy*, vol. 39, pp. 1410-1425, 2011.

[29] G. Caralis, K. Rados, and A. Zervos, "On the market of wind with hydro-pumped storage systems in autonomous Greek islands," *Renewable and Sustainable Energy Reviews*, vol. 14, pp. 2221-2226, 2010.

[30] E.S. Karapidakis, Y.A. Katsigiannis, P.S. Georgilakis, and E. Thalassinakis, "Generation expansion planning of Crete power system for high penetration of renewable energy sources," *Materials Science Forum*, vol. 670, pp. 407-414, 2011.

[31] E.S. Karapidakis, Y. Katsigiannis, and N. Zografakis, "Sustainable power generation expansion of Crete Island," in *Proc. 8th World Energy System Conference*, Targoviste, Romania, 2010.

[32] Y.A. Katsigiannis and E.S. Karapidakis, "Comparing different approaches to solve the unit commitment problem considering hydro-pumped storage stations," in *Proc. International Workshop on*

Deregulated Electricity Market Issues in South-Eastern Europe (DEMSEE'07), Istanbul, Turkey, pp. 147-153, 2007.
[33] A.J. Wood and B.F. Wollenberg, "Power generation, operation and control (2nd edition)," Wiley, New York, 1996.
[34] http://www.dei.gr/Default.aspx?id=3917&nt=18&t=ECPrint.aspx&lang=1 (in Greek)
[35] D. Zafirakis and J.K. Kaldellis, "Economic evaluation of the dual mode CAES solution for increased wind energy contribution in autonomous island networks," *Energy Policy*, vol. 37, pp. 1958-1969, 2009.
[36] D. Zafirakis and J.K. Kaldellis, "Autonomous dual-mode CAES systems for maximum wind energy contribution in remote island networks," *Energy Conversion and Management*, vol. 51, pp. 2150-2161, 2010.
[37] B. Enis, P. Lieberman, I. Rubin, and S. van der Linden, "Transportable compressed air energy storage (T-CAES) system rriven by a 2,500 kW wind turbine," in *Proc. 19th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems*, Aghia Pelagia, Crete, Greece, 2006.
[38] E. Koutroulis, D. Kolokotsa, and G. Stavrakakis, "Optimal design and economic evaluation of a battery energy storage system for the maximization of the energy generated by wind farms in isolated electric grids," *Wind Engineering*, vol. 33, no. 1, pp. 55-81, 2009.
[39] P.M. Anderson and A.A. Fouad, "Power system control and stability (2nd edition)," IEEE Press, Wiley Interscience, 2003.
[40] F.D. Kanellos, G.J. Tsekouras, and C.D. Tsirekis, "Simplified wind turbine model for the simulation of frequency support mode of operation," in *Proc. 15th WSEAS International Conference on Systems*, Corfu Island, Greece, pp. 463-468, 2011.
[41] J. Stefanakis, "Crete: an ideal study case for increased wind power penetration in medium sized autonomous power systems," In *Proc. IEEE Power Engineering Society (PES) Winter Meeting*, vol. 1, pp. 329-334, 2002.
[42] E.S. Karapidakis, "Operation management on autonomous power system," in *Proc. European Computing Conference*, Lecture Notes in Electrical Engineering, vol. 28, pp. 15-24, 2009.
[43] G.J. Tsekouras, F.D. Kanellos, C.N. Elias, V.T. Kontargyri, C.D. Tsirekis, I.S. Karanasiou, A.D. Salis, P.A. Contaxis, A.A. Gialketsi, and N.E. Mastorakis "Short term load forecasting in Greek Interconnected power system using ANN: A study for output variables," in *Proc. 15th WSEAS International Conference on Systems*, Corfu Island, Greece, pp. 440-445, 2011.
[44] N. Hatziargyriou, D. Georgiadis, and E. Karapidakis, "Application of machine learning technologies on the dynamic security of isolated power systems with large wind power penetration," In *Proc. Hellenic Conference on Artificial Intelligence (SETN 2002)*, Thessaloniki, Greece, pp. 257-268, 2002.
[45] E.S. Karapidakis, "Machine learning for frequency estimation of power systems," *Applied Soft Computing*, vol. 7, pp. 105-114, 2007.
[46] L. Wehenkel and V.B. Akella, "A hybrid decision tree neural network approach for power system dynamic security assessment," in *Proc. 4th International Symposium on Expert Systems Application to Power Systems*, North Holland, pp. 397-441, 1993.
[47] E.S. Karapidakis, "Transient analysis of Crete's power system with increased wind power penetration," in *Proc. International Conference on Power Engineering, Energy and Electrical Drives (POWERENG 2007)*, Setubal, Portugal, pp. 18-22, 2007.
[48] E.S. Karapidakis, "Wind power impact on power system dynamic performance," in: S.M. Muyeen (Editor), "Wind Power," InTech, Rijeka, pp. 395-414, 2010.
[49] E.M. Voumvoulakis, A.E. Gavoyiannis, and N.D. Hatziargyriou, "Application of machine learning on power system dynamic security assessment," in *Proc. 14th International Conference on Intelligent System Applications to Power Systems (ISAP 2007)*, Kaohsiung, Taiwan, pp. 118-123, 2007.
[50] E. Karapidakis, A. Tsikalakis, Y. Katsigiannis, and M. Moschakis, "Impact of increased RES generation on power systems dynamic performance," *Materials Science Forum*, vol. 721, pp. 185-190, 2012.
[51] http://www.iene.gr/energyweek09/articlefiles/ea/2ndSession/3_A_XENIOS.pdf (in Greek)
[52] http://www.oadyk.gr/downloads/article/871/Nikolaou_Hmerida%20OADYK_22_3_2013.pdf (in Greek)

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