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Welcome to Soft Energy Applications & Environmental Protection Lab T.E.I. of Piraeus

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Καλώς ήρθατε στην Ιστοσελίδα του Εργαστηρίου Ήπιων Μορφών Ενέργειας & Προστασίας Περιβάλλοντος του Τ.Ε.Ι. ΠΕΙΡΑΙΑ

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1. Renewable - Soft Energy Applications
2. Environmental Protection - Environmental Technology
3. Rational Management - Energy & Natural Resources Saving
4. Financial Evaluation of Investments
5. Development of New Technologies

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1.	***Introduction to Renewable Energy Sources*** **(RES I)**	***5th sem.***
2.	***Lab of Renewable Energy Sources*** **(Lab of RES)**	***5th "***
3.	***Applications of Renewable Energy Sources*** **(RES II)**	***6th "***
4.	***Energy Engineering & Management of Natural Sources*** **(ENE-MNS)**	***4th "***
5.	***Environment & Industrial Development*** **(ENV-ID)**	***2nd "***
6.	***Basic Principles of Ecology*** **(BPE)**	***3rd "***
7.	***Air Pollution – Pollution Prevention Technologies*** **(AP-PPT)**	***4th "***
8.	***Turbomachines*** **(TURBO)**	***5th "***
9.	***Waste Management Systems*** **(WMS)**	***7th "***

In the context of its high quality educational and academic activities, the Soft Energy Applications & Environmental Protection Lab implements the **MSc in Energy** postgraduate course, in cooperation with the British Herriot-Watt University. The MSc course offers scientific knowledge and highlights potential professional opportunities in a wide range of subjects in the field of energy and environmental impacts of energy generation and consumption.

Research Areas

1. "Improving the Hybrid Power Stations Viability for the Region of Aegean Archipelago"

Published Results:

- **Kaldellis J.K., 2008**, "Maximum Wind Potential Exploitation in Autonomous Electrical Networks on the Basis of Stochastic Analysis" *Journal of Wind Engineering & Industrial Aerodynamics*, Vol.9, pp.1412-1424.
- **Kaldellis J.K., Zafirakis D., 2007,** "Present Situation and Future Prospects of Electricity Generation in Aegean Archipelago Islands", *Energy Policy Journal*, Vol.35(9), pp.4623-4639.
- **Kaldellis J.K., 2006**, "An Integrated Model for Performance Simulation of Hybrid Wind-Diesel Systems", *Renewable Energy Journal*, Vol.32(9), pp.1544-1564.
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2. "Estimation of Social - Environmental Cost in the Energy Production Sector"

Published Results:

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3. "Technological Progress in Wind Energy Market"

Published Results:

- **Kalafatis El., Skittides Ph., Kaldellis J.K., 2008**, "Investigating the Relation between the Reliability and the Technical Availability of Wind Energy Applications", MedPower08 International Conference, November 2008, Thessalonica, Greece.
- **Kaldellis J.K., 2008,** "The Wind Potential Impact on the Maximum Wind Energy Penetration in Autonomous Electrical Grids", *Renewable Energy Journal*, Vol.33/7, pp.1665-1677.
- **Kaldellis J.K., 2004**, "Investigation of Greek Wind Energy Market Time-Evolution", *Energy Policy Journal*, Vol.32/7, pp.865-879.
- **Kaldellis J.K., Vlachou D.S., Paliatsos A.G., 2003**, "Twelve Years Energy Production Assessment of Greek State Wind Parks", *Wind Engineering Journal*, Vol.27/3, pp.215-226.
- **Kaldellis J.K., Zervos A., 2002**, "Wind Power: A Sustainable Energy Solution for the World Development", Energy-2002 International Conference, June-2002, Athens, Greece.

4. "Technological Progress in Solar Energy Market"

Published Results:

- **Kaldellis J.K., Spyropoulos G.C., Kavadias K.A., Koronaki I.P., 2009**, "Experimental Validation of Autonomous PV-Based Water Pumping System Optimum Sizing", *Renewable Energy Journal*, Vol.34(4), pp.1106-1113.
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5. "Flow Field Prediction for High Speed Turbomachines"

Published Results:

- **Tachos N.S., Filios A.E., Margaris D.P., Kaldellis J.K., 2008**, "A Computational Aerodynamics Simulation of the NREL Phase II Rotor", *Open Mechanical Engineering Journal,* Vol.2.
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6. "Techno-economic Evaluation of Renewable Energy Applications"

Published Results:

- **Kaldellis J.K., Zafirakis D., Kaldelli El., Kavadias K., 2008**, "Cost Benefit Analysis of a Photovoltaic-Energy Storage Electrification Solution for Remote Islands", *Renewable Energy Journal*, on-line available (11/11/2008) in www.ScienceDirect.com.
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7. "Combined Wind-Photovoltaic Stand-Alone Applications"

Published Results:

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9. "Air Pollution Analysis"

Published Results:

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13."Waste Management and Recycling Techniques"

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- **Kaldellis J.K., Vlachou D., Konstantinidis P., 1999**, "Sea Pollution by Oil Products. A Comparative Study of Combating Oil Spills in the Aegean Sea", 6th International Conference on Environmental Science and Technology, Conference Proceedings, Vol. C, pp. 729-737, University of Aegean, Pythagorion, Samos, Greece.

15."Social Attitude Towards Wind Energy Applications in Greece"

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16."Alternative and Fossil Fuels"

Published Results:

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Research Projects under Development

Participation in Research Programs (2002-2008)

1. "***Experimental Data Analysis and Evaluation of the Hellenic Ministry of Transport Air Pollution Lab***", Hellenic Ministry of Transport and Communications.
2. "***Overview of Incentive Programmes on Alternative Motor Fuels and Review of their Impact on the Market Introduction of Alternative Motor Fuels***", PREMIA Project, sponsored by DG TREN.
3. "***Optimum Micrositing of Selected Wind Parks in Peloponnesus***", supported by the Centre for Technological Research of Piraeus and Islands.
4. "***Maximum Energy Autonomy of Greek Islands on the Basis of Renewable Energy Sources***" Research Program "Archimedes-I" supported by the Greek Ministry of Education
5. "***Advanced Control Systems in the Water Supply Networks***" Research Program "Archimedes-I" supported by the Greek Ministry of Education
6. "***Transformation of a Typical Vapor Compression Air-Conditioning System to a Combined Air Conditioning System Based on Solar Energy***", Research Program "Archimedes-I" supported by the Greek Ministry of Education
7. "***Feasibility Study Concerning the Parameters of Ecological Behavior of Buildings in Natural and Urban Environment***", Research Program "Archimedes-I" supported by the Greek Ministry of Education
8. "***VISION: A New Vision for Engineering Economy***" (TEMPUS, 2004, in collaboration with Italy, Egypt and UK)
9. "***Integrated Study and Prediction of Electricity Related Air Pollution (NO_x, SO_2, CO_2) in Greece in View of the European Efforts for Improving the Air Quality***", Research Program "Archimedes-II" supported by the Greek Ministry of Education
10. "***Simulation-Study of the Energy Behavior of Buildings using Economically Acceptable Passive and Hybrid Solar Systems and Construction Materials in***

order to Improve the Thermal Behavior of Greek Buildings", Research Program "Archimedes-II" supported by the Greek Ministry of Education

11. "***Optimisation of Water Systems in Islands with Limited Water Resources***", Research Program "Archimedes-II" supported by the Greek Ministry of Education

12. Hellenic/French Collaboration Research Program "Platon" entitled "***Advanced Techniques of Automation in Wastewater Treatment Plants***". (Accomplished)

13. "***Development of an Experimental Hybrid Plant based on a Wind Turbine - P/V Station Collaboration***", supported by T.E.I. of Piraeus (Accomplished)

14. "***Reorganization of Mechanical Engineering Department - New Sector Development in the area of Soft Energy Applications & Environmental Protection Technologies***", supported by EPEAEK-Greek Ministry of Education (Accomplished)

15. Program "***RENES-Unet***", for the Diffusion of Renewable/Soft Energy Applications in Greece and European Union

16. "***Techno-economic Study of Small Hydro Power Stations***", supported by the private company EMPEDOS SA

17. "***Water Pumping Storage Systems for Crete Island***", in collaboration with the Technical University of Crete and the Enercon Hellas SA

18. "***Desalination System Based on Gas-Turbines Exhausted Gases***" supported by PPC and Crete Municipalities Union

19. "***NATURA-2000***", supported by the Greek Ministry of Environment, Physical Planning and Public Works

20. "***Natural Gas Cogeneration Opportunities in Urban Areas***", in collaboration with the Municipality of Nikaia

21. "***Energy Saving in TEI Buildings***", supported by TEI of Piraeus

TABLE OF CONTENTS

PART ONE

PART TWO

PART THREE

PART FOUR

PART FIVE

PART ONE

MAXIMUM ENERGY IN MICRO-GRIDS

MAXIMUM WIND POTENTIAL EXPLOITATION IN AUTONOMOUS ELECTRICAL NETWORKS ON THE BASIS OF STOCHASTIC ANALYSIS

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Abstract

The vast majority of Aegean Archipelago islands cover their continuously increasing electricity demand on the basis of oil-fired autonomous thermal power stations, presenting increased operational cost and power insufficiency. On the other hand, this area has a very high wind potential. However, the stochastic behaviour of the wind and the important fluctuations of daily and seasonal electricity load pose a substantial penetration limit for the contribution of wind energy in the corresponding load demand. The problem investigated in the present study concerns the estimation of the maximum wind energy yield, which is acceptable by an autonomous electrical network, on the basis of the probability distribution of the local grid load demand and the corresponding data related to the available wind potential. For this purpose, an integrated numerical method is developed from first principles. More specifically, the proposed calculation method estimates the maximum wind energy contribution on the basis of the existing wind potential data and the information provided by the system operator concerning the corresponding load demand as well as the operational status of the existing thermal power stations. According to the results obtained, one may state that the present situation imposes a quite narrow limit on the wind energy contributing to the fulfilment of the local societies electrical needs. Hence, only by planning and applying an integrated new strategy concerning the incorporation of new wind power in the local networks, including complementary activities, appropriate energy storage installations and improved electrical load management, it is possible to increase the wind energy participation in the autonomous islands electrical networks.

Keywords: Autonomous Electrical Networks; Electricity Production; Wind Potential; Wind Energy; Wind Penetration Constraints; Maximum Wind Energy Contribution; Stochastic Analysis

1. Introduction

The Aegean Archipelago is a remote Hellenic area, east of the mainland, including several hundreds of scattered islands. Unfortunately, the electricity production cost for the vast majority of them is extremely high[1] approaching the 0.25€/kWh, due to the utilization of aged autonomous (based on diesel-electric generators) power stations (APS). At the same time most Aegean Sea islands are characterized by a considerable annual increase of the electrical power demand exceeding the 5% on annual basis[2]. In this context, the existing electrification solution cannot meet with reliability the variable load demand, hence in several cases the existing infrastructure cannot fulfil the excessive power demand during the summer period[3].

On the other hand, these islands, along with the mainland coasts, possess a very high wind potential, since in many locations the average annual wind speed exceeds the 9m/s. Thus wind energy may be an economic attractive solution for their habitants' urgent electrification problem[4]. Unfortunately, the stochastic behaviour of the wind and the remarkable fluctuation of daily and seasonal electricity load, in almost all island grids, lead to substantial wind energy penetration limits[5][6], especially during the low consumption periods of the year. In fact, the island electrical networks manager (i.e. the Greek Public Power Corporation or PPC) defines an instantaneous upper wind energy penetration limit in order to protect the local grid stability in case that the wind energy production is suddenly zeroed. This, up to now empirically chosen value, permits the operating thermal power units to replace the wind power contribution without overloading problems or electrical system voltage and frequency fluctuations.

The proposed analysis is concentrated on developing an integrated methodology which can estimate the maximum wind energy contribution to the existing autonomous electrical grids on the basis of stochastic analysis. For this purpose one takes into account the electrical demand probability density profile of every island under investigation as well as the operational characteristics of the existing thermal power stations[2]. Accordingly, one also uses the corresponding wind potential characteristics, on the basis of the available wind speed probability density profiles[7]. Thus, by combining the electrical load with the corresponding wind potential probability values one may estimate the resulting wind energy contribution to the local network electricity generation. The proposed methodology is applied to a representative Aegean Archipelago island, in order to demonstrate its applicability in similar problems solution. Finally, the proposed analysis is integrated with an appropriate parametrical analysis, investigating the impact of the available wind potential quality on the expected maximum wind energy contribution.

2. Position of the Problem

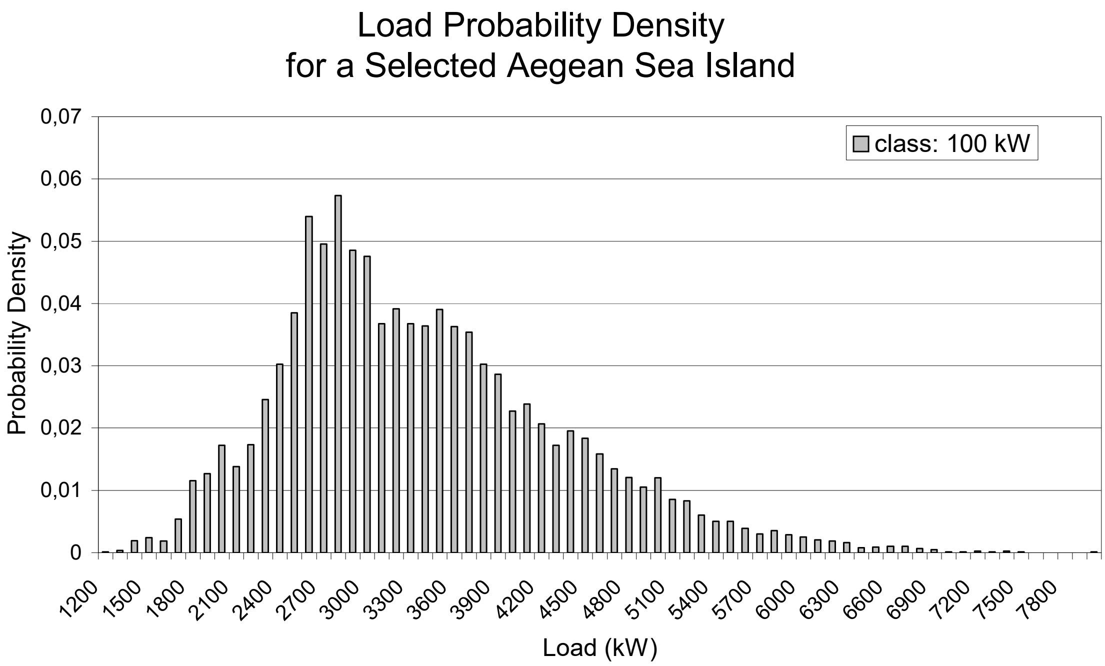

Figure 1: Load demand probability distribution for a selected Aegean Sea island

The problem to be solved in the present study concerns the estimation of the maximum wind energy yield that is acceptable by an autonomous electrical network on the basis of the stochastic distribution of the local grid load demand as well as the corresponding data related to the available wind potential. Hence, for the estimation of the maximum wind energy contribution one needs firstly the corresponding load demand. According to the available measurements[2] one may use either the long-term load demand time-series or the corresponding probability density distribution "f_L", see figure (1). In fact, one may estimate the probability "P_L" the load demand to vary between two specific values "N_{L1}" and "N_{L2}" as follows:

$$P_L(N_{L_1} \le N_L \le N_{L_2}) = \int_{N_{L_1}}^{N_{L_2}} f_L(N_L) \cdot dN_L \qquad (1)$$

Hence, for example according to figure (1) the probability of the load demand to vary between 2750kW and 2850kW during the time-period examined is approximately 5.73%.

Subsequently, one should define the maximum wind power penetration acceptable by the local electrical grid "N_w^*" on the basis of the local electrical system constraints. More precisely, taking into account that the island autonomous electricity generation systems are based on diesel or heavy oil powered engines, one should note that these units are not permitted to operate below a certain limit, in order to avoid increased wear and maintenance requirements. This limit is mentioned as the "technical minimum" of each engine, hence the minimum output power of the "in operation" thermal units "N_{dmin}" is calculated as:

$$N_{d_{min}} = \sum_{i=1}^{i=i_{max}} N_{d_i}^{min} = \sum_{i=1}^{i=i_{max}} k_i \cdot N_{d_i}^* \qquad (2)$$

where the technical minimum of each engine is expressed via an appropriate factor "k_i" and the rated (or maximum) output power "N_{di}^*" of the unit under investigation. Typical values of "k_i" are 30%-50% for heavy oil powered units and 20%-35% for diesel-fired engines (including gas turbines), depending very much on the age and the overall condition of the engine. On top of this, the annual maintenance plan of the system, affecting the number (i_{max}) of engines "in operation" during the year, should be also considered.

In addition, due to the stochastic behaviour of the wind one cannot disregard the probability of an unexpected loss of a significant part of the "in operation" wind parks. To avoid (or to minimize) loss of load events[8][9] in similar situations, the local system operator should maintain full spinning reserve in the thermal power units, which suffices to cover the total load demand. For practical applications, the above mentioned constraint is written in the following simplified and widely used form, i.e.:

$$N_w^* \le \lambda_1 \cdot N_L \qquad (3)$$

where "N^*_w" is the maximum acceptable by the local network wind power, "N_L" is the instantaneous load demand and "λ_1" is the corresponding maximum instantaneous participation limit.

Finally, in order to avoid annoying system frequency excursions and increasing wear of the existing thermal power units, an additional penetration limit is also imposed, dictated by the instantaneous rate that the "in operation" units can compensate any power deficit of the system. This dynamic penetration limit[10] is characteristic of the local electrical network as well as the spatial distribution and the type of the system wind turbines[11]. Generally speaking, this limit "λ_2" is selected by the system operator (also incorporating subjective/personal attitude) and is up to now empirically set in the range of 20% to 40%. In case of emergency this value may drop down to 15% or even be zeroed[3]. In this context, the dynamic penetration constraint is expressed as:

$$N_w^* \le \lambda_2 \cdot N_L \qquad (4)$$

On the basis of the above analysis, the maximum absorbed wind energy " N^*_w (t)" by the local electrical system can be estimated according to the following equations, i.e.:

$$\text{If} \quad N_L(t) \le N_{d_{min}}(t) = \sum_{i=1}^{i=i_{max}} k_i \cdot N_{d_i}^* \quad \text{then} \quad N_w^* = 0 \qquad (5)$$

In this case there is no wind energy absorption by the local network; hence all the wind energy production is rejected.

If $N_{d\min}(t) \le N_L(t) \le (1+\lambda) \cdot N_{d\min}(t)$ then $N_w^* = N_L(t) - N_{d\min}(t)$ (6)

where "λ" is the wind power upper participation limit depending on the optimum operation of the system thermal power units (λ_1) and the dynamic stability of the local network (λ_2), i.e.:

$$\lambda = \min\{\lambda_1, \lambda_2\} \tag{7}$$

Finally,

If $N_L(t) \ge (1+\lambda) \cdot N_{d\min}(t)$ then $N_w^* \le \min\{[\lambda \cdot N_L(t)], [N_L(t) - N_{d\min}(t)]\}$ (8)

In this last case the wind energy penetration is bounded by the upper wind power participation limit "λ" and the instantaneous load demand of the system.

Applying the proposed analysis on the load time-series of a typical island electrical system, one may estimate the resulting maximum wind energy penetration time-series in the local grid. Accordingly, one may reproduce the corresponding maximum wind energy penetration probability density profile "$f(N_w^*)$", figure (2). Thus, using the information of figure (2) one may state that the local network accepts wind power of 810kW during the 10.3% of the time-period analyzed. On top of this, one may also note that the wind power contribution up to 360kW is absorbed for the entire period, while there is no possibility of more than 2260kW wind power being imported to the local network, under the normal constraints that the local network manager imposes, see equations (2) to (4).

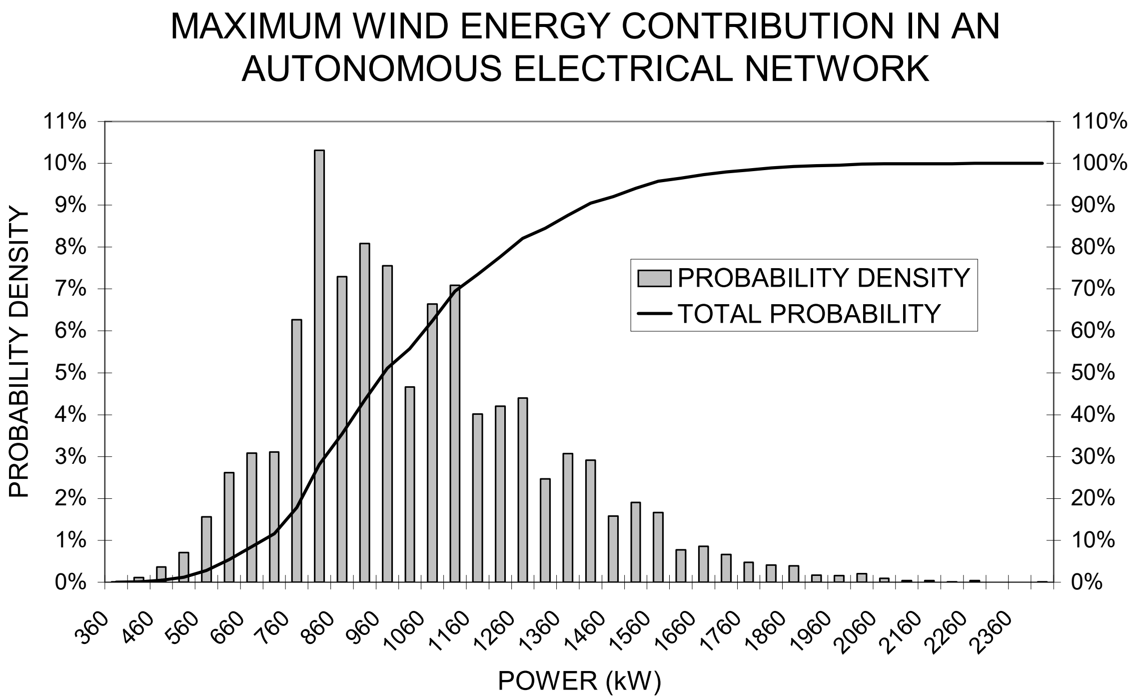

Figure 2: Maximum acceptable wind energy by an autonomous electrical network

On the other hand, it is important to calculate the expected wind energy production by one or more wind turbines operating in the area under investigation, on the basis of the available wind potential. Generally speaking the wind potential of an area is described by the average wind speed and the corresponding probability density value "$f_V(V)$", i.e. the probability of the wind speed to be between V-ΔV and V+ΔV[12][13]. Hence, using long-term wind speed measurements one may define the corresponding probability density distribution as well as the resulting duration curve, see figure (3). Using the "$f_V(V)$" value one can estimate the probability of the expected wind speed being between two specific values (i.e. $V_1 \le V \le V_2$) using the following relation:

$$P_V(V_1 \le V \le V_2) = \int_{V_1}^{V_2} f_V(V) \cdot dV \tag{9}$$

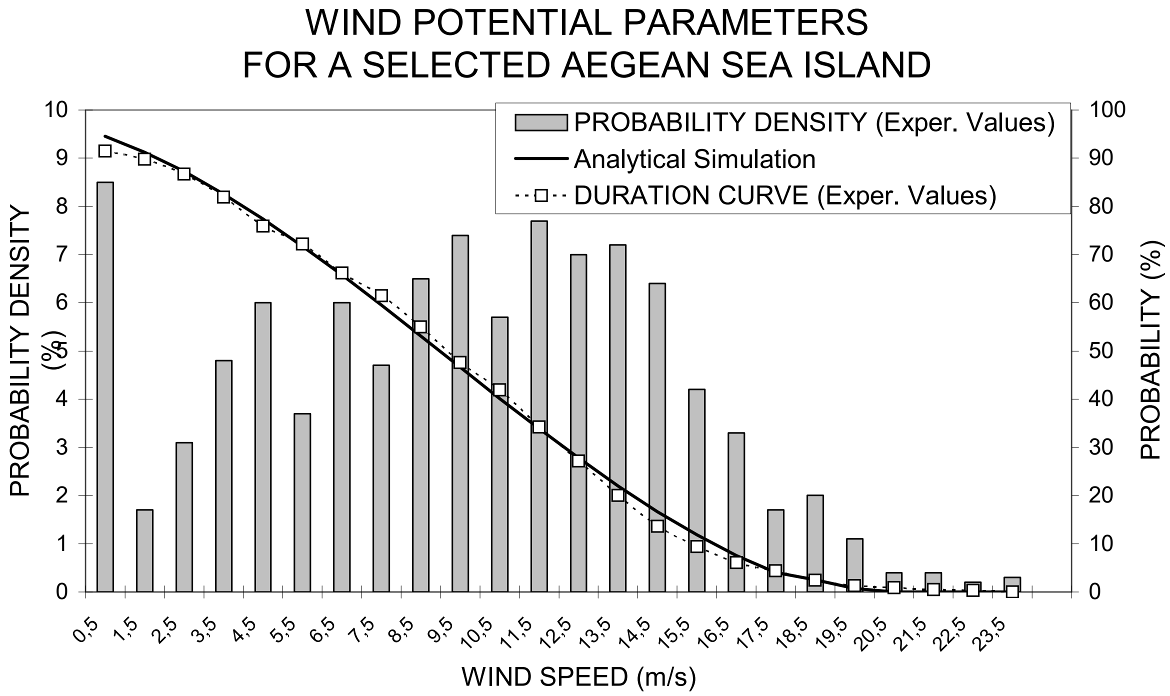

Figure 3: Measured and calculated wind potential parameters for a selected Aegean Sea island

Taking into account the available wind potential one may estimate the expected wind power output on the basis of the operational characteristics of the wind turbines to be used. More precisely, the expected wind power probability density distribution "$f_N(N_w)$" of a wind turbine of rated power "N_o" located in a region with wind potential described by the corresponding probability density function $f_V(V)$ can be computed using the following equation:

$$f_N(N_w) = f_V(V; V = V(N_w)) \tag{10}$$

i.e. one should take into account all the cases that a specific wind turbine produces "N_w" kW. For this purpose the wind turbine power characteristic "$N_w=N(V)$" should be given by the wind turbine manufacturer, properly modified to take into account the local ambient conditions (air density) impact[14], see also figure (4).

According to equation (10) one may estimate the possibility of the wind turbine output varying between "Nw_1" and "Nw_2" by the following relation, see also figure (5), i.e.:

$$P_N(N_{w_1} \le N_w \le N_{w_2}) = \int_{N_{w1}}^{N_{w2}} f_N(N_w) \cdot dN_w \tag{11}$$

Using the data of figure (5) one may notice that for low wind speed periods the wind turbine yield is zero, while in cases that the local wind speed exceeds the wind turbine rated power (for pitch controlled engines) the installation output equals the corresponding rated power.

Summarizing, one should mention that up to now we have computed the probability density distribution of the maximum accepted by the local network wind contribution (figure (2)) along with the corresponding wind energy production probability density profile (figure (5)), resulting by the local wind potential characteristics, the number and the operational data of the wind turbines to be used[15].

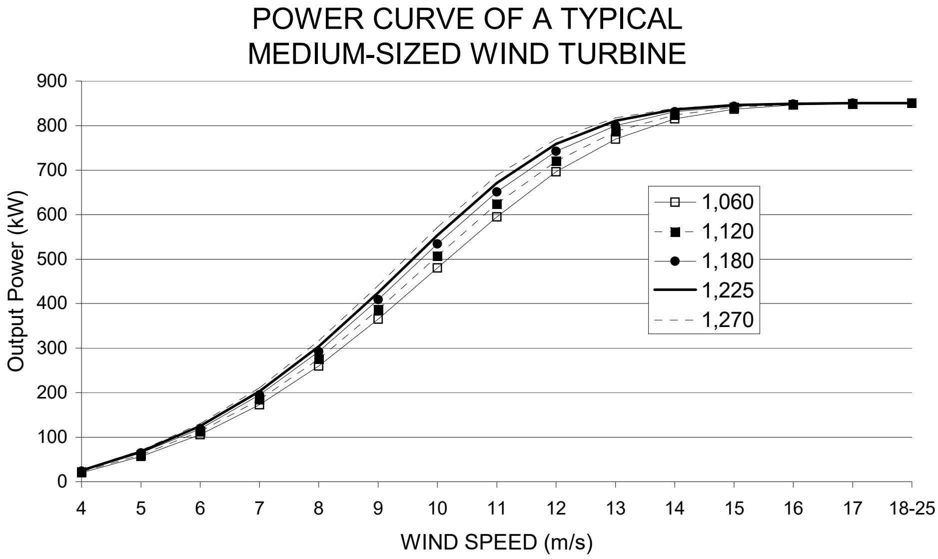

Figure 4: Typical power curve of a selected medium-sized wind turbine for various air density values

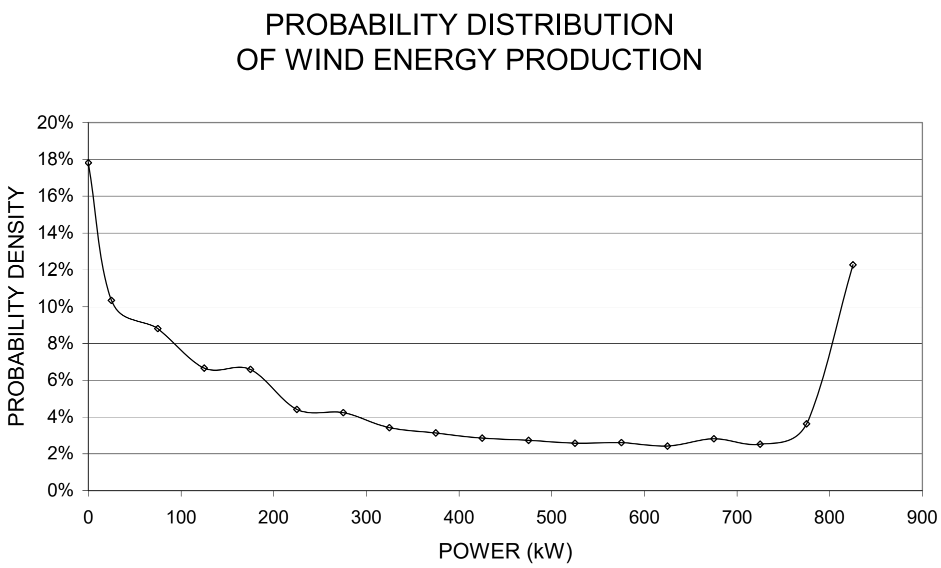

Figure 5: Probability distribution of wind energy production in a specific Greek island

3. Proposed Solution

For the estimation of the wind energy contribution to the local autonomous electrical network one should first estimate the corresponding energy yield of the wind turbines used on the basis of the existing wind potential. Thus, taking into account the available wind potential one may estimate the expected wind power output on the basis of operational characteristics of the wind turbines to be used[16]. More precisely, the statistically averaged energy yield "E" of a wind turbine of rated power "N_o", located in a region where the wind potential is described by the corresponding probability density function $f_V(V)$, can be computed[17] using the following relation:

$$E = CF \cdot z \cdot N_o \cdot \Delta t - \delta E \tag{12}$$

where "δE" describes the line transmission and the transformer loss as well as any self-consumption of the power station, while "Δt" is the time period examined (Δt=8760 hours for one year) and "CF" is the installation capacity factor defined as:

$$CF = \Delta \cdot \omega \tag{13}$$

More precisely, the capacity factor can be expressed as the product of the mean technical availability factor "Δ" and the mean power coefficient "ω" of the installation. For practical application purposes one may assume[18] that Δ=95%, while the mean power coefficient, expressing the yearly-averaged energy production during an hour per kW of nominal power of the machine ("V_C" cut-in and "V_F" cut-out wind speed of a wind turbine), is defined by the following equation, i.e.:

$$\omega = \int_{V_c}^{V_F} \frac{N(V)}{N_o} \cdot f_V(V) \cdot dV \tag{14}$$

In equation (14) the "$N(V)/N_o$" distribution is given by the wind turbine manufacturer, properly modified to take into account the local ambient conditions (air density) impact[14], see also figure (4).

Subsequently, one may estimate the wind energy rejection by the local network operator on the basis of the existing constraints already described in section two. In this context, one should compare the expected wind energy production "N_w" (probability $P_N=f_N(N_w).dN_w$) with the maximum acceptable wind energy contribution to the local grid "N_w^*" (probability $P_w^*=f(N_w^*).dN_w^*$). Hence, for every load segment (i.e. N_{Li} to $N_{Li}+\delta N_L$) of the network we estimate the corresponding maximum acceptable wind energy contribution "N_{wi}^*". The predicted value is combined with all the expected wind energy production values, i.e. "N_{wj}", taking into account the corresponding probability value "$f_N(N_{wj}).dN_w$". Hence, for every combination "i x j" we estimate the expected wind energy deficit or surplus as follows:

$$\delta N_{ij} = N_{w_j} - N^*_{w_i} \tag{15}$$

along with the corresponding probability (under the assumption that the local wind speed values and the corresponding load demand of the system are two independent variables), i.e.:

$$P_{ij} = P_{N_i} \cdot P^*_{w_j} \tag{16}$$

In view of equation (15) one may note that:

If $\delta N_{ij}>0$ there is wind energy surplus, i.e. the energy yield of the existing wind turbines cannot be entirely absorbed by the local network due to the existing constraints and the corresponding load demand of the consumption, while

If $\delta N_{ij}<0$ wind energy deficit is encountered, thus the wind turbines production cannot cover the maximum acceptable wind energy by the local electrical grid.

For the computation of the statistical averaged wind energy surplus "ΔE" of the local network during a specific time period "Δt" one may use the following equation, i.e.:

$$\Delta E = \sum_i \sum_j \delta N_{ij} \cdot P_{ij} \cdot \Delta t \qquad (\delta N_{ij} \succ 0) \tag{17}$$

Finally, the wind energy contribution to the local system "E_f" can be calculated by the difference between the expected wind energy production and the corresponding statistical averaged wind energy surplus, thus one may write:

$$E_f = E - \Delta E \tag{18}$$

4. Application Results

The proposed methodology is accordingly applied to a typical autonomous electrical network of a selected Aegean Sea island, i.e. Karpathos island. In figure (1) one may find the necessary information of the corresponding annual load demand for the year 2004. According to the data presented the peak load demand of the system is 7960kW, while the most commonly appeared load demand is between 2600kW and 3000kW. Thus the statistically averaged load demand is approximately 3200kW and the corresponding annual energy consumption is 28,200MWh/year.

In figure (3) one may find the necessary information about the local wind potential based on three-year long wind speed measurements[7]. The mean wind speed of the area is 9.4m/s, which represents an excellent wind potential case. The wind turbine selected to be installed in the island is a medium-sized pitch-control wind turbine of 850kW rated power, see figure (4). The selection procedure of the specific wind turbine is mainly based on the local infrastructure situation and on the expected energy production-investment cost ratio. However, this analysis is beyond the scope of the present study, see also [15] and [18].

Applying the proposed methodology for an 850kW wind turbine one gets the calculation results (i.e. the P_{ij}-δN_{ij} relation) of figure (6). According to the results obtained one may state that the wind energy production of one 850kW wind turbine cannot cover the maximum acceptable by the local network wind energy demand, while wind energy surplus ($\delta N_{ij}>0$) exists only for a very small percentage of the year. In figure (6) one may observe two distinct wind energy deficit curves. The first one corresponds to the low wind speed periods of the year (wind speed less than the cut in speed of the wind turbine used, i.e. 3.4m/s). The second curve describes the possibility of the produced wind energy (due to the installed rated wind power) being less or greater than the maximum acceptable one. The total energy balance results from the addition of these two curves, see also figure (7).

Consequently, the statistical averaged wind energy surplus of the 1x850kW wind turbine is only 40.97MWh/year, while the expected annual wind energy yield (CF=36.4%) is 2710.3MWh. Thus, the maximum wind energy finally absorbed by the local network (see equation (18)) is 2669.4MWh, representing the 98.5% of the annual wind turbine production and the 9.5% of the local system electrical consumption.

At this point it is important to note that the energy deficit corresponding to the first curve of figure (6) cannot be removed, since it is due to the existing calm spells in the region examined. Only by using another wind turbine with considerably lower cut in wind speed (not available up to now) it will be possible to decrease this energy deficit. On the other hand, the energy deficit, described by the second curve, can be substantially decreased as the installed wind power is amplifying, figure (7).

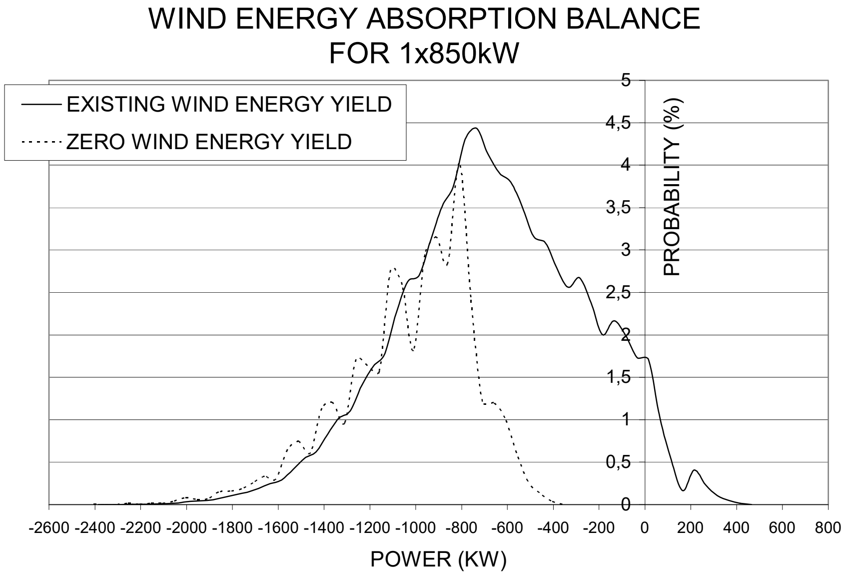

Figure 6: Wind energy balance probability distribution for a specific autonomous island grid

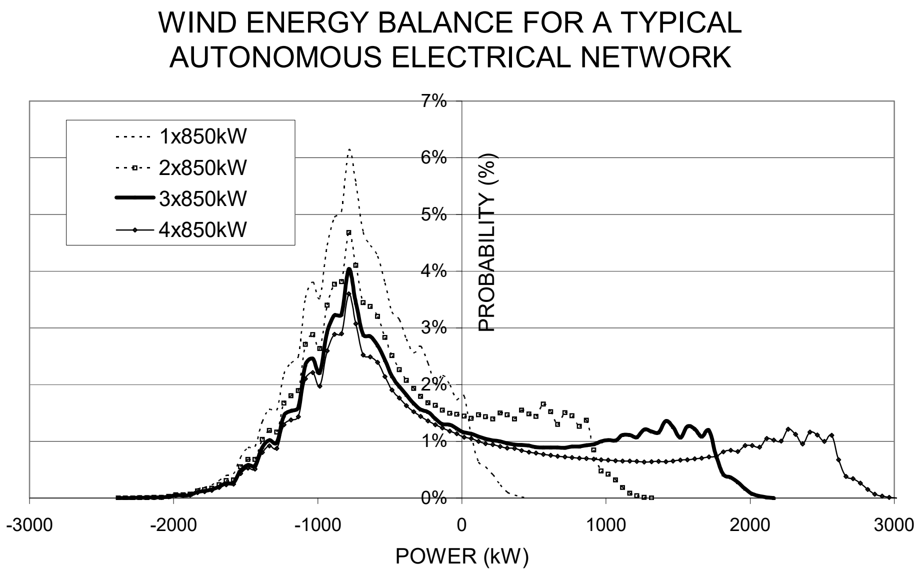

Figure 7: Wind energy balance probability distribution for a typical autonomous electrical network with variable wind power penetration

In fact, it is interesting to investigate in the following the impact of the installed wind power (i.e. by increasing the number of the wind turbines) on the wind energy rejection by the local network as well as on the final wind energy contribution to the local system energy consumption. Applying the proposed methodology for z=2, z=3 and z=4 wind turbines one gets the results of the figure (7). At this point it is important to note that the maximum permitted wind power to be installed in the local system is equal to 30% of the corresponding peak load demand. Consequently, according to the existing legislation[10], only three wind turbines of 850kW can be installed in this specific network. However, the utilization of one additional wind turbine is included for the proposed analysis purposes.

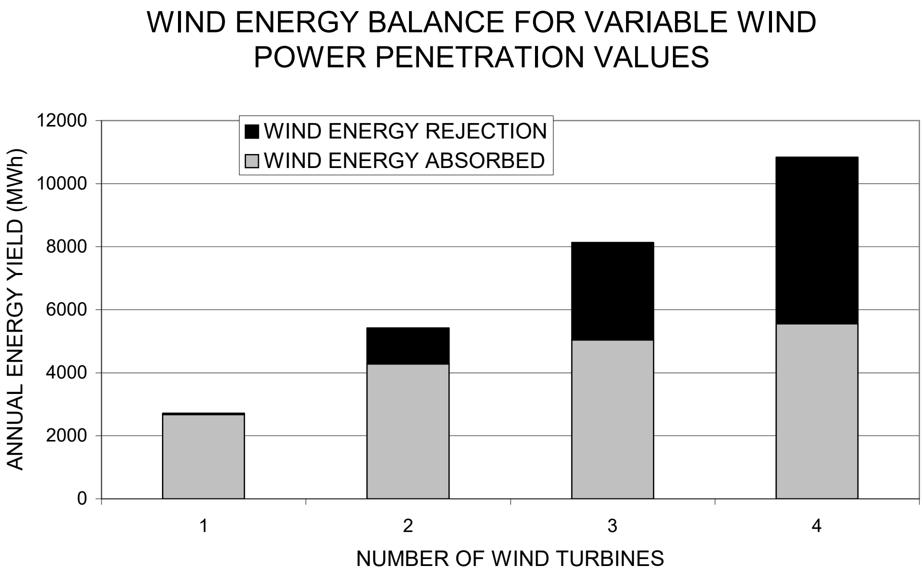

Figure 8: Wind energy balance for variable wind power penetration values in an autonomous island network

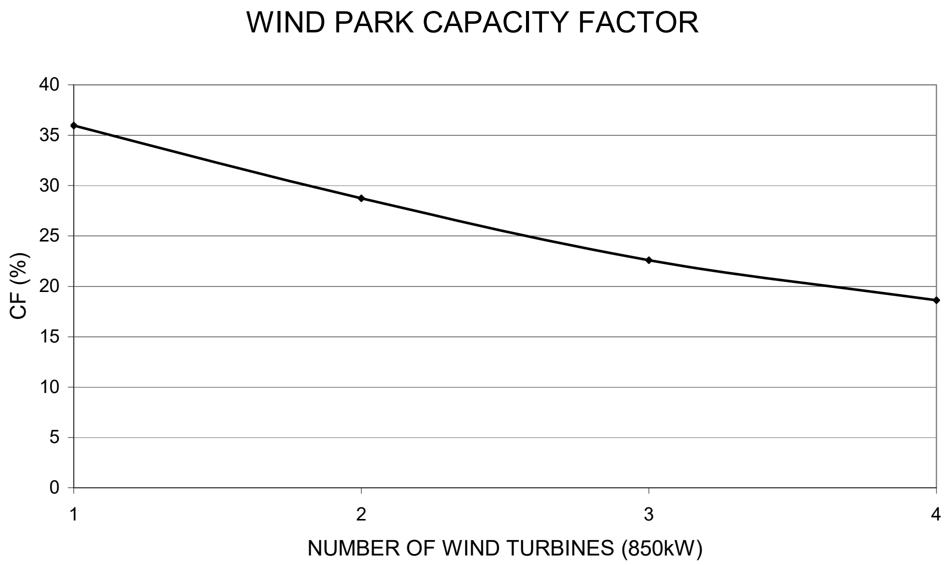

Figure 9: Wind park capacity factor evolution as a function of the wind power penetration in an island autonomous electrical network

According to the results obtained it is obvious that the wind energy surplus increases remarkably along with the wind turbines number increase. On the other hand, the wind energy deficit is equivalently reduced. More specifically, the wind energy rejection takes off from 40.97MWh in case of one wind turbine up to 5500MWh for four installed wind turbines. This negative evolution bounds significantly (i.e. less than 17.5% of the corresponding annual consumption) the wind energy contribution to the local energy demand, figure (8), since almost the half energy yield of the "in operation" wind turbines cannot be absorbed by the local network as the number of wind turbines exceeds three ($z \geq 3$). This fact direct result is the significant decrease of the wind park capacity factor (figure (9)), which is 36% for one wind turbine and drops down to 17% for the case that four wind turbines of 850kW operate in the electrical system.

Summarizing, one may state that (using the available stochastic wind potential and electrical load data) the wind energy contribution to the local system electricity demand is significantly decelerated as the number of the installed wind turbines is increased. On top of this, a significant decrease of the wind turbines utilization degree (capacity factor value) is encountered, strongly questioning the financial viability of a potential installation using more than two (2) wind turbines.

5. Wind Potential Impact on the Maximum Wind Energy Contribution

In order to underline the applicability of the proposed analysis for various practical cases, possessing different wind potential values, we extend the above described analysis in cases with quite different wind potential than the one of figure (3). In most practical cases, the wind potential of an area is expressed via the well-known Weibull probability density distribution "$f_w(V)$", which defines the probability of the wind speed being between "V-δV" and "V+δV", on the basis of two parameters[12][16]. At this point it is important to mention that there is a considerable amount of research work concerning the analytical simulation of wind speed experimental measurements, using the Weibull distribution or other more recently presented functions, see for example [19], [20], [21]. More specifically, the corresponding probability density distribution is given as:

$$f_w(V) = \frac{k}{C} \cdot \left[\frac{V}{C}\right]^{k-1} \cdot \exp\left\{-\left[\frac{V}{C}\right]^{k}\right\} \tag{19}$$

where "C" is the wind speed normalizing factor and "k" is the corresponding shape factor. Both parameters are related with the mean wind speed of an area as well as with the corresponding standard deviation, via the Gamma function[22]. In fact, one may estimate the mean wind speed of a specific location using the corresponding values of "C" and "k" as follows:

$$V_{av} = C \cdot \Gamma(1 + \frac{1}{k}) \tag{20}$$

where "V_{av}" is the average wind speed for the time period examined. The accuracy of the applied analytical functions to reproduce the experimental data is usually very good, see for example figure (3) describing the analytical simulation of the real data used in Section 4. However, in specific cases the stochastic behaviour of the wind may hinder the up to now used analytical equations to describe the real data. In fact, in most cases examined[17][19][21][23] concerning the annual energy production one may definitely state that the discrepancy encountered between the energy yield calculations based on analytical models and experimental measurements does not exceed the 5%. According to detailed wind speed measurements[7][23] the long-term mean wind speed value in the Aegean Archipelago varies between 5.0m/s and 8.0m/s, thus the corresponding "C" values range between 5.5 and 8.5. On the other hand, in most cases the "k" takes values slightly less than 2.0, hence the value k=1.8 may be used as a typical shape factor value for the area investigated.

In figure (10) one may find representative probability density distributions on the basis of equation (19). According to the information provided, as the "C" value increases the corresponding wind potential is higher, while as the "k" value increases the wind speed values are concentrated around the mean value. Generally speaking, "C" values of the order of 5.5 describe areas with medium-low wind potential, while "C" values of the order of 8.5 describe areas with very high wind potential.

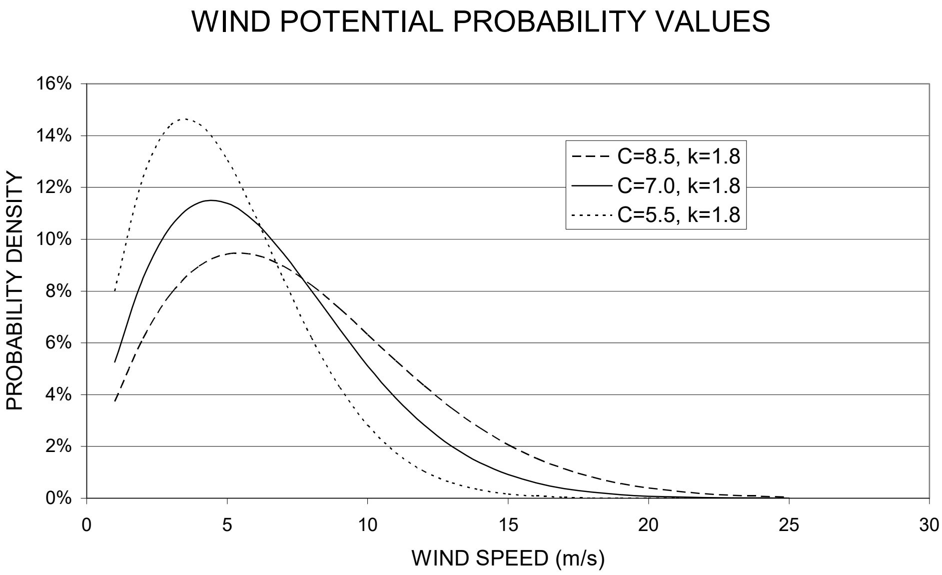

Figure 10: Typical wind speed probability density distributions according to Weibull analysis

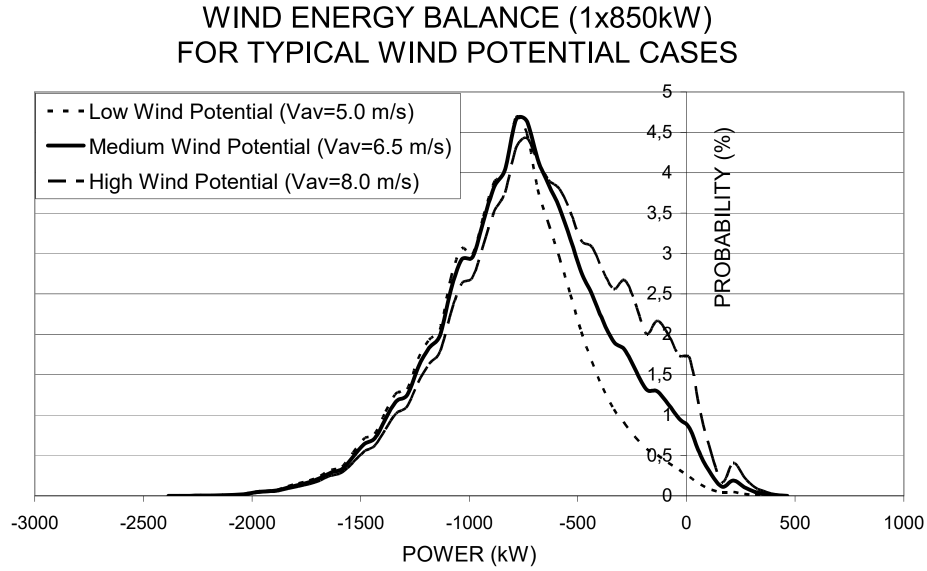

Figure 11: Wind energy balance for typical wind potential cases and low wind power penetration in the autonomous electrical network

In an attempt to study the wind potential impact on the wind energy absorption-rejection from the local network, we repeat the calculation of section 4 for selected representative "V_{av}" values for the Aegean Archipelago, assuming that k=1.8. The calculation results are summarized in figure (11) for the case of low wind energy penetration (i.e. 1x850kW). As expected for medium-low wind potential (V_{av}=5.0m/s) cases the wind energy surplus is minimal, since the wind turbine does not work for a considerable time period due to low wind speed values (extended calm spells). The energy surplus increases as "V_{av}" tends to considerably higher values, Table I. Note that for this low wind penetration scenario (wind park rated power 850kW-local network peak load 7960kW) the wind energy yield represents the 4% (V_{av}=5.0m/s) up to 10% (V_{av}=8.0m/s) of the corresponding annual consumption of 28200MWh/y.

Table I: Wind energy generation balance (in MWh/y)

	Low Wind Speed, Low Wind Penetration	Medium Wind Speed, Low Wind Penetration	High Wind Speed, Low Wind Penetration	Low Wind Speed, High Wind Penetration	Medium Wind Speed, High Wind Penetration	High Wind Speed, High Wind Penetration
Wind Energy Production	1116.9	1928.5	2710.3	3350.7	5785.5	8131.0
Absorbed Wind Energy	1111.5	1908.6	2669.4	2636.2	3916.0	4909.0
Wind Energy Surplus	5.4	19.9	41.0	714.5	1869.5	3222.0

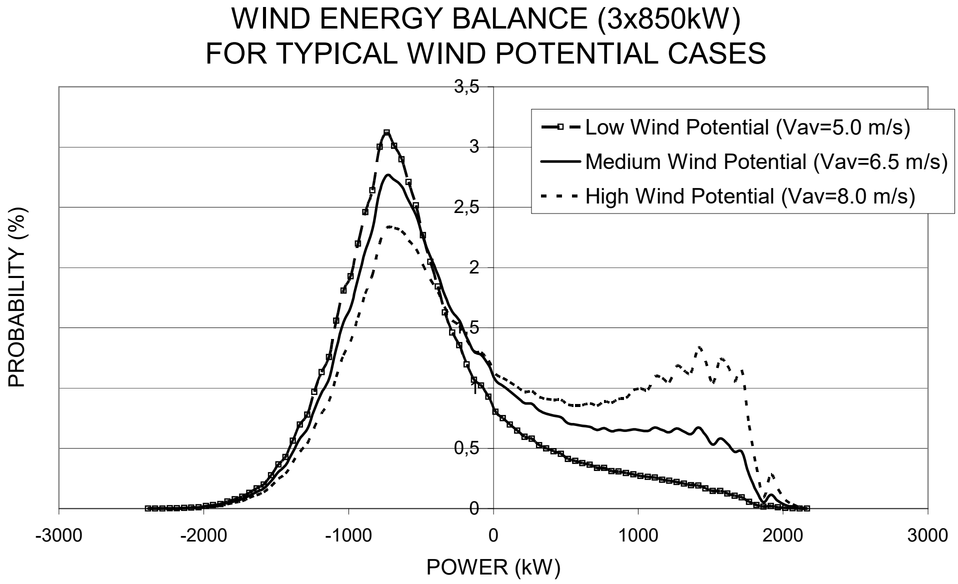

Figure 12: Wind energy balance for typical wind potential cases and high wind power penetration in the autonomous electrical network

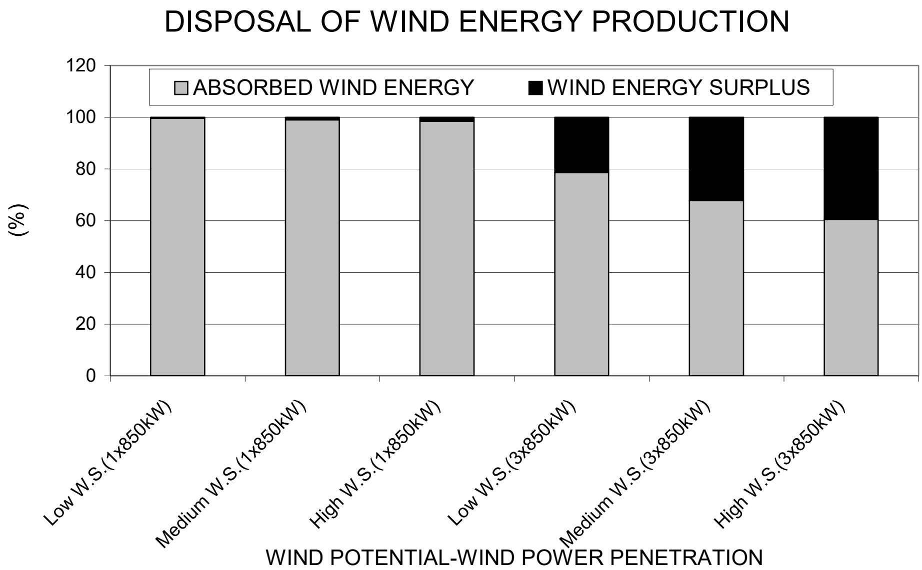

Figure 13: Wind energy balance for typical wind potential cases and variable wind power penetration in a selected autonomous electrical network

A quite different picture is valid for the case of high wind penetration (i.e. 3x850kW) in the local network, figure (12), since considerable wind energy surplus is encountered, especially as "V_{av}" exceeds 6.5m/s. It is important to note that for high wind penetration scenarios the wind energy surplus remain minimal for low wind potential cases. Of course the calculated amount of wind energy rejection in this last scenario is definitely higher than the one of the (1x850kW) case, Table I. In fact, for the high wind potential case the 40% of the wind park annual production cannot absorbed by the local network (figure (13)), while for the low wind potential case this amount drops to 21.3%. As a result the maximum wind energy contribution varies between 13% and 17.5% of the local network annual consumption, depending on the available wind potential.

6. Conclusions

An integrated numerical method, able to estimate the maximum wind energy penetration in existing autonomous electrical networks is developed using stochastic analysis, taking into consideration the area wind potential and the corresponding load demand. More precisely, the calculation method developed estimates the maximum wind energy contribution on the basis of the existing wind potential data and the information provided by the system operator concerning the corresponding load demand and the operational status of the existing thermal power stations. For this purpose extensive wind speed and load demand measurements for a considerable time-period are taken into account, using the appropriate mathematical tools.

The calculation results indicate that the wind energy absorption by the local network decreases significantly as the rated power of the installed wind parks increases. Thus, if one wants to amplify the wind energy contribution to covering the energy consumption of autonomous island grids, a considerable part of the wind energy yield cannot be absorbed. The problem is much more intense in regions with high wind potential, since the energy surplus increases with the quality of the available wind potential. Only by finding complementary applications of the wind energy (e.g. desalination or hydrogen production) or by building appropriate energy storage installations it will be possible to further increase the wind energy participation in similar autonomous electrical markets.

Recapitulating, it is important to note that the proposed methodology gives us the capability to estimate the maximum wind energy contribution to any autonomous electrical network, on the basis of the available wind potential and the operational parameters of the existing thermal power units. Using this model, one may state that the present situation imposes a quite narrow limit for the wind energy contribution to fulfil the electrical needs of the local societies. Unfortunately, this situation minimizes the possibility of new wind parks to be erected in these remote islands without energy storage applications. Hence, only by planning and applying an integrated new strategy, concerning the incorporation of new wind power in the local networks, including complementary activities, appropriate energy storage installations and improved electrical load management, it is possible to increase the wind energy participation in the continuously increasing electricity demand of autonomous islands networks.

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A NEW COMPUTATIONAL ALGORITHM FOR THE CALCULATION OF MAXIMUM WIND ENERGY PENETRATION IN AUTONOMOUS ELECTRICAL GENERATION SYSTEMS

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Abstract

The entirety of Aegean Sea islands, including Crete, is characterized during the last decade by a considerable annual increase of the electrical power demand exceeding the 5% in annual basis. This continuous amplifying electricity consumption is hardly fulfilled by several outmoded internal combustion engines usually at a very high operational cost. On the other hand most of the islands possess high wind potential that may substantially contribute in order to meet the corresponding load demand. However, in this case some wind energy absorption problems related with the collaboration between wind parks and the local electricity production system cannot be neglected. In this context, the present study is devoted to realistically estimating the maximum wind energy absorption in autonomous electrical island networks. For this purpose a new reliable and integrated numerical algorithm is developed, using the available information of the corresponding electricity generation system, in order to calculate the maximum acceptable wind power contribution in the system, under the normal restrictions that the system manager imposes. The proposed algorithm is successfully compared with existing historical data as well as with the results of a recent investigation based almost exclusively on the existing wind parks energy production.

Keywords: Numerical Algorithm; Electricity Production; Thermal Power Stations; Wind Energy; Penetration Constraints; Maximum Wind Energy Absorption; Autonomous Island Networks

Nomenclature

N_D	local network load demand (kW_e)
N_i^f	historical data concerning the wind energy absorption by the local network (kW_e)
N_i^r	predicted (expected) wind energy absorption by the local network (kW_e)
N_i^*	rated power of wind park "i" (kW_e)
N_{min}	technical minima of thermal power stations of the network (kW_e)
N_w	wind energy production (kW_e)
N_w^*	maximum permitted wind energy absorption by the local network (kW_e)
δN	wind energy curtailment due to the operational problems of the local network (kW_e)
ΔN_w	wind power rejection (curtailment) by the local electrical network (kW_e)
ε	discrepancy between the expected (predicted) and the real wind energy absorption by the local electrical network (kW_e)
λ	upper wind energy participation limit in the instantaneous load demand
ν_i	the contribution of wind park "i" in the total wind energy generation

1. Introduction

Wind energy applications are recently characterized as an economic attractive solution for the urgent electrification problem of most Aegean Sea islands, especially in regions with high or medium high wind potential[1][2][3]. On the other hand, the fluctuation of daily and seasonal electricity load in almost all island grids leads to substantial wind energy penetration limits[4][5], especially during the low

Kaldellis J.K., Kavadias K.A., Filios A.E., 2008, "A New Computational Algorithm for the Calculation of Maximum Wind Energy Penetration in Autonomous Electrical Generation Systems", Applied Energy Journal, on-line available (04/12/2008) in www.ScienceDirect.com.

consumption periods of the year. This paradoxical situation, i.e. "desperate" need of additional power[6] during the summer and electricity production rejection during the rest of the year, influences negatively the financial efficiency of the existing wind parks[7] and discourages the new investors of the sector[8].

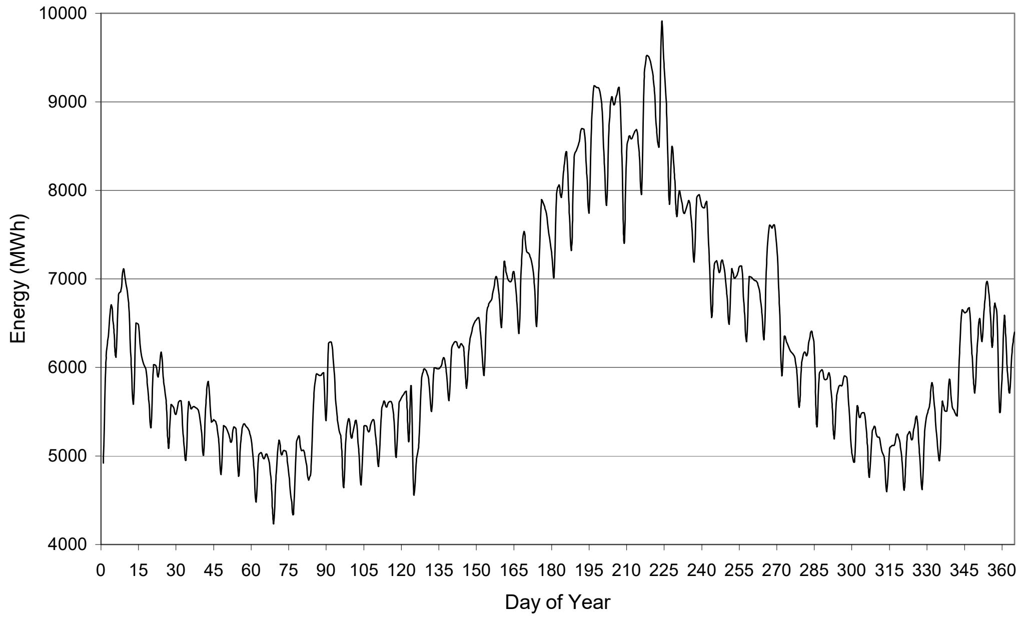

Figure 1: Daily electrical load variation for Crete island during 2002

One of the most interesting case studies[9][10] concerning the incorporation problems of wind parks in an autonomous electrical network, is the island of Crete. As in most islands, the electricity demand in Crete strongly varies during the year, see for example figure (1). In an attempt to meet the continuously increasing (on annual basis) electricity demand of the existing autonomous electrical grids, several outmoded internal combustion engines are utilized to cover base load[11]. For technical reasons, all these engines have specific power outlet minima, which cannot be violated without endangering the existing equipment. As a result, during very low consumption periods no wind power contribution is possible, since the entire system base load units should operate at power level higher than their technical minima.

In addition, even in high load demand periods the island electrical networks manager (i.e. the Greek Public Power Corporation or PPC) defines an instantaneous upper wind energy penetration limit "λ"[12] in order to protect the local grid stability, in case that the wind energy production is suddenly zeroed. This properly selected value permits the operating thermal power units to replace the wind power contribution without overloading problems or electrical system voltage and frequency fluctuations and dipping.

Finally, additional wind energy rejection is evident in cases that serious failures of the local grid branches are taken place or the quality of the wind energy production is not in accordance with the existing standards, i.e. high demand of reacting power, load phase asymmetry, system short-circuit, flicker etc.[13]. These problems are more frequent when stall control wind turbines are operating, while there are almost negligible for variable speed-pitch control machines.

For all the above presented reasons, serious wind energy rejection was encountered during the last five years, see for example figure (2), which is continuously increasing on annual basis. In this context, the present study is devoted to realistically estimating the maximum acceptable wind energy absorption (and hence the minimum wind energy rejection) in autonomous electrical island networks. For this purpose a new reliable and integrated numerical algorithm is developed, using the available information of the corresponding electricity generation system (EGS), in order to calculate the maximum acceptable wind power contribution to the system, under the normal restrictions that the system manager imposes. The proposed algorithm is successfully compared with existing historical data as well as with the results of a parallel investigation based almost exclusively on the energy behaviour of wind parks[14].

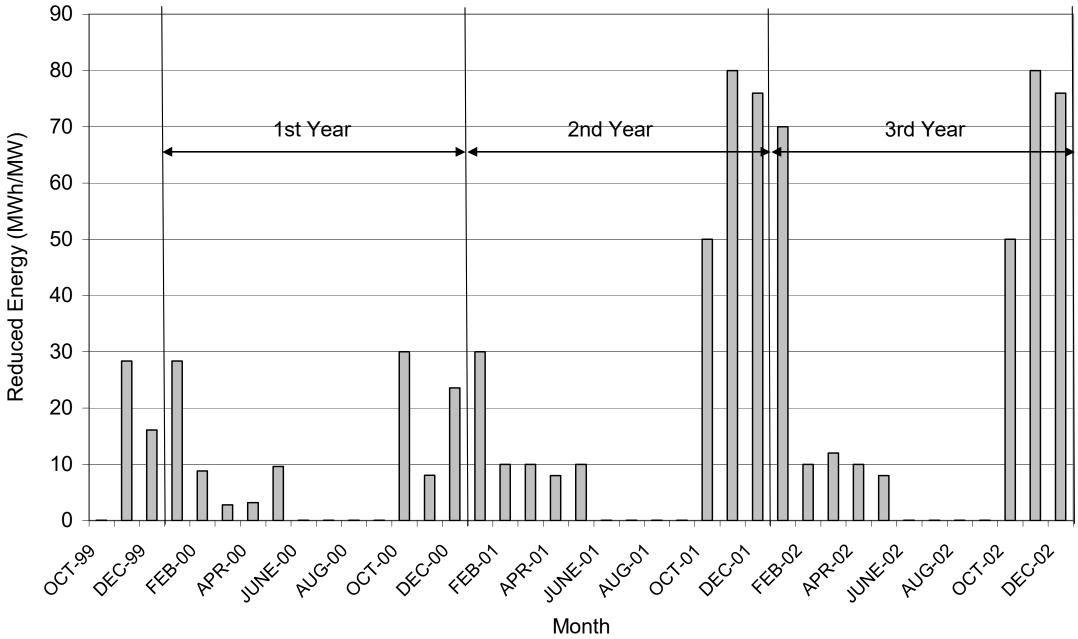

Figure 2: Wind energy rejection per installed MW for the wind parks of Crete island

Accordingly, comparing the real wind energy absorption by the local system and the maximum permitted one, it is possible to locate either specific technical problems of the local grid branches or unreasonable settings concerning the wind energy absorption upper limit by the system operator. In any case, further examination is required to maximize the clean wind energy penetration in the corresponding electrical systems, minimizing also the wind energy investors' financial loss.

On top of this, one of the most advantageous characteristics of the developed algorithm is its capability to be extended in the near future in order to predict the expected maximum wind energy absorption under specific EGS situations, including grid stability constraints.

2. Existing Situation of Crete Island Electricity Generation System

2.1 Thermal Power Stations of Crete Island

Crete island electricity generation system is based, since its foundation in mid-sixties, on oil-fired thermal power units located either near Chania (west of Crete) or at Linoperamata (location outside of Heraklion), see figure (3). Recently, two internal combustion engines (2x51MW) started their operation in the new Atherinolakkos power station. The official capacity of the local EGS is 742.9MW, although the real power of the system is 693MW for winter and 652MW for summer operation. As it is obvious from figure (3) the conventional thermal power stations (TPS) are not equally distributed throughout the island, since almost 320MW (real winter capacity) of thermal power is located in West Crete and the rest 260MW (real winter capacity) in the middle of the island. To face this problem, the new (200MW) TPS of Atherinolakkos is situated in SE of Crete.

According to official data[6][15] the local EGS is based (see also Table I) on six (6) relatively outmoded steam turbines of total capacity amounting at 111.25MW, operating since the seventies in Linoperamata TPS, one combined cycle power unit of 135MW located in Chania and four (4) internal combustion engines (diesel units) of 49MW operating since 1990 at Linoperamata. The technical minima of all these units are approximately 100MW, excluding the annual service periods, while their mean specific fuel consumption (SFC) of heavy-oil (mazut) is almost 350gr/kWh.

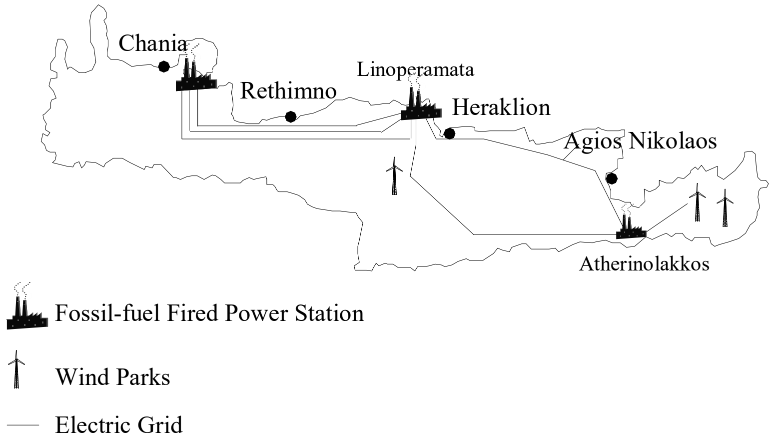

Figure 3: Existing wind farms and fossil-fuel fired power stations location in Crete

Table I: Crete island electricity generation system (EGS), end 2004

	Unit Type	Location	Fuel Used	Start Up Time	Rated Power (MW)	SFC (gr/KWh)	Techn. Minimum (MW)
1	Steam Turbine	L-H	Mazut	1965	6.2	366	4
2	Steam Turbine	L-H	Mazut	1970	15.0	330	7
3	Steam Turbine	L-H	Mazut	1970	15.0	330	7
4	Steam Turbine	L-H	Mazut	1977	25.0	285	12
5	Steam Turbine	L-H	Mazut	1981	25.0	285	18
6	Steam Turbine	L-H	Mazut	1981	25.0	285	18
7	Diesel Engine	L-H	Mazut	1989	12.3	200	3
8	Diesel Engine	L-H	Mazut	1989	12.3	200	3
9	Diesel Engine	L-H	Mazut	1990	12.3	200	3
10	Diesel Engine	L-H	Mazut	1990	12.3	200	3
11	Gas Turbine	L-H	Diesel	1973	16.3	450	3
12	Gas Turbine	L-H	Diesel	1974	16.3	450	3
13	Gas Turbine	Ch	Diesel	1969	16.2	540	3
14	Gas Turbine	Ch	Diesel	1979/85	24.0	450	3
15	Gas Turbine	Ch	Diesel	1979/87	36.0	450	3
16	Steam Turbine	Ch	Diesel	1993	44.4	250	18
17	Gas Turbine	Ch	Diesel	1992	45.0	380	7
18	Gas Turbine	Ch	Diesel	1992	45.0	380	7
19	Gas Turbine	Ch	Diesel	1998	59.40	315	8
20	Gas Turbine	Ch	Diesel	1998	59.40	315	8
21	Gas Turbine	L-H	Diesel	1982/01	15.50	270	3
22	Gas Turbine	L-H	Diesel	2002	43.30	270	5
23	Gas Turbine	L-H	Diesel	2003	30.00	300	4
24	Gas Turbine	Ch	Diesel	2003	30.00	300	4
25	Diesel Engine	A	Diesel	2004	51.00	210	12.3
26	Diesel Engine	A	Diesel	2004	51.00	210	12.3
TOTAL					742.9		

**   The Units (1 to 6 and 16 to 18) are used to cover base load*
*** The Units 16, 17 and 18 constitute a combined cycle system*
****"L-H" is the Linoperamata TPS at Heraklion, "Ch" is Chania TPS and "A" is Atherinolakkos TPS*
+ *The Engines 7 to 15 and 19 to 22 normally should not be used to cover base load*

In order to cover the surplus power demand, eleven (11) gas turbine generators (by the end of 2004) of rated power of 345MW operate in the island, in excess of the two gas turbines of the combined cycle. The corresponding mean specific fuel consumption (diesel-oil) is quite high, exceeding in several cases the 450gr/kWh, Table I.

Finally, the Atherinolakkos new station is based on two internal combustion engines of 2x51MW and two steam turbines of 2x50MW. However, the erection of this new station was strongly opposed by the local inhabitants, on the basis of environmental impacts[16]. Consequently, the first two engines (2x51MW) were brought into operation during 2004, while the full operational year of the Atherinolakkos TPS has officially been transferred to 2006. Additionally, the Greek Regulatory Authority of Energy (RAE) recently called for tenders in order to build a new TPS of approximately 220MW near the city of Rethimno[6]. The whole procedure is about to start and the authors estimate the operation of Rethimno TPS not earlier than 2008.

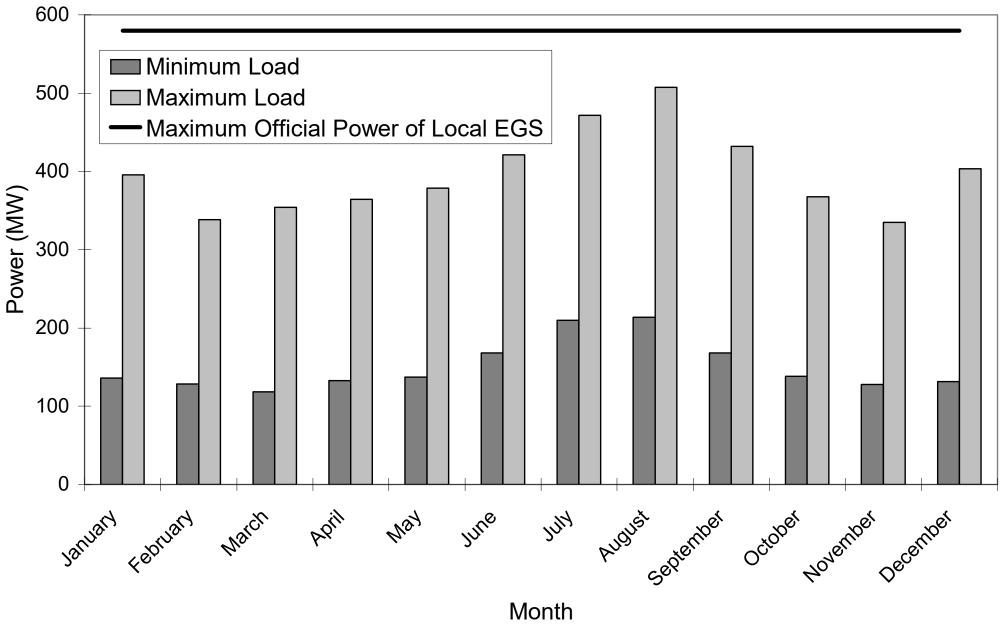

Figure 4: Monthly variation of minimum & maximum electrical energy demand for Crete island during 2002. Comparison with the maximum official power of the local EGS

Taking into consideration the touristic character of the island and the overall economic development, serious power insufficiency problems appear, especially during the summer, dictating expensive solutions for coping with the peak power load, mainly due to the overuse of the gas turbine generators. To get a clear-cut picture of the problem importance one may examine in figure (4) the monthly wide minimum and maximum load demand during 2002 along with the corresponding maximum rated power of the local system thermal power units, Table I (6^{th} column). Based on the sited data, the summer peak load demand is hardly covered by the existing TPS, operating in lower -by almost 10%- capacity due to the engine cooling problems. This fact underlines the remarkable power contribution of the existing wind parks, which have a share in facing peak load demand situations along with their contribution to the fuel saving. In addition, even during winter time, the utilization of high operational cost gas turbines is obligatory so as to meet the daily load demand, Table I.

2.2 Electricity Consumption Time Variation in Crete Island

Using official long-term data (1975-2004) concerning the Crete EGS[15] several conclusions may be drawn, see also figure (5), i.e.:

- There has been a considerable annual increase of electricity demand approaching the 7% during the last decade (1996-2005), when the corresponding national figure is 3.5%. As a result, the annual energy consumption during 2005 surpassed the 2650GWh in comparison with the modest 280GWh of 1975.
- The corresponding power increase was also high, since the official hourly peak load demand appearing during August 2005 has been 571MW, more than ten-times the value of 1975.
- Due to the development of the tertiary sector, i.e. services, commerce and primarily tourism, a high seasonal variation of electricity demand has been encountered during the last years. For example, the (1998-2004) mean monthly electricity demand of summer (≈250GWh) was more than 50% higher than the corresponding winter one (≈150GWh). In addition, comparing the mean hourly load demand variation between the four seasons of a typical year (figure (6)), one may easily conclude that there was a considerable electricity generation diversification between the year periods (e.g. summer versus other seasons). However, even during the low consumption periods of the year, the minimum load demand was greater than the local EGS technical minimum (i.e. 100MW).

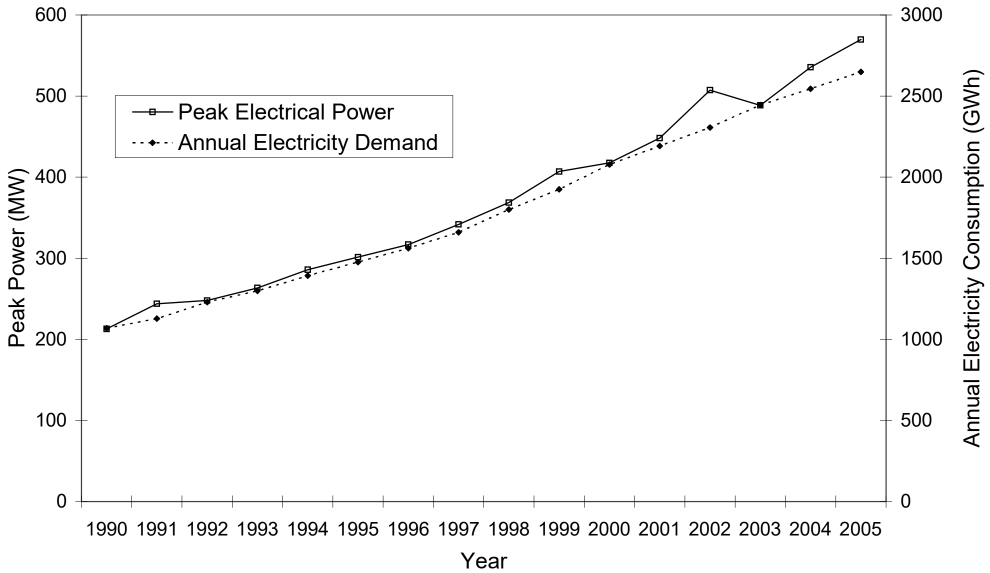

Figure 5: Time evolution of Crete island electricity system main parameters

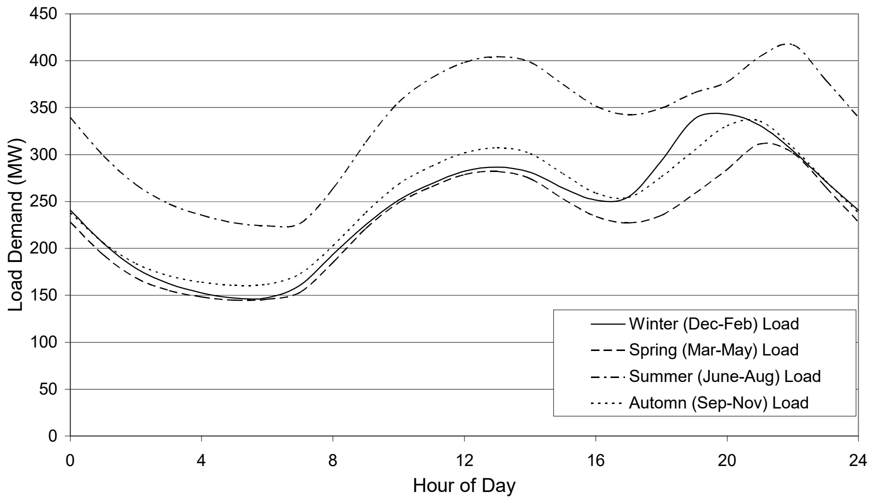

Figure 6: Seasonal mean hourly load comparison for Crete island during a typical year

2.3 Crete Island Wind Power Stations

It is widely accepted that Crete possesses very high wind potential[17][18][19], while the wind energy exploitation activities started since mid eighties[20]. Taking also into account the size of the island (4th biggest of Mediterranean) and the rather good infrastructure situation, as well as the definitely positive attitude of local people towards wind energy applications[21], wind energy was characterized as an advantageous option to meet the increased electricity demand requirements of local economy.

As a result, a remarkable wind park installation activity has started since 1992, leading by 2004 to the existence of sixteen (16) wind power stations of rated power 90MW (end of 2004), Table II. More specifically, four of the island wind farms belong to local electricity utility (PPC), two wind parks belong to local municipalities and the rest installations (representing almost the 87% of the island capacity) were erected by private investors. Up to now the centre of wind energy production is the East part of the island (Lasithi prefecture), although recently significant investment interest is expressed for the other parts of the island, see Table III. According to the available information ten new wind parks are under planning for the near future (realization time up to 2008) pushing the total wind power of the area above 120MW. For the entirety of these new wind parks a substantial subsidy (approximately 30% to 40% of the initial capital to be invested) has been approved either via the National Competitiveness Program (Ministry of Development) or via the National Development Law 3299/04 (Ministry of Economy)[8].

Table II: Existing wind parks in Crete island (end of 2004)

	Location	Prefecture	Owner	Start Up Time	Rated Power (MW)	Turbines Number
1	Toplou	Lasithi	PPC	1993	5.10	17x300kW
2	Toplou	Lasithi	PPC	1993	1.00	2x500kW
3	Toplou	Lasithi	PPC	1995	0.50	1x500kW
4	Xirolimni	Lasithi	PPC	2000	10.20	17x600kW
5	Mitato	Lasithi	Private	1998	10.20	17x600kW
6	Chandras	Lasithi	Private	1999	9.90	18x550kW
7	Meg. Vrisi	Heraklio	Private	1999	4.95	9x550kW
8	Achladia	Lasithi	Private	1999	10.00	20x500kW
9	Anemoessa	Lasithi	Private	1999/2000	5.00	10x500kW
10	Krya	Lasithi	Private	1999/2000	10.00	20x500kW
11	Plativolo	Lasithi	Munic.-Priv.	2000	2.50	5x500kW
12	Mare	Lasithi	Municipality	1993	0.5	1x500kW
13	Vrouchas	Lasithi	Private	2003	7.65	9x850kW
14	Xirolimni	Lasithi	Private	2004	3.0	5x600kW
15	Plativolo	Lasithi	Private	2004	3.0	4x750kW
16	Krousona	Heraklio	Private	2004	5.95	7x850kW

Table III: New planned wind parks in Crete island (end of 2004)

	Location	Prefecture	Owner	Start Up Time	Rated Power (MW)
1	Xirolimni	Lasithi	PPC	2005	3.0
2	Epanosifi	Heraklio	Private	2005	6.3
3	Modi	Lasithi	Private	2006	2.7
4	Ierapetra	Lasithi	Private	2006	4.6
5	Mires	Heraklio	Private	2007	5.2
6	Platanos	Chania	Private	2007	3.3
7	Spatha	Chania	Private	2007	4.6
8	Chonos	Lasithi	Private	2008	4.5
9	Mare	Lasithi	Municipality	2008	1.2

2.4 Position of the Problem: Estimation of Maximum Wind Energy Absorbance

Recapitulating the above presented information, one can state the following:

- ✓ There has been a continuous electricity demand increase during the last 25 years, hence the corresponding peak power value by 2005 is 570MW, see figure (5).
- ✓ The real summer capacity of the existing thermal power units is approximately 650MW, while during this period the energy consumption achieves its maximum value of the year, figure (6).
- ✓ Besides the remarkable wind power penetration, there is a significant interest for developing new wind farms in the island due to its favourite techno-economic conditions[8].

However, according to official data, a significant wind power rejection has been encountered in the Crete island EGS during the last years, figure (2), which in annual basis exceeds the 300MWh per MW installed. This evolution leads the owners of the existing installations to considerable financial loss and discourages the new investors, since any wind power addition to the existing EGS should provoke further diminution of the wind energy absorption by the local electrical network[14].

This problem was already analyzed by the present research group on the basis of wind parks operation data[14]. In the present study an alternative and supplementary approach is developed, where emphasis is put on estimating the maximum acceptable wind energy absorption, from the EGS point of view. For this purpose an integrated and reliable numerical algorithm is developed, able to realistically calculate the wind energy rejection on hourly basis, using the operational characteristics of the local EGS and the island wind farms as well as the instantaneous electrical load demand of the system. The results of this new algorithm can be compared with the results of the direct calculation method, already presented and the most recent official wind energy rejection values available (for 2000-2002), in order to prove its reliability. Finally, in excess of the direct calculation method, the proposed algorithm can be extended to simulate the expected situation of the local EGS in the near future.

3. Proposed Algorithm for the Prediction of Wind Energy Absorption/Rejection

For the estimation of the wind energy absorption "$N_w^*(t)$" or equivalently the corresponding wind energy rejection "$\Delta N_w(t)$" by the local EGS in course of time, the following information is needed, expressed as a function of time "t":

- ➢ The instantaneous electrical load demand of the system, i.e. "$N_D(t)$". For example, in figure (7) one may see typical electrical load profiles for February and August of a typical year.
- ➢ The technical minima "$N_{min}(t)$" of the local EGS. The specific numerical value of "$N_{min}(t)$" results by the operational characteristics (Table I) of the existing engines and the corresponding dispatch order. However, due to the age of the system engines the assignment of these values includes remarkable empirical information. In figure (8) the distribution of the technical minima of the local EGS is given as a function of the year month. It is obvious that the technical minima demonstrated represent a specific unit commitment for the year under investigation, taking into consideration the corresponding maintenance and renovating plan applied by PPC. For the current situation of the system the corresponding values vary between 70MW on March (maintenance period) and 100MW during summer (full operation period).
- ➢ The instantaneous wind energy production "$N_w(t)$" of the island existing wind parks, excluding any wind energy rejection (only in case that the wind energy rejection should be also calculated). The total wind energy system production is the sum of the electricity generation of all wind parks (i_{max}=16, for 2004) of the island in operation (see Table II), i.e.:

$$N_w(t) = \sum_{i=1}^{i=i_{max}} N_{w_i}(t) \tag{1}$$

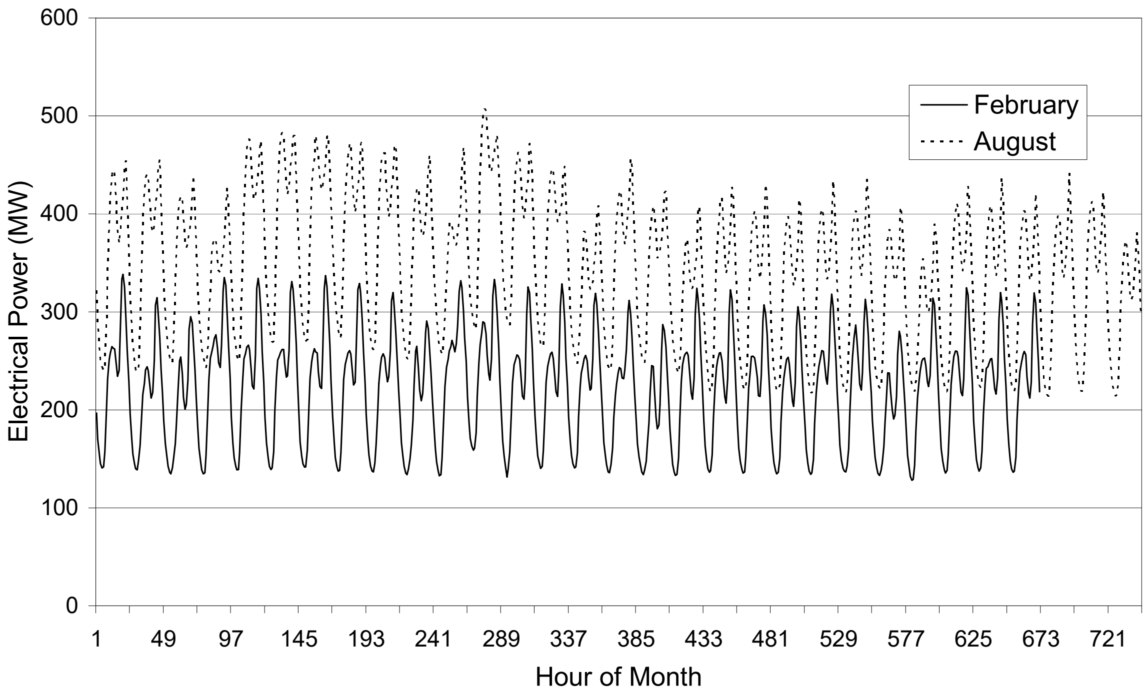

Figure 7: Comparison between February and August load demand for Crete island, 2002

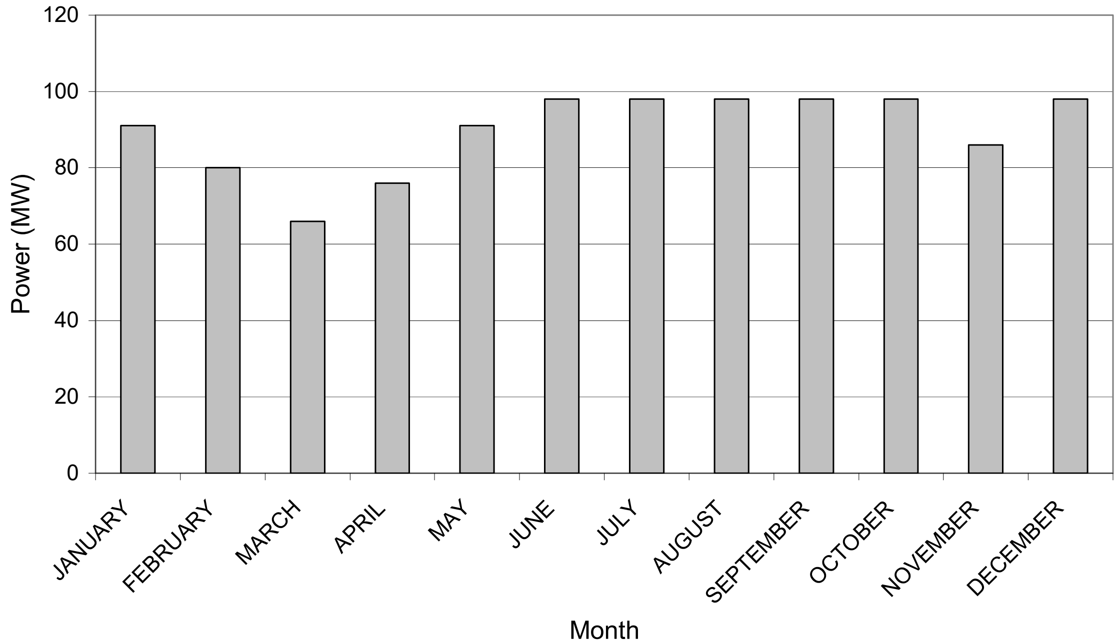

Figure 8: Technical minima of Crete island TPS (end of 2004)

Subsequently, the proposed algorithm named "WINDENEREJ" is based on the next four steps:

Step I: For every time point "t" define the local EGS load demand "$N_D(t)$" and the corresponding technical minima "$N_{min}(t)$"
Step II: Estimate the maximum approved wind energy production "$N_w^*(t)$" by the local EGS[22] according to the following equations, i.e.:

If $N_D(t) \le N_{min}(t)$ then $N_w^* = 0$ (2)

In this case there is no wind energy absorption by the local network, hence all the wind energy production is rejected.

$$\text{If} \quad N_{min}(t) \le N_D(t) \le (1+\lambda)\cdot N_{min}(t) \qquad \text{then} \quad N_w^* = N_D(t) - N_{min}(t) \tag{3}$$

where "λ" is the upper wind energy participation limit in the instantaneous electrical power demand, defined by the local electricity utility (PPC) in order to face undesirable local network problems[13][22]. The definition of the limit should be based on an on-line analysis of the local electrical network taking into account both static and dynamic security criteria[3][4][5][22]. Actually, the limits set take into account the whole system energy balance as well as the local transmission constraints of the main system branches. Usually, the value selected results from the "in operation" thermal power units technical characteristics and the time depending electricity load profile "$N_D(t)$". Moreover, the experience of the system operator is of vital importance. In most cases, this value is set less or equal to 30%, i.e. $\lambda \le 0.3$, although in some circumstances different values have been encountered.

$$\text{If} \quad N_D(t) \ge (1+\lambda)\cdot N_{min}(t) \qquad \text{then} \quad N_w^* \le \lambda \cdot N_D(t) \tag{4}$$

In this last case the wind energy penetration is bounded by the upper wind energy participation limit "λ" and the instantaneous load demand of the consumption.

Subsequently, one has the ability to estimate the maximum acceptable wind energy absorbance "N_{wi}^*" by the local EGS for each wind park "i" according to the above described algorithm and the following relation:

$$\begin{aligned}
&\text{If} \quad N_w^*(t) \ge \left[N_{w_1}(t) + N_{w_2}(t) + N_{w_{12}}(t)\right] \\
&N_{w_i}^*(t) = \nu_i(t)\cdot\left[N_w^*(t) - N_{w_1}(t) - N_{w_2}(t) - N_{w_{12}}(t)\right] \quad \text{for} \ (i = 3 \ \text{to} \ i_{max}) \\
&\text{and} \\
&N_{w_i}^*(t) = N_{w_i}(t) \quad \text{for} \ (i = 1, 2 \ \text{and} \ 12) \\
&\qquad \text{otherwise} \\
&N_{w_i}^*(t) = 0 \quad \text{for} \ (i = 3 \ \text{to} \ i_{max}) \\
&\text{and} \\
&N_{w_j}^*(t) = N_w^*(t)\cdot\frac{N_{wj}(t)}{N_{w1}(t) + N_{w2}(t) + N_{w12}(t)} \quad \text{for} \ (j = 1, 2 \ \text{and} \ 12)
\end{aligned} \tag{5}$$

In order to fully understand the wind energy distribution model depicted in Eq. (5) one should take into account that:

- The wind parks operating before the law 2244/94 (i.e. corresponding to lines 1,2 and 12 of Table II) are not obliged to reject more production than the one dictated by the EGS technical minima, hence they enter first in the local grid.
- The wind energy absorbance of the rest wind parks is distributed officially according to the instantaneous output "$N_{wi}(t)$" of each wind park and practically according to their rated power "N_i^*", see Eq. (6).

$$\nu_i(t) = \frac{N_{w_i}(t)}{\sum_{i=3}^{i=i_{max}} N_{w_i}(t)} \quad (i = 3,\ i_{max})$$

or (6)

$$\nu_i = \frac{N_i^*}{\sum_{i=3}^{i=i_{max}} N_i^*} \quad (i = 3,\ i_{max})$$

where "$\nu_i(t)$" is the time depending contribution of the wind park "i" in the total wind energy generation of Crete island. Fortunately, the old (before the law 2244/94) wind parks (i=1,2 and 12 of Table II) are relatively small ones (i.e. total rated power 6.6MW), thus their operation does not seriously affect the wind energy rejection of the younger and bigger wind parks. Note that the above described procedure is officially established in cases of normal operation and it is validated by the accuracy of the calculation results depicted in section 4.

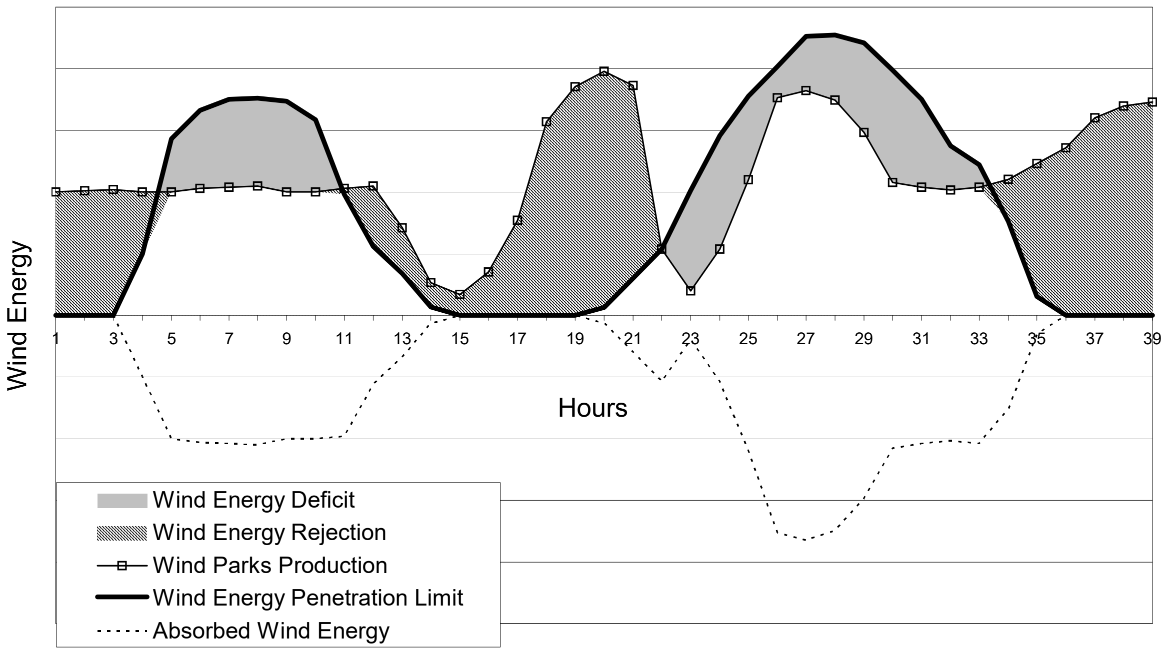

Figure 9: Schematic presentation of absorbed versus wind energy production, in view of the maximum wind energy penetration constraints in autonomous electrical networks

On the other hand, if the instantaneous wind energy production is inferior to the corresponding wind energy absorbance (local network problems included), due to low wind speed values in the wind park area, only the available wind energy yield will be absorbed and no wind energy rejection will take place. In figure (9) one may find a schematic (qualitative) presentation of the produced wind energy disposal in the course of time, in order to clarify the possible operational status of the existing wind parks. In fact one may find:

a. The maximum acceptable wind energy by the local electrical network
b. The expected wind energy production on the basis of the available wind potential
c. The absorbed wind energy by the local electrical network
d. The rejected (by the local network) wind energy

In this context one has the opportunity to compare, for a given period of time, the maximum wind energy approved by the local EGS with the existing wind parks real output. According to the data presented, in several cases ($4 \le t \le 11$ and $22 \le t \le 33$) the wind energy production, due to the low wind speed values, is not able to cover the local system absorbance capability, while in several low electrical load demand periods ($1 \le t \le 3$, $11 \le t \le 22$ and $34 \le t \le 39$) there is significant wind energy surplus, which is finally rejected since it is not absorbed by the local system operator. In the same figure (9) and in the negative y-axis the real wind energy production finally absorbed by the local electrical network is also sited. As it is obvious from the results demonstrated the real wind energy absorbance is quite lower than the maximum permitted one, while in several other cases there is no wind energy production (low wind speed values), despite the local system capability of absorbing it.

Recapitulating, the predicted wind energy absorption "$N_i^r(t)$" by the local EGS for the "i-th" wind park is finally given as:

$$N_i^r(t) = \min\left\{\left(N_{w_i}^*(t) - \delta N_i(t)\right), N_{w_i}(t)\right\} \tag{7}$$

where additional wind energy rejection "δN_i" is possible due to the EGS subsystem problems or technical constraints imposed by the electricity transmission equipment (like voltage and frequency instability, excess reactive power demand, etc.).

The resulting from Eq. (7) value can be directly compared with the existing historical data concerning the wind energy amount forwarded by each wind park to the consumption "$N_i^f(t)$". Thus one should expect that:

$$N_i^f(t) \to N_i^r(t) \qquad \text{with} \quad N_i^f(t) \le N_i^r(t) \quad \text{for} \ \ (i = 1,\ i_{max}) \tag{8}$$

In fact, any discrepancy "$\varepsilon_i(t)$" defined as:

$$\varepsilon_i(t) = N_i^r(t) - N_i^f(t) \tag{9}$$

should be appropriately explained and validated by the local EGS manager. Similar attention should be paid to the term "$\delta N_i(t)$", attributed to additional wind energy rejection due to problems of the network branch, which the wind park "i" is connected with. For the maximization of the wind energy penetration in the local EGS both "$\varepsilon_i(t)$" and "$\delta N_i(t)$" terms should be minimized or zeroed. Generally speaking, the following relation should be validated:

$$\varepsilon_i(t) \to \min \ \wedge \ \delta N_i(t) \to 0 \tag{10}$$

In case that equation (10) is not fulfilled, the proposed method may identify any additional wind energy curtailments, resulting by unexpected technical problems of the overall system.

If the wind energy rejection is necessary to be computed, the next steps of the algorithm will also be executed, i.e.

Step III: Estimate the total wind production of the island "$N_w(t)$"[14]

Step IV: Estimate the wind energy rejection "ΔN_w" for each wind park imposed by the local EGS manager, i.e.:

$$\begin{aligned} &\Delta N_{w_i}(t) = \left(N_{w_i}(t) - N_{w_i}^*(t)\right) + \delta N_i(t) \quad \text{if} \ \ (N_{w_i}(t) \ge N_{w_i}^*(t)) \\ &\text{otherwise} \\ &\Delta N_{w_i}(t) = 0 \end{aligned} \tag{11}$$

4. Application Results-Comparison with Existing Data

4.1. Data Preparation

The above presented algorithm is accordingly applied to estimate the maximum wind energy absorbance for three selected wind parks (corresponding to lines 8-10 of Table II), on hourly basis for the 2000-2002 time period, where detailed official data exist. More precisely, historical data exist for this specific time period concerning:

- The instantaneous electrical load demand "$N_D(t)$", see for example figure (7)
- The technical minima of the local EGS "$N_{min}(t)$", e.g. figure (8)
- *In case that the wind energy rejection is also needed*, one needs either the theoretical wind energy output of each wind park, without any wind energy rejection "$N_{wi}(t)$", or the wind speed values "$V_i(t)$" and ambient density[23] for every wind park of the island and the corresponding power curves of each wind park, in order to calculate the expected wind energy production, in case the wind parks were operating without any barriers by the local EGS manager.

For comparison purposes only, one may use the wind power sold finally to the local network (including wind rejection) by each wind park under operation, i.e. "$N_i^f(t)$".

Thus, one may apply Eqs. (2) to (4) in order to calculate the maximum acceptable absorbance of wind energy by the local EGS and Eq. (5) to estimate the corresponding share of each wind park of the island.

4.2 Wind Energy Absorbance Calculation Results

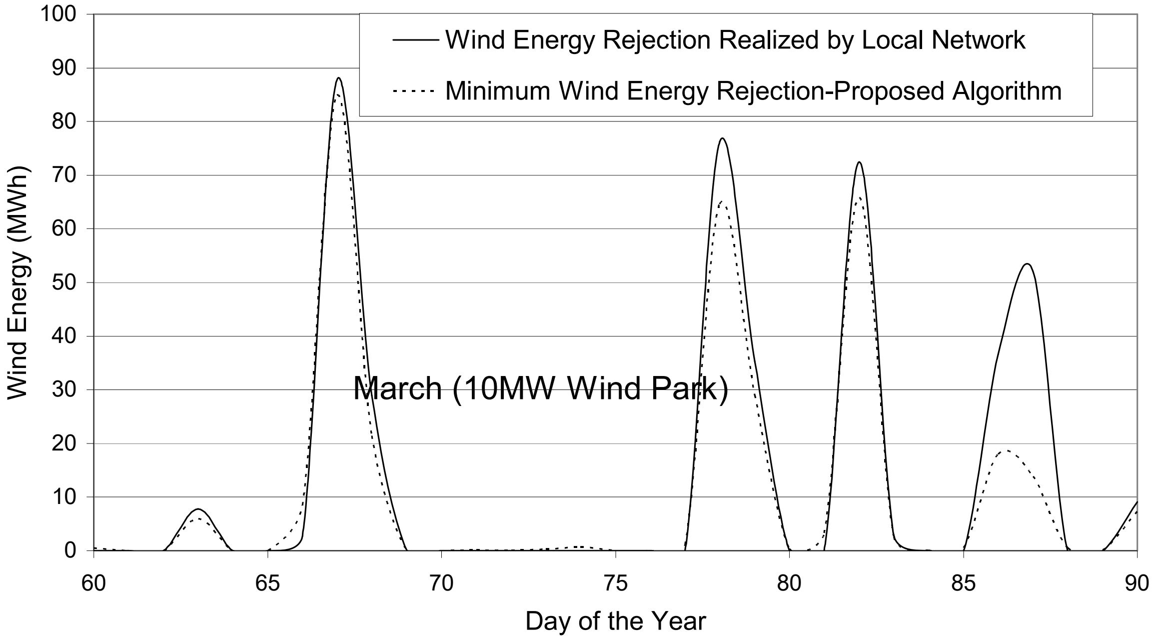

Figure 10: Calculated minimum wind energy rejection vs. rejection values realized by Crete EGS during March for a 10MW wind park

After presenting the information needed, we proceed to use the local EGS information to compute via the "WINDENEREJ" algorithm the resulting wind energy absorption and the corresponding rejection, see also Eqs. (7) and (11). For the calculation of the maximum wind energy penetration we shall use the hourly distribution of the system load demand and the corresponding technical minima for the time period examined. Thus, in figure (10) one has the possibility to compare the calculation results for Achladia (10MW) wind park during March 2001 with data measured by the PPC and the wind park owner. According to the results of figure (10) no remarkable differences are existing between the calculated and the real wind energy rejection realized by the local network. This fact also indicates that the local network manager (PPC) applies the normal wind energy penetration (absorption) procedure, while no serious (instability, black out, etc.) problems appeared in the island electrical network, which may lead to additional wind energy curtailment. Similar conclusions are drawn from the comparison between the calculated and the realized by PPC wind energy rejection for the January of the same year, figure (11). At this point it is worthwhile to mention that usually during January significant wind energy rejection takes place, due to the combination of high wind speeds and low electrical load demand of the island especially during nights.

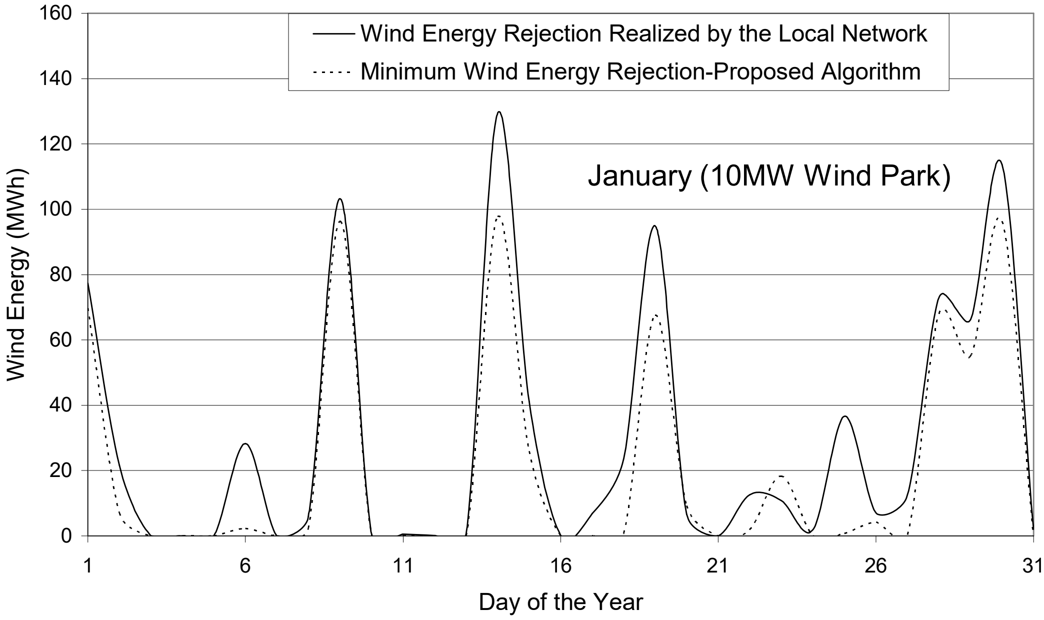

Figure 11: Calculated minimum wind energy rejection vs. rejection values realized by Crete EGS during January for a 10MW wind park

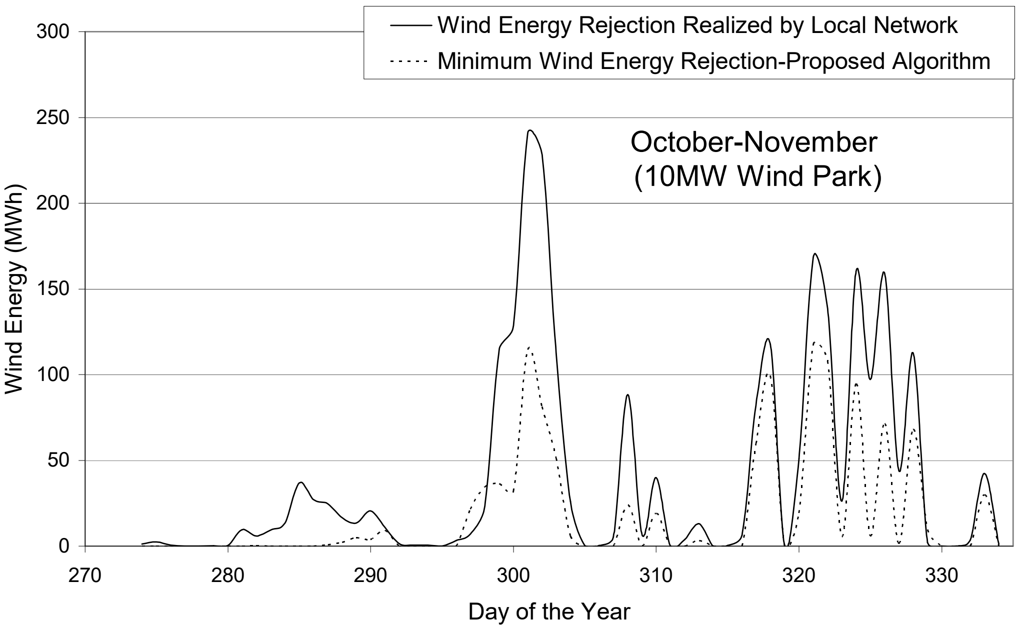

Figure 12: Calculated minimum wind energy rejection vs. rejection values realized by Crete EGS during October-November for a 10MW wind park

On the other hand, important differences between the calculated and the realized wind energy rejection are encountered during the analysis of the same wind park for October/November 2001, figure (12). Taking into consideration that the proposed algorithm is estimating the minimum wind energy curtailment under the normal operation of the local electrical network, the discrepancies appearing in figure (12) may be attributed to the following two reasons:

i. The first one implies a decreased "λ" value (lower than 30% which is normally adopted) utilized by the local electrical system manager. Actually, during November (t>304) the calculated wind energy rejection profile is similar to the grid realized one, but quite lower in absolute terms. In fact, according to numerical analysis of the available data, a value of parameter "λ" equal to 15% or 25% was temporarily used (see also figure (14)). In this case the value of "$\varepsilon_i(t)$" term of Eq. (9) is considerable.
ii. The second type of disagreement can be, more or less, characterized as located wind energy curtailment during specific time intervals (280<t<300) of the examined period. According to the available information, during mid-October of 2001 major operational problems of the local network have taken place leading to two severe black outs of the Crete island network. Unfortunately, these problems have been attributed to the operation of the island wind parks. Consequently, the island electrical network operator did not follow the normal procedure and practically "turned off" the existing wind parks every time he wanted to stabilize the electrical system. In similar cases, one should have known (in advance) the exact "$\delta N_i(t)$" profile for each branch of the network in order to correctly estimate the wind energy rejection time distribution.

Despite the remarkable discrepancy between the calculated and the realized wind energy curtailments during the above examined period, the proposed numerical algorithm may be equally well used in order to locate any serious wind energy absorption problem by the local electrical network. In these cases the normal operation conditions of Eq. (10) are violated and the financial efficiency of the existing wind parks is further decreased[7][8].

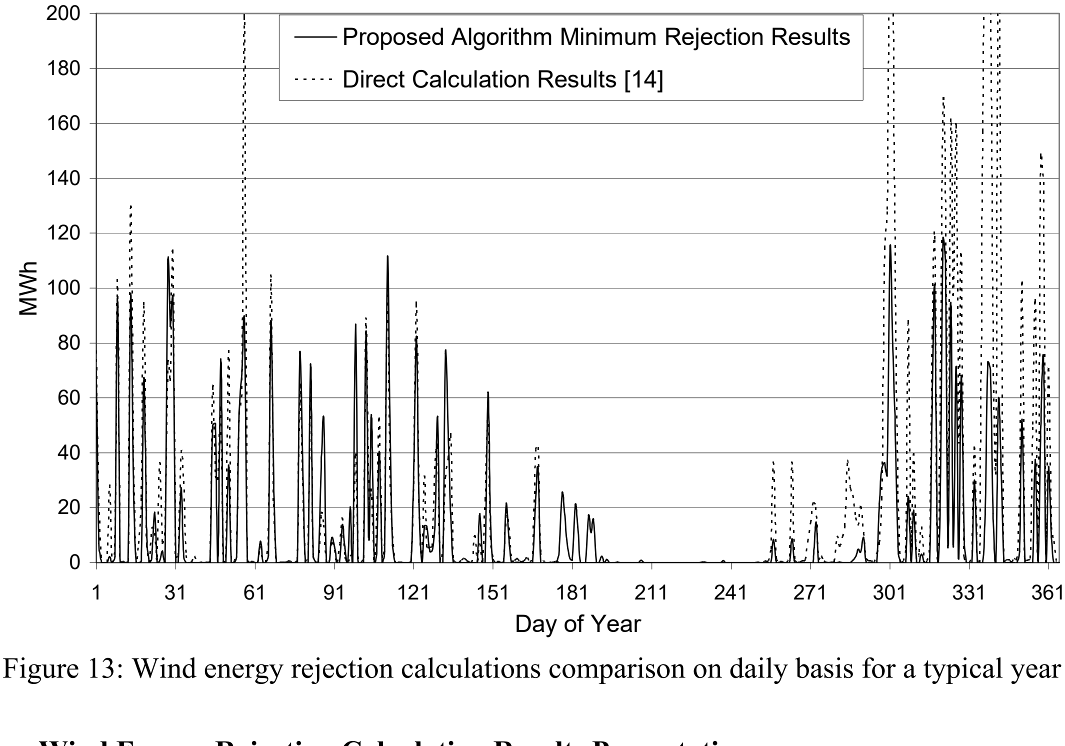

Figure 13: Wind energy rejection calculations comparison on daily basis for a typical year

4.3 Wind Energy Rejection Calculation Results Presentation

In an attempt to estimate the annual income loss of the wind parks owners, the corresponding wind energy rejection distribution is also needed. For this purpose one also needs the instantaneous output of the island wind parks, Eq. (11). For the estimation of the wind energy production, we shall use for every wind park of the island the appropriate analytical power curves. Accordingly, the results of "WINDENEREJ" are going to be compared with the results of the direct calculation method[14] and with the corresponding official data. Thus, applying the proposed algorithm "WINDENEREJ" one can calculate the hourly time-depending distribution of the expected wind energy rejection, according to the barriers set from the local electrical network manager on the basis of the instantaneous electrical demand and the operational characteristics of the EGS thermal power units. As expected, the wind energy rejection is zero during summer and quite important during the low electricity consumption periods. Bear in mind that during the last three months of the year the wind energy rejection may be smaller in size but much more frequent than the one during the first months of the year. Hence, we expect rather greater wind energy rejection during October to December than during January to April.

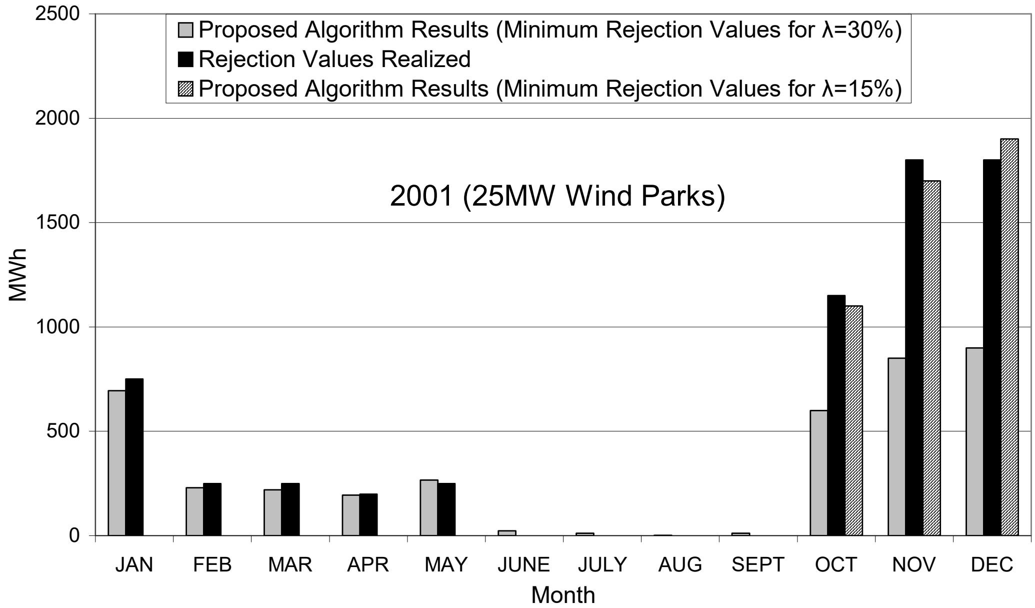

Figure 14: Wind energy rejection calculation results, comparison with official data (2001)

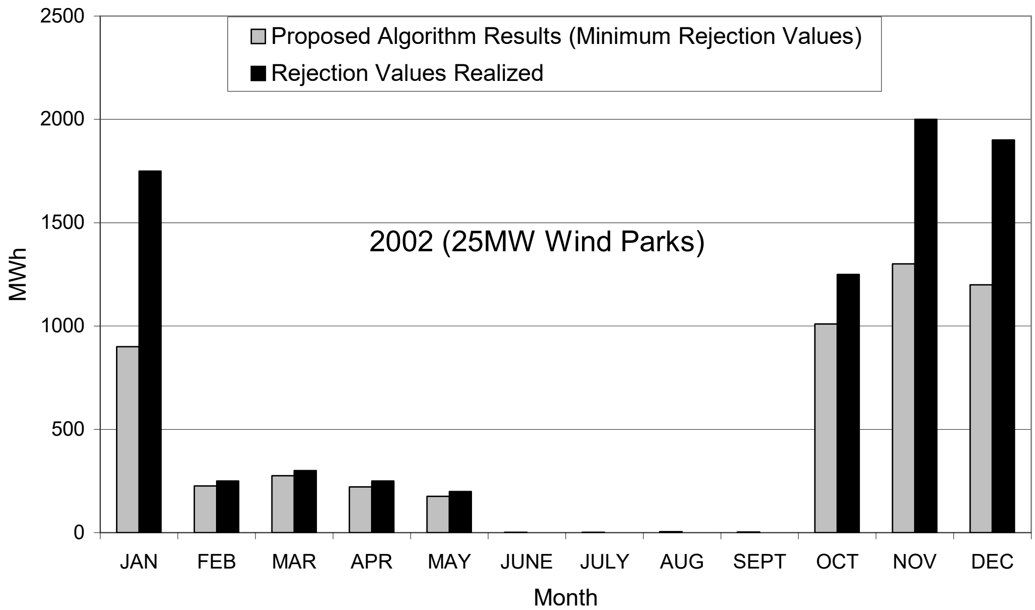

Figure 15: Wind energy rejection calculation results, comparison with official data (2002)

In figure (13) we compare the daily wind energy rejections, resulting by the measurements of the wind park owners[14] and the proposed numerical algorithm for 2001. As a general conclusion, one may state that up to mid-October the present calculation method describes well the official data. After the 11st of October two major black outs of the local EGS took place, attributed to existing wind parks by the local utility, see also figure (12). After that (and for the next two months) much more strict barriers to the local wind energy penetration are imposed, leading to almost double wind energy rejection in comparison with the ones given by the proposed algorithm. After December of 2001, the situation returned to the normal operation.

Finally, for practical reasons, emphasis in put on the monthly wide wind energy rejection, since the available official data are given on monthly basis. Thus, in figures (14) and (15) one can compare the calculation results of the present method with the official data for 2001 and 2002 respectively. From this comparison (figures (10) to (15)) the following conclusions may be drawn:

- There is a fair agreement between the calculations results of the direct method and the "WINDENEREJ" algorithm, indicating that the proposed algorithm can be used to realistically simulate the wind energy rejection in future operation forecasting efforts.
- Both calculations describe fairly well the official data, although in some cases remarkable discrepancies appear.
- During summer (June to September) the calculated wind energy rejection is practically zero, since the local EGS absorbs any available electrical power to meet the high electrical load demand.
- There was a remarkable wind energy rejection increase from 6000MWh during 2001 to 13000MWh during 2002 concerning the wind parks under investigation.
- During the low demand periods of the year (October to May) the monthly wide wind energy absorption is quite limited leading to significant wind energy rejection/loss, i.e. up to 2000MWh per month.

5. Conclusions and Proposals

An integrated numerical algorithm, able to estimate the maximum wind energy penetration in a given autonomous electrical network is presented. The calculation method developed 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. For the prediction of the minimum wind energy rejection one takes into consideration, besides the operational characteristics of the local system, the island wind parks energy production without energy rejection.

The calculation results can be characterized as reliable, since they are based on detailed and long-term data and measurements and describe fairly well the existing official wind energy rejection in the course of time. On top of this, one may use the proposed methodology as an evaluation procedure concerning the wind energy cut outs by the grid operator and contribute on solving any argument between private investors and PPC.

One of the most interesting findings of the present analysis is that the local electrical utility imposes, often, more strict barriers to wind energy penetration than the analytical model calculates, in order to eliminate any grid instability problems, usually attributed to wind parks operation. Thus, a better wind energy production management will be possible if the proposed algorithm is utilized. In any case, the existing (Power Purchase Agreement) PPA is not violated by the local utility, although during 2002 the wind energy rejection attained the upper limit of the agreement. As a result any wind energy investor loses almost 25,000€ per MW of installed power, a quite higher amount than the one of 2000 and 2001.

Recapitulating, it is quite irregular that despite the considerable electricity deficit of most Greek islands, Crete included, a significant wind energy rejection is taking place at the same time. This situation is going to be worsening during the next years, especially if new wind power is installed in the islands. In this context, the application of an integrated electricity management system, considering the steady-state and the dynamic grid analysis, should improve considerably the current electrical network management performance.

A future extension of the present study is the utilization of the proposed algorithm -already well compared with the official data- in order to simulate the expected wind energy rejection in the near future and for different wind power and EGS development scenarios. This new calculation may be used to underline the importance of the problem for the case of significant wind energy penetration to the island electrical networks and contribute on solving the severe problem of the continuously increasing electricity demand on the basis of minimum carbon dioxide production power stations.

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ENERGY BASED SIZING OF A WIND-HYDRO SOLUTION FOR MAXIMUM WIND ENERGY PENETRATION IN LESBOS ISLAND

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Abstract

The island of Lesbos as all the Aegean Archipelago islands lacks any indigenous solid fuel sources; hence it depends on imports to cover the needs for electricity production, transport and heating. In this context, the existing thermal power station consumes significant oil-fuel quantities emitting also remarkable air pollutants and contributing to the environment degradation. On the other hand, the renewable energy potential of the island is quite significant but its contribution to energy supply remains restricted. As a result, remarkable wind energy amounts should be rejected leading to severe financial loss of the wind park owners and discouraging any additional investment in new wind energy applications. In order to ameliorate the current situation and to maximize the wind energy penetration in the island energy balance an integrated wind-powered pumped hydro storage (wind-hydro) solution is proposed. All numerical calculations are based on real data, like long-term wind speed measurements, electrical load distribution and operational characteristics of the local system components. During the sizing procedure one defines the size and the number of the wind converters, the rated power and the operational characteristics of water pumps and hydro turbines as well as the capacity of the water reservoirs required. For this purpose a well established methodology by the authors is applied, properly modified to utilize either statistically weighed (probability density) distributions or detailed time-series data. According to the results obtained, using the proposed wind-hydro solution one may maximize the wind energy participation in the island electrical balance, contributing also in stable and safe energy supply, in reducing the dependency from imported oil, in minimizing the environmental impacts, in improving the regional development without excessive initial capital requirements.

Keywords: Pumped-Hydro Storage; Wind Energy Surplus; Probability Analysis; Hybrid System

1. Introduction

The island of Lesbos is located in the North-Eastern part of the Aegean Sea and it is the third in size island of Greece with an area of 2,154 km^2. Mytilene is the capital of the island as well as the administrative centre of the North Aegean Prefecture. According to the 2001 census, the total population of the island is around 108,000 inhabitants presenting an increase of 4% since 1991. The climate of Lesbos is a mild, Mediterranean one, with sunlight all the year round and excellent wind potential, figure (1). The local economy is based on the rural production and specifically on the cultivation of olive trees, stock-farm and fishery, while a large part of the habitants is professionally involved with tourism.

The island, as all of the Aegean Archipelago islands, lacks any indigenous solid fuel sources; hence it depends on imports to cover the needs for electricity production, transport and heating. In this context, the existing autonomous (thermal) power station (APS), located at the east part of the island at the borders of Mytilene (figure (2)), consumes[1] significant oil-fuel quantities (approx. 60,000tn/year) emitting also remarkable air pollutants and contributing to the environment degradation[2]. In fact, the existing APS comprises eight quite old internal combustion engines which use mainly heavy-oil (mazut) and one gas turbine consuming diesel-oil. The official rated power of the existing units is slightly above 80MW, while the real maximum power available is almost 60MW. The corresponding

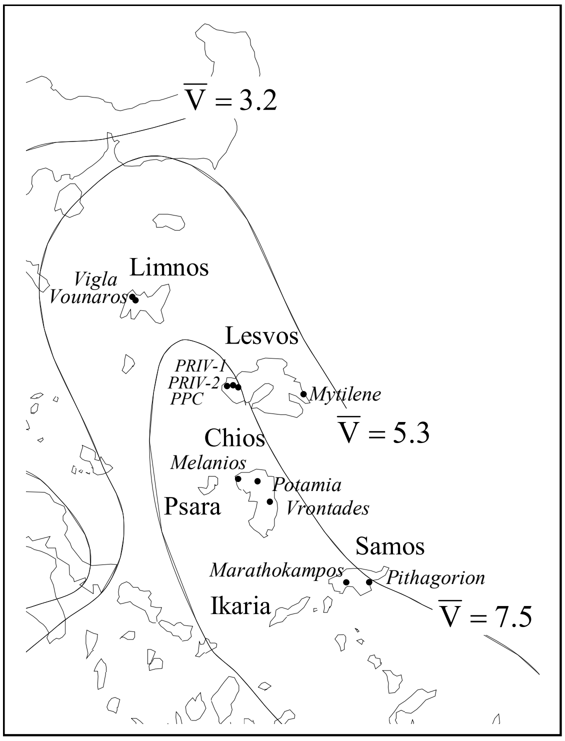

Figure 1: The wind potential in N. Aegean

specific fuel consumption (SFC) of the existing internal combustion engines varies between 0.2 and 0.25kg/kWh, while the local gas turbine presents an average SFC value of 0.35kg/kWh.

Figure 2: The power stations at Lesbos island

On the other hand, the total installed wind power of the island is almost 12MW, based on three medium-sized wind parks located in the west part of the island (figures (1) and (2)) and one small wind park located outside Mytilene. More specifically, in the east part of the island one may find the small wind park of Mytilene municipality. This wind park was created in 1994 and started its full operation in 1995, being one of the first wind parks in Greece belonging to local municipalities. In 1997 its rated power was increased from 600kW to 825kW. According to the official data[3] for the period 1995-2004 the corresponding long-term average value of the wind park capacity factor (CF) was slightly above 12.5%. During 2003, major failures of the two HMZ-300 wind turbines were encountered with the second wind turbine being completely destroyed. Since then only a Micon-225kW wind turbine is still in operation.

In 1999, nine V-27 wind turbines were installed by the Greek PPC at the west part of the Lesbos island, constituting a wind park of 2025kW rated power. These wind turbines were operating for two years with very good energy production performance[4]. However, during 2002 major problems appeared, leading one of the machines to complete destruction, while three other turbines presented serious malfunctions. These problems were solved in 2004, thus since then the wind park has been operating with only eight (8) wind turbines (rated power of 1800kW). Recently, two private wind parks (4800kW and 4200kW) based on fifteen E-40 (600kW) wind turbines started their operation in the west part of the island. According to the official data[3], the two new-erected private wind parks show up to now excellent performance, since their annual average CF values exceed 35%.

Recapitulating, the "in operation" wind power of the island is 11025kW, located at the west part of the island. It is worth mentioning that the west part of the island, which concentrates many locations of high wind potential, is an uncultivated part, something that contributes to the creation of favourable circumstances for the installation of wind turbines.

2. Problem Definition

Taking into account the continuous electricity consumption increase (figure (3)) along with the problematic condition of the local electrical grid and the insufficient power capacity of the local APS, several black outs have been encountered on annual basis, especially during the summer. Figure (4) illustrates the total electricity production time variation "$N_L(t)$" for 2007, where one may detect at least eight (8) major black outs of the system. Besides, the current electrification solution is related with a high operational cost, which for the case of Lesbos exceeds 0.25€/kWh, presenting also a continuous increase[5].

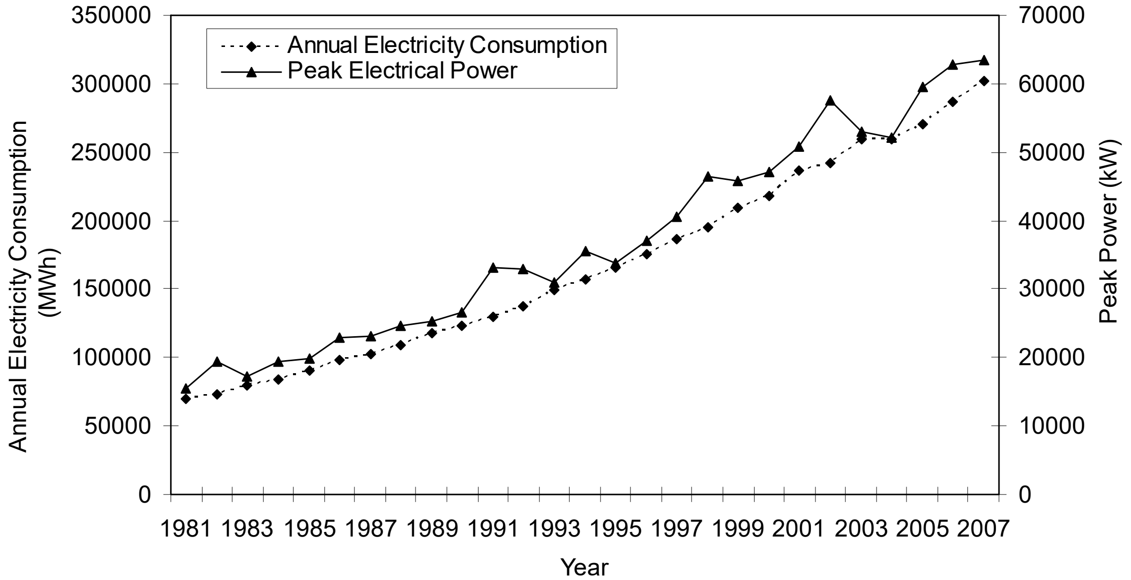

Figure 3: Time evolution of the Lesbos island electricity system main parameters

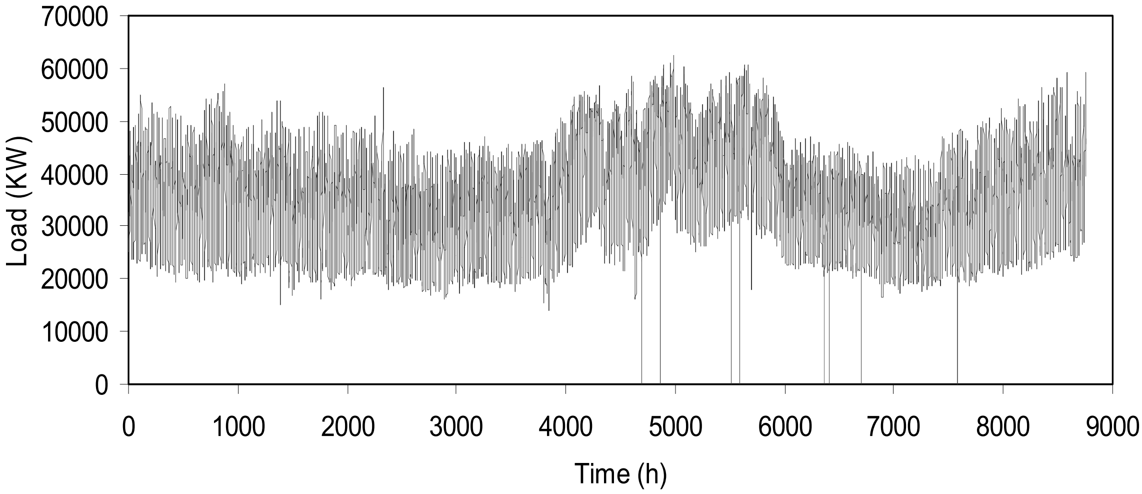

Figure 4: Profile of electricity production for the island of Lesbos, 2007

On top of these, the operation of the local thermal power station is assumed responsible for several -dangerous for the human health- air pollutants, while it needs remarkable quantities of sea water for the engine cooling process. In this context, the local population is against the operation of the APS, being also negative in any proposal for relocation of the APS to another place of the island. In fact, despite the existence of three possible new candidate areas the local population and the municipality councils strongly oppose to the installation of the new plant on the basis of environmental impacts and its influence on the mild touristic development of the area.

On the other hand, the wind energy potential of the island is quite significant since in many regions the long-term average wind speed approaches 9m/s. Unfortunately, up to now the existing wind parks contribution to the energy supply remains restricted, since the contribution of almost 12MW of wind parks of the island in the annual electricity consumption hardly approaches 10%[5]. This unfavorable situation is mainly due to the inability of the local electrical system to absorb the stochastic wind energy production, especially during low electricity demand periods[6]. As a result, remarkable wind energy amounts being rejected lead to severe financial losses of the wind park owners[7] and discourage any additional investment in new wind energy applications.

More specifically, one may estimate[8] the instantaneous maximum wind power penetration in the local grid "N_w*" as follows:

$$\text{If} \quad N_L(t) \le N_{d_{min}}(t) \quad \text{then} \quad N_w^* = 0 \tag{1}$$

where "N_{dmin}" is the technical minimum of the local system. In this case there is no wind energy absorption by the local network; hence all the wind energy production is rejected.

$$\begin{aligned} &\text{If} \quad N_{d\,min}(t) \le N_L(t) \le (1+\lambda)\cdot N_{d\,min}(t) \\ &\quad \text{then} \quad N_w^* = N_L(t) - N_{d\,min}(t) \end{aligned} \tag{2}$$

where "λ" is the wind power upper participation limit of the system. Finally,

$$\begin{aligned} &\text{If} \quad N_L(t) \ge (1+\lambda)\cdot N_{d\,min}(t) \\ &\quad \text{then} \quad N_w^* \le \min\{[\lambda \cdot N_L(t)],[N_L(t) - N_{d\,min}(t)]\} \end{aligned} \tag{3}$$

In this last case the wind energy penetration is bounded by the upper wind power participation limit "λ" and the instantaneous load demand of the system, while the technical minima of the existing thermal units are also respected[6][8].

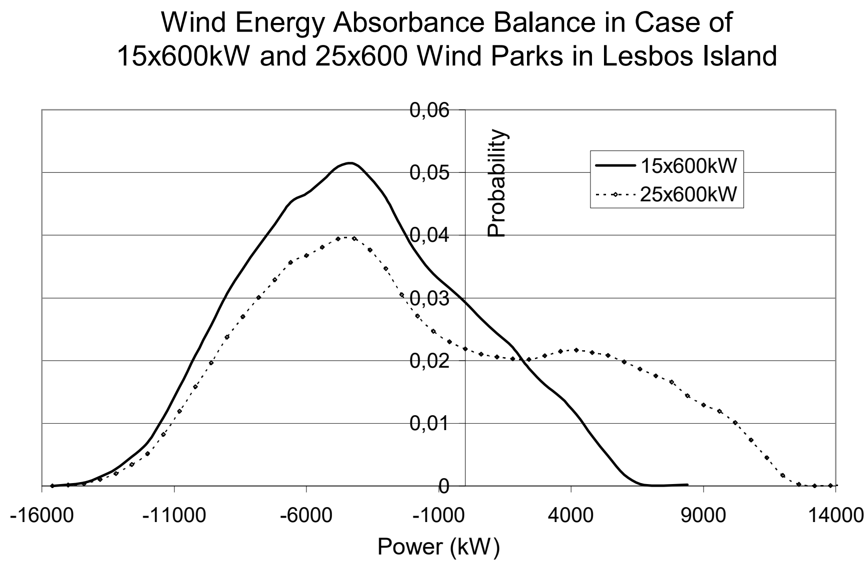

Figure 5: Wind energy balance for Lesbos island

Applying the proposed analysis on the load time-series of the Lesbos electrical system[9], one may estimate the resulting maximum wind energy penetration time-series in the local grid as well as the corresponding wind power curtailments. Using the proposed by the authors model one may also estimate the corresponding maximum wind energy penetration probability profile "p(N_w^*)", see for example figure (5), describing the expected absorbance-rejection of the wind energy production by 15x600kW wind turbines operating in Lesbos along with their probability profile. Actually, the negative values of the horizontal axis describe the situations where the wind energy production is less than the one accepted by the local grid. On the other side, the positive x-axis values describe the cases that there is wind energy surplus, i.e. the wind energy production cannot be completely absorbed by the local electrical system, hence the corresponding wind energy is rejected.

3. Proposed Solution

In order to ameliorate the current situation and to maximize the wind energy penetration in the Lesbos island energy balance, an integrated wind-powered pumped hydro storage (wind-hydro) solution is proposed, figure (6). This solution is based[10][11] on:

- a number of wind turbines spread over the island
- a water pump station able to absorb the wind power surplus of the system
- a small hydroelectric power plant able to contribute on meeting the local grid maximum demand and
- two water reservoir groups (an upper and a lower one) working in closed circuit along with the corresponding pipelines.

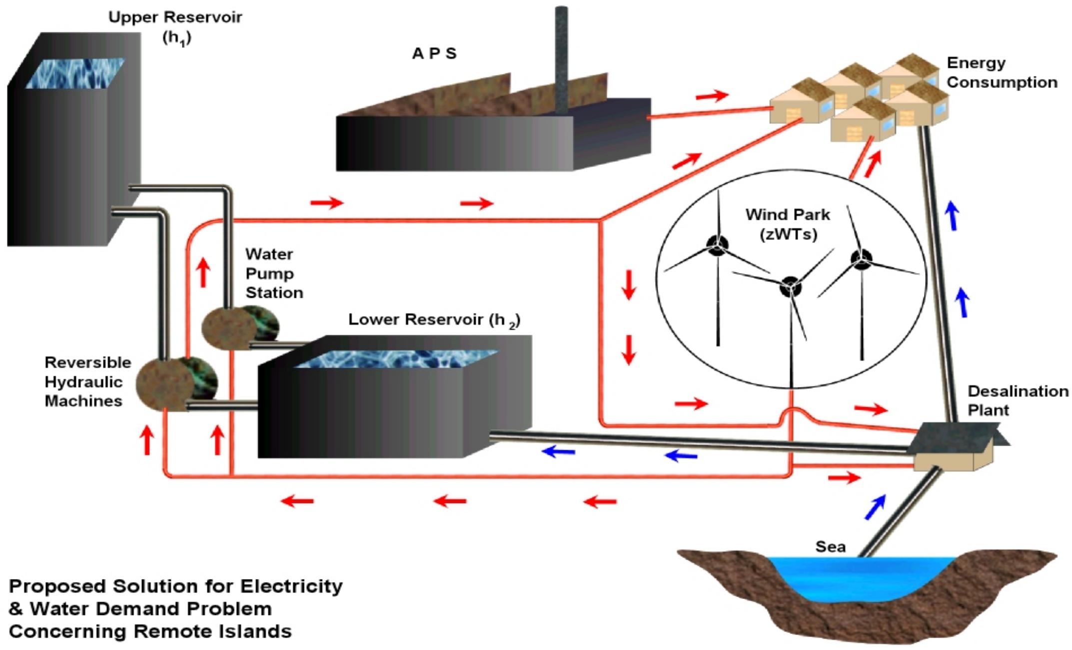

Figure 6: Proposed wind-hydro solution

During the long-lasting operation of the proposed energy production plant, the following situations may appear:

a. The wind park feeds the local electrical network. Any energy surplus is forwarded to an appropriate water pumping station in order to transfer water from the low to the high water reservoirs.
b. The wind energy is not absorbed by the local electrical system, while the energy surplus is bigger than the water pumping capacity of the installation or the upper reservoir is full. In this case the energy surplus is transferred to low priority loads.
c. The wind energy production is lower than the electricity demand. In this case the energy reserves of the upper water reservoir are used via the existing small hydro turbines[12] of appropriate size in order to cover the load demand of the system.

4. Sizing Methodology

The problem to be solved consists of a specific electrical micro-grid (i.e. Lesbos island) where one or more wind parks operate without having the opportunity to sell their entire energy production to the local grid manager. The idea examined is to find the appropriate water-pumping station which should have the capability to store the wind energy surplus to an appropriate reservoir situated at a certain elevation. This hydraulic energy amount is accordingly forwarded to the consumption via a small hydro power station during peak load demand periods to cover the increased energy consumption[10][11][12].

The optimum sizing solution (given the characteristics of the existing wind parks) for maximum wind energy penetration includes -at this preliminary stage- the estimation of:

- The rated power "N_p" and operational range of the water pumps
- The size "N_H" and the operational characteristics of the small hydro power station
- The energy storage capacity "E_s" of the water reservoirs
- The energy surplus "Nr_i" that may be absorbed by the proposed water pumping installation

All numerical calculations will be based on real data, like long-term wind speed measurements (e.g. wind speed probability density profiles), electrical load distribution and operational characteristics of the local electrical system components. During the entire sizing procedure one should define the size and the number of the wind converters, the rated power and the operational characteristics of water pumps and hydro turbines as well as the capacity of the water reservoirs required. For this purpose a well established methodology by the authors is applied[6][7][8][13], properly modified to utilize statistically weighed (probability density) distributions. In the following, the basic principles of predicting the operational characteristics of the hybrid station components are briefly presented.

The water pumping system is chosen in order to transfer water from the lower to the higher reservoirs, absorbing the wind energy surplus "Nr_i" ("p_i" is the corresponding probability) of the wind parks of the system, where "i" represents the annual wind energy surplus values. If "N_p" is the nominal power of the water pumping station, then the energy absorbed "E_p" is given by the following relation:

$$E_p = \left[\sum_k p_k \cdot Nr_k + \sum_m p_m \cdot N_p \right] \cdot 8760 \quad (4)$$

where the first term of the RHS of equation (4) expresses the cases that the wind energy surplus is less than the nominal power of the water pumping station, while the second term describes the cases that the the wind energy surplus is greater or equal to "N_p".

Accordingly, the energy finally stored "E_s" in the water reservoir is expressed as:

$$E_s = \eta_s \cdot E_p \quad (5)$$

with "η_s" being the energy storage transformation coefficient, including[10] water pump loss, friction loss in the penstocks etc.

Finally, the hydro turbine(s) rated power "N_H" depends on the available energy[11][12], on the upper reservoir and on the hours per day "h_o" that the small hydro power plant will provide electricity to the local grid (e.g. peak load demand hours, see also figure (4)). Actually, the following relation should be validated:

$$N_H = \frac{\eta_h \cdot \left(E_s / 365 \right)}{h_o} \quad (6)$$

where "η_h" is the efficiency of the electricity production branch.

5. Application Results

The above analysis is accordingly applied to the micro-grid of Lesbos, taking into account that 15 wind turbines E-40 (rated power 600kW) operate on the island. In figure (5) one may find the corresponding energy absorbance balance. According to the calculation results there is a remarkable possibility (17.8%) to obtain wind energy surplus, since wind rejection values up to 6000kW have been encountered.

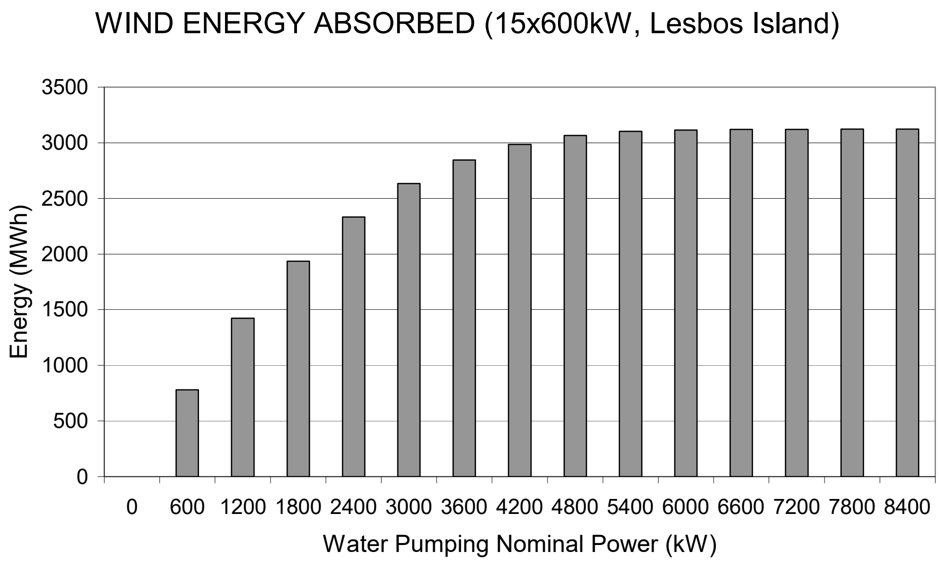

Figure 7: Absorbed wind energy, Lesbos island

Using equation (4) one may find in figure (7) the wind energy absorbed by the corresponding water pumping station as a function of the water pumps nominal power. As we can see from this figure the total wind energy surplus of the 9MW wind park is approximately 3.2GWh (i.e. 11.3% of the wind park annual production), representing a net financial loss of almost 300,000€ or 4% of the initial capital invested for the specific wind park installation. Additionally, one may also conclude that the absorbance of the wind energy surplus is gradually decelerated, see figure (8).

Hence, by setting a limit "ξ" (e.g. ξ=300MWh) concerning the accepted wind energy absorbance increase due to the corresponding water pumping nominal power increase (e.g. from 2400kW to 3000kW) one may estimate the maximum water pumping station size.

Accordingly, the corresponding energy storage capacity results from the maximum daily energy amount to be stored and the efficiency of the entire energy storage procedure. For the case of N_p=3MW the corresponding two water reservoirs storage volume (at 50m elevation difference) is almost 400,000m^3, or (5500m^2x70m).

Finally, the nominal power of the system hydro turbines varies between 1.2MW and 7.2MW, depending on the energy providing strategy of the proposed wind-hydro installation. More specifically, by selecting hydro turbines with relatively low nominal power it is almost sure that these hydro turbines will operate most of the days of the year covering peak load demand, however in some cases the upper water reservoir may remain full, limiting the next day wind energy absorbance capacity of the proposed system. On the other hand, in case that the high hydro power nominal power value is selected, the hydro power station will contribute on absorbing all the wind energy stored by the water pumping system, however the initial cost of the small hydro power installation may be too high[12]. In this context, the size of the hydro power station should be the outcome of a complete cost-benefit analysis. Recapitulating, the maximum wind energy to be forwarded to the consumption by the proposed wind-hydro solution is approximately 1.5GWh, representing 48.1% of the entire wind energy surplus of the local wind parks.

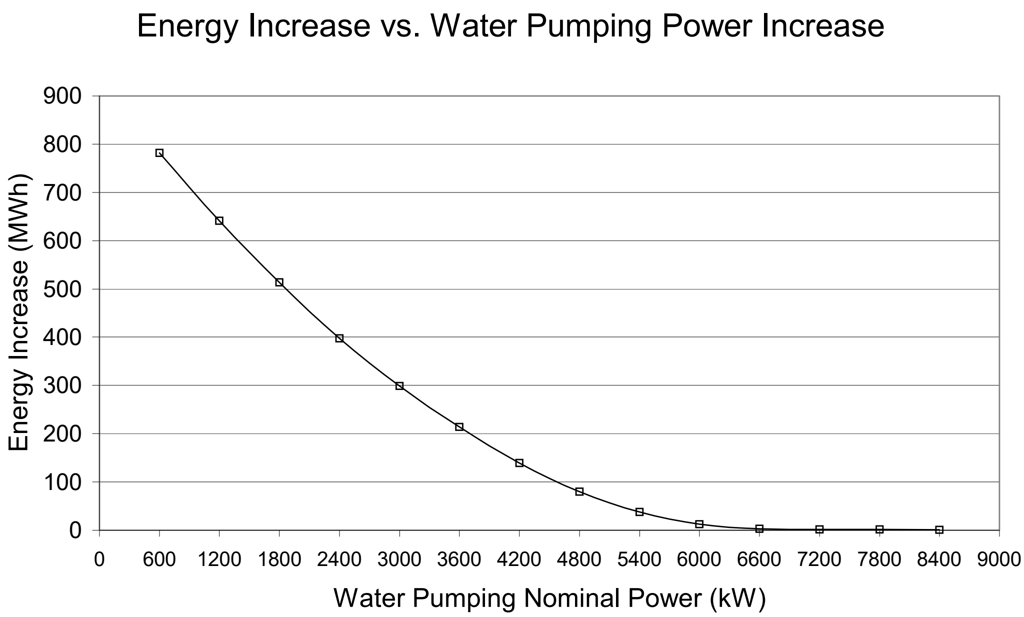

Figure 8: Wind energy absorbance rate

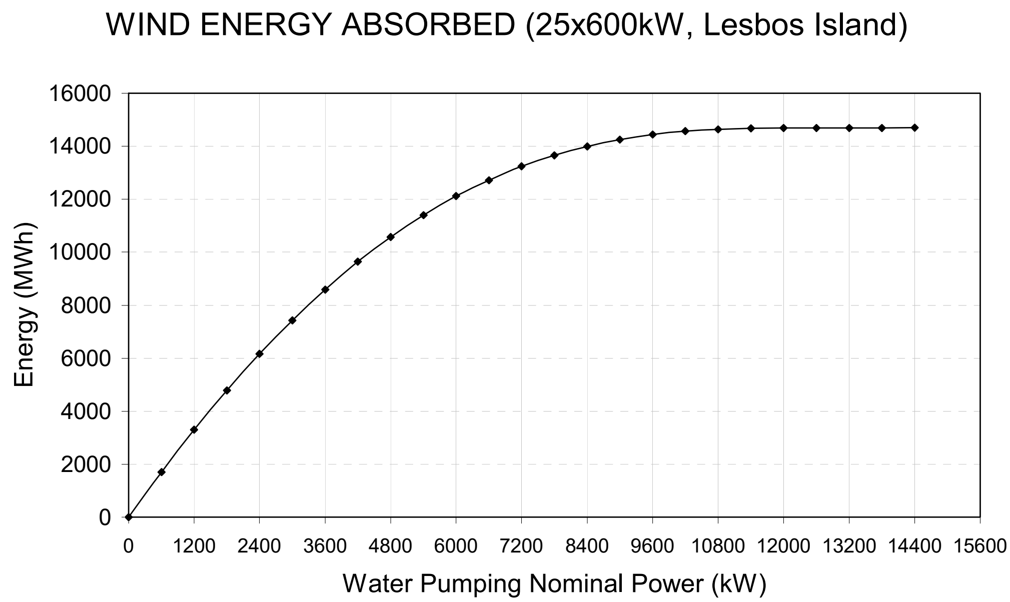

Figure 9: Absorbed wind energy, Lesbos island

In order to underline the possibility of increased wind-hydro penetration in the Lesbos island electrical network, one may investigate the theoretical case of adding another 10 E-40 wind converters in the existing wind parks, hence the total wind power of the island micro-grid will be 15MW. In this case the wind energy surplus is almost 14.9GWh, representing 30.2% of the total wind energy production, see also figure (5). As it is obvious for this scenario (25x600kW) the financial loss of the wind park owners is much higher than the 15x600kW case, i.e. 1,340,000€ corresponding to 11.1% of the initial capital invested.

Applying the same analysis as in the previous case, one may find in figure (9) the wind energy absorbance profile as a function of the water pumping nominal power. It is important to mention that by using a 3MW water pumping station one has the possibility to absorb almost 7.5GWh in comparison with the 2.6GWh of the initial (15x600kW) case, strongly supporting the financial attractiveness of such an installation. In this context, one may state that by using a 6MW water pumping station, 82.5% of the wind energy surplus can be finally absorbed, thus remarkably improving the wind energy contribution on the solution of the energy problem of Lesbos island.

6. Conclusions

An integrated energy based analysis concerning the optimum sizing of a wind-hydro installation for medium size remote islands is presented. The best size of the main components of the proposed hybrid station may be determined, using a systematic probabilistic analysis. All the numerical calculations are based on real data, like wind speed measurements, electrical load profile, operational characteristics of the components etc.

According to the results obtained, using the proposed wind-hydro solution one may maximize the wind energy participation in the island electrical balance. Benefits also arising include the stable and safe energy supply, the reduction of the imported oil dependency, the minimization of environmental impacts and the improvement of the regional development without excessive initial capital requirements.

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PART TWO

ENERGY STORAGE

INTEGRATED ELECTRIFICATION SOLUTION FOR AUTONOMOUS ELECTRICAL NETWORKS ON THE BASIS OF RES AND ENERGY STORAGE CONFIGURATIONS

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Abstract

Most medium and small islands of the Aegean Archipelagos face serious infrastructure problems, strongly related with the limited electrical energy available at extremely high cost. On the other hand, the area is characterized by very high wind speeds and abundant solar energy, thus the exploitation of the available renewable energy sources (RES) may significantly contribute to the fulfillment of the local societies energy demand at minimum environmental and macroeconomic cost. However, the stochastic availability of wind energy and the variable availability of solar energy, the daily and seasonal electricity demand fluctuations, as well as the limited local electrical network capacity result in serious restrictions concerning the maximum renewable power penetration. In this context, the present paper investigates the possibility of creating a combined electricity generation facility based on the exploitation of wind or/and solar potential of an area as well as on the utilization of an appropriate energy storage configuration in order to replace the existing thermal power stations with rational investment requirements. For this purpose, the major parameters of the proposed integrated configuration are firstly calculated and its financial viability is accordingly analyzed. One of the main targets of the proposed solution is to maximize the RES exploitation of the area at a minimum electricity generation cost, while special emphasis is given in order to select the most cost-efficient energy storage device available. According to the results obtained the proposed solution is not only financially attractive but also improves the quality of the electricity offered to the local communities, substituting the expensive and heavily polluting existing thermal power stations.

Keywords: Renewable Energy Sources; Energy Storage; Autonomous Electrical Network; Wind Energy; Photovoltaic Generator; Electricity Production Cost; Island

1. Introduction

The Aegean Archipelagos is a remote Hellenic area at the east of mainland, including several hundreds of scattered islands of various sizes, figure (1). For administrative purposes these islands are divided in five groups, i.e. the islands belonging to Lesvos, Chios, Samos, Cyclades and Dodecanese prefectures. One of the major problems of the area is the insufficient infrastructure, which is strongly related to the limited electrical energy available and the extremely high electricity generation cost of most islands, see for example figure (2). In fact, the electricity demand in the Aegean Archipelagos islands has up to now been covered[1] by the existing (thirty) Autonomous Power Stations (APS), based on internal combustion engines and gas turbines, which belong to the former Greek Public Power Corporation (PPC). The existing APS total installed capacity is approximately equal to 800 MW, while the corresponding electricity generation during 2005 is almost 2200GWh[2]. Unfortunately there is a significant variation (figure (3)) of the electricity consumption throughout the year since in most islands the electricity demand during summer season (June-August) represents more than 40% of the total annual consumption, while the corresponding peak load demand is usually two or even three times greater than the mean annual electricity demand[3]. On the other side, the electricity production cost varies between 0.12€/kWh for the big islands and 0.6€/kWh for the small remote Greek islands (figure (2)), presenting a mean annual increase rate of 5%, during the last fifteen years. Note that the corresponding electricity price for domestic users in all Greece is slightly above 80€/MWh, hence the operation of the Aegean Archipelago APS leads to severe financial loss, for the Greek PPC,

Kaldellis J.K., 2008, "Integrated Electrification Solution for Autonomous Electrical Networks on the Basis of RES and Energy Storage Configurations", Energy Conversion and Management Journal, Vol.49(12), pp.3708-3720.

approaching the 200,000,000€/year. Finally, in almost all these islands there is an extremely urgent need for additional power on annual basis, since the existing APS can hardly meet the corresponding peak load demand[3]. On top of this, the vast majority of the existing thermal power units is very old and should be replaced in the next few years.

Figure 1: Aegean Archipelagos complex of islands

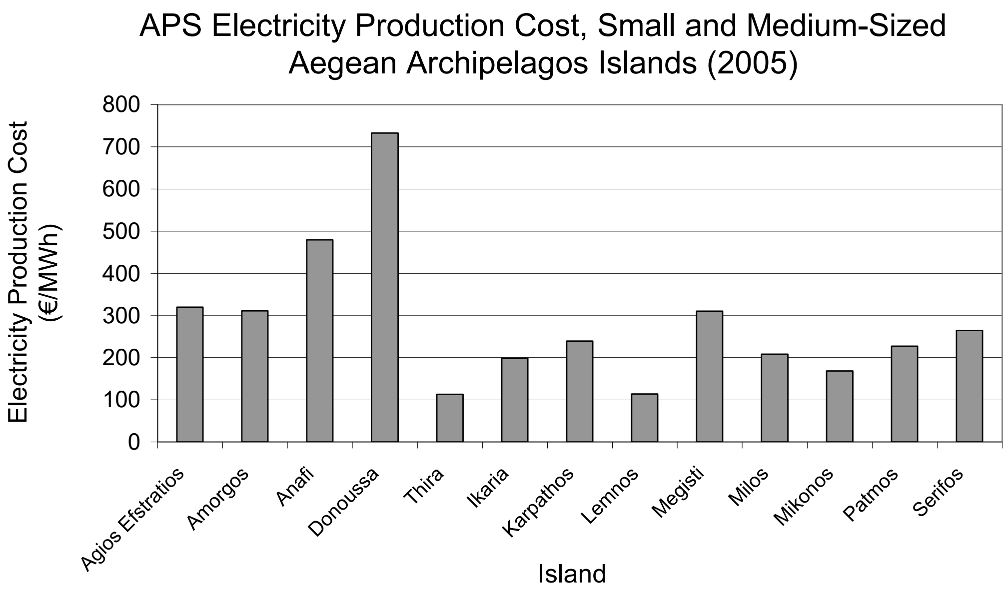

Figure 2: Electricity production cost of selected Greek APS (PPC, 2005)

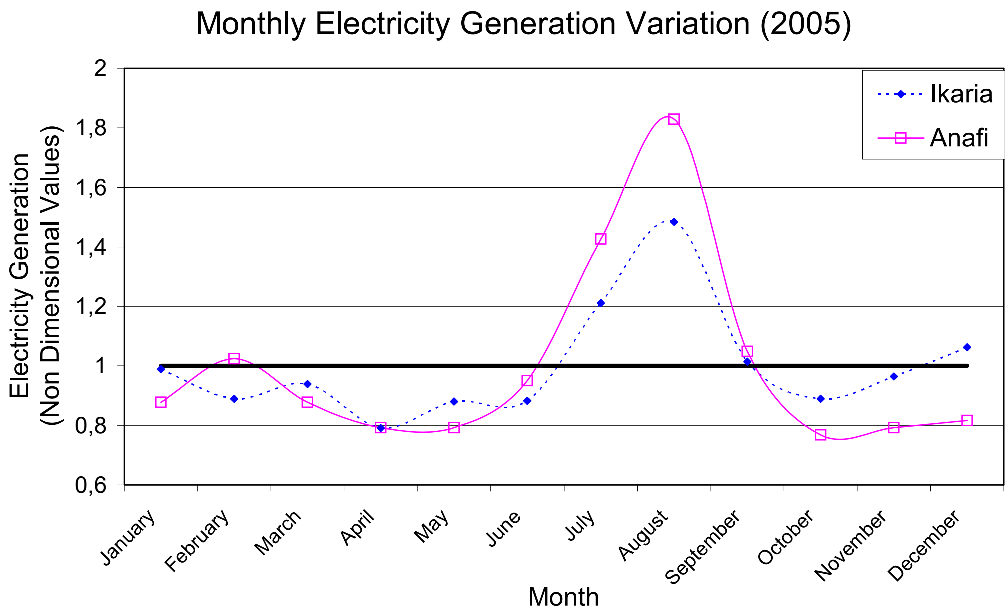

Figure 3: Electricity generation annual variation for typical island cases.

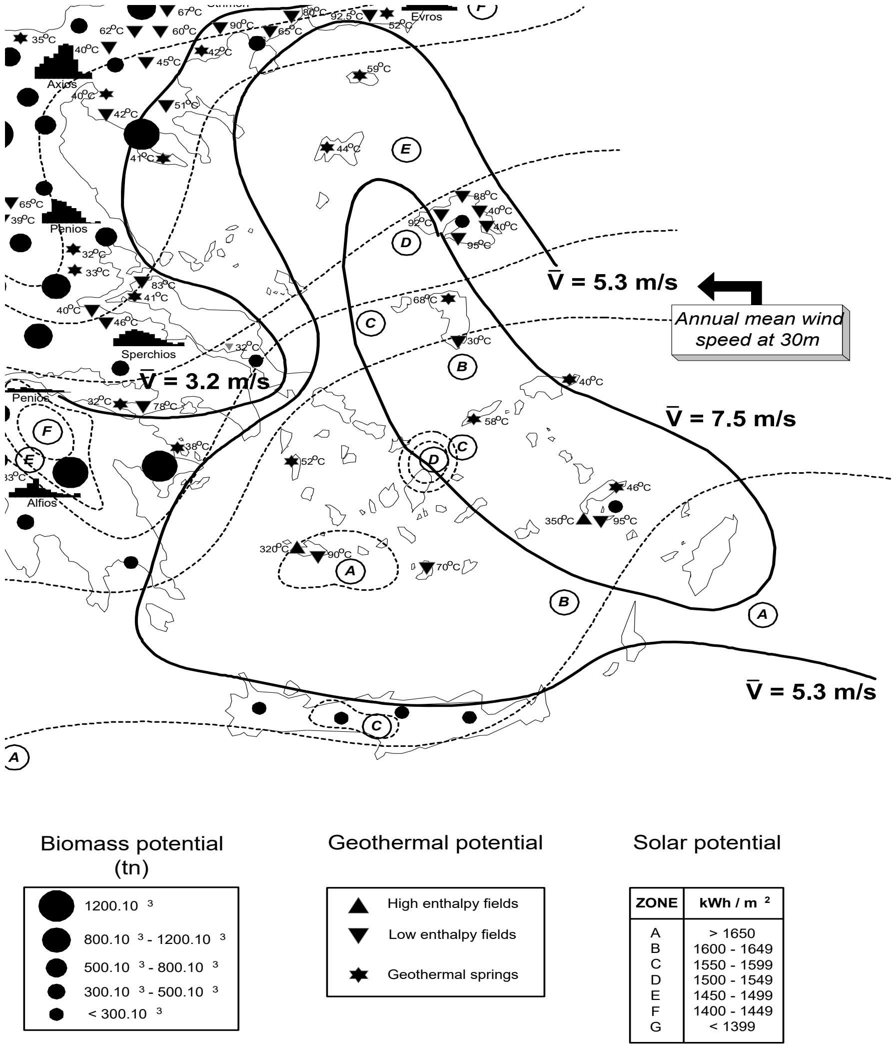

Figure 4: RES potential in the Aegean Archipelagos region

At this point it is worthwhile mentioning that the area is characterized by very high wind speeds and abundant solar energy, figure (4). Thus the exploitation of the available renewable energy sources (RES) potential may significantly contribute to the fulfillment of the local societies energy demand at minimum environmental and macroeconomic cost[4]. However, the stochastic availability of wind energy and the variable availability of solar energy, the daily and seasonal electricity demand fluctuations, as well as the limited local electrical network capacity result in serious restrictions concerning the maximum renewable power penetration, in order to maintain the local grid stability[5]. For example, until recently, the local electricity utility (PPC) posed a 30% wind power penetration barrier to guarantee the local grid stability. However, even this strict limit has theoretical value, since economic viability criteria[6] deteriorate the maximum wind energy contribution to single digit numbers (i.e. ≤10%).

According to previous research[7][8][9][10] the prospect of creating a combined RES based energy production station with an appropriate energy storage system (ESS) is the only available -for those regions- solution, provided that the central target is to maximize the renewable energy sources penetration in small and medium-sized islands, under the precondition of rational electricity production cost. Although the first installation cost of a combined RES-ESS power station is relatively higher than the corresponding cost of an equivalent thermal power station, the excellent RES potential and the extremely high production cost of local APS provide the proposed solution with an undoubted competition advantage even in terms of economic efficiency. On top of this, an energy storage system, when sized appropriately[11][12], not only can match a highly variable RES based energy production to a generally variable and hardly predictable system demand, but also improves the system reliability and contributes to the energy production cost reduction. Additionally, by reducing the operation hours of the existing thermal power units their service life is prolonged, therefore the need for extra investments concerning the installation of new internal combustion engines is postponed.

In this context, the present paper investigates the possibility of creating a combined electricity generation facility that is based on the exploitation of wind or/and solar potential of an area as well as on the utilization of an appropriate energy storage configuration in order to replace the existing thermal power stations with rational investment requirements. More precisely, one should first calculate the major parameters of the proposed integrated solution and accordingly analyze the financial viability of the resulting solution. As already mentioned one of the main targets of the proposed solution is to maximize the RES exploitation of the area at a minimum electricity generation cost, while special emphasis is given to improve the local network reliability. Besides, the most cost-efficient energy storage configuration is selected[12] on the basis of the developed minimum cost methodology, after analyzing various available ESS. Finally, the complete methodology is applied to representative island (autonomous electrical network) cases with very enlightening results.

2. Proposed Solution

The proposed by the authors[7][9] integrated solution comprises a RES-based power station (usually a wind park or a photovoltaic generator) able to meet the electricity demand as well as an appropriate energy storage facility that guarantees the local community energy autonomy for a desired time period. Besides, the existing thermal power station may be also used either as a back up solution or to cover unexpected high load demand. More precisely the proposed configuration (figure (5)) includes:

a. One or more power stations based on the exploitation of the available wind or solar potential. The most attractive solutions are either wind parks for medium and large-sized islands or photovoltaic generators for small or very small islands. The rated power of the proposed installation is "N_{RES}".
b. A number of energy storage devices (e.g. lead-acid or Na-S batteries, a group of water reservoirs, etc.) combined with their corresponding energy production equipment (e.g. inverters, small hydro-turbines, etc.). The energy storage capacity of the installation is equal to "E_{ss}" and the input and output rated power values are "N_{in}" and "N_{ss}", respectively. The selected ESS should be able to

cover the local network electricity requirements for "d_o" typical hours without the contribution of any other electricity generation device.

c. The existing thermal power units of the already operating APS, with rated power equal to "N_o", may contribute on meeting the local system electricity consumption under specific circumstances by "δE". The main target of the proposed solution is to minimize the contribution of the local APS to the local system electricity consumption (δE→0), as well as to use by priority the most cost-effective thermal power units.

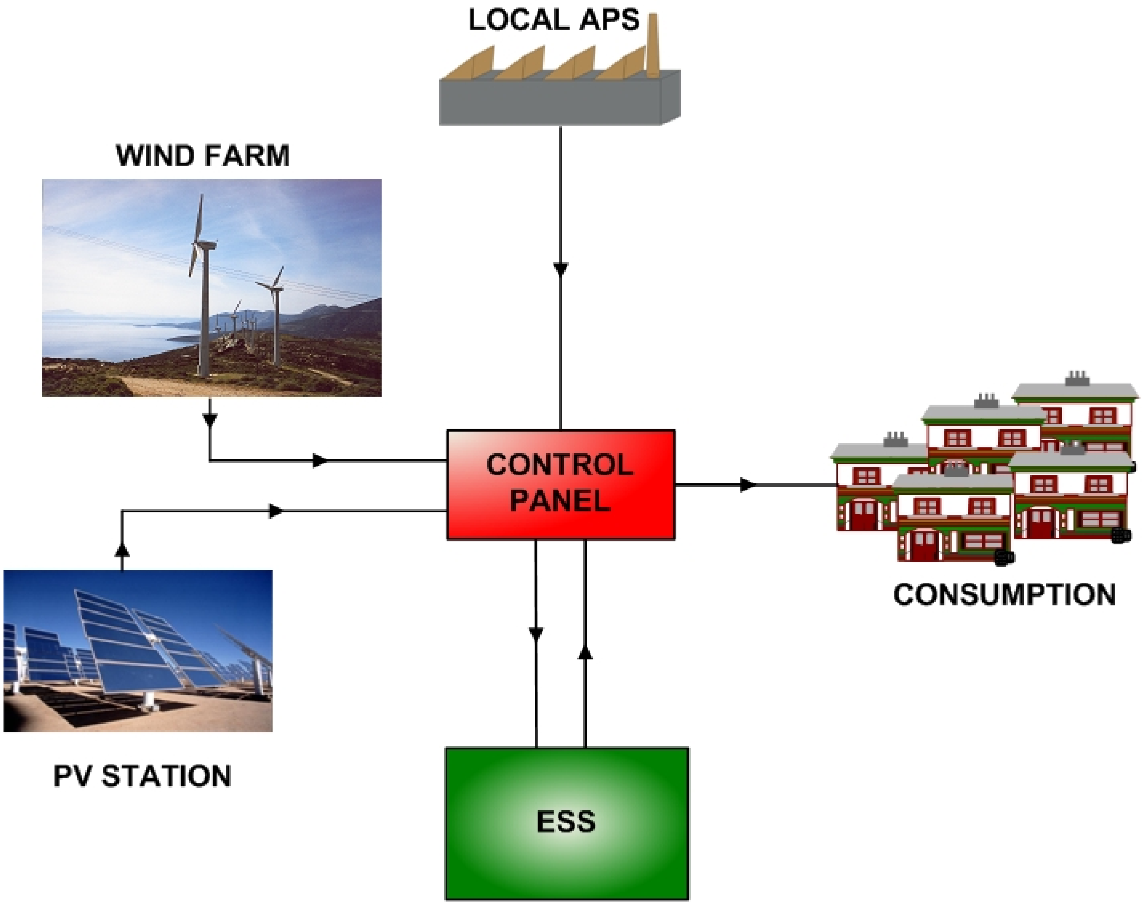

Figure 5: Proposed electricity generation configuration for autonomous electrical grids

During the long-term operation of the proposed system several operational situations may appear, i.e.:

i. If the energy production of the RES-based power stations is greater than the local community consumption, the energy surplus is stored at the existing ESS. In case that the ESS is full, the excess energy is forwarded to low priority loads.
ii. If the RES-based production is lower than the corresponding electricity demand and the ESS is not empty, the electricity deficit is covered via the ESS.
iii. If the RES-based production is lower than the electricity demand and the ESS is practically empty, the electricity deficit is covered by the existing thermal power units, using diesel or heavy oil.
iv. Finally, for practical reasons, the utilization of all available power units may be required in order to face unexpected energy production/demand problems or situations related to "Force Majeure" events.

In the following sections one should initially define the major dimensions of the proposed integrated electricity production system and accordingly evaluate the financial behavior of the entire solution in comparison with the up to now existing systems based almost exclusively on a number of internal combustion engines.

3. Sizing a RES-ESS Based System

The present analysis concerns an autonomous (island) electrical network with annual energy consumption equal to "E_{tot}", while the corresponding peak load demand is "N_p". The main target of the proposed solution is to meet the local demand using electrical power stations mainly based on renewable energy sources (RES) and appropriate energy storage systems (ESS), with rational production cost. Up to now the electrification solution[1] was based on the existing outmoded thermal power stations, which operate using diesel or heavy (mazut) oil with mean electricity production cost equal to "c^*" (figure (2)) and provoking serious environmental and macroeconomic impacts[3][4]. For increased reliability purposes the most efficient thermal power units may be used as back up engines with annual energy contribution equal to "δE", where "$\delta E \ll E_{tot}$".

In this context, one may assume that the total energy demand is covered either directly by the existing power stations "E_{dir}" (mainly wind parks, photovoltaic generators and complementary by thermal power stations) or via the energy storage system "E_{stor}". In order to describe the contribution of the storage system to the total energy consumption we define the parameter "ε" as:

$$\varepsilon = \frac{E_{stor}}{E_{tot}} = 1 - \frac{E_{dir}}{E_{tot}} \tag{1}$$

since:

$$E_{tot} = E_{dir} + E_{stor} \tag{2}$$

As it is obvious, theoretically "ε" takes values between zero (no storage system usage) and one (all the energy consumption is covered through the storage system), i.e. $0 \le \varepsilon \le 1.0$. In practice, between these two extreme values, a contribution range determined by the existing power units' principle features (including photovoltaics and wind turbines) in relation with the corresponding load demand time-variation dictates the potential use of the ESS (i.e. the exact "ε" value) on an annual basis.

Taking into consideration that the RES based power stations should cover the major part of "E_{dir}" and provide also the necessary energy to the ESS (total energy efficiency η_{ss}), the corresponding annual energy production "E_{RES}" is estimated as:

$$E_{RES} = (E_{dir} - \delta E) + \frac{E_{stor}}{\eta_{ss}} = (1-\varepsilon) \cdot E_{tot} - \delta E + \frac{\varepsilon \cdot E_{tot}}{\eta_{ss}} \tag{3}$$

Defining the capacity factor of the local electrical network "CF_p" and the RES-based power stations "CF_{RES}" using equations (4) and (5), i.e.:

$$CF_p = \frac{E_{tot}}{8760 \cdot N_p} \tag{4}$$

and

$$CF_{RES} = \frac{E_{RES}}{8760 \cdot N_{RES}} \tag{5}$$

one may calculate the necessary nominal power of the proposed RES-based power stations as:

$$N_{RES} = \max\left\{(1+SF)\cdot N_p\,;\frac{E_{RES}}{8760\cdot CF_{RES}}\right\}\Rightarrow$$
$$N_{RES} = N_p\cdot\max\left\{(1+SF);\frac{CF_p}{CF_{RES}}\cdot\left[(1-\varepsilon)-\frac{\delta E}{E_{tot}}+\frac{\varepsilon}{\eta_{ss}}\right]\right\} \qquad (6)$$

where "$SF\geq 0$" is an appropriate safety factor in order to guarantee that the RES-based power station can meet the local consumption peak load demand. In order to ensure the system reliability one should take into account that at the same time one may use either the ESS power units (inverters, hydro-turbines etc.) or the existing (back up) thermal power units.

Subsequently, the ESS -to be utilized in order not only to increase the RES penetration in the local electrical market but also to improve the reliability of the local system and the quality of the electrical energy provided to the consumption- is characterized by the energy storage capacity "E_{ss}" and the nominal input "N_{in}" and output power "N_{ss}" of the entire energy storage subsystem. More precisely, the energy storage capacity of ESS may be estimated by the following relation:

$$E_{ss} = d_o\left(\frac{\varepsilon\cdot E_{tot}}{8760}\right)\frac{1}{\eta_{ss}}\cdot\frac{1}{DOD_L} = \varepsilon\cdot\left(d_o\cdot E_h\right)\frac{1}{\eta_{ss}}\cdot\frac{1}{DOD_L} \qquad (7)$$

where one should take into account the desired hours of energy autonomy "d_o", the maximum depth of discharge "DOD_L" and the energy transformation efficiency of the ESS "η_{ss}". Note that "E_h" is the average hourly load demand of the electrical network under investigation defined as:

$$E_h = \frac{E_{tot}}{8760} \qquad (8)$$

In regard to the nominal output power "N_{ss}" of the storage unit, it is the power efficiency "η_p" that must be considered as well, i.e.:

$$N_{ss} = \zeta\cdot\frac{N_p}{\eta_p} = \zeta\cdot\frac{E_h}{CF_p}\cdot\frac{1}{\eta_p} \qquad (9)$$

where "ζ" is the peak power percentage of the local network that the energy storage branch should be able to cover, see also equation (4).

Accordingly, the input nominal power "N_{in}" of the ESS depends on the available power excess of the existing electricity generation units and the corresponding probability distribution[13] as well as the desired charge time of the installation. For practical cases and assuming that the charge and the discharge time period of the ESS are comparable one may finally write:

$$N_{in} = \lambda\cdot N_{ss} \qquad (10)$$

where "λ" depends on the ratio of charge and discharge periods as well as on the efficiency of the energy transformation procedures involved. Generally speaking "λ" takes values in the range of 1.0 to 3.0.

4. Financial Evaluation of the Proposed Solution

4.1 Initial Investment Cost

The total investment cost (after -n years of operation) of the proposed solution[14][15][16] is a combination of the initial installation cost and the corresponding maintenance and operation (M&O)

cost, both quantities expressed in present values. In this context the initial investment cost "IC_o" takes into account the initial cost of the RES-based power station and the ESS as well as the balance of the plant, expressed as a function "f" of the initial cost of the RES-based power station, i.e.:

$$IC_o = IC_{RES} + f \cdot IC_{RES} + IC_{ss} \tag{11}$$

According to the available information the purchase cost of the RES-based station can be expressed by the following relation:

$$IC_{RES} = Pr \cdot N_{RES} \tag{12}$$

where "Pr" is the specific price (€/kW) of the RES-based power stations, see for example[14][15][16].

Accordingly, the initial cost "IC_{ss}" of an ESS can be expressed as a function of two coefficients. The first "c_e" (€/kWh) is related to the storage capacity and type of the system, and the second "c_p" (€/kW) is referring to the nominal power and type of the storage system in view of equation (10). Hence one may use the following relation:

$$IC_{ss} = c_e \cdot E_{ss} + c_p \cdot N_{ss} = E_h \cdot \left[\frac{c_e \cdot d_o \cdot \varepsilon}{\eta_{ss} \cdot DOD_L} + \frac{c_p \cdot \zeta}{CF_p \cdot \eta_p} \right] \tag{13}$$

In order to obtain a first idea of the numerical values of the above mentioned parameters (i.e. DOD_L, η_{ss}, η_p, c_e, c_p) the data of Table I can be used, based on the available information in the international literature[17][18][19][20]. In the same Table I, the service period "n_{ss}" and the corresponding annual M&O factor "m_{ss}" for every ESS are also included. As it is obvious from Table I, a wide range of values has been found for most energy storage systems under investigation. In the present analysis the corresponding mean values have been adopted.

Table I: Major Characteristics of the Energy Storage Systems Examined[17][18][19][20]

Storage System	Service Period n_{ss} (years)	DOD_L (%)	Power Efficiency η_p (%)	Energy Efficiency η_{ss} (%)	Specific Energy Cost c_e (€/kWh)	Specific Power Cost c_p (€/kW)	M&O m_{ss}(%)
P.H.S.	30÷50	95	85	65÷75	10÷20	500÷1500	0.25÷0.5
Flywheels	15÷20	75÷80	90÷95	80÷86	250÷350	150÷400	1÷1.5
Regenesys	10÷15	100	75÷85	60÷70	125÷150	250÷300	0.7÷1.3
F.C.	10÷20	90	40÷70	35÷45	2÷15	300÷1000	0.5÷1
Lead Acid	5÷8	60÷70	85	75÷80	210÷270	140÷200	0.5÷1
Na-S	10÷15	60÷80	86÷90	75÷85	210÷250	125÷150	0.5÷1

According to the existing legislation there is a considerable subsidization by the Greek State for RES-based applications on the basis of the current development law (e.g. 3299/04) or the corresponding National Operational Competitiveness Program. Actually, the subsidy percentage "γ" equals to 30%-50% of the total investment cost. However, in the current analysis the subsidization impact is neglected, hence "γ" is taken equal to zero.

4.2 Total Investment Cost

In addition to the initial investment cost one should also take into consideration the maintenance and operation cost of the entire installation, including the RES-based power station and the ESS. The M&O cost can be split[14] into the fixed maintenance cost "FC" and the variable one "VC". Expressing the annual fixed M&O cost as a fraction "m_{RES}" and "m_{ss}" (see [14], [15], [16] and Table I) of the initial capital invested and assuming an annual increase of the cost equal to "g_{RES}" and "g_{ss}" respectively, the present value of "FC" is given as:

$$FC = FC_{RES} + FC_{ss} = m_{RES} \cdot IC_{RES} \cdot \sum_{j=1}^{j=n} \left(\frac{(1+g_{RES})}{(1+i)} \right)^j + m_{ss} \cdot IC_{ss} \cdot \sum_{j=1}^{j=n} \left(\frac{(1+g_{ss})}{(1+i)} \right)^j \quad (14)$$

where "i" is the capital cost of the local market. The distinctive nature of a Compressed Air Energy Storage (CAES) principle operation imposes the need of the fuel factor to be also included[21]. However, in the proposed solution an attempt is made to minimize the fossil fuel consumption, thus the utilization of CAES is excluded from the present analysis[22].

Subsequently, the variable maintenance and operation cost mainly depends on the replacement of "k_o" and "k_s" major parts of the RES-based power station and the energy storage facility respectively, which have a shorter lifetime "n_k" or "n_j" compared to the complete installation "n^*". Using the symbol "r_k" or "r_j" for the replacement cost coefficient of each one of the "k_o" and "k_s" major parts of the entire installation, the "VC" term can be expressed as:

$$VC = IC_{RES} \cdot \sum_{k=1}^{k=ko} r_k \cdot \left\{ \sum_{l=0}^{l=l_k} \left(\frac{(1+g_k)(1-\rho_k)}{(1+i)} \right)^{l \cdot n_k} \right\} + IC_{SS} \cdot \sum_{j=1}^{j=ks} r_j \cdot \left\{ \sum_{l=0}^{l=l_j} \left(\frac{(1+g_j)(1-\rho_j)}{(1+i)} \right)^{l \cdot n_j} \right\} \quad (15)$$

with "l_k" and "l_j" being the integer part of the following equation (16), i.e.

$$l_k = \left[\frac{n-1}{n_k} \right] \quad \text{and} \quad l_j = \left[\frac{n-1}{n_j} \right] \quad (16)$$

while "g_k" or "g_j" and "ρ_k" or "ρ_j" describe the mean annual change of the price and the corresponding level of technological improvements for the "k-th" major component of the RES-based power station or the "j-th" major component of the energy storage installation, respectively.

Recapitulating, the total cost "C" ascribed to the proposed RES-based installation and operation after "n" years (in present values) may be estimated using equation (17).

$$C = IC_o \cdot (1-\gamma) + EC + FC + VC - \frac{Y_n}{(1+i)^n} + APS \Rightarrow \quad (17)$$

where "Y_n" is the residual value of the installation after n-years of operation in current values and "EC" describes the cost of the input energy "δE" absorbed from the existing thermal power station. For practical applications this term can be estimated using the following relation, i.e.:

$$EC = \delta E \cdot c_w \cdot \sum_{j=1}^{j=n} \left(\frac{(1+w)}{(1+i)} \right)^j \quad (18)$$

where "c_w" is the specific input energy cost value ($c_w \approx c^*$) and "w" is the mean annual escalation rate of the input energy price. Finally, "APS" is the cost of keeping the existing thermal power station as a back up station.

Substituting equations (11), (14), (15) and (18) into equation (17) concludes to:

$$C = \left[IC_{RES} \cdot (1+f) + IC_{ss} \right] \cdot (1-\gamma) + m_{RES} \cdot IC_{RES} \cdot \sum_{j=1}^{j=n} \left(\frac{(1+g_{RES})}{(1+i)} \right)^j + m_{ss} \cdot IC_{ss} \cdot \sum_{j=1}^{j=n} \left(\frac{(1+g_{ss})}{(1+i)} \right)^j + \\ + \delta E \cdot c_w \cdot \sum_{j=1}^{j=n} \left(\frac{(1+w)}{(1+i)} \right)^j + VC - \frac{Y_n}{(1+i)^n} + APS \quad (19)$$

4.3 Comparison of the Available Solutions

The proposed RES and ESS-based configuration should be compared with the existing solution, which is based on the utilization of the existing thermal power station in order to cover the electricity demand "E_{tot}" of the local society. In this scenario, the current electricity production cost is assumed equal to "c^*", while the annual electricity price escalation rate "e" should also be included. More precisely, the total electricity production cost "C*" of the existing thermal power station for a n-year time period can be approximated by the following relation:

$$C^* = c^* \cdot E_{total} \cdot \sum_{j=1}^{j=n} \left(\frac{(1+e)}{(1+i)} \right)^j - \frac{Y_n^{TPS}}{(1+i)^n} \tag{20}$$

where "Y_n^{TPS}" is the residual value of the existing thermal power units after n-years of operation in current values.

The time evolution of the total gains (or cost savings) "R" between the proposed and the existing electricity generation solutions can be expressed as:

$$R = C^* - C \tag{21}$$

In case that R>0 the RES-based solution is more cost efficient than the utilization of the existing APS, while the opposite is valid if R<0. Note that in the above presented analysis the following factors have been implicitly neglected:

a. The increased reliability and the improved quality of the electricity offered by the RES and ESS-based solution.
b. The reduction of the environmental (air pollution, oil leakages, thermal waste etc.) and macroeconomic (exchange loss and political dependency due to oil imports etc.) impacts.
c. The need for gradual replacement of the existing outmoded internal combustion engines in the course of time.

Finally, in order to clarify the impact of the ESS on the improvement of the financial efficiency of the proposed solution, one may also repeat the calculation without the utilization of an ESS. In this case ε=0 and the contribution of the ESS to the total cost of the installation is zeroed. Note that due to the existing penetration limits of the RES-based electricity production in the local electrical network[5][6] the existing thermal power units should cover the major part (approximately $\delta E \geq 0.75 . E_{tot}$) of the local community electricity demand, see also [23].

5. Application Results

Table II: Main Parameters of Anafi and Ikaria Islands

Island	Peak Power Demand kW-2005)	Total Annual Energy Consumption (MWh-2005)	RES-Based Power Unit	Population (2001 census)	Area (km^2)
Anafi	420	984	PV	272	38.35
Ikaria	7,550	24,119	Wind Turbines	8,354	255.26

The developed methodology is accordingly applied to two representative cases of Aegean Archipelago islands, i.e. the islands of Ikaria and Anafi, see Table II. The scope of the analysis described is twofold: first to investigate the viability of an integrated RES and ESS-based electricity generation solution in comparison with the existing solution based on fossil fuel utilization and secondly to find the most appropriate energy storage configuration that maximizes the gains of the proposed solution.

5.1 Wind Energy Based Solution for a Medium-Sized Island

Ikaria is a medium-sized island (population 8,354 habitants, area of 255km²) of the East Aegean Sea, located approximately 240km from Athens and belonging to the Samos prefecture, figure (1). Its major town is Agios Kirikos with 2688 habitants, and the main economic activities of the local society are agriculture, fishing, merchant marine and tourism. The annual energy production of the local APS was 24,200MWh for 2005, see also figure (6). The peak load demand -approximately 7550kW- appears also during summer, while the corresponding minimum value is 1100kW. The island has an excellent wind potential, since in several locations the annual mean wind speed approaches 9m/s, at 10m height, see for example figure (7). What is more, there is a remarkable natural water reservoir at almost 700 meters elevation, which can be used as a basis for the application of a pump-hydro storage (PHS) solution[7].

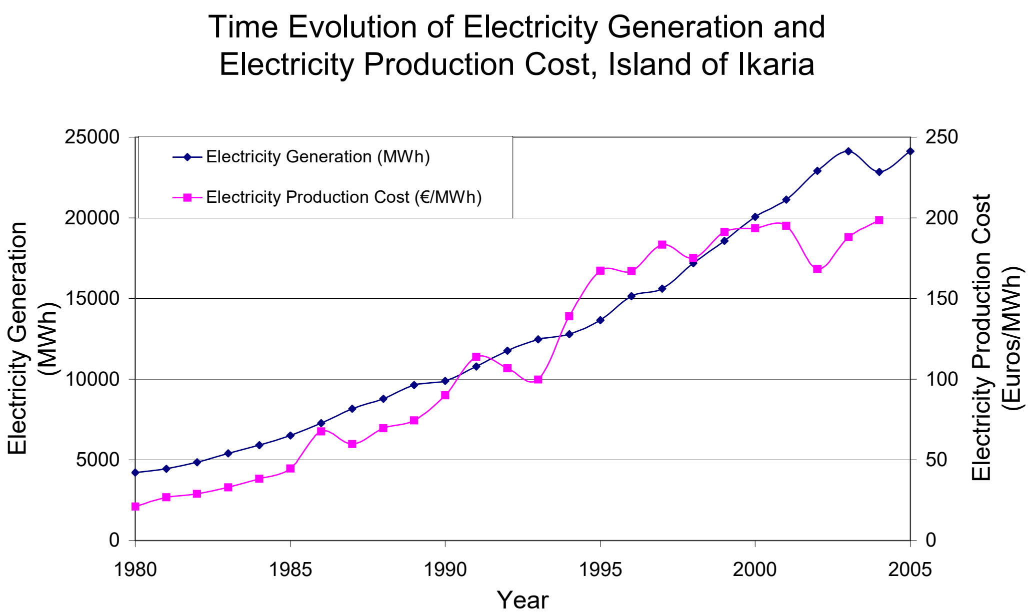

Figure 6: Electricity consumption and electricity price time variation for Ikaria Island

On the other side, the evolution of the local APS production cost presents an average annual increase of 7.3%, see figure (6), while an important part of it (≈45%) is due to the fuel cost. The autonomous power station of Ikaria consists of seven internal combustion engines along with their electrical generators, and their specific fuel consumption is almost 270gr/kWh. The rated capacity of the APS is 11360kW, while in the island a small wind park of seven (7x55kW) outdated WM-15S wind turbines[24], rated power 385kW, as well as a private wind turbine of 600kW exist. Finally, the annual cost of the existing APS is approximately 5M€[1][3].

In order to face the gradually increasing electricity demand of the island one may install several wind turbines of total nominal power resulting from equation (6) in collaboration with an appropriate ESS. Taking into account the wind potential of the area and the corresponding load demand time distribution the corresponding ESS contribution varies[23] between 50% and 60%, i.e. $0.5 \leq \varepsilon \leq 0.6$. In the current analysis the parameter "ε" is taken equal to 55%.

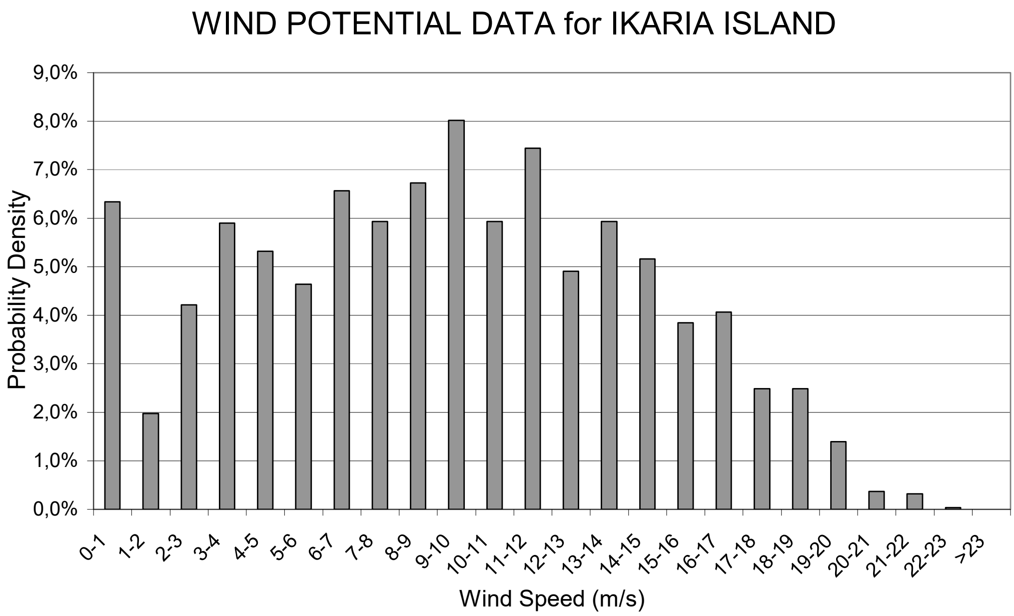

Figure 7: Wind potential data for Ikaria Island

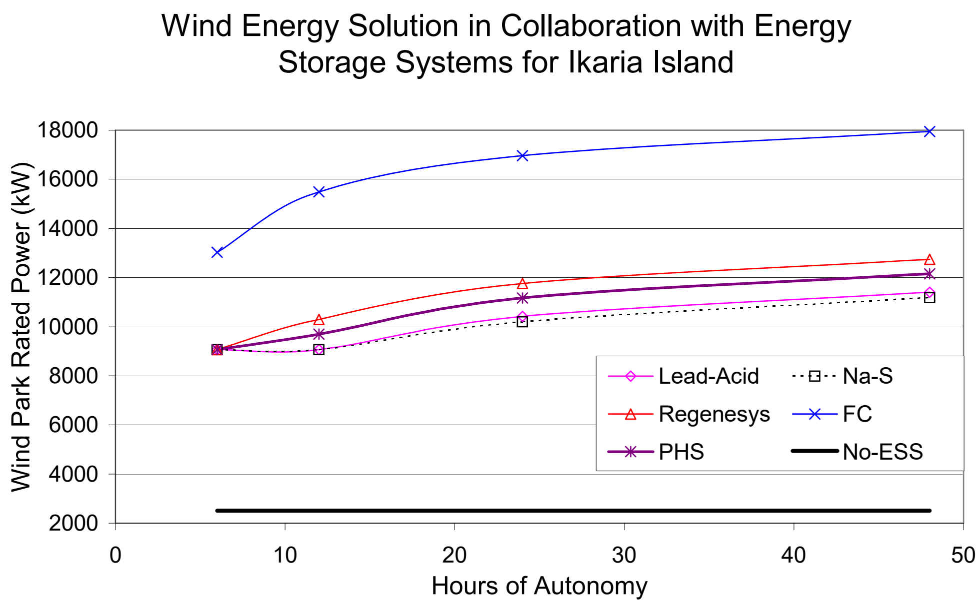

Figure 8: RES-based power station rated power vs. energy autonomy hours of the ESS, Ikaria Island

Accordingly, the ESS selected in order to collaborate with the proposed wind power station include on top of the well known lead-acid batteries and the pump-hydro storage systems, the Na-S batteries, the Flow batteries (Regenesys) and the Fuel Cells (FC)[12][25]. The major characteristics of the technologies examined are summarized in Table I, see also [17], [18], [19] and [20]. At this point it is important to note that one of the main parameters influencing the techno-economic behavior of the proposed solution is the desired energy autonomy of the local electrical network, expressed via the hours of energy autonomy "d_o" of the system. In this context "d_o" varies between 6h and 48h, while the contribution of the existing APS ($\delta E/E_{tot}$) takes values between 50% and 0%, respectively.

According to the results obtained, the rated power of the wind park required to cover the desired energy autonomy of the local network depends not only on the ESS technology adopted but also on the "d_o" value, see also figure (8). Actually, the wind park size increases (from 9MW up to 12.5MW) as the desired energy autonomy increases for all ESS analyzed, while for the Fuel Cells solution the corresponding range is between 13MW and 18MW due to their low energy transformation efficiency obtained up to now[25]. It is important to mention that for low "d_o" values the wind park rated power is defined (9MW) by the peak load demand of the local network and the corresponding safety factor (SF=0.2), see equation (6). For higher "d_o" values the "N_{RES}" value is dictated by the energy demand of the proposed installation and the APS contribution (δE), i.e. from the second term of the RHS of equation (6).

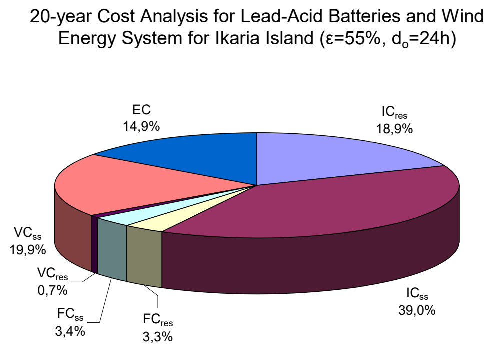

Figure 9a: Total cost analysis of the combined RES-Lead Acid Batteries based solution for Ikaria Island

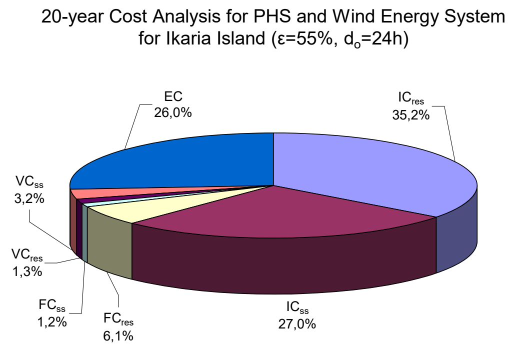

Figure 9b: Total cost analysis of the combined RES-PHS based solution for Ikaria Island

On the other side, the energy storage capacity "E_{ss}" of the ESS is directly analogous to "d_o" (equation (7)), while the corresponding rated power "N_{ss}" depends only on the peak load demand of the local network, see equation (9). In this context, one may examine the contribution of the various cost components (equation (19)) on the total operational cost of the proposed solution for a 20-year long service period. According to the data of figure (9) concerning the Lead-Acid and the PHS solutions for 24hours energy autonomy of the system two different cost patterns appear. The first category demonstrates (figure (9a)) significant contribution of the ESS (initial cost and replacement or variable M&O cost), which represent almost the 60% of the total configuration cost. In the second alternative (figure (9b)) the RES-based power station represents the main part of the total installation cost. In both cases the contribution of the input energy from the existing APS (representing only the 10% of the total annual consumption) is also remarkable (15%-25%).

Accordingly, the total gains (or cost savings) of the proposed solution in relation to the operation of the existing APS are presented in figure (10) as a function of the desired hours of energy autonomy (R-d_o) for all the ESS tested. In the same figure one may also find the corresponding gains of a wind-only based solution, i.e. without the existence of an ESS. In this specific case the contribution of the wind-based power station in the annual electricity demand is rather low[23], i.e. approximately 20% ($\delta E/E_{tot} \approx 0.8$). As it is obvious from the results presented, all the RES and ESS based configurations tested are more cost-efficient than the APS based solution. On top of this, the utilization of an ESS improves the financial behavior of the RES-based power station, decreasing at the same time the utilization of imported oil.

After a closer inspection of figure (10) one may also state that the ESS analyzed present two different cost-saving distributions, at least in the autonomy range examined. More precisely, all the battery type ESS (Lead-Acid, Na-S and Flow batteries) present one maximum cost saving value for a specific "d_o" value, after which the gains are decreasing. This is not the case for PHS and FC systems which present a continuously increasing gain distribution, at least in the autonomy range examined. In this context, Flow batteries and Na-S batteries present (figure (11)) comparable gains for low "d_o" values, while for "d_o" values of 12h-24h the PHS and Flow batteries solutions are the most cost-efficient ones. Finally, in case of high energy autonomy PHS and Fuel Cells present a significant cost saving advantage.

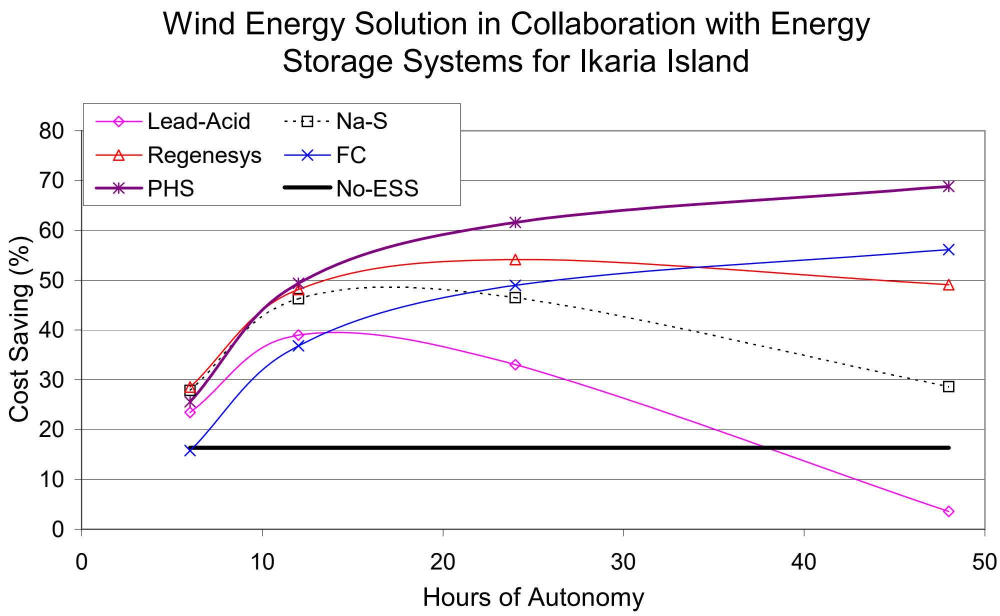

Figure 10: Cost saving distribution of the Wind-ESS based power station in comparison with the existing APS for Ikaria Island

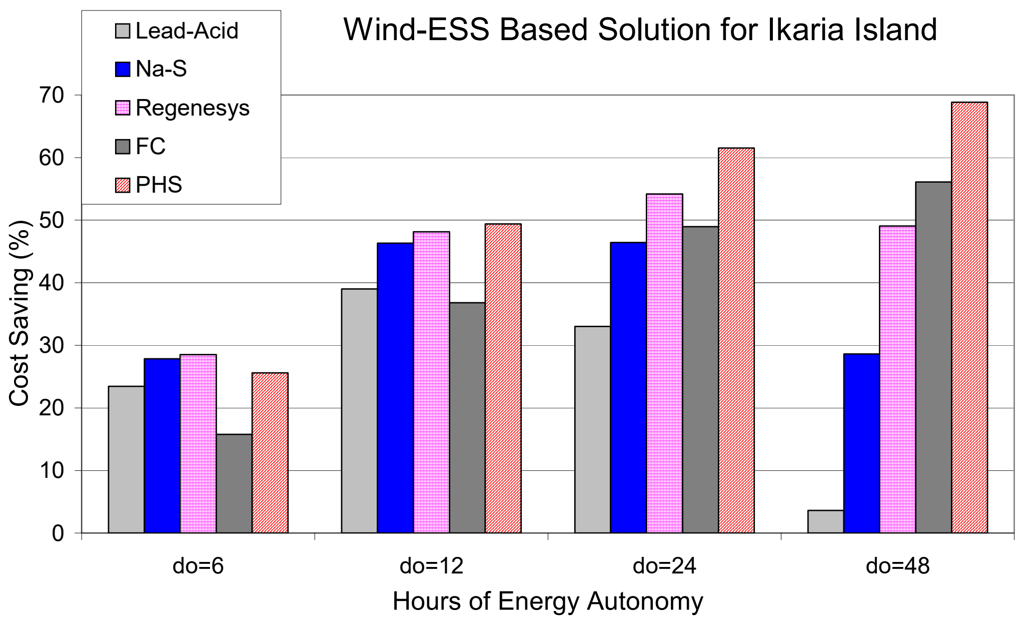

Figure 11: The impact of the energy autonomy on the cost saving distribution of the Wind-ESS based power station in comparison with the existing APS for Ikaria Island

Recapitulating for the Ikaria island case, the exploitation of the excellent wind potential of the area remarkably reduces the electricity generation cost of the local network. However, the only possibility to significantly increase the contribution of the RES in the local system energy balance is by introducing an appropriate ESS. In this case, considerable energy production cost saving is encountered (50%-70% cost decrease) which depends on the selected energy autonomy degree of the system (without the utilization of the local APS). According to the results obtained the pump-hydro storage is the most cost effective energy storage technology, especially for "d_o" values higher than six hours (d_o>6h), while the Flow batteries and the Fuel Cells may constitute an interesting alternative solution for low and high "d_o" values, respectively.

5.2 Photovoltaic Based Solution for a Small Island

Anafi is a very small island (population 272 habitants -approximately 70 families- area of 39km²) at the southeast edge of Cyclades complex. There is a complete lack of fresh water in the island, thus it has no remarkable flora and fauna. The local terrain is quite relief, including rocky hills and absence of flat fields. The main economic activities of the local society are fishing, and tourism. The annual energy production of the local APS was almost 1000MWh for 2005, see also figure (12). The peak load demand -approximately 420kW- appears during mid-August, while the corresponding minimum value is 50kW (during winter). The island has very good solar potential, since the annual mean solar energy approaches 1700kWh/m^2, at horizontal plane, figure (13).

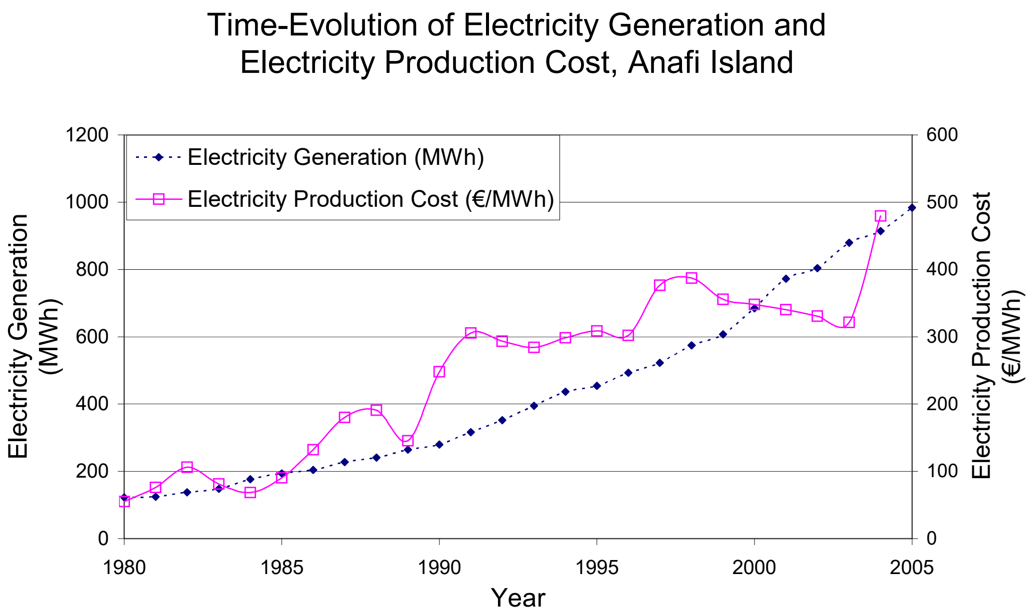

Figure 12: Electricity consumption and electricity price time variation for Anafi Island

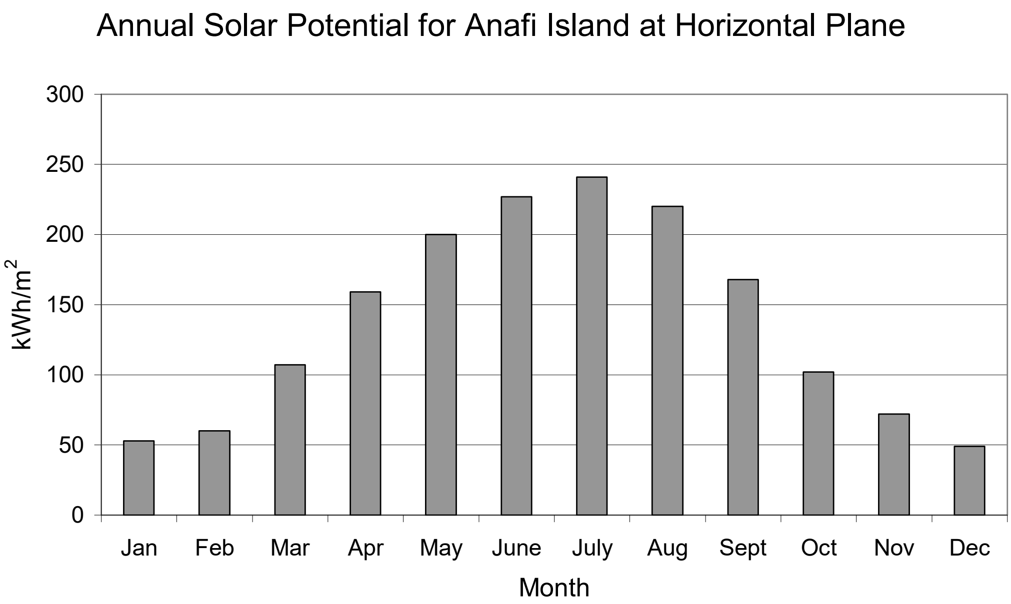

Figure 13: Solar potential of Anafi Island

The small APS of the island includes five small internal combustion engines of total rated capacity of 670kW, while their mean specific fuel consumption is 242gr/kWh. The high solar potential of the island

and the extremely high electricity generation cost of the local APS, see also figure (12), exceeding the 480€/MWh, are two significant parameters that encourage the installation of a photovoltaic (PV) generator in the island. Besides the proposed PV-based solution requires minimum maintenance effort.

For this purpose, one may install a new PV generator of nominal power resulting from equation (6), which in collaboration with an appropriate ESS can meet the electricity demand of the local community. Taking into account the solar potential of the area (available during daytime) and the corresponding load demand time distribution the resulting ESS contribution varies[23] between 70% and 80%, i.e. $0.7 \leq \varepsilon \leq 0.8$. In the current analysis the parameter "ε" is taken equal to 75%.

Accordingly, the ESS examined in order to collaborate with the proposed photovoltaic generator include on top of the well known lead-acid and Na-S batteries, the relatively new Flow batteries (Regenesys) and the Fuel Cells (FC). Due to the very small size of the network one may also examine the installation of a Flywheel based system, while the utilization of a PHS is not recommended taking into consideration the size and the topography of the island as well as the total absence of local water reserves. However, the possibility of combined electricity and clean water production on the basis of the solar energy exploitation is an interesting idea to be examined[9].

As in the previous case, the major characteristics of the technologies examined are summarized in Table I, see also [17], [18], [19] and [20]. Also note that the desired energy autonomy of the local electrical network, expressed via the hours of energy autonomy "d_o" of the system, is still the major parameter influencing the techno-economic behavior of the proposed solution. In this context "d_o" varies between 6h and 48h, while the contribution of the existing APS ($\delta E/E_{tot}$) takes values between 50% and 0%, respectively.

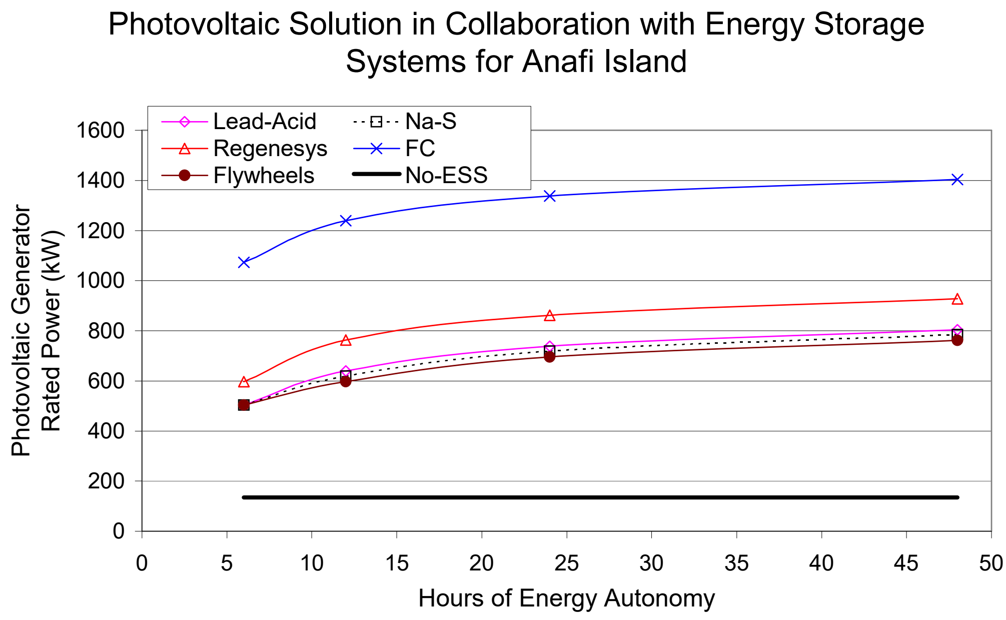

Figure 14: RES-based power station rated power vs. energy autonomy hours of the ESS, Anafi Island

As in the wind park case of Ikaria, the PV rated power required to guarantee the desired energy autonomy of the local network depends not only on the ESS technology adopted but also on the "d_o", see also figure (14). More specifically, the PV generator size increases (from 500kW up to 800W) as the desired energy autonomy increases for most ESS analyzed. This is not the case for the Fuel Cell solution, since the corresponding rated power exceeds the 1.1MW. Note that the Flow batteries system requires also quite high PV rated power. At this point, it is important to mention that for low "d_o" values the PV station rated power (500kW) is defined by the peak load demand of the local network and the corresponding safety factor (SF=0.2), see equation (6). For higher "d_o" values the "N_{RES}" value is imposed by the energy demand of the proposed installation and the APS contribution (δE), i.e. the second term of the RHS of equation (6).

Interesting conclusions may be achieved by examining the contribution of the various cost components (equation (19)) on the total operational cost of the proposed PV-based solution for a 30-year long service period. According to the information of figure (15) concerning the Lead-Acid and the Na-S batteries solutions for 24hours energy autonomy of the system, one should mention the dominant impact of the PV station initial cost, representing almost the 60% of the total 30-year long operational cost of the installation. This fact reduces the impact of the best ESS choice encountered for the wind-based case, see also figure (9). However, there is an implicit impact of the ESS type selected via the required rated power of the PV generator, figure (14). Finally, in both cases presented in figure (15a) and (15b), the contribution of the input energy cost from the existing APS (representing only the 10% of the total annual consumption) is also remarkable (≈15%).

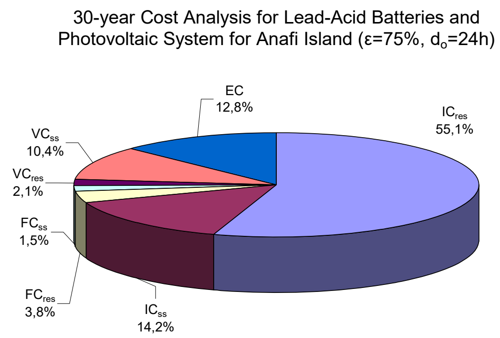

Figure 15a: Total cost analysis of the combined RES-Lead Acid Batteries based solution for Anafi Island

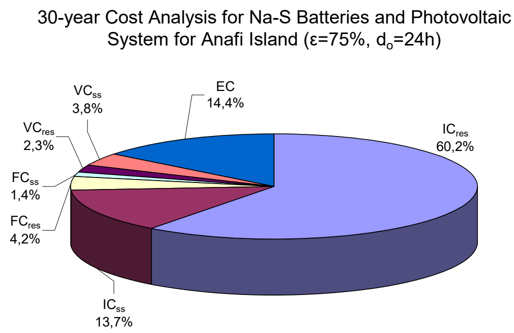

Figure 15b: Total cost analysis of the combined RES-Na-S Batteries based solution for Anafi Island

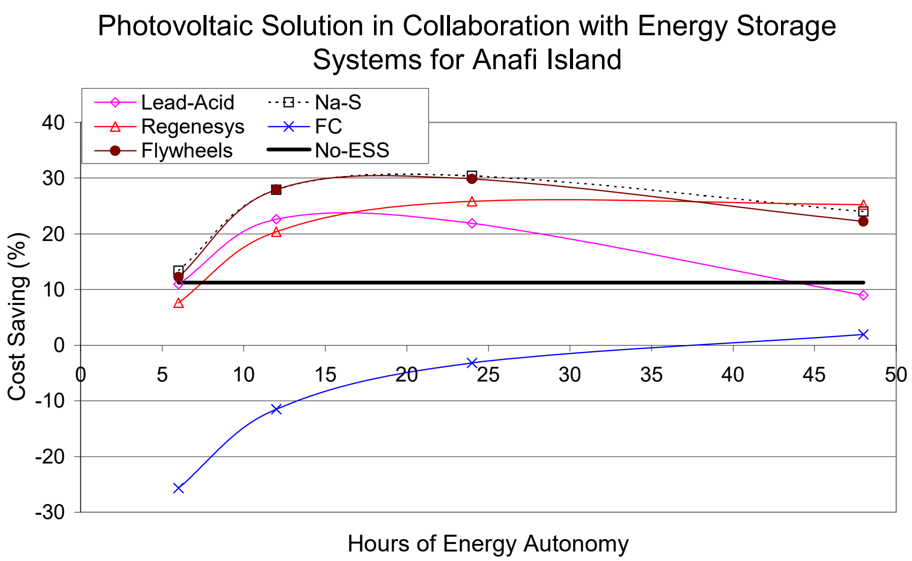

Figure 16: Cost saving distribution of the PV-ESS based power station in comparison with the existing APS for Anafi Island

In figure (16) the variation of the proposed solution total gains in comparison with the operation of the existing APS as a function of the desired hours of energy autonomy (R-d_o) for all the ESS analyzed can be examined. In the same figure one may see the corresponding gains of a PV-only based solution, i.e. without the existence of an ESS. In this case, the contribution of the RES-based power station in the annual electricity demand is approximately 20% (i.e. $\delta E/E_{tot}\approx0.8$). As it is obvious from the results presented, several RES and ESS based configurations tested are more cost efficient than the APS based solution. This is not the case for the Fuel Cells based option taking into consideration the small size of the installation. On top of this, the utilization of an ESS improves in most cases the financial behavior of the RES-based power station, especially for 12h and 24h of energy autonomy.

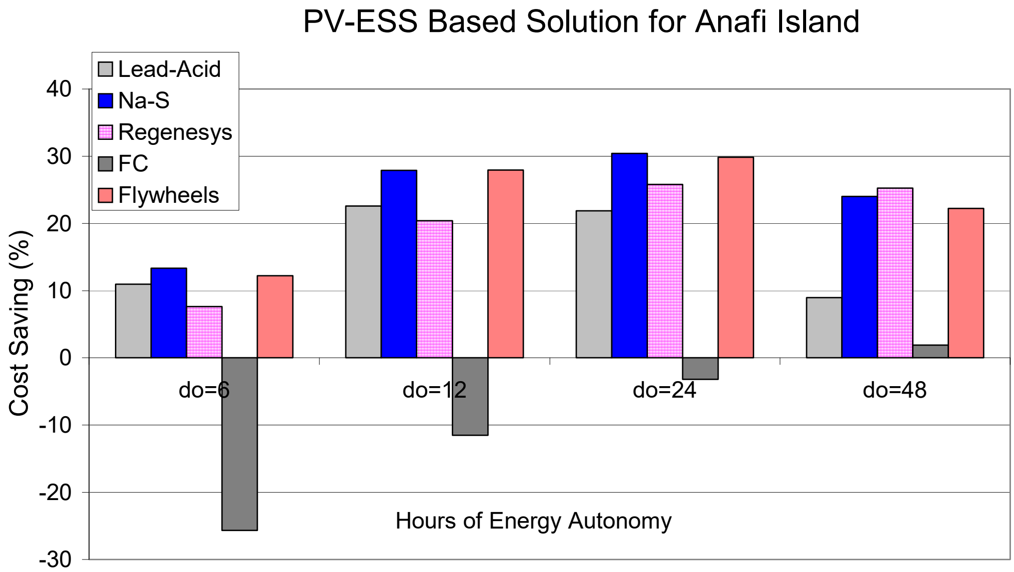

Figure 17: The impact of the energy autonomy on the cost saving distribution of the PV-ESS based power station in comparison with the existing APS for Anafi Island.

After a closer inspection of figure (16), one may note that for all the cost-efficient ESS examined (excluding the Fuel Cells) the estimated gains present initially an increase approaching a maximum value between d_o=12h and d_o=24h, which is followed by a remarkable reduction as "d_o" approaches the 48h. In this context Na-S batteries and Flywheels present (figure (17)) the best financial behavior for up to 24hours of energy autonomy, while for higher "d_o" values the Flow Batteries solution is slightly better than the Na-S batteries one.

Summarizing the Anafi island case, the exploitation of the high solar potential of the area is expected to reduce the electricity generation cost of the local network. In fact, remarkable energy production cost saving is estimated (≈30% cost decrease), which depends on the selected energy autonomy degree of the system, in relation to the local APS operation. According to the calculation results, the Na-S battery solution is the most cost effective energy storage technology applied, especially for "d_o" values less than twenty-four hours (d_o<24h), while the Flywheels and the Flow batteries may constitute an interesting alternative solution for low and very high "d_o" values, respectively.

Comparing now the two island cases examined one may state the following:

- The wind-based solution needs relatively lower energy storage support (at least for high wind potential areas) in comparison with the solar-based electricity generation configuration.
- In terms of total cost analysis, the PV-based configuration is dominated by the cost of the PV generator, while for the wind energy based solution both ESS and wind parks share the corresponding total cost of the installation.
- Finally, the financial gains of the wind-based solution is quite higher than the corresponding ones of the PV-based installation, although the electricity production cost[3] of the existing APS is much higher for the small island (PV solution) than for the medium-sized island (Wind energy solution). This is mainly due to the higher specific price of PV generators in comparison with the commercial wind turbines as well as due to their lower capacity factor in relation to wind parks[26].

6. Conclusions

An integrated methodology, investigating the possibility of creating a combined electricity generation system based on the exploitation of wind and solar potential of the numerous islands of the Aegean Archipelagos as well as on the utilization of an appropriate energy storage configuration, is developed. The proposed electrification solution can replace the existing thermal power stations based on imported oil with considerable production cost reduction. In this context, the main parameters of the combined RES-ESS based installation are calculated first and accordingly used in order to prove the economic viability of the proposed solution.

During the analysis special attention is paid to select the most cost-effective energy storage strategy in order to maximize the RES penetration (minimizing at the same time the oil consumption) and to minimize the electricity generation cost. The developed methodology is subsequently applied on two representative autonomous island cases, based on the exploitation of the available wind and solar potential respectively. The calculation results are very encouraging, since in both cases the proposed configuration leads to quite lower electricity production cost than the existing thermal power stations. On top of this, the utilization of an appropriate ESS improves the financial behaviour of the RES-based power station leading also to much higher wind or solar energy penetration levels in the local energy market.

According to extensive calculations, the pump-hydro storage for medium-sized islands and the Na-S batteries for small sized islands are the most cost effective energy storage techniques. Besides, flow batteries (i.e. Regenesys technology) are also a techno-economic interesting alternative for both cases analyzed, while the fuel cells based systems cannot compete with the existing energy storage systems, excluding the high energy autonomy cases. Finally, lead-acid batteries and flywheel systems may be an interesting energy storage option for small systems and limited energy autonomy scenarios.

Recapitulating, it is important to mention that the proposed integrated electrification solution based on the exploitation of the available RES potential in collaboration with an appropriate energy storage configuration is a financially attractive solution for the existing autonomous island networks of the Aegean Archipelagos. In fact, the proposed power stations are able to substitute the expensive and heavy polluting existing thermal power stations, improving the reliability of the local electrical networks and the quality of the energy offered to the local communities.

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COST BENEFIT ANALYSIS OF A PHOTOVOLTAIC-ENERGY STORAGE ELECTRIFICATION SOLUTION FOR REMOTE ISLANDS

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Abstract

A large number of various sized islands are spread throughout the south-east Mediterranean Sea. Most of these small islands face serious infrastructure problems, like the insufficient power supply and the low quality of electricity available at very high production cost. In an attempt to improve the life quality of all these isolated communities, an investigation concerning the financial viability of an integrated electrification solution based on one or more photovoltaic generators and an appropriate energy storage system is described. The main target of a similar solution is to maximize the contribution of the photovoltaic generator and minimize the life-cycle electricity generation cost of the remote island networks investigated. In addition, special emphasis is given in order to select the most cost-efficient energy storage configuration available. According to the results obtained for high and medium-high solar potential regions, the proposed configuration is found to be more cost-effective than the existing thermal power stations. Several side benefits like the improved electrical network reliability and the minimization of the environmental and macroeconomic impacts resulting from the replacement of the imported oil should also be considered.

Keywords: Autonomous Electrical Network; Electricity Generation Cost; Photovoltaic Generator; Energy Storage; Hybrid System

1. Introduction

The Greek territory includes a large number of islands of various sizes, spread throughout the Aegean and Ionian Archipelagos, figure (1). Although most large and medium-size islands present an acceptable status of life, this is not the case for the small and very small ones. In this context, due to the severe infrastructure problems and the imported oil-based electricity generation, the corresponding production cost is extremely high, figure (2). Additionally, the considerable increase of population during the summer season, owed to the visiting tourists, often leads to extensive electrical black outs due to the insufficient power supply[1]. On the other hand, the specific areas are favoured by a considerable RES potential[2], both wind and solar, that should not be neglected.

To confront the electrification problems and ameliorate the life quality of the specific areas[3][4][5], the adoption of alternative electricity generation schemes, such as RES based energy storage configurations[6][7][8][9][10], should be investigated. In this context, the aim of the present study is the financial evaluation of combining photovoltaic (PV) plants with energy storage systems (ESS) for the electrification of small, remote island electrical grids. Several small and tiny Greek islands with a population of less than 2000 and 500 habitants[11] respectively, comprise the target group of the specific research. Their hourly electricity consumption being less than 1MWh and their peak load demand being inferior to 3MW (see also figure (2)) justify the decision to test the PV-ESS solution. Besides, one cannot neglect the support expected from the local habitants in favour of the RES based solution proposed[12][13].

Further, although the first installation cost of a combined PV-ESS configuration is relatively higher than the corresponding of an equivalent thermal power station, the high solar potential of the area and the extremely high production cost of the local APS already mentioned, allow for the comparison of the two electricity generation schemes. In this context, by applying an appropriate sizing methodology, various representative PV-ESS configurations are dimensioned in order to minimize the operation of the local thermal power station (APS). Finally, since the optimum sizing of an ESS[14][15][16] ensures higher system reliability and potential financial gains[17], by using different energy storage technologies[18][19] the designation of minimum life-cycle cost solutions[20][21] may be configured.

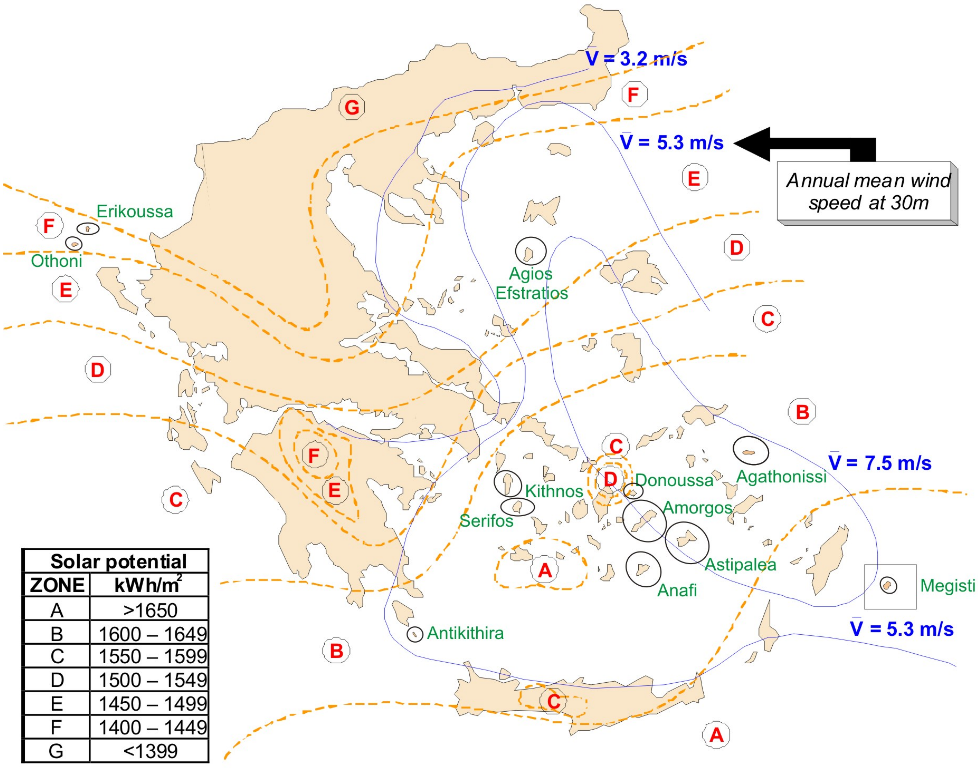

Figure 1: Aegean-Ionian islands investigated and solar potential distribution of the Greek territory[2]

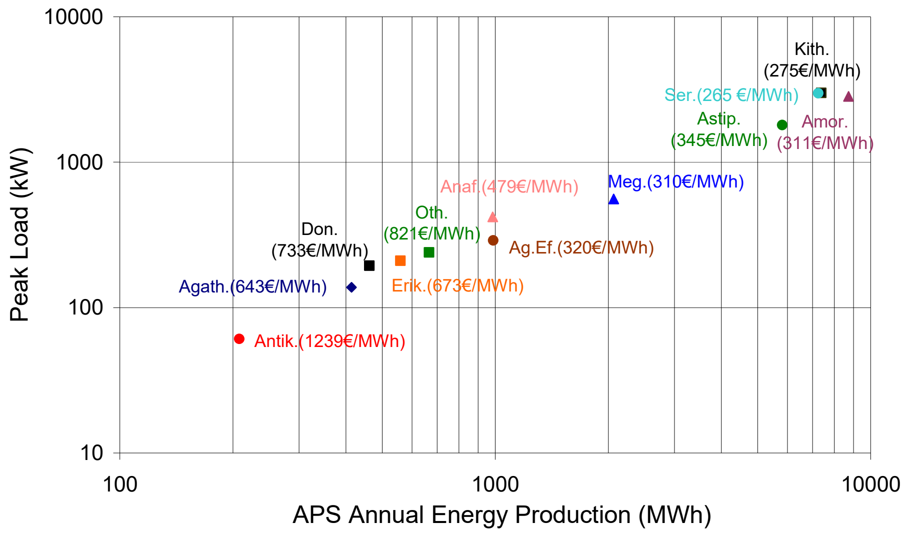

Figure 2: Small Greek islands' peak load demand, APS annual energy production and electricity generation cost (€/MWh)[1]

2. Description of the Problem- Proposed Solution

The problem to be solved concerns the definition of the most-cost effective PV-ESS configuration, able to meet the electricity requirements of the existing small, remote islands. For this purpose one needs:

a. *The electrical load demand time variation*. Note that for almost all small islands under investigation there is a serious seasonal electricity consumption variation, figure (3). In fact, during the summer season, electricity consumption is more than twice the corresponding spring one. In addition, there is also an important daily load demand variation, usually presenting two distinct maxima, one around noon "N_{p1}" and the other (which is normally the biggest one) during late evening "N_{p2}", figure (4). Due to the specific character of the PV production one should separate the daily electricity consumption in two separate periods, i.e. one during sunlight "E_{t1}" and the other during the rest of the day "E_{t2}"[22]. According to the analysis of the available data[1][22], "E_{t1}" represents approximately 30% of the total annual consumption "E_{tot}", taking values between 15% and 45% on a daily basis. Note also that:

$$E_{tot} = E_{t1} + E_{t2} \tag{1}$$

and

$$N_p = \max\{N_{p1}; N_{p2}\} \tag{2}$$

where "N_p" is the peak load demand of the electrical network under investigation.

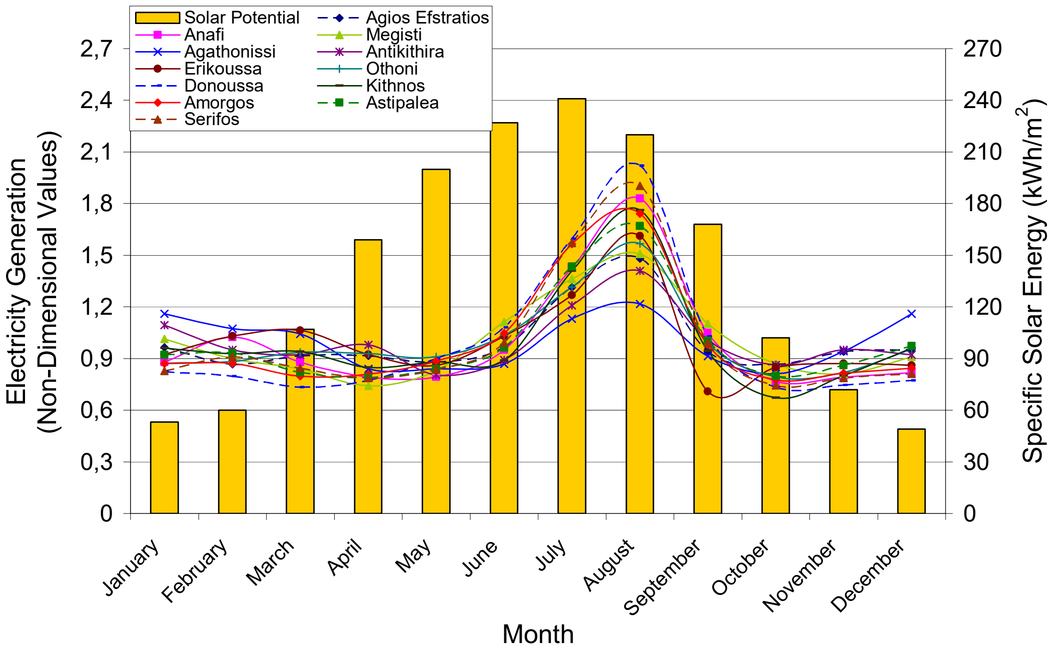

Figure 3: Seasonal electricity consumption variation for various small remote islands vs. typical seasonal solar potential variation[1][23]

b. *The solar irradiance levels of the area*. At this point it is worthwhile mentioning that the entire Greek island territory is characterized by high or medium-high solar irradiance. In fact, the annual solar energy at horizontal plane[23] varies between 1500 kWh/m^2 and 1700kWh/m^2, figure (1). In this context, the exploitation of the available solar potential may significantly contribute to the fulfillment of the local societies energy demand, at minimum environmental and macroeconomic cost[24][25]. As a result, the inhibition of the local societies' economic growth may be encountered[26].

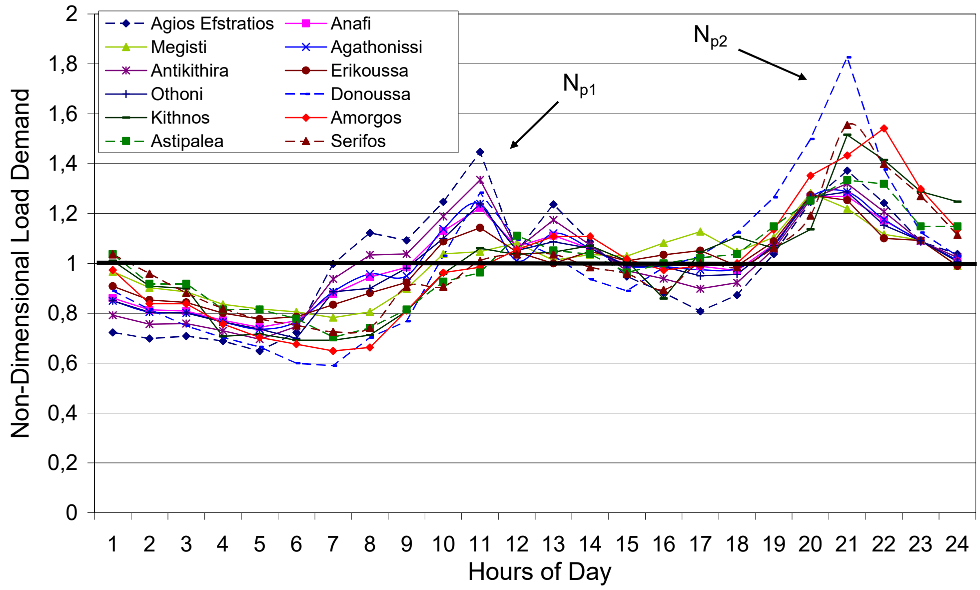

Figure 4: Daily electricity consumption variation for various small remote islands[1]

c. *The appropriate energy storage techniques available*. An energy storage system (ESS) is utilized in order to store energy during high electricity production periods and return it to the consumption at low solar irradiance periods or at nights. This system is characterized by the energy storage capacity "E_{ss}" and the nominal input "N_{in}" and output power "N_{ss}" of the entire energy storage subsystem. One should also take into account the desired hours of energy autonomy "d_o" of the installation, the maximum permitted depth of discharge "DOD_L", the energy transformation efficiency of the ESS "η_{ss}", the power efficiency "η_p", as well as its two initial cost components, "c_e" and "c_p". In fact, "c_e" (€/kWh) is related to the storage capacity and type of the system, while the second "c_p" (€/kW) is referring to the nominal power and type of the storage system. Note that the contribution of the ESS to the operation of the proposed integrated solution is expressed via the energy contribution parameter "ε", defined as:

$$\varepsilon = \frac{E_{stor}}{E_{tot}} = 1 - \frac{E_{dir}}{E_{tot}} \quad (3)$$

where "E_{stor}" is the total energy contribution of the ESS to the annual electricity demand and "E_{dir}" is the energy demand covered directly by the existing power stations, i.e. mainly photovoltaic generators and complementary thermal power stations.

In order to obtain an idea of the numerical values of the above mentioned parameters (i.e. DOD_L, η_{ss}, η_p, c_e, c_p) the data of Table I can be used, based on the available information in the international literature[27][28][29][30]. In the same Table I, the service period "n_{ss}" and the corresponding annual M&O factor "m_{ss}" for every ESS are also included. A wide range of values have been found for most energy storage systems under investigation, while the most common application range of the respective technologies must be also taken into account[31]. Taking into consideration the size and the infrastructure of the examined islands as well as the target to minimize the fossil fuel contribution, certain energy storage systems may be selected. The most appropriate energy storage configurations to be tested include the Lead-acid and the Na-S batteries as well as the Pumped-Hydro and the Flow Batteries (Regenesys). For the very small islands one may also include the Flywheel option, while for the bigger islands, Fuel Cells may also present an interesting alternative, especially in the near future[32].

Table I: Major Characteristics of the Energy Storage Systems Examined[27][28][29][30]

Storage System	Service Period n_{ss} (years)	DoD (%)	Power Efficiency η_p (%)	Energy Efficiency η_{ss} (%)	Specific Energy Cost c_e (€/kWh)	Specific Power Cost c_p (€/kW)	M&O m_{ss}(%)
P.H.S.	30÷50	95	85	65÷75	10÷20	500÷1500	0.25÷0.5
Flywheels	15÷20	75÷80	90÷95	80÷86	250÷350	150÷400	1÷1.5
Regenesys	10÷15	100	75÷85	60÷70	125÷150	250÷300	0.7÷1.3
F.C.	10÷20	90	40÷70	35÷45	2÷15	300÷1000	0.5÷1
Lead Acid	5÷8	60÷70	85	75÷80	210÷270	140÷200	0.5÷1
Na-S	10÷15	60÷80	86÷90	75÷85	210÷250	125÷150	0.5÷1

Finally, in order to evaluate all potential solutions the collection of certain data is required. Data concerning the time-evolution of electricity production parameters for each small island as well as information describing the local topography, the ambient temperature and the wind speed, the demographic profile and the economic activities, must all be obtained.

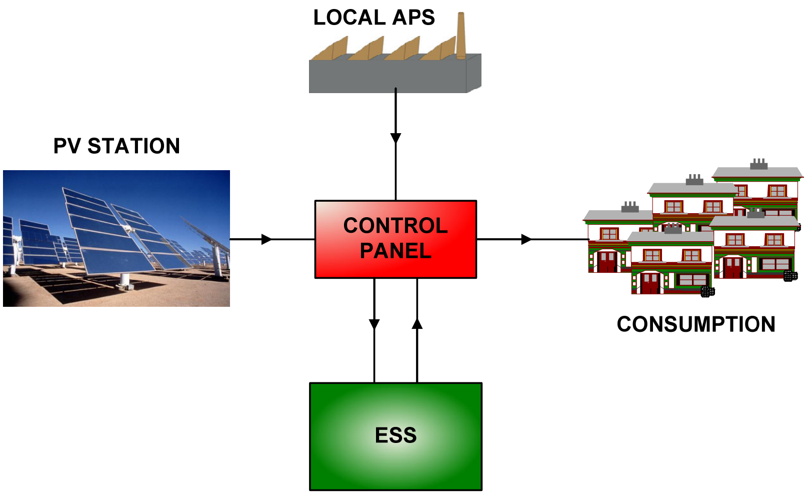

Figure 5: Proposed electricity generation configuration for small autonomous islands

In order to face the pressing electricity requirements of all these small remote islands on the basis of the available solar potential, an integrated solution comprising of a photovoltaic generator -able to meet the electricity demand of the island- as well as an appropriate energy storage facility that guarantees the local community energy autonomy for a desired time period, is evaluated. What is more, the existing (usually outmoded) thermal power stations may be also used either as a back up solution or to cover unexpected high load demand. More precisely the proposed configuration (figure (5)) includes:

i. One or more photovoltaic generators based on the exploitation of the available solar potential. The rated power of the proposed installation is "N_{PV}".
ii. A number of energy storage devices (e.g. Lead-acid or Na-S batteries, a group of water reservoirs, etc.) combined with their corresponding energy production equipment (e.g. inverters, small hydro-turbines, etc.). The energy storage capacity of the installation is equal to "E_{ss}" and the input and output rated power values are "N_{in}" and "N_{ss}", respectively. The selected ESS should be able to cover the local network electricity requirements for "d_o" typical hours without the contribution of any other electricity generation device.
iii. The existing thermal power units of the already operating APS, with rated power equal to "N_o",

may contribute in meeting the local system electricity consumption under specific circumstances by "δE". The main target of the proposed solution is to minimize the contribution of the local APS to the local system electricity consumption (δE→0).

In the following, one should initially define the major dimensions of the proposed integrated electricity production system and accordingly estimate the corresponding life-cycle electricity generation cost. The expected electricity production cost should be compared with the up to now existing solution, based almost exclusively on a number of internal combustion engines.

3. Presentation of the Developed Methodology

3.1 Sizing of the PV-ESS Configuration and Prediction of Main Parameters

The main parameters of the proposed solution, some already discussed, include the PV generator rated (peak) power "N_{PV}", the ESS energy storage capacity "E_{ss}" related to the hours of energy autonomy of the installation "d_o", the corresponding nominal input "N_{in}" and output power "N_{ss}", the energy yield of the PV installation "E_{PV}", the contribution of the energy storage facility to the total energy consumption "ε", the participation of the existing APS on the coverage of the electricity demand "δE", and the electricity generation cost -in present values- "c_o". In order to result to the sizing of the PV-ESS configuration and also determine the main parameters of the problem, a two-stage methodology is developed. In the first part following, the sizing of the configuration as well as the determination of energy related parameters is presented.

a. *Photovoltaic component of the PV-ESS configuration*

Taking into consideration that the PV based power station should cover the major part of "E_{dir}" and also provide the necessary energy to the ESS (total energy efficiency "η_{ss}"), the corresponding annual energy production "E_{PV}" is estimated as:

$$E_{PV} = (E_{dir} - \delta E) + \frac{E_{stor}}{\eta_{ss}} = (1-\varepsilon) \cdot E_{tot} - \delta E + \frac{\varepsilon \cdot E_{tot}}{\eta_{ss}} \qquad (4)$$

Defining the capacity factors of the local electrical network "CF_p" and the PV-based power station "CF_{PV}" using equations (5) and (6), one may calculate the necessary nominal power of the proposed PV-based power station. Note that "CF_{PV}" results as a combination of the available solar potential and the operational characteristics of the photovoltaic panels in use. Typical values of "CF_{PV}" for the area under investigation vary between 13% and 21%[33].

$$CF_p = \frac{E_{tot}}{8760 \cdot N_p} \qquad (5)$$

and

$$CF_{PV} = \frac{E_{PV}}{8760 \cdot N_{PV}} \qquad (6)$$

Subsequently, the required nominal power of the proposed PV-based power station "N_{PV}" is estimated by equation (7).

$$N_{PV} = \max\left\{(1+SF)\cdot N_{p1} ; \frac{E_{PV}}{8760\cdot CF_{PV}}\right\} \Rightarrow$$
$$N_{PV} = N_p \cdot \max\left\{(1+SF)\cdot \frac{N_{p1}}{N_p} ; \frac{CF_p}{CF_{PV}}\cdot\left[(1-\varepsilon)-\frac{\delta E}{E_{tot}}+\frac{\varepsilon}{\eta_{ss}}\right]\right\} \quad (7)$$

where "$SF \geq 0$" is an appropriate safety factor (usually $SF \leq 25\%$) in order to guarantee that the PV-based power station can meet the local consumption daytime power demand, (see also equation (2)). In order to ensure the reliability of the system, one should take into account that at the same time either the ESS power units (inverters, hydro-turbines etc.) or the existing (back up) thermal power units could be used. Accordingly, using the energy balance during the daytime one gets:

$$E_{t1} = E_{PVdir} + E_{st1} + \delta E_1 \quad (8)$$

where "E_{st1}" is the contribution of the ESS during daytime while "δE_1" and "E_{PVdir}" are the APS and the PV station participation during the same period respectively. Besides, the energy yield of the PV installation absorbed directly by the local network "E_{PVdir}" is given by equation (9):

$$E_{PV\,dir} = x_3 \cdot E_{t1} \quad (9)$$

where "x_3" results as a combination of the solar irradiance and ambient temperature with the corresponding load demand of the local network during daytime. Defining the parameter "ξ" as:

$$\xi = \frac{E_{st1}}{E_{t1}} \quad (10)$$

one may describe the contribution of the storage system "E_{st1}" to the total daytime energy consumption "E_{t1}". Accordingly, by substituting the definitions of equations (9) and (10) equation (8) yields:

$$x_3 = (1-\xi) - \frac{1}{s}\cdot\frac{\delta E_1}{E_{tot}} \leq (1-\xi) \quad (11)$$

where "s" is the electricity consumption during the daytime period expressed as a fraction of the total energy consumption of the island, i.e.

$$s = \frac{E_{t1}}{E_{tot}} \quad (12)$$

Note, that in most cases, especially when $N_{PV} \geq N_p$, the "$\delta E_1/E_{tot}$" term is very small, thus the inequation (11) may be treated as equation, while

$$x_3 \leq (1-\xi) = 0.95 \quad (13)$$

since in practical cases (when $N_{PV} \geq N_p$) $\xi \to 5\%$.

b. *Energy storage system component of the PV-ESS configuration*
Subsequently, the ESS is characterized by the energy storage capacity "E_{ss}" and the nominal input "N_{in}" and output power "N_{ss}" of the entire energy storage subsystem. More precisely, the energy storage capacity of the ESS may be estimated by the following relation:

$$E_{ss} = d_o\left(\frac{E_{tot}}{8760}\right)\frac{1}{\eta_{ss}}\cdot\frac{1}{DOD_L} = d_o\cdot\frac{E_h}{\eta_{ss}}\cdot\frac{1}{DOD_L} \tag{14}$$

where one should take into account the desired typical hours of energy autonomy "d_o", the maximum depth of discharge "DOD_L" and the energy transformation efficiency of the ESS "η_{ss}". Note that "E_h" is the average hourly load of the electrical network under investigation defined as:

$$E_h = \frac{E_{tot}}{8760} \tag{15}$$

For the estimation of the ESS contribution "ε" to the fulfillment of the local electricity consumption one may use equations (3) and (9) as well as the energy balance of the local network for the entire time period examined given by equation (16):

$$E_{tot} = E_{PVdir} + E_{stor} + \delta E \tag{16}$$

Introducing in equation (16) both equations (3) and (9) one gets:

$$\varepsilon = (1 - s\cdot x_3) - \frac{\delta E}{E_{tot}} \le (1 - s\cdot x_3) \tag{17}$$

What is interesting to note (equation (17)) is that for a given electricity demand profile and a specific solar potential case, the "ε" distribution varies inversely with the local APS contribution "$\delta E/E_{tot}$". Besides, the contribution of the ESS may be alternatively expressed by equation (18):

$$\varepsilon = \sum_{j=1}^{jmax}\min_{\Delta t_j}\left\{\frac{E_{PV}(\Delta t_j) - E_{PV_{dir}}(\Delta t_j)}{E_{tot}};\frac{d_o}{8760\cdot\eta_{ss}}\cdot\left[\frac{1}{DOD_L} - \frac{1}{DOD(\Delta t_j)}\right]\right\} \tag{18}$$

where "j_{max}" is the number of time-steps of "Δt" duration in which the entire period (e.g. one year) under investigation is divided.

In regard to the nominal output power "N_{ss}" of the storage unit, it is the power efficiency "η_p" that must be considered as well, i.e.:

$$N_{ss} = \zeta\cdot\frac{N_p}{\eta_p} = \zeta\cdot\frac{E_h}{CF_p}\cdot\frac{1}{\eta_p} \tag{19}$$

where "ζ" is the peak power percentage of the local network that the energy storage branch should be able to cover, (see also equation (5)).

Accordingly, the nominal power input "N_{in}" of the ESS depends on the available power excess of the existing PV generator, the corresponding probability distribution and the desired charge time of the installation. For practical cases and taking into account the limited availability of solar energy determining the charge and discharge periods of the ESS, one may finally write that:

$$N_{in} = \lambda\cdot N_{ss} \le N_{PV} \tag{20}$$

where "λ" depends on the ratio of charge and discharge periods as well as on the efficiency of the energy transformation procedures involved. Generally speaking, for PV applications "λ" takes values in the range of 1.5 to 3.0.

c. *Autonomous power station*
Finally, if considering equation (17), the contribution of the existing APS may also result:

$$\delta E = E_{tot} \cdot (1 - s \cdot x_3 - \varepsilon) \tag{21}$$

3.2 Life Cycle Electricity Generation Cost Analysis of the PV-ESS Configuration

After configuring the size of the PV-ESS plant and determining the system main parameters, in the second leg of the methodology developed, the corresponding life cycle electricity generation cost is estimated.

At first, the total investment cost (after -n years of operation) of the proposed solution[18][21] is a combination of the initial installation cost and the corresponding maintenance and operation cost, both quantities expressed in present values. In this context the initial investment cost "IC_o" takes into account the initial cost of both the PV power station and the ESS as well as the balance of the plant, expressed as a function "f" of the initial cost of the PV power station, i.e.:

$$IC_o = IC_{PV} + f \cdot IC_{PV} + IC_{ss} \tag{22}$$

According to the available information[21][33][34], the purchase cost of the PV-based station can be expressed by the following relation:

$$IC_{PV} = Pr \cdot N_{PV} \tag{23}$$

where "Pr" is the specific price (€/kW) of the PV power stations, described by the following semi-empirical formula[33] for installations up to 2MW with regards to the Greek socio-economic environment only.

$$Pr = 6186.1 \cdot N_{PV}^{-0.0437} \quad (1kW \le N_{PV} \le 2000kW) \tag{24}$$

Following, the initial cost "IC_{ss}" of an ESS can be expressed[18][27][28][29][30] as a function of two coefficients. The first "c_e" (€/kWh) related to the storage capacity and type of the system, and the second "c_p" (€/kW) referring to the nominal power and type of the storage system in view of equation (20). Hence one may use the following relation:

$$IC_{ss} = c_e \cdot E_{ss} + c_p \cdot N_{ss} = E_h \cdot \left[\frac{c_e \cdot d_o}{\eta_{ss} \cdot DOD_L} + \frac{c_p \cdot \zeta}{CF_p \cdot \eta_p} \right] \tag{25}$$

with the values of main parameters included in Table I.

In addition to the initial investment cost one should also consider the maintenance and operation cost (M&O) of the entire installation, including the PV-based power station and the ESS. The M&O cost can be split into the fixed maintenance cost "FC" and the variable one "VC". Expressing the annual fixed M&O cost as a fraction "m_{PV}" and "m_{ss}" (see [20], [21] and Table I) of the initial capital invested and assuming a mean annual increase of the cost equal to "g_{PV}" and "g_{ss}" respectively, the present value of "FC" is given as:

$$FC = FC_{PV} + FC_{ss} = m_{PV} \cdot IC_{PV} \cdot \sum_{j=1}^{j=n} \left(\frac{(1 + g_{PV})}{(1+i)} \right)^j + m_{ss} \cdot IC_{ss} \cdot \sum_{j=1}^{j=n} \left(\frac{(1 + g_{ss})}{(1+i)} \right)^j \tag{26}$$

where "i" is the capital cost of the local market.

Subsequently, the variable maintenance and operation cost mainly depends on the replacement of "k_o" and "k_s" major parts of the PV-based power station and the ESS respectively, which have a shorter lifetime "n_k" or "n_j" compared to the complete installation "n^*". Using the symbol "r_k" or "r_j" for the replacement cost coefficient of each one of the "k_o" and "k_s" major parts of the entire installation, the "VC" term can be expressed as:

$$VC = IC_{PV} \cdot \sum_{k=1}^{k=ko} r_k \cdot \left\{ \sum_{l=0}^{l=l_k} \left(\frac{(1+g_k)(1-\rho_k)}{(1+i)} \right)^{l \cdot n_k} \right\} + IC_{SS} \cdot \sum_{j=1}^{j=ks} r_j \cdot \left\{ \sum_{l=0}^{l=l_j} \left(\frac{(1+g_j)(1-\rho_j)}{(1+i)} \right)^{l \cdot n_j} \right\} \quad (27)$$

with "l_k" and "l_j" being the integer part of the following equation (28), i.e.

$$l_k = \left[\frac{n-1}{n_k} \right] \quad \text{and} \quad l_j = \left[\frac{n-1}{n_j} \right] \quad (28)$$

while "g_k" or "g_j" and "ρ_k" or "ρ_j" describe the mean annual change of the price and the corresponding level of technological improvements for the "k-th" major component of the PV-based power station or the "j-th" major component of the energy storage installation, respectively.

Recapitulating, the total cost "C" ascribed to the proposed PV-ESS based installation after "n" years of operation (in present values) may be estimated using equation (29).

$$C = IC_o \cdot (1-\gamma) + EC + FC + VC - \frac{Y_n}{(1+i)^n} + APS \Rightarrow \quad (29)$$

where "Y_n" is the residual value of the installation after n-years of operation in current values and "EC" describes the cost of the input energy "δE" absorbed from the existing thermal power station. For practical applications this term can be estimated using the following relation, i.e.:

$$EC = \delta E \cdot c_w \cdot \sum_{j=1}^{j=n} \left(\frac{(1+w)}{(1+i)} \right)^j \quad (30)$$

where "c_w" is the specific input energy cost value ($c_w \approx c^*$) and "w" is the mean annual escalation rate of the input energy price. Finally, "APS" is the cost of keeping the existing thermal power station as a back up station.

Substituting equations (22), (26), (27) and (30) into equation (29) one gets:

$$C = \left[IC_{PV} \cdot (1+f) + IC_{ss} \right] \cdot (1-\gamma) + m_{PV} \cdot IC_{PV} \cdot \sum_{j=1}^{j=n} \left(\frac{(1+g_{PV})}{(1+i)} \right)^j + m_{ss} \cdot IC_{ss} \cdot \sum_{j=1}^{j=n} \left(\frac{(1+g_{ss})}{(1+i)} \right)^j + \\ + \delta E \cdot c_w \cdot \sum_{j=1}^{j=n} \left(\frac{(1+w)}{(1+i)} \right)^j + VC - \frac{Y_n}{(1+i)^n} + APS \quad (31)$$

Finally, one may express the present value of the electricity generation cost (€/kWh) of the proposed PV-ESS based installation by dividing the total cost of the installation during the n-year service period with the total energy generation during the same period, taking into consideration the produced electricity price mean annual escalation rate "e". Therefore, the corresponding electricity generation cost is given as:

$$c_o = \frac{C}{E_{tot} \cdot \sum_{j=1}^{j=n} \left(\frac{(1+e)}{(1+i)} \right)^j} = \frac{C}{E_{tot} \cdot Q} \quad (32)$$

where "Q" is defined as:

$$Q = \sum_{j=1}^{j=n} \left(\frac{(1+e)}{(1+i)} \right)^j \quad (33)$$

In order for the proposed PV and ESS-based configuration to be financially attractive in comparison with the -up to now- adopted solution, which is based on the utilization of the existing thermal power station, one should compare the value of equation (32) with the current electricity production cost "c^*", see also figure (2). In case that $c_o<c^*$ the PV-based solution is more cost efficient than the utilization of the existing APS, while the opposite is valid if $c_o>c^*$.

4. Main Considerations on the Methodology Application

The developed methodology described in the algorithm of figure (6) is accordingly applied to one representative small island case with annual energy consumption "E_{tot}" equal to 2000MWh and peak load demand "N_p" equal to 600kW. The seasonal and daily load energy demand distributions are given in figures (3) and (4), while the corresponding solar potential is also provided (figure (3)). Regarding the ESS employed, the relatively new Na-S batteries solution is adopted as a representative, promising energy storage technology (see also Table I for the numerical values adopted). However, for a complete analysis to be provided other ESS are also investigated (Table I).

During the presentation of the calculation results (see also section 5), emphasis is at first given in order to demonstrate the energy contribution of the various electricity production subsystems to the total annual consumption. Accordingly, the expected life-cycle electricity generation cost is estimated as a function of both the PV generator rated power and the ESS energy autonomy hours. The results presented are compared with the existing electrification solution based on the operation of the local APS. In this context, the target of the analysis described is to define the optimum configuration of the integrated PV-ESS electricity generation solution that minimizes the energy production cost and maximizes the penetration of the available solar energy in the local energy balance.

Following, a parametrical analysis considering the solar irradiance levels and the major parameters of the local economy is carried out. Concerning the solar irradiance influence, two cases are considered. The first examining the electricity generation cost variation in relation to the PV rated power and the second in relation to the energy autonomy (from d_o=2h to d_o=24h). In the first case, a direct comparison of resulting costs between high and medium-high solar irradiance levels is investigated. In the second case, low and high capacity factors "CF_{PV}" for the PV-units employed are encountered. Taking also into account the important role of the local economy factors, representative parameters including the State subsidy "γ", the local market capital cost "i" and the annual escalation rate of the electricity generation cost "e" are investigated in accordance to the following.

During the last twenty-year period, the E.U. and country members remarkably subsidize investments in the electricity production sector, under the precondition of clean energy production, e.g. installation of PV generators. According to the existing legislation[35] there is a considerable subsidization by the Greek State for PV-based applications on the basis of the current development law (e.g. 3299/04) or the corresponding National Operational Competitiveness Program. Actually the subsidy percentage "γ" equals to 45%-55% of the total investment cost. However, the selected values refer to either highly subsidized investments (γ=50%) or more moderate ones (γ=30%), while a non-subsidization scenario is also included (γ=0%).

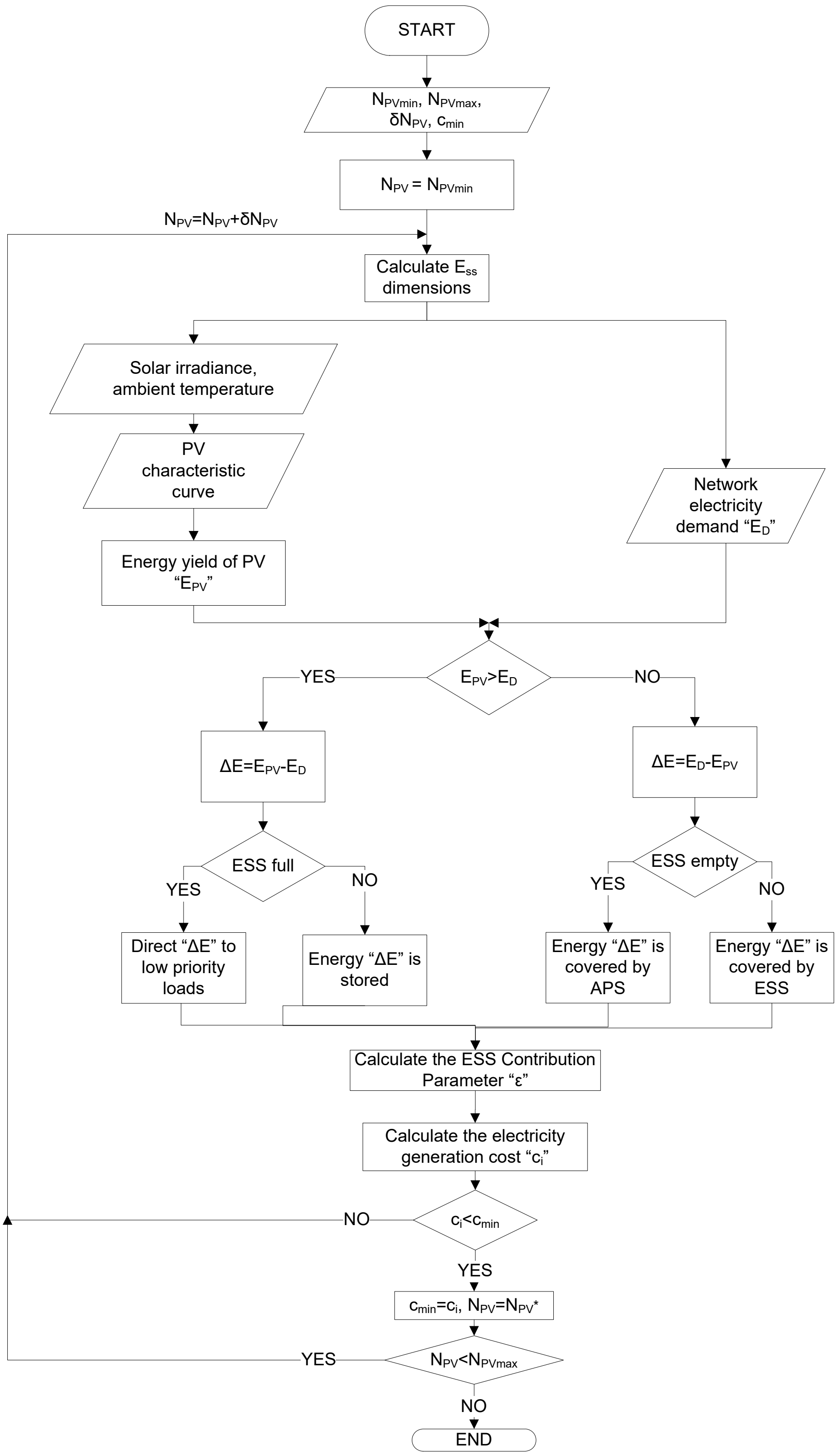

Figure 6: "ENERGY STORAGE" numerical algorithm

On the other hand, the local market capital cost "i" mainly depends on the local market economic wealth and more precisely on the existing investment opportunities, the timing of repayment, the risk of investment etc. In addition, the value of the capital cost varies with the inflation rate of the economy, in order to obtain positive inflation-free capital return. The selected variation range is presently selected to be from 8% to 13%.

Finally, the term electricity price escalation rate "e" is hereby used to describe the annual rate of change of the electrical energy (and power) market prices, as according to the existing legislative frame (Laws 2244/94 and 2773/99), the electricity generated by the PV stations is finally sold to the local network at a price directly related to the corresponding retail price. The respective variation range takes values from 2% to 8%.

In this context, the representative values selected for each of the parameters are examined in relation to the variation of energy autonomy provided by the storage system (from d_o=2h to d_o=24h). Note that the cases investigated and corresponding to different autonomy periods only regard minimum cost solutions.

5. Discussion of Application Results

5.1 Energy Contribution Results

Regarding the low energy autonomy scenarios (i.e. d_o=2h or d_o=6h), one may observe in figure (7) the considerable contribution of the photovoltaic electricity generation to the local consumption, which increases almost linearly with the PV generator's rated power, bounded only by the ESS storage capacity. In case that additional PV power is installed, a considerable photovoltaic energy surplus is encountered, even exceeding 60% of the PV generator annual yield. On the other hand, the contribution of the existing APS is significantly decreasing as the PV generator rated power increases, thus the minimum APS participation percentage is also defined by the storage capacity of the ESS. Finally, the contribution of the ESS is mainly controlled by the desired hours of energy autonomy, so the lowest of values realized is due to the low "d_o" values examined.

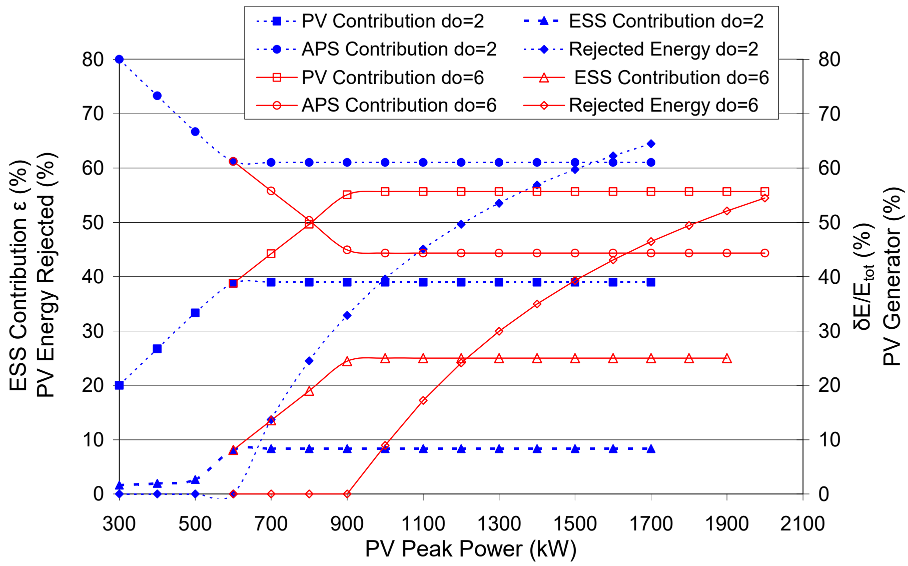

Figure 7: Distribution of the main parameters of a PV-ESS configuration in case of low energy autonomy

Subsequently, for high energy autonomy configurations (i.e. d_o=12h or d_o=24h) similar linear contribution of the PV generator is demonstrated (figure (8)). As it may result, a PV generator of rated power higher than 1700kW may practically cover the entire electricity consumption of the system if it collaborates with a Na-S battery system of d_o=24h. Due to the increased storage capacity of the proposed ESS, the corresponding PV energy surplus is quite low, while for maximum energy autonomy configurations, it may be zeroed. At the same time the contribution of the existing APS is minimized, however the electricity production cost of similar solutions must be taken into account.

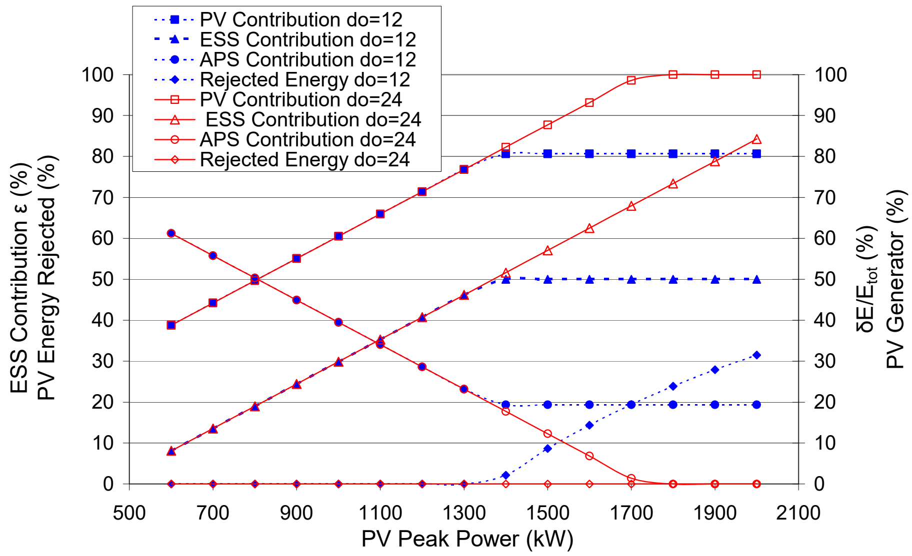

Figure 8: Distribution of the main parameters of a PV-ESS configuration in case of high energy autonomy

5.2 Electricity Generation Cost Results

Accordingly, in figure (9) one may find the electricity generation cost of the proposed installations as a function of the rated power of the PV-generator "N_{PV}" and the storage capacity "E_{ss}" of the ESS. More specifically, for all "d_o" values analyzed there is a minimum electricity production cost configuration. Note also that almost all of the PV-ESS configurations tested are more cost-effective than the existing APS solution. Finally, the minimum electricity production cost solution is realized for high energy autonomy, i.e. d_o=24h, at 0.18€/kWh (in present values), almost 0.13€/kWh less than that of the APS solution. On top of this, if this solution is adopted, the contribution of the local APS is practically zeroed, eliminating also the environmental and macroeconomic impacts related to the oil consumption[24][25].

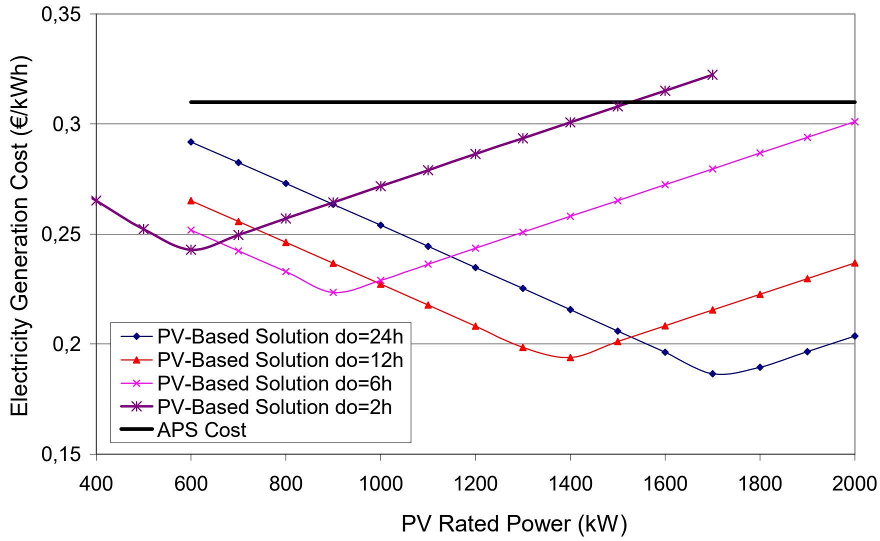

Figure 9: The electricity generation cost of representative PV-ESS configurations in present values, for various PV generator peak power values and energy autonomy combinations (high solar potential case and Na-S batteries as ESS)

Applying the proposed analysis for all the available energy storage technologies of Table I, it is important to mention that for a typical energy autonomy scenario (d_o=12h) all the PV-ESS combinations are definitely more cost-effective than the operation of the existing APS, figure (10). The minimum electricity generation cost technologies are the pumped-hydro (PHS), the Na-S batteries and the Flow batteries for the bigger islands, while for very small islands one may also examine the installation of a system of Flywheels. On the other hand, the Lead-acid batteries' solution, although commonly applied, present the higher long-term cost value, while the Fuel Cells technology may be more attractive for bigger installations. However, one should also keep in mind that the maturity of the Lead-acid batteries[36] both ensures the safe operation of the proposed system and implies minimum variation of cost parameters (see also Table I).

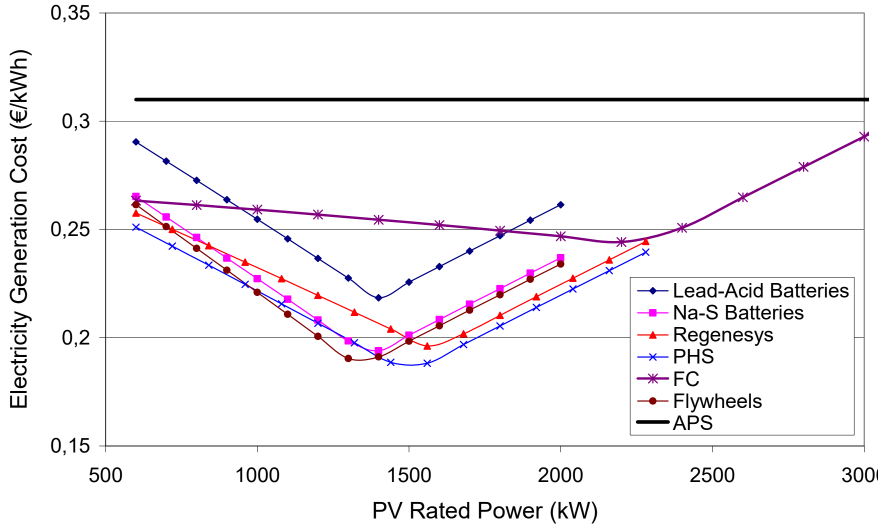

Figure 10: The impact of the energy storage technology applied on the electricity generation cost of a PV-ESS configuration (small remote island case and d_o=12h)

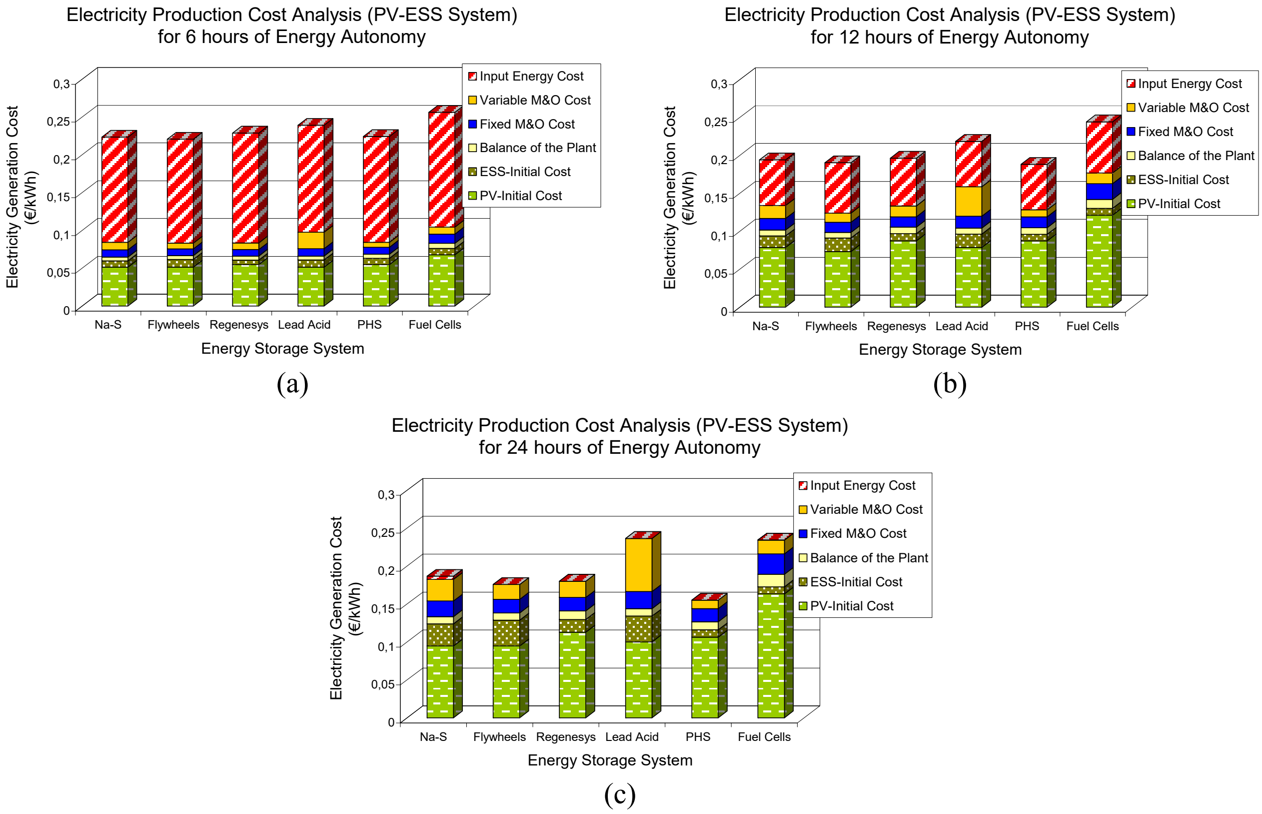

Figure 11: Electricity generation cost analysis for several optimal PV-ESS configurations and variable energy autonomy scenarios

In order to obtain a better idea concerning the major components of the electricity generation cost, one may observe in figures (11a), (11b) and (11c) the cost analysis of optimum configurations for every ESS examined and for three energy autonomy scenarios investigated (i.e. from d_o=6h to d_o=24h). According to the information available, for low "d_o" values the electricity production cost is determined by the input energy cost (taken equal to the production cost of the local APS at 0.31€/kWh) and secondly by the PV generator initial cost. Besides, as the energy autonomy increases, the input energy cost gradually decreases, being zero for d_o=24h. At the same time there is a remarkable PV-station initial cost increase, while one should not disregard the ESS initial and variable M&O cost augmentation. Finally, although for low energy autonomy a clear advantage cannot be obtained, for the medium and the high energy autonomy cases, PHS and Na-S constitute the most attractive options since the Flywheel solution is not applicable for such high energy storage cases.

5.3 Influence of the Solar Irradiance Levels

Regarding the influence of the solar irradiance levels (figures (9) and (12)), a first conclusion supports the increase of electricity generation cost when referring to the medium-high solar potential case. If the same output power of photovoltaics is to be considered, the lower annual utilization owed to the more moderate solar potential implies the need for greater energy inputs. Moreover, a drift of lines to the right in figure (12) means that for a given electricity generation cost and a selected energy autonomy, greater PV-power must be installed. For example, while the most cost effective solution for the d_o=6h case is found in the range of 600kW to 1000kW for the high solar potential, for analogous cost-effectiveness to be achieved by the moderate solar irradiance case, 800kW to 1200kW must be considered. Note however that the electricity generation cost expected is relatively higher.

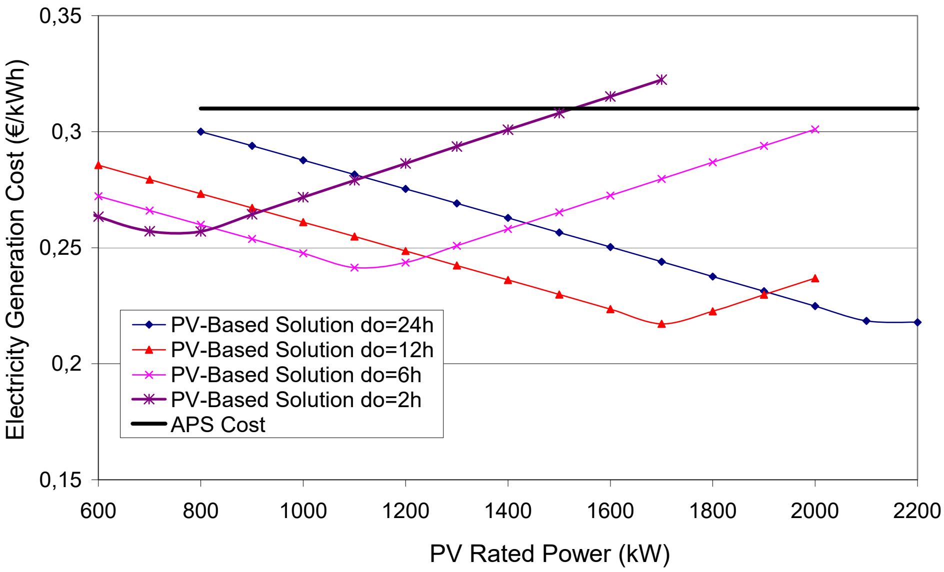

Figure 12: The electricity generation cost of representative PV-ESS configurations, for various PV generator peak power values and energy autonomy combinations (medium-high solar potential case and Na-S batteries as ESS)

Furthermore, the results obtained in respect of the minimum electricity generation PV-Na-S solutions for both a high local solar potential and a respective lower, are demonstrated in figure (13). As already seen, a more moderate local solar potential, described by analogous capacity factors "CF_{PV}" for the employed photovoltaics, implies higher electricity generation costs.

The lower annual utilization of the PV-generator requires greater PV-power for the same energy yield, therefore suggesting both greater initial and maintenance costs. In fact, for the d_o=2h case, the overall increase (6%) of the generation cost is only owed to the PV-unit. An analogous increase observed for the d_o=6h case also involves the rest of cost components, apart from the ESS remaining constant for each of the high-low potential pairs examined. Similar behaviour is demonstrated by the d_o=12h and

d_o=24h cases as well. Nevertheless, for d_o=24h, no input energy should be considered, however a significant ESS initial cost must be taken into account.

Overall, a cost difference of 5% to 15% between the high and the medium-high solar potential depends on the energy autonomy selected. Besides, it becomes evident that even for medium-high local solar potential the resulting minimum cost configurations remain cost-effective, clearly outmatching the local APS operation.

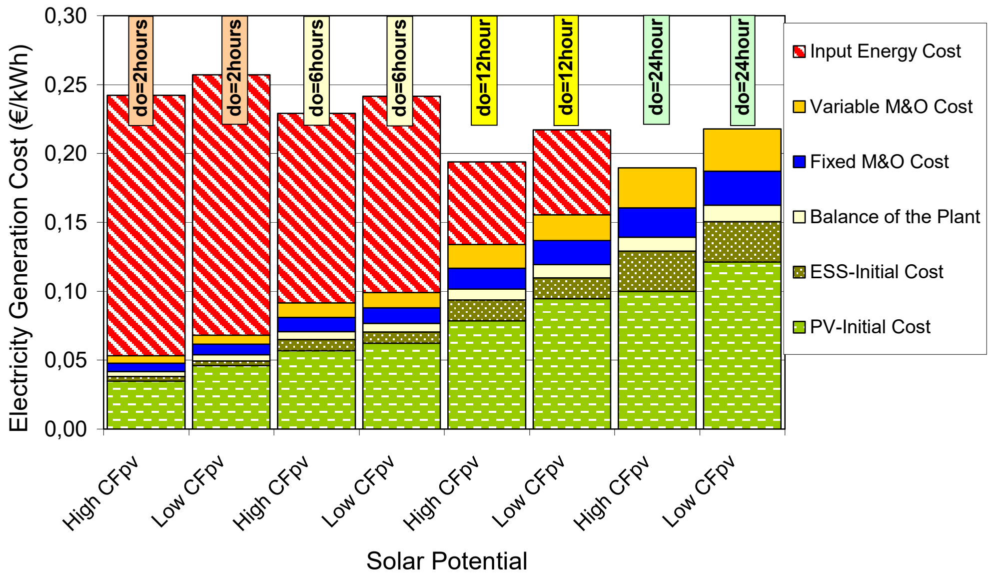

Figure 13: The impact of solar potential on the electricity generation cost of a representative PV-ESS configuration applied to a remote small island

5.4 Influence of the Local Economy Parameters

In figure (14), one may obtain the influence of the representative local economy parameters - previously seen- on the life-cycle electricity generation cost of the optimum PV-Na-S solutions. For the complete analysis, both low and high energy autonomy cases are investigated.

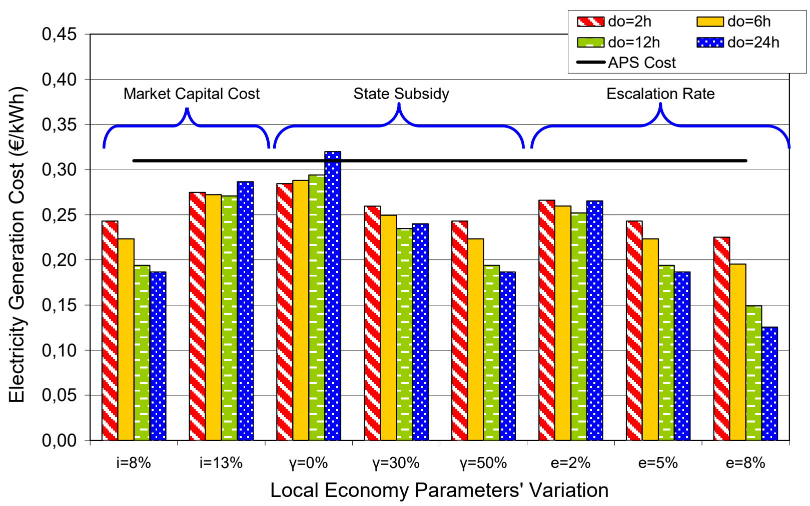

Figure 14: The influence of the local economy parameters' variation on the life-cycle energy production cost of the PV-ESS configuration, in relation to energy autonomy

Regarding the local market capital cost, an increase of 5% for the "i" parameter suggests analogous increase for the PV-ESS electricity generation cost, ranging from 13% for the d_o=2h case to 53% for the d_o=24h case. The reduction of cost following the increase of energy autonomy for the i=8% case, is also valid for i=13%, up to d_o=12h of autonomy. Afterwards, between d_o=12h and d_o=24h, a slight cost increase is encountered. Finally, although for i=8% the cost effectiveness of optimum configurations is evident, for i=13% the resulting cost tends to equate with the APS values.

Concerning the State subsidy parameter, in the case of γ=50%, a constant decrease with energy autonomy is encountered. On the other hand, an opposite behaviour is observed for the non-subsidy scenario where the generation cost increases, even exceeding the corresponding APS value for d_o=24h. Concerning the moderate scenario of 30%, the decrease noted up to d_o=12h is not the case for the d_o=24h case presenting a slight increase. What is interesting to observe is that for the combinations of d_o=24h with γ=30% and of d_o=2h with γ=50%, similar resulting generation costs are encountered, thus supporting the d_o=24h solution even for milder subsidy values. Overall, the increase noted in the electricity generation cost presents a comparatively milder variation for low autonomy, while the opposite is valid for high autonomy (even 70% increase between γ=0% and γ=50% for the d_o=24h case). With regards to the non-subsidy scenario, the PV-ESS generation cost is either approaching or even exceeding the local APS operation cost (for d_o=24h), thus emphasizing on the significance of State subsidies.

Finally, the influence of the electricity price mean annual escalation rate "e" is also investigated. For low values of "d_o", by increasing "e" from 2% to 8%, a slight cost reduction is caused. On the other hand, significant reduction is expected for higher autonomy periods. In fact, for the d_o=24h case, a reduction of more than 200% is noted between e=2% and e=8%. Concerning the e=8% case, a significant decrease of electricity generation cost observed from d_o=2h to d_o=24h approximates 46% with the respective value for e=5% estimated at 25%. Regarding the case of e=2%, a slight decrease noted up to d_o=12h is reversed for d_o=24h of energy autonomy provided by the ESS.

6. Conclusions

In the current paper, an integrated methodology is developed in order to determine optimum PV-ESS configurations for the electrification of small remote islands. The criteria for the adoption of the proposed solution encounter maximum energy contribution of the PV-ESS configuration and electricity generation cost lower than the respective of the local APS. In this context, the developed methodology is applied in small remote island typical cases. Both mature and more novel energy storage technologies are tested, while the influence of significant factors such as the solar irradiance levels and the local economy main parameters is evaluated.

From the results obtained, the electricity generation cost of the proposed solution is in most cases significantly lower than the marginal production cost of the existing autonomous power stations, even reaching 0.18€/kWh, i.e. 42% less than the respective value for the APS operation. Significant change of results is caused by the variation of both the solar irradiance values and the local economy factors. Note however that only in few cases of maximum energy autonomy "d_o" and zero State subsidy "γ" did the electricity generation cost of the PV-ESS exceed the respective of the local APS.

Under the given circumstances, the proposed photovoltaic-energy storage configuration is thought to comprise a cost-effective energy scheme, able to solve the urgent electrification problem of the numerous small, remote islands. Apart from the financial gains expected, the increased reliability regarding the security of supply along with the minimization of atmospheric pollution and macroeconomic cost due to the imported oil, should also be considered.

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EVALUATION OF THE WIND-CAES ENERGY SOLUTION FOR THE AEGEAN ISLANDS. THE CASE OF A PRIVATE WIND PARK IN CRETE

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Abstract

The electrification of autonomous electrical networks in the Aegean Archipelago Islands is principally undertaken by local, oil-dependent power stations. On the other hand, the exploitation of wind energy in the specific area is subject to strict constraints that lead to the rejection of substantial amounts of wind energy. In order to deal with the situation encountered, the concept of energy storage systems collaborating with renewable energy sources suggests an appreciable solution that may compensate wind energy rejections. In this context, the adoption of a Wind-Compressed Air Energy Storage (Wind-CAES) configuration on the island of Crete, where the installation of a natural gas terminal is under schedule, is presently investigated. To achieve maximum potential profitability, the provision of guaranteed amounts of energy to the local electricity grid during peak demand hours is examined. Next, to ensure that the system will be able to fulfil its peak demand energy requirements, the CAES unit will be able to shift its mode to the typical gas turbine cycle as well. A simulation algorithm considering the potential operational modes of the proposed configuration comprises the mathematical tool for the CAES system optimum sizing. Based on the criterion of maximum wind energy exploitation, optimum configurations selected are afterwards financially evaluated. From the results obtained the viability of the proposed solution is validated, this supporting the implementation of similar configurations in the rest of Aegean Islands as well.

Keywords: Wind Energy; Energy Storage; Wind-CAES; Aegean Islands; Crete

1. Introduction

Apart from being dependent on conventional fossil-fueled power plants and large amounts of energy imports (e.g. diesel and heavy oil imports), autonomous island networks often present significant electrical grid constraints that hinder the extensive exploitation of wind energy[1]. Due to the operational features of the employed diesel/heavy oil units and the stochastic wind energy production, wind parks operating in similar areas are faced with large amounts of energy curtailments[2][3]. A typical example encounters the complex of islands located in the Aegean Archipelago area, on the eastern side of the Greek mainland. Although most of the specific islands are favored with an excellent wind potential[4][5], the disharmony noted between wind energy production and the respective electricity demand, the stochastic availability of wind energy production previously mentioned and the upper limit on the wind energy penetration -set by the local grid operator-, have led to the depreciation of wind energy in the area[1][2]. As a result, only 10% of the area's electrical energy demand is covered by local wind parks, this illustrating both the decay of wind parks already operating and the opportunity of exploiting a rather appreciable wind potential remaining unexploited.

Meanwhile, a constant annual increase of the long-term electricity generation and peak load demand figures is determined by mean average values in the order of 10%[6]. Given also the high electricity production cost and the environmental impacts, both owed to the oil-based electricity generation, the concept of energy storage systems collaborating with renewable energy sources suggests an appreciable solution that may compensate wind energy curtailments and ameliorate the existing situation. Acknowledging the different characteristics determining the operation of each storage system[7] as well as the need to develop optimum energy configurations that ensure maximum wind energy exploitation, an investigation concerned with the application of a wind-energy storage configuration in the island of Crete is the subject of the specific study.

2. The electrification system of Crete

As far as the electrification system of Crete is concerned, a constant increase of both the electricity generation and the corresponding peak load demand noted is described by mean annual increase rates in the levels of 6% to 7%, this revealing the requirements for the reinforcement of the island's electricity capacity. In fact, according to the latest official data concerning the installed power of Crete[8][9], one may encounter a total of 715MW concerning thermal power plants along with 124.5MW of wind power. Besides, with regards to the most recent announcements concerning the future energy planning of Crete[10], the introduction of natural gas in the local energy balance shall satisfy both electricity and other forms of energy requirements. More specifically, an LNG terminal will be installed in the area of Korakia, in the north side of the island (capacity of 160,000 to 180,000 m^3). A call for the installation of 500MW (two combined cycle units, 250MW each) operating on natural gas further promotes the initial rescript of the Greek Regulatory Authority for Energy[11] regarding the installation of a 250MW combined cycle power plant in Crete by 2012, recently licensed by the Greek Ministry of Development.

In the meantime, although a significant power share is covered by the existing wind parks, a satiation met in the corresponding installations may be directly related to the wind power limitations present in Crete, similar to the ones of autonomous island networks[1]. More specifically, the local network's confined ability to absorb fair amounts of wind energy along with the existing scepticism concerning the profitability of wind power investments[12] have encaged the future of wind energy on the island. In fact, according to the latest official data[10], the 2006 wind energy generation only reached 335GWh, equal to 38% of the onshore wind energy potential of the island, estimated at 900GWh/year[13].

3. Proposed Energy Solution Configuration

Considering the high amounts of wind energy rejections noted in Crete, even reaching 13% of the wind parks' annual energy yield[2], and the future supply of natural gas, the application of the Wind-Compressed Air Energy Storage (Wind-CAES) solution is currently investigated. In this context, in order to achieve maximum potential profitability for the proposed configuration, the provision of "agreed" amounts of energy to the local electricity grid during peak demand hours is examined.

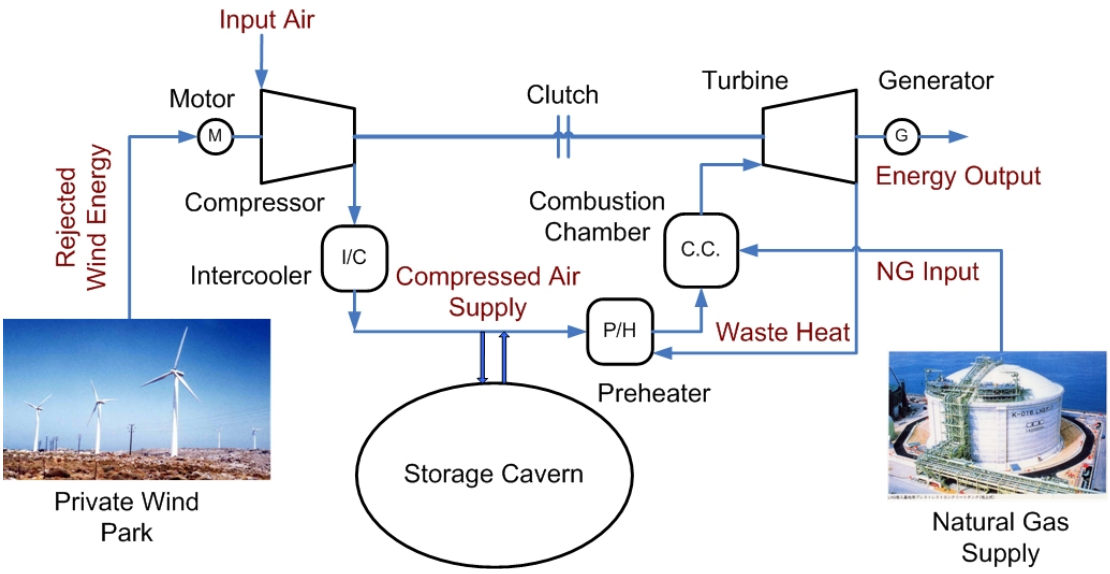


Figure 1: The Wind-CAES proposed configuration

More specifically, the proposed configuration (figure (1)) is based on a dual mode CAES system, i.e. a clutch is used to shift the unit to the compressor-turbine cycle. In this way, when the amounts of compressed air stored in the cavern cannot satisfy the commitment of the guaranteed amounts of energy, the system mode shifts from the CAES cycle to the respective classical cycle operation. Actually, the proposed solution main components include the following (figure (1)):

- One or more existing wind parks, total rated power "N_{WP}", suggesting an annual wind energy curtailments' potential equal to $E_{wrej} = \sum_{t=1}^{8760} N_{wrej} \cdot \Delta t$, with "$N_{wrej}$" being the hourly ($\Delta t$=1h) wind energy rejection.
- A compressor used in order to pressurize air into a storage cavern by exploiting the wind energy surplus via the use of a motor, the former rated power being "N_{cr}".
- A gas turbine, "N_{To}" being its rated power, operating either coupled with the compressor (compressor-turbine cycle) or by utilizing the amount of compressed air inside the cavern (CAES cycle). Coupled with an electrical generator ("N_{gen}","η_{gen}"), the amounts of guaranteed electrical energy may be delivered.
- An air storage cavern/tank of a given energy and volume capacity, "E_{ss}" and "V_{ss}" respectively, able to at least satisfy the guaranteed energy requirements for the hours of energy generation "d_o" per day, i.e. "$N_{To} \cdot d_o \cdot \eta_{gen}$".
- The balance of the system components (BOS) including an intercooler used to cool down the air pressurized before entering the cavern, a recuperator used to preheat the air released by the cavern before entering the combustion chamber, a combustion chamber used to heat up the mixture of compressed air and natural gas and allow the gas turbine to operate, a natural gas storage tank in order to meet the fuel requirements of the installation, etc.

4. Sizing methodology of the CAES component

Regarding the specific case study, the problem to be solved investigates the provision of agreed amounts of energy by the Wind-CAES configuration, on a daily basis, during peak load periods, e.g. from 12:00 to 15:00. For this purpose, the energy surplus deriving from selected wind parks, rated power 25MW, is presently used (figure (2)). As one may see, a significant rejection of wind energy may be encountered, even reaching 150MWh on a daily basis. Further, although a lack of wind energy rejections during the summer period is evident, the configuration currently investigated shall ensure agreed amounts of energy during the whole year by shifting to the classical cycle operation (i.e. compressor-gas turbine cycle).

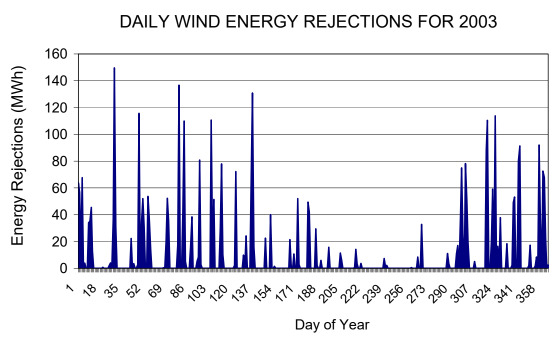


Figure 2: Daily wind energy rejections' profile

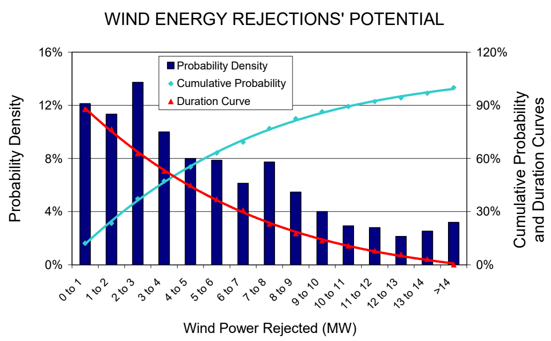


Figure 3: Wind energy rejections' potential on the basis of probability density

Additionally, for the solution of the problem, the following should also be considered:

- If analyzing the wind energy rejections' potential (figure (3)), one should not recommend the use of a compressor power higher than 10-12MW.
- The amount of electricity to be delivered on a daily basis to the local grid, "$E_g=N_{ex}\cdot d_o$", is currently selected to vary between 3MWh and 30MWh, i.e. 1MWx3h up to 10MWx3h.
- The rated power of the gas turbine "N_{To}", called on the one hand to provide the amounts of energy guaranteed per hour "N_{ex}" during the operation of the CAES cycle, and on the other to satisfy both the agreed energy requirements and the compressor's operation during the classical cycle mode, i.e. $N_{T_o} = \max\left\{\frac{N_{ex}}{\eta_{gen}}; \frac{N_{ex}}{\eta_{gen}} + N_{cr}\right\}$
- The sizing of the storage cavern utilized. 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 "$E_g=N_{ex}\cdot d_o$".

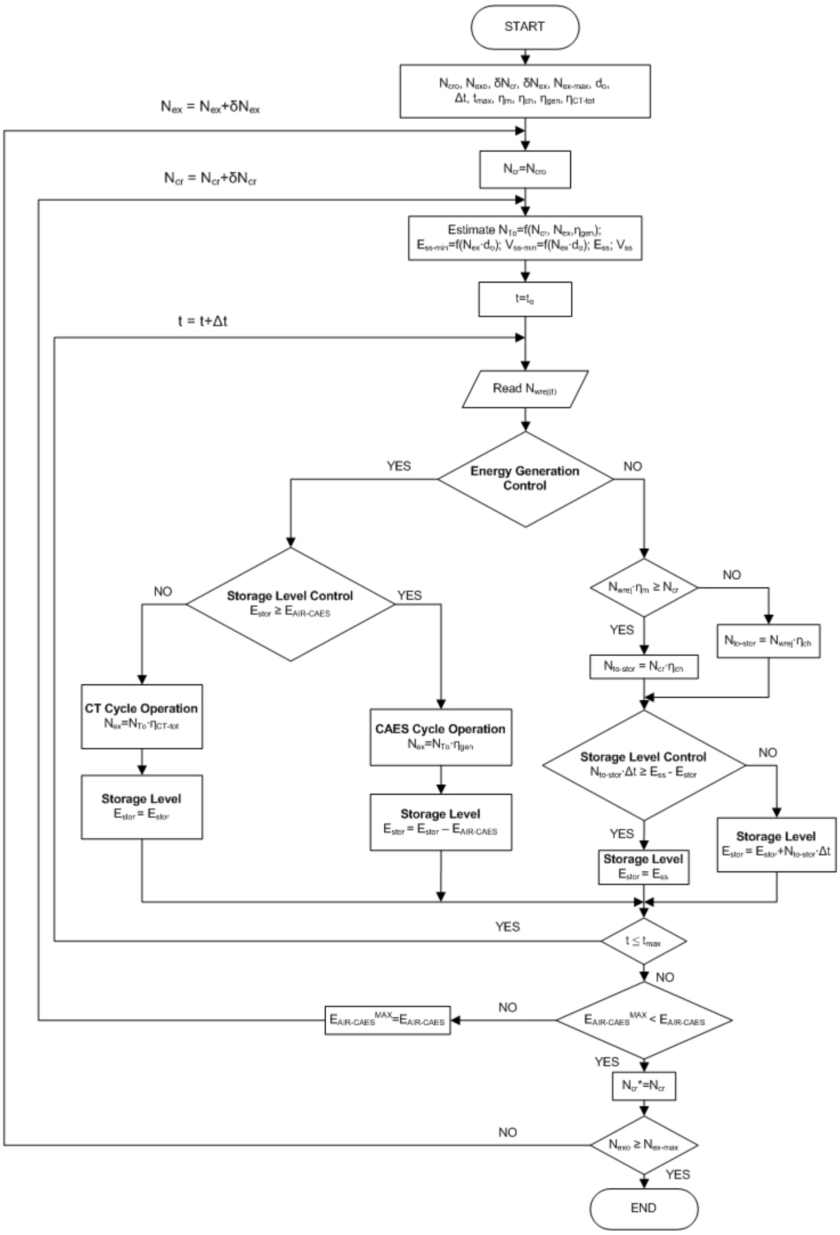


Figure 4: CAES-I Algorithm

Next, in order to proceed to the sizing of the configuration, the following considerations should be taken into account. The two governing parameters of the system used during the sizing procedure are the rated power of the compressor "N_{cr}" and the hourly guaranteed amount of energy "N_{ex}", or equivalently the daily amounts of guaranteed energy "$E_g=N_{ex}\cdot d_o$". To confront similar problems, a computational algorithm (CAES-I), is devised (figure (4)). The developed numerical code is used to carry out the necessary parametrical analysis on an hourly energy production-storage basis. More precisely, for each pair of "N_{cr}" and "N_{ex}", the algorithm is executed for the specific time period selected (currently a year's time) with emphasis laid on obtaining the maximum wind energy surplus exploitation (i.e. when $N_{cr}=N_{cr}*$). If this is not achievable, 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 energy guaranteed "N_{ex}" is selected and the calculations are repeated.

5. Energy Related Application Results

The results presented in the figures following (figures (5)(6)(7)) are concerned with the evaluation of two distinct cases. The first regards a moderate range of energy given to the local grid by the CAES system, i.e. from 3MWh/day to 15MWh/day, and the second a high wind energy penetration case, i.e. from 3MWh/day to 30MWh/day. In both cases the minimum storage volume regarding the highest guaranteed energy scenario, i.e. V_{ssmin}(15MWh/day) and V_{ssmin}(30MWh/day) respectively, is used in order to examine the influence of the storage capacity size on the maximum wind energy exploitation under variable values of guaranteed energy.

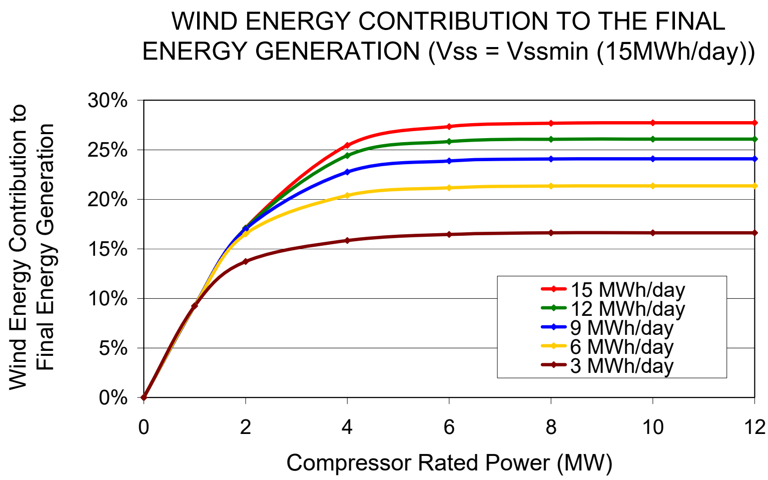


Figure 5: Wind energy rejections' contribution to the final energy generation

In figure (5) one may obtain the compressed air contribution to the final energy generation (or equivalently the exploitation of the wind park energy rejections in order to produce the amounts of guaranteed energy) in relation with the rated power of the compressor utilized. As one may configure, by increasing the power of the compressor utilized, maximum wind energy exploitation is achieved, while the magnitude of exploitation is analogous to the amount of energy provided by the system and the energy storage capacity available.

Following, in figure (6) one may obtain the annual fuel savings deriving from the operation of the CAES unit, as the latter may result from the comparison with the full-time operation on the basis of a classical gas turbine cycle. As it may be noted, higher levels of fuel savings (even 40%) are encountered both when the compressor power increases and when the storage capacity becomes significantly higher than the corresponding minimum "$V_{ssmin}=V_{ssmin}(E_g)$" (e.g. in the cases of 3MWh/day and 6MWh/day one could use minimum storage capacities of 3MWh and 6MWh instead).

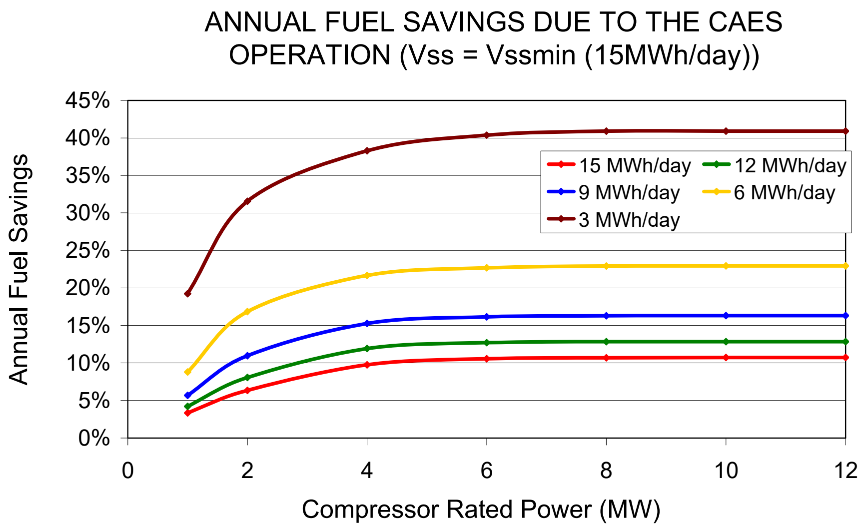


Figure 6: The benefit of fuel savings due to the CAES system operation

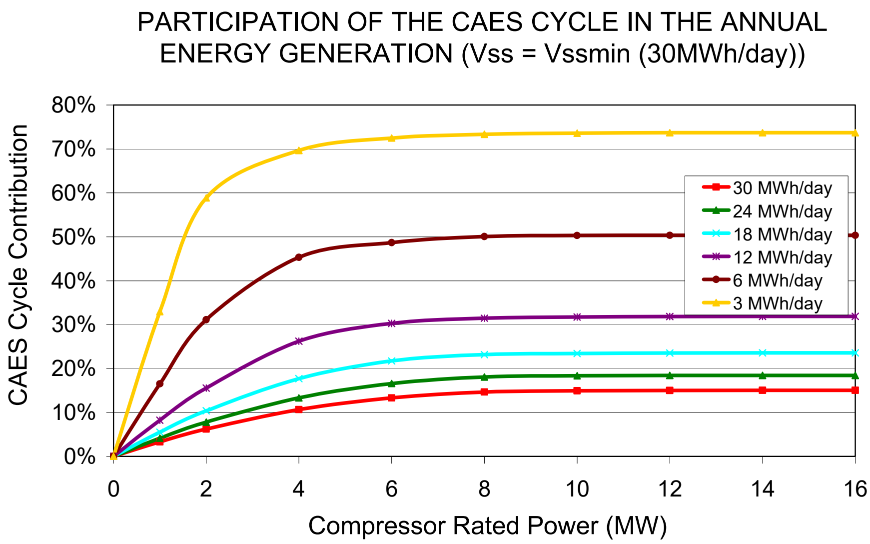
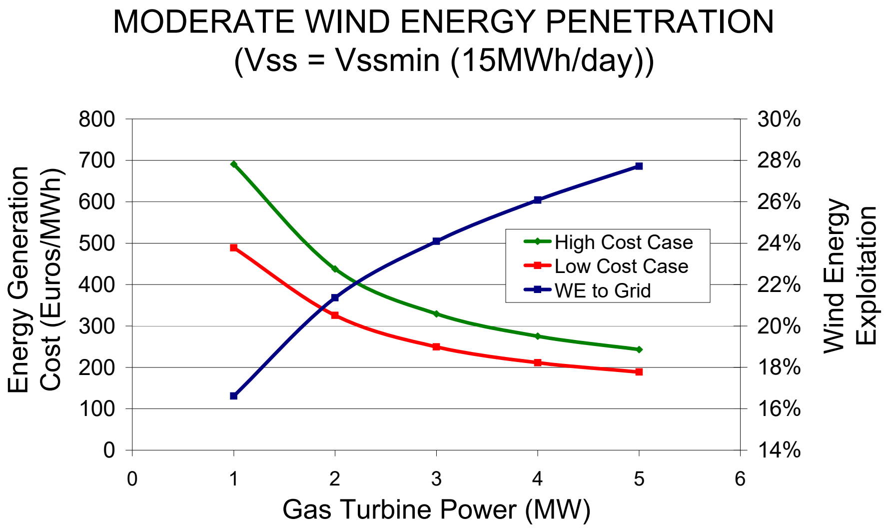


Figure 7: Contribution of the CAES system to the annual energy yield

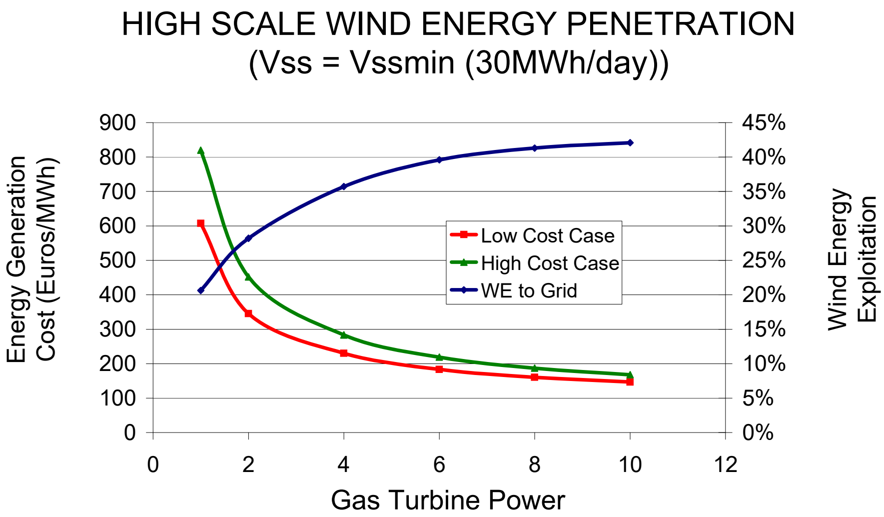
Regarding the higher penetration levels of wind energy, in figure (7), the participation of the CAES cycle in the annual energy generation is presented. More specifically, given a constant storage volume and allowing the increase of energy provided to the local grid, the CAES cycle contribution to the configuration's energy balance is minimized. On the other hand, for the 3MWh/day case, the maximum CAES contribution reaching 75% is directly related with the employment of a storage capacity ten times greater than the corresponding minimum.

6. Financial Evaluation of the Optimum Configurations

Optimum CAES configurations resulting from the criterion of maximum wind energy exploitation for the two cases examined, are next financially evaluated. Considering the model of economic evaluation[14][15] currently applied (see also Appendix), in figures (8a) and (8b) one may encounter the respective electricity production cost versus the contribution of the wind energy exploitation to the final energy production. Besides, in order to face the uncertainty concerned with the capital cost of the system's components, a high and a low cost scenario are currently provided, while zero State subsidies (γ=0%) is to consider for all cases examined.



(a)



(a)

Figure 8: Economic evaluation of the CAES system for moderate (a) and high (b) wind energy penetration and storage capacity utilized

What must be underlined is that the CAES investment becomes financially attractive if the energy production cost is less than the energy purchase price offered by the local operator during the peak demand hours (given at ~250€/MWh for the case of Crete). The higher the sale price of the guaranteed energy to the local grid, the greater the profitability, while, any case given, the guaranteed energy pricing must satisfy the minimum requirements of the configuration's energy production cost.

As one may configure from figures (8a) and (8b), the increase of the gas turbine power implies higher utilization of the storage capacity and suggests lower energy production cost rates, even less than 200 Euros/MWh. Besides, although a high capital cost must be considered, the high scale wind energy penetration implies both greater profitability opportunities and maximum wind energy exploitation (figure (8b)).

Finally, in figure (9) one may obtain the breakdown of the future cost ascribed to the storage system installation and operation after "n" years. As it becomes evident, exploiting an already existing cavern significantly reduces the required investment while providing greater amounts of guaranteed energy implies comparably increased fuel cost requirements.

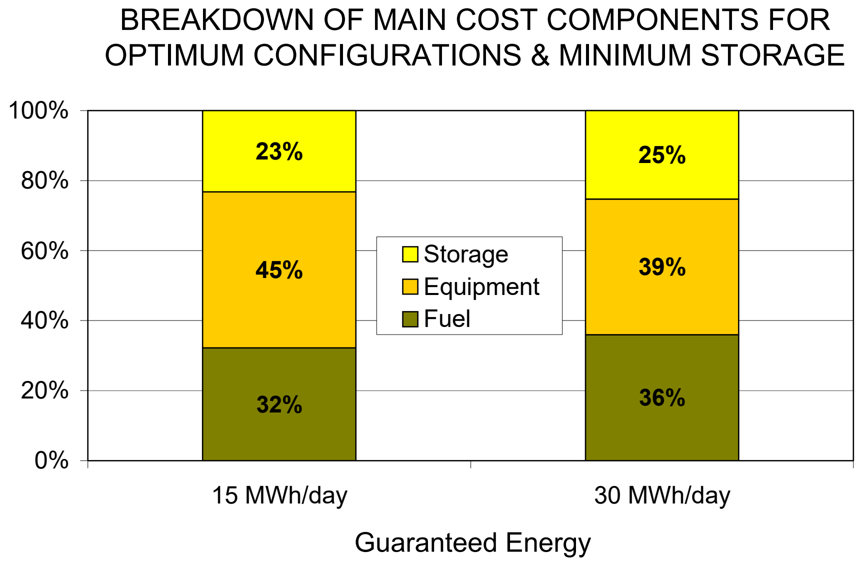


Figure 9: Comparison of the cost distribution for optimum CAES configurations

7. Conclusions

An integrated evaluation methodology developed is able to provide both the optimum sizing of a CAES system under the condition of maximum wind energy exploitation and investigate the proposed system's cost-effectiveness.

From the results obtained, the cost effectiveness of the proposed solution may be validated, while the profitability margins may in several cases imply rather attractive investment opportunities. Benefiting from the forthcoming natural gas introduction and encouraging further wind energy exploitation on the island of Crete, the proposed Wind-CAES configuration is thought to perfectly match the future electricity patterns and requirements of the island.

Finally, considering the potential expansion of the LNG network in autonomous island networks, the support of wind energy storage and the establishment of the Wind-CAES concept in particular aim to support the perspective concerned with increased levels of energy autonomy, cost effective energy solutions and minimization of the electricity generation based pollution.

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APPENDIX

Energy Production Cost Evaluation Model

Having determined the sizing of the CAES system, the corresponding initial cost may be given by equation (A-1)

$$IC_{CAES} = c_e \cdot V_{ss} + c_t \cdot N_{To} + c_c \cdot N_{cr} + C_{BOS} \qquad \text{(A-1)}$$

where the coefficients "c_e", "c_t" and "c_c" correspond to the specific cost (€/m^3 and €/kW) for the construction and installation of a storage tank (if an appropriate storage cavern does not exist) and the procurement of the gas turbine and the compressor sets respectively (Table A-I). Additionally, one should also consider the initial cost for the procurement of the BOS equipment "C_{BOS}".

Next, the future value (after -n years of operation) of the total investment cost of an energy storage installation[14][15] is a combination of the initial installation cost and the corresponding maintenance and operation cost, both quantities expressed in current values

$$IC_n = IC_{CAES} \cdot (1-\gamma) \cdot (1+i)^n \qquad \text{(A-2)}$$

where "γ" is the subsidization percentage by the Greek State and "i" is the capital cost of the local market.

In addition to the initial investment cost one should also take into consideration the input energy cost "C_{NG}", i.e. the cost of fuel supplied to the storage system in order to be able to provide the amount of energy expected. The corresponding fuel input energy cost for a time period of "n" years can be expressed as:

$$C_{NG} = E_{NG-(annual)} \cdot c_f \cdot \sum_{j=1}^{j=n} \left(\frac{(1+e_f)}{(1+i)} \right)^j \cdot (1+i)^n \qquad \text{(A-3)}$$

where "$E_{NG-(annual)}$" is the total annual natural gas consumption expressed in terms of energy content, including both the annual fuel consumption during the CAES cycle operation "$E_{NG-CAES(annual)}$" and the respective during the classical cycle operation "$E_{NG-CT(annual)}$".

$$E_{NG-(annual)} = E_{NG-CT(annual)} + E_{NG-CAES(annual)} \qquad \text{(A-4)}$$

Moreover, the "c_f" coefficient is the specific fuel cost (€/MWh_{NG}), while "e_f" expresses the mean annual escalation rate of the fuel price.

Similarly, the input cost of the wind energy bought from the collaborating wind park should also be taken into account. By considering the portion of annual wind energy rejections "$E_{wrej-(annual)}$" utilized as well as the corresponding purchase price "c_{wrej}" and annual escalation rate "e_{wrej}", the wind power input energy cost "C_{WP}" for a time period of "n" years can be expressed as:

$$C_{WP} = E_{wrej-(annual)} \cdot c_{wrej} \cdot \sum_{j=1}^{j=n} \left(\frac{(1+e_{wrej})}{(1+i)} \right)^j \cdot (1+i)^n \qquad \text{(A-5)}$$

Accordingly, the M&O cost can be split into the fixed maintenance cost "FC_{CAES}" and the variable one "VC_{CAES}". Expressing the annual fixed M&O cost as a fraction "m" of the initial capital invested and assuming an annual increase of the cost equal to "g_{CAES}", the future value of "FC_{CAES}" is given as:

$$FC_{CAES} = IC_{CAES} \cdot m \cdot \sum_{j=1}^{j=n} \left(\frac{(1+g_{CAES})}{(1+i)} \right)^j \cdot (1+i)^n \qquad \text{(A-6)}$$

Concerning the variable maintenance and operation cost "VC_{CAES}", it mainly depends on the replacement of "k_o" major parts of the installation which have a shorter lifetime "n_k" than the complete installation "n_{CAES}".

Recapitulating, the future cost ascribed to the storage system installation and operation after "n" years may be estimated by using equation (A-7).

$$C_{CAES} = IC_{CAES}\left\{(1-\gamma) + m \cdot \sum_{j=1}^{j=n}\left(\frac{(1+g_{CAES})}{(1+i)}\right)^{j}\right\} \cdot (1+i)^{n} + VC_{CAES}$$
$$+ E_{NG-(annual)} \cdot c_{f} \cdot \sum_{j=1}^{j=n}\left(\frac{(1+e_{f})}{(1+i)}\right)^{j} \cdot (1+i)^{n} + E_{wrej-(annual)} \cdot c_{wrej} \cdot \sum_{j=1}^{j=n}\left(\frac{(1+e_{wrej})}{(1+i)}\right)^{j} \cdot (1+i)^{n} \quad \text{(A-7)}$$

For the estimation of the energy production cost of the CAES installation (in present values), one should divide the total cost of the installation "C_{CAES}" with the corresponding total annual energy production "$E_{g-(annual)}$", i.e.

$$c_{CAES} = \frac{C_{CAES}}{E_{g-(annual)} \cdot \sum_{j=1}^{j=n}\left(\frac{(1+e)}{(1+i)}\right)^{j} \cdot (1+i)^{n}} \quad \text{(A-8)}$$

where the electricity price annual escalation rate "e" should also be included. Note that an energy storage investment is financially attractive if the energy production cost value of equation (A-8) is less than the energy production cost of the existing thermal power stations during the periods of peak demand. One should also take into account the additional benefits related to the energy storage system operation, due to the increased reliability of the entire electrical network and the improved quality of the electricity offered.

Finally, some representative values of the various cost parameters mentioned so far may be presented in the following Table A-I.

Table A-I: Representative values for the main cost parameters of the CAES configuration

Parameter	Value
Service period "n" (years)	30
Specific storage cost "c_e" (Euros/m^3)	1,500-3,000
Specific gas turbine cost "c_t" (Euros/kW)	400-800
Specific compressor cost "c_c" (Euros/kW)	400-800
Subsidization percentage "γ" (%)	0-40
Capital cost "i" (%)	8
Fixed M&O coefficient "m" (%)	2
Annual increase of the M&O cost "g_{ss}" (%)	5
Specific fuel cost "c_f" (Euros/MWh)	25-30
Specific rejected wind energy cost "c_{wrej}" (Euros/MWh)	0-15
Fuel price escalation rate "e_f" (%)	5
Rejected wind energy price escalation rate "e_{wrej}" (%)	3
Electricity price escalation rate "e" (%)	5

PART THREE

PHOTOVOLTAIC APPLICATIONS

EXPERIMENTAL VALIDATION OF AUTONOMOUS PV-BASED WATER PUMPING SYSTEM OPTIMUM SIZING

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Abstract

The progress met in the world market of photovoltaics underlines the maturity of investments realized, guarantees the reliability of the technology utilized and designates the variety of applications in covering the energy demands of both stand -alone and grid connected consumers. Concerning stand-alone systems, the incorporation of photovoltaic systems in water pumping applications is thought to be one of the most popular and ideal uses of solar energy exploitation, especially under the common allegation of coincidence between insolation and water demand. In the present study, an attempt to investigate the opportunities of a PV powered water pumping system able to meet additional -apart from the water pump- electricity loads, results in the development of an optimum sizing methodology which is accordingly validated by experimental measurements. From the results obtained, it becomes clear that a properly designed PV-pumping configuration of 610W_p is capable of covering both the electricity (max 2kWh/day) and the water (max 400L/h) management demands of a large variety of remote consumers.

Keywords: PV-Pumping; Optimum Sizing; Experimental Measurements; Remote Consumer

1. Introduction

The progress met in the world market of photovoltaics during the last fifteen years -described by an exponential rate of installed power increase[1], underlines the maturity of investments realized, guarantees the reliability of the technology utilized and designates the variety of applications possible. At the same time, promotion policies and supportive measures undertaken in several countries, especially inside the European Union borders[2], have in many occasions proved to be rather effective[3][4].

Moreover, it is long admissible that photovoltaic technology comprises an advisable solution, able to support applications that cover the energy demands of both stand-alone and grid connected consumers. In this context, the incorporation of photovoltaic systems in water pumping applications is thought to be one of the most popular uses of solar energy exploitation[5][6][7][8]. If also taking into account the direct relation between sunlight and water demand, i.e. the water demand increase being usually analogous to the insolation increase, the implementation of photovoltaics serving the water pumping concept proves to be an ideal energy solution[9][10]. The above mentioned solution may be used in a wide range of applications, i.e. while in North America, Australia and Europe the use of PV-pumping is almost exclusively oriented towards the satisfaction of large agricultures' and rural dwellings' water needs, the need for potable water and small-scale irrigation purposes comprises the main objective for PV-pumping in developing countries[11][12][13][14].

In an attempt to investigate the opportunities of a PV powered water pumping system where the employed PV-panels are also used to meet additional -apart from the water pumping- electricity loads, the Soft Energy Application and Environmental Protection (SEA & Envi-Pro) Lab has managed to design and implement an integrated PV-based autonomous energy production system, figure (1), able to fulfill the above mentioned requirements. The arising need for the PV-based installation proper sizing as well as the accurate determination of the system's energy and water autonomy underline the urgency for a reliable sizing-methodology establishment. In the present study, the sizing methodology developed is accordingly validated by detailed experimental measurements deriving from the long-term operation of the system under investigation. According to the results obtained, the adaptation of the developed methodology may lead to the design of a properly-sized PV-pumping system, capable of both meeting the water demands of a remote consumer and satisfying a certain portion of the additional electrical loads.

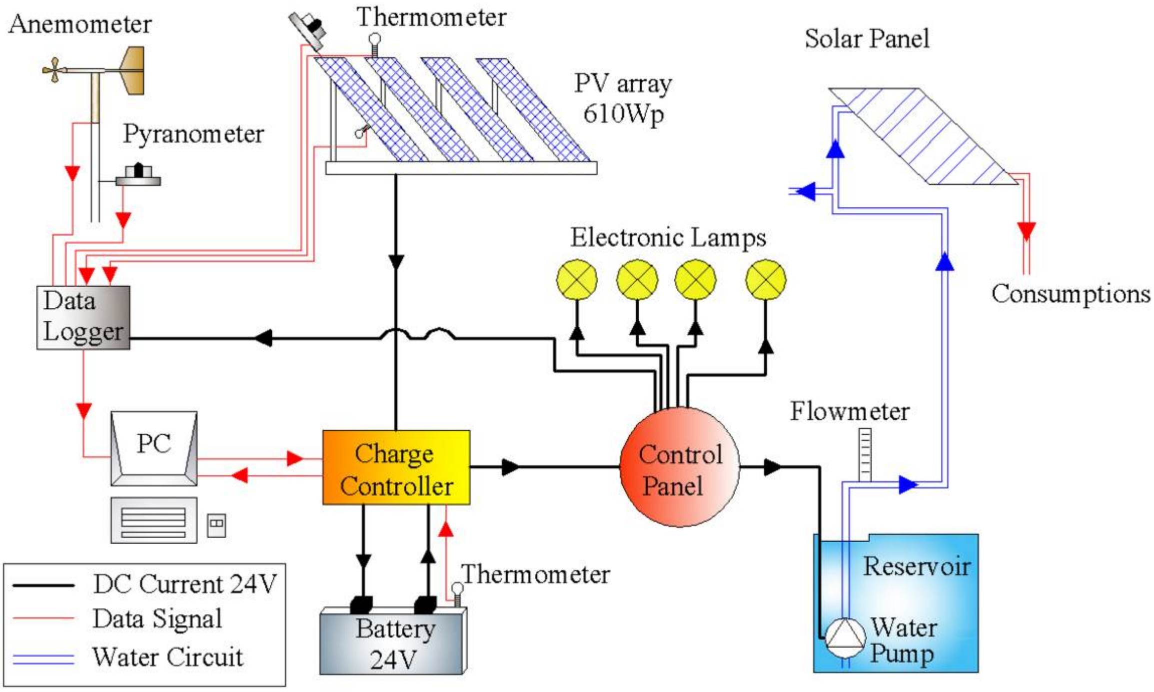

Figure 1: Schematic presentation of the proposed PV-based water pumping installation

2. Description of the Problem

The installation under investigation is used to cover a number of electricity consumption needs as well as the clean water requirement on the roof of the SEA & Envi-Pro Lab building. In fact, a similar installation can meet the electrical load of 2kWh/day (the daily consumption of a rural family in most developing countries) and the corresponding water pumping needs of 400L/day. More precisely, in figure (2) one may find the electricity consumption profile for a typical winter and summer day. As it becomes obvious from the data provided, the PV generator is used in order to cover:

- The electricity consumption of the water pumping system, operating usually between 8pm and 6am to transfer the water for the operation of the solar collectors and the other experimental facilities of the Lab. The rated power of the water pump is N_1=40W.
- The safety lighting of the Lab, mainly operating between midnight and early morning, consisting of two (2) spots of 50W each, i.e. N_2=100W. These spots are also used as low priority loads in cases that a dump load is required for the energy excess appearing.
- The internal lights of the Lab operating between 9 pm and 9 am with a peak load N_3=100W. Note that due to the building design and structure one needs five 20W electronic lights of high efficiency and low consumption.
- The electricity demand of the measurement apparatus, which is however very low, i.e. N_4=1-3W.

At this point one should also note that the entire installation is predominantly used for educational and research purposes, hence its operation may be sometimes slightly different from the one illustrated in figure (2).

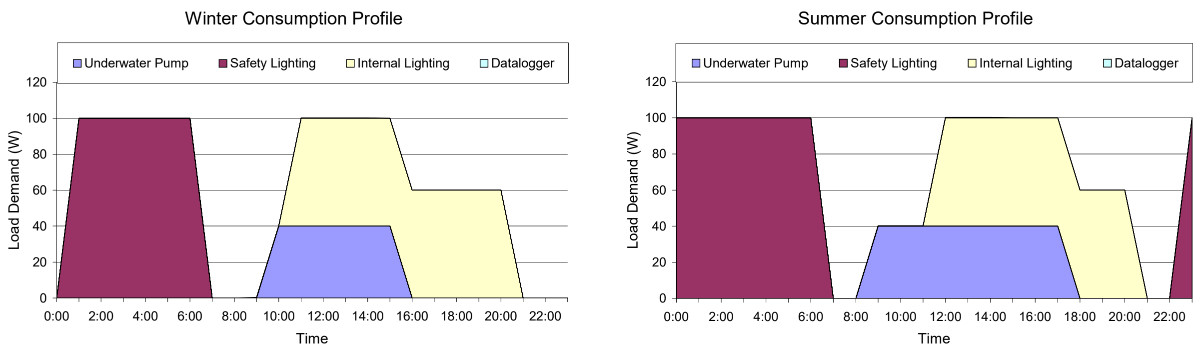

Figure 2: Typical winter/summer electricity consumption profile of the SEA & Envi-Pro Lab

3. Proposed Solution

The proposed installation, according to figure (1), includes:

i. A photovoltaic generator of "z" panels (with "N_o" being the maximum power of every panel) properly connected (z_1 in parallel and z_2 in series) to feed the charge controller with the voltage required.
ii. A lead acid battery storage system able to support "d_o" days of energy autonomy, this being equivalent with a total capacity of "Q_{max}", operation voltage "U_b" and maximum discharge capacity "Q_{min}" (or equivalently maximum depth of discharge "DOD_L").
iii. A DC/DC charge controller of "N_c" rated power, charge rate "R_{ch}" and charging voltage "U_{CC}".
iv. A small water pump of "N^*" kW nominal power, while the corresponding head is "H^*" and the volumetric flow rate is "Q^*".
v. A water reservoir of "V_o" m^3 volume capacity along with the corresponding pipes for the water transportation.

Table I: Technical Characteristics of "LA361 K51S" photovoltaic panel

Main Characteristics	Units	Values
Peak power (N_p)	W	51.0
Voltage at maximum power (U_{mp})	V	16.9
Current at maximum power (I_{mp})	A	3.02
Open circuit voltage (U_{oc})	V	21.2
Short circuit current (I_{sc})	A	3.25
Length	mm	988
Width	mm	448
Thickness	mm	36
Weight	kg	5.9

More precisely, the photovoltaic unit consists of two independent photovoltaic arrays of poly-Si with a total of 12 "LA361-K51S" photovoltaic panels involved (see also Table I). The photovoltaic panels are south oriented while their tilt-angle may be adjusted[15] in a range between 0° and 90° with the help of an appropriately designed and self-constructed mechanism, thus enabling the experimental study of the PV performance under different operational conditions[16]. In order to measure the available solar irradiance[17][18] two "Li-Cor" pyranometers are utilized. Based on the design of the experimental installation, the first pyranometer is placed horizontally while the second is fitted coplanar on the PV-panels in order for the instrument to have the same tilt-angle and orientation. Solar irradiance measurements are also available from the nearby solar radiation experimental station[19]. Finally, the temperature values of the PV panels' surface and the ambient are also measured via properly adjusted thermometers.

Regarding the storage of the electrical energy produced, the system includes four closed-type batteries (12V, 200Ah) characterized by slow discharge rates and high depth of discharge (DOD_L=50%). The batteries are connected in pairs of two, first in series and next in parallel, therefore providing an output voltage of 24V, available to the consumption. As far as the charge controller is concerned, a twofold purpose supports the controller's internal operation as a charge controller in series and the corresponding external as a "Shunt"[20] controller device. Electric switches placed on the secondary direct voltage electric panel of 24Volt DC are connected with the preselected electrical loads.

Finally, the water pumping system employed is comprised by a water storage tank of 500 L and a "Shurflo 9300" underwater pump of 24 Volts DC, placed inside the tank located in the interior of the SEA & Envi-Pro Lab and used to pump water to the building roof thus feeding the solar collectors as well as covering Lab hot water requirements. The water pump is activated by an appropriate current relay placed on the secondary electrical panel as well. In order to ensure the water pump's protection, a floater placed inside the water tank and used to check the tank's water level is ready to switch the pump off when necessary, i.e. when a considerable water level decrease is noted. According to the manufacturer's data, in figure (3) one may find plots showing the operational characteristic (H_A-Q_A) of the water pump as well as the corresponding efficiency (η_A-Q_A) distribution. In the same figure the corresponding characteristics of the water transportation system for minimum and maximum flow rate "Q_A" values are also presented.

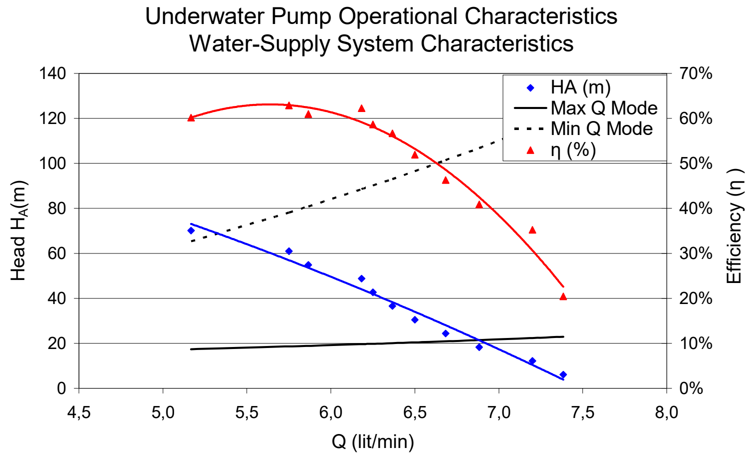

Figure 3: Experimental and theoretical water pump operational characteristics vs. water-supply system characteristics

During the long-lasting operation of the proposed PV-based electricity generation and water pumping system, the following situations may appear:

a) The power output of the photovoltaic generator "N_{PV}" is higher than the power demand "N_D" of the installation (including the water pump). Then the energy surplus ($\Delta N=N_{PV}-N_D$) is stored via the battery and the charge controller. If the battery is full ($Q=Q_{max}$), the residual energy is forwarded to low priority loads.

b) In the case that the power demand is greater than the photovoltaic generator power output ($N_{PV}<N_D$) and the battery bank has enough energy ($Q>Q_{min}$), the energy deficit ($\Delta N=N_D-N_{PV}$) is covered by the batteries via the battery and the charge controller of the installation.

c) Finally, if the power demand is greater than the photovoltaic generator power output ($N_{PV}<N_D$) and the battery bank is near its maximum depth of discharge point ($Q\approx Q_{min}$ or $DOD\approx DOD_L$) an emergency load management plant is activated, otherwise load rejection takes place.

4. Sizing the PV-based Installation

4.1 First Order Analysis

Taking into account the operational characteristics of the PV-panels, one may use a number (integer) of "z_1" panels connected in series in order to provide the necessary voltage "U_{PV}". Note that the value required should take into consideration any voltage drop throughout the installation network, as well as a voltage margin ($\delta U \approx 1.5 \div 3V$) needed for the battery charging. For this purpose[18] one gets:

$$z_1 \geq \frac{U_{PV}}{U_{mp}} = \frac{26}{16.9} = 1.54 \Rightarrow z_1 = 2 \qquad (1)$$

with "U_{mp}" being the maximum power voltage value of the panels used at 50°C.

In addition, for the estimation of the total number of PV-panels needed one should consider the energy requirements by the installation for "d_o" successive days, i.e.:

$$z \geq \max_{i=1}^{i=366-d_o} \frac{\sum_{j=0}^{j=d_o-1} E^D_{i+j}}{\sum_{j=0}^{j=d_o-1} E^{PV}_{i+j}} \quad \text{or for } d_o=2 \quad z \geq \max_{i=1}^{i=364} \frac{E^D_i + E^D_{i+1}}{E^{PV}_i + E^{PV}_{i+1}} \qquad (2)$$

where "E_i^{PV}" is the electricity generation of a PV panel during the time period "i" (e.g. during the day "i") and "E_i^D" is the energy demand of the consumption during the same time-period. More precisely, "E_i^D" (for a given time period "Δt", e.g. Δt=1day=86,400s) is estimated by the following relation (see also figure (2)):

$$E^D_{\Delta t} = \int_{t=0}^{t=\Delta t} N_1(t)\cdot dt + \int_{t=0}^{t=\Delta t} N_2(t)\cdot dt + \int_{t=0}^{t=\Delta t} N_3(t)\cdot dt + \int_{t=0}^{t=\Delta t} N_4(t)\cdot dt \qquad (3)$$

with:
N_1: The power absorbed by the water pump subsystem
N_2: The power demand of the safety lights
N_3: The power demand of the internal lighting
N_4: The power demand of the measurement apparatus

For example, the water pump power demand is depending upon[21][22] the volumetric flow rate requirement of the installation "Q_A", the pressure head "H_A" and the corresponding efficiency "η_A", see also figure (3), thus:

$$N_1 = \frac{\rho \cdot g \cdot Q_A \cdot H_A}{\eta_A} \qquad (4)$$

Using the available long-term solar radiation measurements from the existing solar radiation measurement station[19], see also figure (4), and the typical daily energy consumption profile of figure (2), equation (2) leads to $z \geq 12.6$.

Finally, the lead-acid battery capacity requirement "Q_{max}" can be estimated[23] using equation (5):

$$Q_{max} = \max_{i=1}^{i=366-d_o} \frac{\sum_{j=0}^{j=d_o-1} E_{i+j}^{D}}{\eta_s \cdot DOD_L \cdot U_b} \qquad (5)$$

where "η_s" is the battery total (round-trip) efficiency (e.g. η_s=75%) and "DOD_L" is taken equal to 40% for increased service period of the batteries, although the manufacturer states a value of 50%. Substituting the numerical values in equation (5), for d_o=2days of energy autonomy with zero PV-electricity generation, one gets that Q_{max}=375Ah.

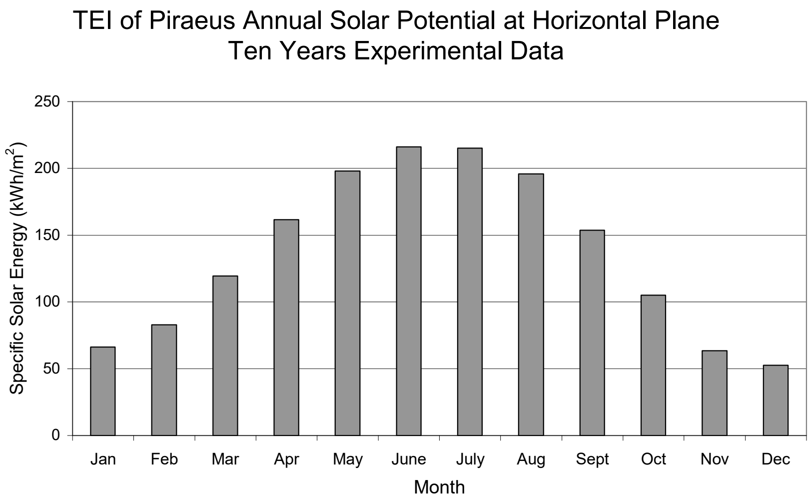

Figure 4: Long-term solar potential values for the SEA & Envi-Pro Lab area

4.2 Second Order Analysis

For increased reliability of the calculation results, when estimating the optimum dimensions of the above described PV-based installation, the authors have also developed an appropriate numerical algorithm "PHOTOV-IV" properly adapted to analyze a typical PV-water pumping installation. Actually, the proposed algorithm is able to investigate in details the energy behaviour of stand-alone photovoltaic systems (including water pumping) for a selected time period. The main steps of this algorithm are (see also figure (5)):

i. For every case analysed, select a "z" and "Q_{max}" pair from a pre-selected value range.
ii. For every time point of a given time period (with a specific time step) estimate the energy produced "N_{PV}" by the photovoltaic generator, taking into account the current solar radiation, the ambient temperature and the selected photovoltaic panel power curve.
iii. Compare the energy production with the remote consumer energy demand "N_D", taking also into consideration the corresponding water pumping needs. If any energy surplus occurs ($N_{PV}>N_D$), then energy is stored to the battery bank and a new time point is examined (i.e. proceed to step ii). Otherwise, proceed to step (iv).
iv. The energy deficit (N_D-N_{PV}) is covered by the energy storage system, if the battery is not near the lower limit ($Q>Q_{min}$). Proceed accordingly to step (ii). In case the battery is practically empty ($Q \le Q_{min}$), the load is rejected for one hour period. If the load rejection number "h" exceeds a pre-chosen limit value "h_{max}" (e.g. h_{max}=0, for the no-load rejection case) the battery size is increased (by a given quantity) and the complete analysis is repeated, starting from step (i).

Following the integration of the energy balance analysis, a (z-Q^*) curve is predicted under a given maximum load rejection "h_{max}" value. To get an unambiguous picture, keep in mind that for every pair of (z-Q^*) the stand-alone photovoltaic system is energy autonomous for the period investigated, excluding a small period of "h_{max}" hours per annum. Finally, the optimum pair may be selected from the resulting (z-Q^*) curve, on the basis of a financial (e.g. minimum first installation cost) criterion of the entire installation[16].

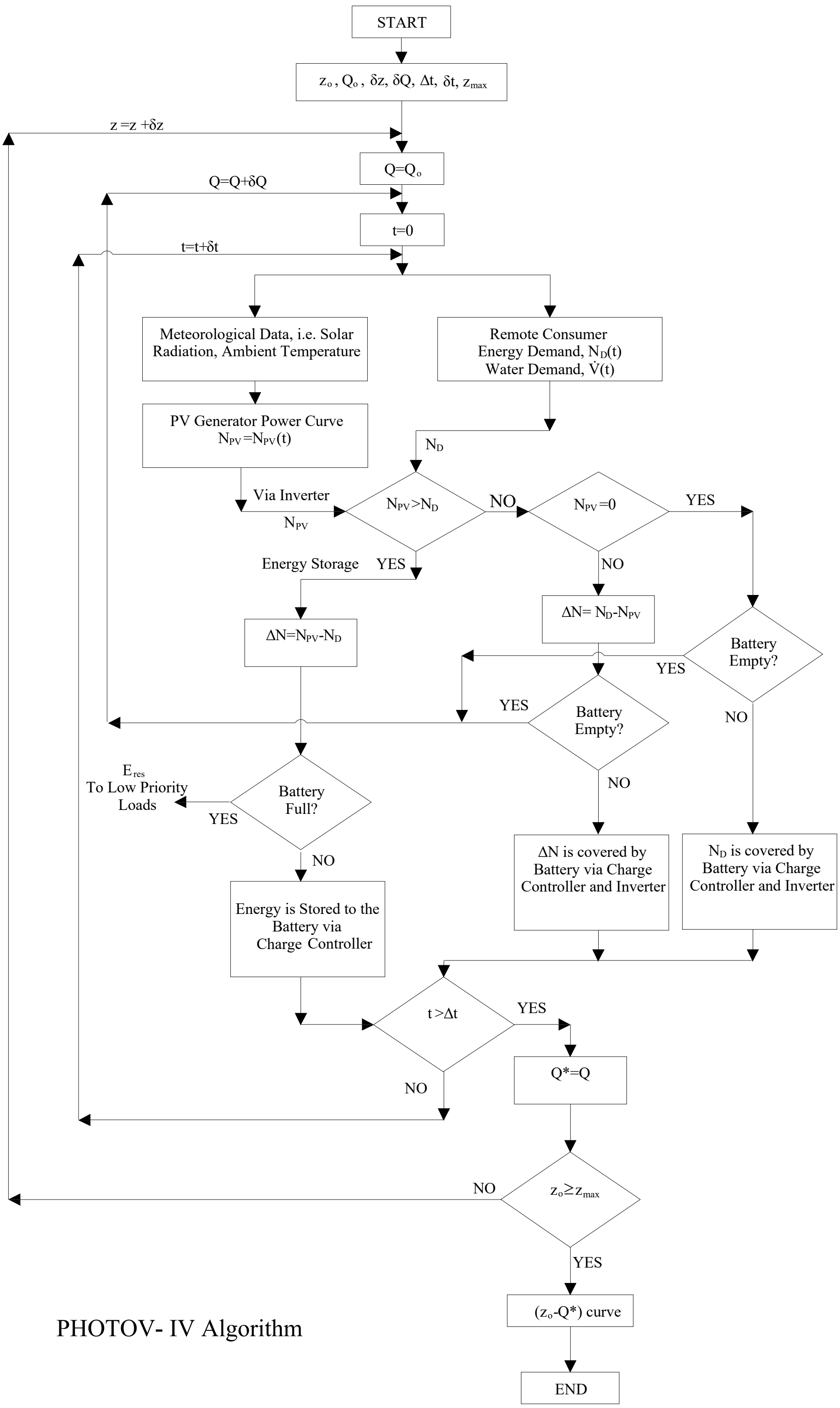

Figure 5: PHOTOV-IV Algorithm

In this context, the above mentioned algorithm is executed for a wide range of "z" and "Q_{max}" pairs (see figure (5)) and for the entire time-period selected (e.g. one year) in order to guarantee desired reliability level operation. More precisely, for every time point investigated, the system energy demand is compared to the photovoltaic generator energy production, including electronic equipment and power line losses. The photovoltaic generator output is defined by the solar radiation at the selected tilt angle "β", the ambient temperature and the manufacturer power curve (I-U). Taking also into account the financial budget of the project the application of "PHOTOV-IV" suggests:

z=11.2 panels and Q_{bat}=413Ah (for U_{bat}=24Volt) at PV generator tilt angle β≈55°.

The above calculated values are comparable with the ones estimated from equations (1) to (5). Thus taking into account the restrictions concerning the PV-generator models and the available lead-acid batteries in the local market, one finally selects z=12 PV-panels of 51W_p each and four lead acid batteries of 12Volt and 200Ah maximum capacity.

5. Proposed Configuration Experimental Evaluation

After sizing the system and creating the PV-based water pumping installation (figure (1)), one should investigate the proper operation of the entire system on a daily basis using detailed experimental measurements. For this purpose one may use the energy balance of the system as well as the charge status of the battery bank[24]. More precisely, in a theoretical approach[18][25], the energy production of the PV-generator results are obtained based on the PV-panels operational map (I-U), the instantaneous solar irradiance "G_T" at the panel surface and the corresponding temperature value "θ", i.e.:

$$N_{PV} = z \cdot U_{op} \cdot I_{op} \tag{6}$$

where the operational voltage of each panel is given as:

$$U_{op} = \frac{U_{PV}}{z_1} = \frac{U_{PV}}{2} \tag{7}$$

The corresponding current value could be estimated using the manufacturer’s (I-U) operational curves taking into account the instantaneous solar irradiance and the panel surface temperature. Note that additional voltage drop is expected due to the installation line losses and the operation of the electronic (control) devices of the stand-alone system. In this context, one may write:

$$I_{op} = I(U_{op}, G_T, \theta) \tag{8}$$

The present analysis, however, utilizes measured values including the voltage and current output of each panel and the entire PV-generator as well, see for example figure (6).

The corresponding load demand "N_D" of the installation is the sum of the existing consumptions, figure (2), i.e.:

$$N_D = N_1 + N_2 + N_3 + N_4 \tag{9}$$

Comparing the results of equations (6) and (9), one may calculate the power surplus (ΔN>0) or the power deficit (ΔN<0) using equation (10), i.e.:

$$\Delta N = N_{PV} - N_D \tag{10}$$

More specifically, during high solar irradiance days there is an energy surplus "ΔE", see figure (7), thus energy is stored to the battery bank leading to the increase of the corresponding "Q" value. On the contrary, during low solar irradiance periods the energy deficit "ΔE" encountered, figure (8), is covered by the system battery bank, under the condition that $Q>Q_{min}$ or $DOD<DOD_L$. Using the detailed experimental values selected from a rather extensive data set of measurements (e.g. figure (9)) and shown on figures (7) and (8), it is obvious that during the high solar irradiance periods the PV-generator easily meets the consumption needs, while, even in low solar potential periods, the entire installation has the capability to cover the corresponding load demand using the energy surplus stored during the previous days.

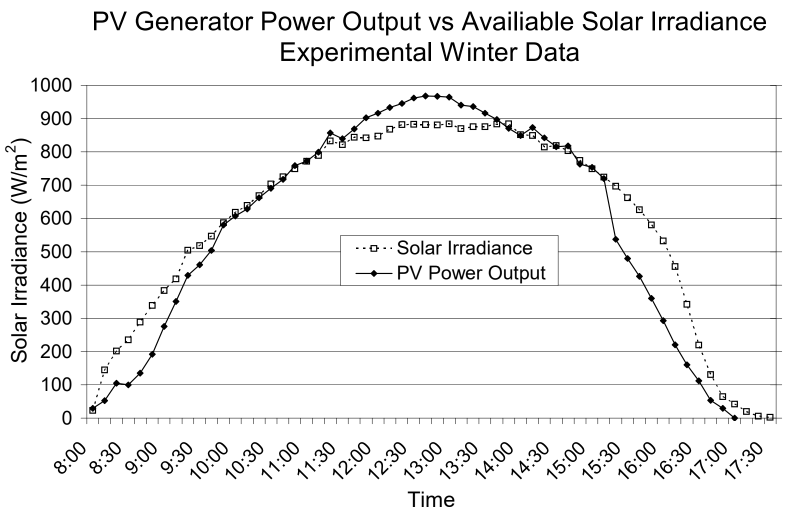

Figure 6: Experimental values concerning the solar irradiance and power output of the proposed PV-generator

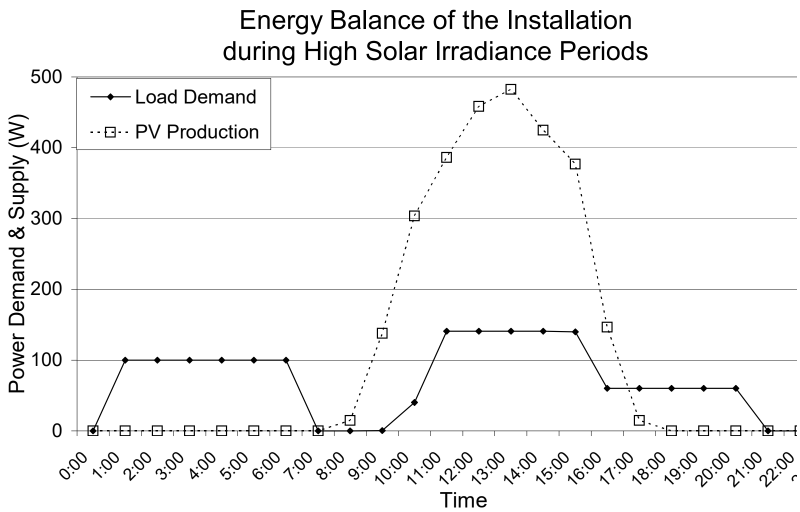

Figure 7: Energy balance of the installation during a high solar irradiance winter day

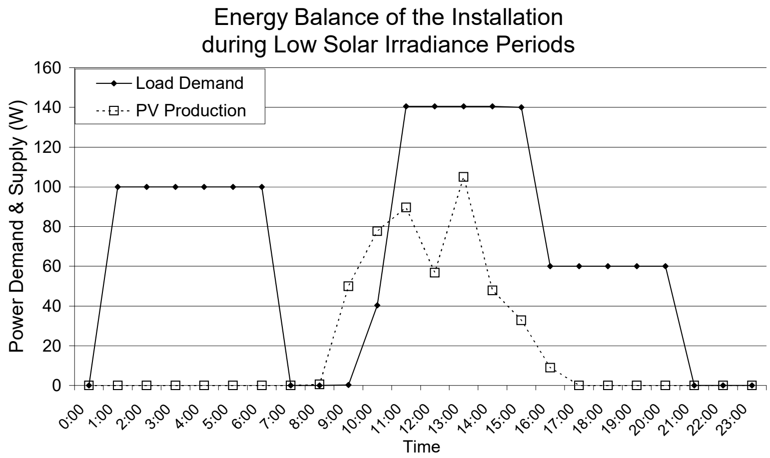

Figure 8: Energy balance of the installation during a low solar irradiance winter day

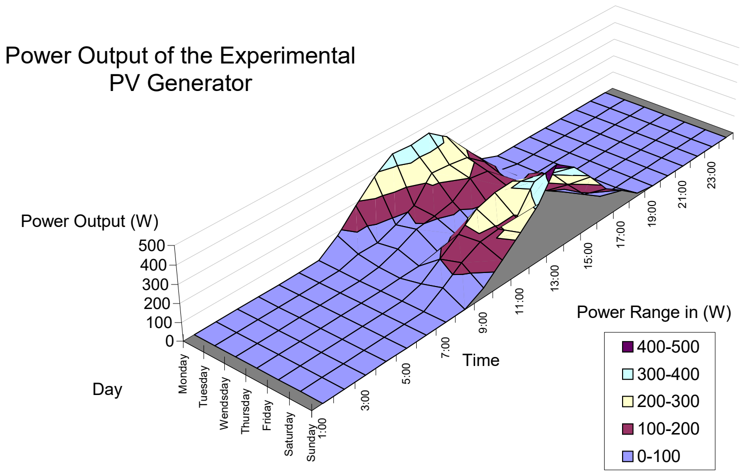

Figure 9: PV-generator energy production for a representative winter week

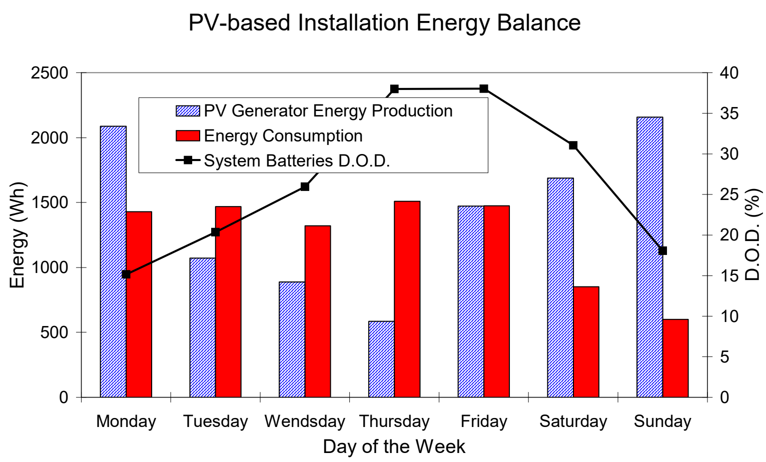

Figure 10: Energy balance of the PV-based installation for a representative winter week

In order to obtain a more comprehensive picture concerning the energy behaviour of the proposed installation one may use the daily-integrated measurements concerning the energy production (figure (9)) and consumption of the system for a representative winter week of the previous year, figure (10).

According to the results obtained, energy deficit is encountered during three successive days of the week, while the other four days (including the weekend) present an energy surplus. It is worthwhile to mention that despite the continuous three-days low solar irradiance values, the system proves its capability to cover the corresponding electrical loads, without violating the pre-selected DOD_L=40% limit. In fact, at the end of the week, the corresponding battery depth of discharge is almost 18% (DOD≈18%<<DOD_L=50%), i.e. $Q=0.82Q_{max}$.

Finally, in order to check the long-term operation of the PV-based water pumping experimental installation, one may analyze its energy balance for the two most unfavorable (from the solar potential point of view) winter months of the year, i.e. during December and January. In this context, figure (11) shows the entire monthly energy balance of the installation. According to the experimental measurements, the vast majority of the photovoltaic generation is consumed either by the internal lights (28% and 31%) or by the water pump (21% and 19%) of the Laboratory. The corresponding energy losses of the system are fairly high (13% and 12%), while the energy surplus values are minimum (5% and 3%), justifying the correct sizing of the experimental installation. Finally, a remarkable (30% and 32%) amount of energy is absorbed by the safety lighting, especially during the winter period. In any case, the system under evaluation did not present any serious energy deficit and the operation of the existing devices showed no remarkable mishaps.

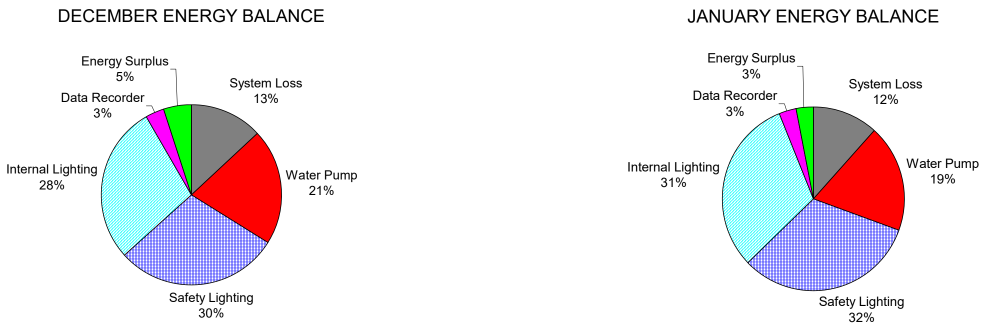

Figure 11: Analysis of photovoltaic generator energy production disposal for December and January

Recapitulating, a detailed energy balance analysis of the proposed system, on the basis of experimental measurements, has been carried out in order to validate the proper sizing of the PV-based installation. In this context, using the operational characteristics of the PV panels and the corresponding water pump (provided by the manufacturers), the following actions have been implemented:

a) Detailed energy balance on daily basis, presenting almost all the possible operational situations, figures (6), (7) and (8). The data used are measured every minute, although ten-minute average values are depicted.
b) Energy balance for a typical (low solar irradiance) winter week demonstrating also the status of the system batteries, proving the energy autonomy of the installation, despite the problematic availability of solar potential during this specific time period, figures (9) and (10).
c) Energy balance of the system for the two most unfavourable months of the year, i.e. December and January, proving the marginal coverage of the energy demand of the installation and hence the appropriate sizing of the PV-generator, figures (11).

6. Conclusions

In the present study, a real world PV-water pumping application has been demonstrated, developed almost exclusively by an educational institute, including the design, the implementation and the experimental validation of the entire system. The specific installation investigated is able to cover the water demand needs for more that five people as well as a remarkable part (30%) of the electricity consumption needs of our Laboratory. Additionally, a reliable methodology for the dimensioning of an integrated stand-alone energy production system, including water pumping, is presented. This technique is applicable in any case that a similar solution is required.

More specifically, for the sizing of the installation, the two-level analysis used is supported by an analytical approach based on both the fundamental equations and the use of a numerical algorithm "PHOTOV-IV" as well. Combination of the results thus obtained, determine the size of the components comprising the PV-pumping configuration. The theoretical calculations have been validated using detailed (taken every minute) long-term measurements, especially for the winter period, where low solar irradiance values are encountered. Based on experimental data concerning the energy balance of the system and the batteries' state of charge, evaluation of the system's performance in terms of load demand level reached, revealed the configuration's effectiveness in both short and long-term operational periods.

In conclusion, it has been proved analytically and experimentally that a proper designed PV-based electricity generator in collaboration with an appropriate energy storage device not only has the capability to cover the electricity needs of remote consumers but also contribute to water pumping in order to meet additional water management needs.

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ENERGY BALANCE ANALYSIS OF A HYBRID PHOTOVOLTAIC BASED SOLUTION FOR REMOTE TELECOMMUNICATION STATIONS

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Abstract

During the last years, autonomous photovoltaic systems have turned into one of the most promising ways to handle the electrification requirements of numerous isolated consumers worldwide. In addition, the mobile telecommunication (T/C) sector has experienced an extremely rapid growth. Taking into consideration that the necessary antennas must be placed -for obvious reasons- at elevated locations, existing in rural areas and mountainous regions, these installations are in several cases far away from the electrical grid. Up to now and in most cases, autonomous supply systems are usually based on diesel-electric generators. However, considering the continuously increasing oil price as well as the significant environmental impacts of oil-based power stations, one may propose an alternative energy solution based on the utilization of contemporary PV panels. In this context, the present study is concentrated initially on investigating the energy needs of the remote Greek telecommunication stations. Accordingly, taking into account the available solar irradiance as well as the corresponding ambient temperature, one may calculate the optimum PV generator rated power and the battery capacity required in order to minimize the imported oil consumption or the life cycle operational cost of the entire installation. The analysis undertaken, for every selected combination of PV generator peak power and battery energy storage capacity, calculates the corresponding oil consumption as well as the corresponding energy generation of the PV generator. Recapitulating, according to the results obtained the proposed solution presents not only financial but also considerable environmental benefits and may be an attractive solution for the energy support of remote telecommunication stations, providing also increased reliability.

Keywords: Battery Capacity; Oil Consumption; Minimization Procedure; Solar Irradiance

1. Introduction

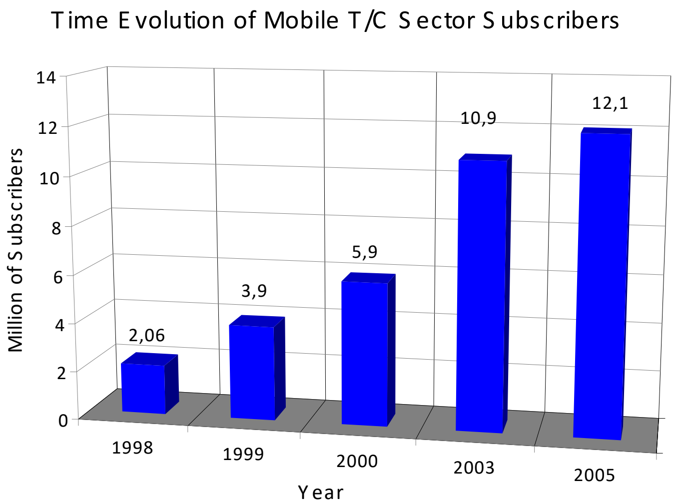

Figure 1: Time evolution of T/C activity in Greece

During the last years, autonomous photovoltaic systems have turned into one of the most promising

Figure 2: Installed PV-based T/C station in Greece

ways to handle the electrification requirements of numerous isolated consumers worldwide. Actually, photovoltaic systems are characterized as noiseless, reliable, durable and expandable depending on one's needs. Moreover, they require minimal maintenance[1][2].
At the same time, the mobile telecommunication (T/C) sector in Greece has experienced an extremely rapid growth (figure (1)) approaching nowadays 5000 T/C stations, 10% of them being not grid connected[3]. Taking into consideration that the necessary antennas must be placed -for obvious reasons- at elevated locations, existing in rural areas and mountainous regions (see for example figures (2) and (3)), it is quite rational that these installations are in several cases far away from the electrical grid. In this context, the energy solution adopted up to now was based on using a diesel-electrical generator in order to cover the corresponding load demand.

The result of this solution is the high operational cost of the remote T/C station, mainly due to the necessary fuel consumed (more than 20tn of diesel-oil annually) by the existing internal combustion engines and the increased maintenance and operation cost. On top of these, the T/C stations operating using diesel engines present additional disadvantages like noise and exhaust gases emission (CO_2, SO_2, NO_x), along with a constant need for fuel transferring.

In this context and considering the high solar potential of Greece as well as the need for environmental friendly energy solutions that would help both Greece to achieve the Kyoto Protocol's targets and telecommunication companies to demonstrate a "green" profile, a considerable effort is made to apply the photovoltaic solution in remote T/C stations. Similar installations are operating in several areas around the world, while recently PV-based T/C stations have also been installed in Greece, figures (2) and (3).

For the encouragement of this strategy, since 2000, mobile telecommunication companies were subsidized in order to install hybrid photovoltaic systems at rural based stations throughout Greece, in the frame of the last two Community Support Programs (1999-2007).

The main target of the present study is to analyze the long-term operation of typical T/C stations all around Greece on an energy balance basis. In fact, special emphasis is laid on the detailed energy balance analysis of the selected configurations, since the proposed methodology has the ability to investigate the energy behaviour of any stand-alone photovoltaic system on an hourly basis (at least). Accordingly, the contribution of the solar energy in fulfilling the corresponding energy demand is examined for several representative PV-based cases. Finally, the main directions for obtaining the optimum hybrid station dimensions are provided, taking also into consideration the energy behaviour of the installations under investigation.

2. Problem Definition

The problem to be solved concerns the energy balance analysis of hybrid PV-based power stations

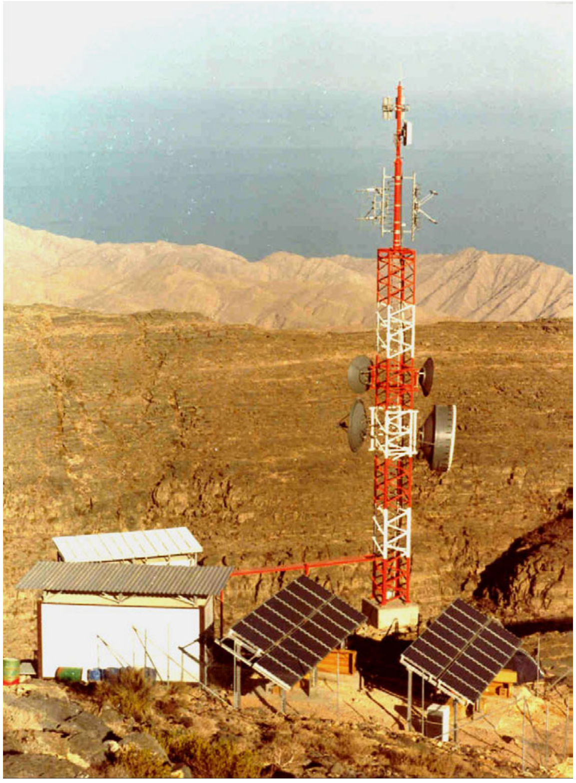

Figure 3: Installed PV-based T/C station in Greece

able to cover the energy requirements of remote T/C stations without load rejections during an entire year period. The proposed solution may be quite attractive in cases where the electrical grid is not available in the area under investigation or the corresponding connection cost is too high[4]. Up to now and in most cases, autonomous energy supply systems are usually based on diesel-electric generators.

However, considering the continuously increasing oil price as well as the significant environmental impacts of oil-based power stations, one may propose an alternative energy solution based on the utilization of contemporary PV panels[5][6]. More precisely, if taking into account the high solar potential of most Greek territories, the photovoltaics' low maintenance requirements and the gradually decreasing price of PV modules, one may propose an appropriate hybrid PV-based solution that may provide clean electricity to the numerous remote T/C stations at a rational life cycle cost and also suggest minimum environmental impacts.

For the analysis of a typical T/C station one needs the energy consumption time distribution of the installation. More precisely, a representative T/C station includes:

- The T/C equipment which operates continuously, while the corresponding load demand varies between 1kW and 5kW.
- The air conditioning machines which are usually the basic energy consumers, mainly during the summer (3kW-5kW), in order to maintain the T/C station temperature between the limits (14°C and 24°C) dictated by the equipment manufacturer for their proper operation.
- The safety lights (e.g. 2x100W), operating at the top of the antenna tower during the night for safety reasons.
- Additional lighting used during the inspection and the service of the T/C station.

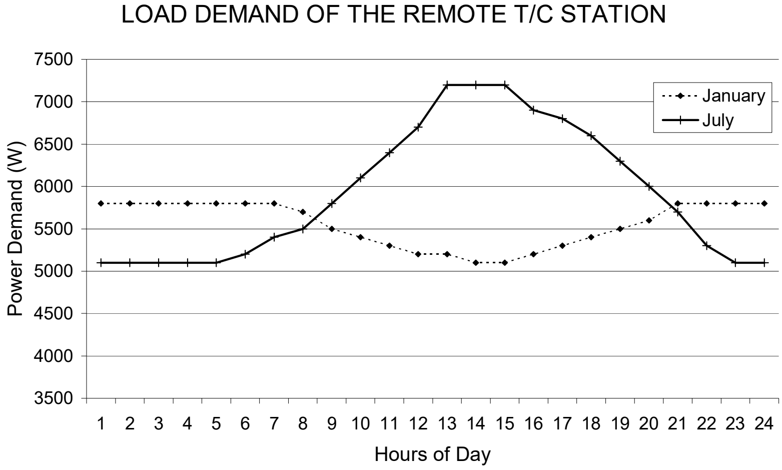

Figure 4: Typical load demand of a T/C station

In figure (4) one may see the load demand of a typical T/C station during the winter and the summer[7]. The T/C station under investigation presents peak load demand of 8kW, while the corresponding annual electricity consumption approaches 46MWh. Note that one needs approximately 20tn of diesel-oil (specific heat content, Hu=40MJ/kg) in order to cover the above mentioned electrical load demand using a 15kW diesel-electric generator (total electricity generation efficiency η_d=21%).

3. Proposed Solution

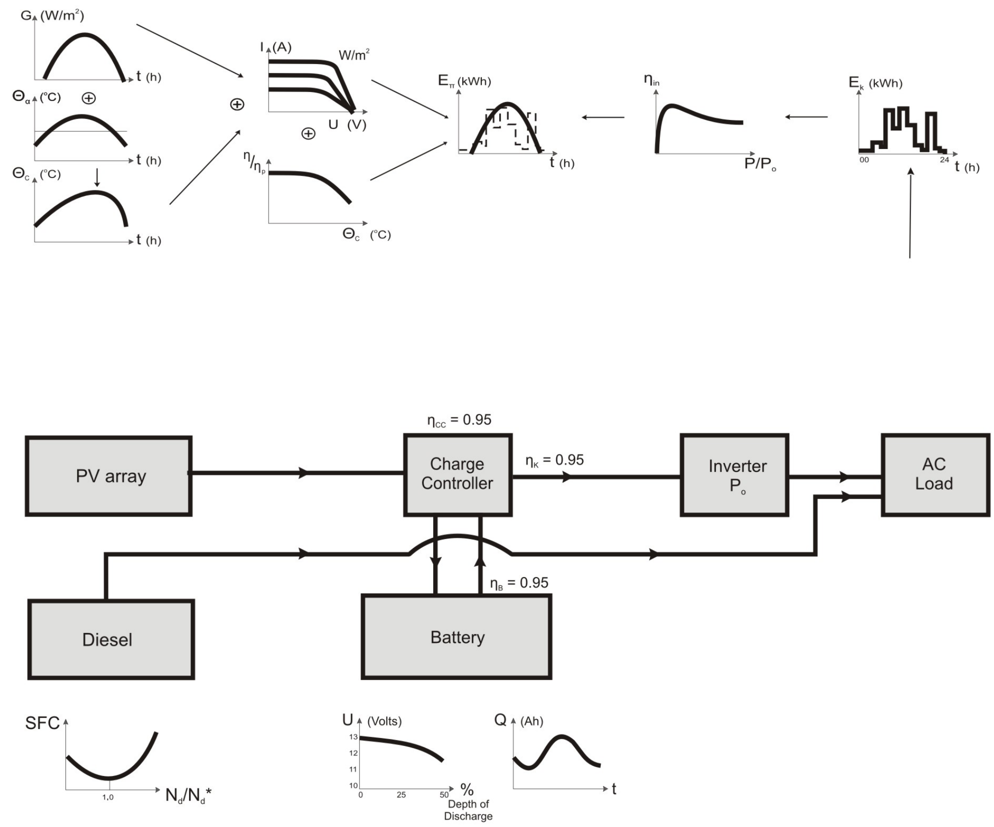

Figure 5: Proposed hybrid PV-based solution

According to the existing experience, a similar solution is based[5][6][8] on a number of PV panels, properly connected to provide the necessary power at a given voltage value, an appropriate energy storage device (usually lead-acid batteries) and a diesel-electric generator selected to operate as a back up engine. More precisely, the proposed (figure (5)) hybrid photovoltaic-based power system is based on:

i. A photovoltaic system of "z" panels ("N^+" maximum power of every panel) properly connected (z_1 in parallel and z_2 in series) to feed the charge controller to the voltage required
ii. A lead acid battery storage system for "h_o" hours of autonomy, or equivalently with total capacity of "Q_{max}", operation voltage "U_b" and maximum discharge capacity "Q_{min}" (or equivalently maximum depth of discharge "DOD_L")
iii. A DC/DC charge controller of "N_c" rated power, charge rate "R_{ch}" and charging voltage "U_{CC}"
iv. A DC/AC inverter of maximum power "N_p" able to meet the consumption peak load demand
v. A small internal combustion engine of "N_d" (kW), able to meet the consumption peak load demand "N_p" (i.e. $N_d \geq N_p$)

where "N_p" is the maximum load demand of the consumption, including a safety margin (e.g. 30%).
During the long-term system operation, the following energy production scenarios exist:

- ✓ Energy (DC current) is produced by the PV generator and sent directly to the consumption via the inverter of the system
- ✓ Energy is produced (AC current) by the small diesel-electric generator and is forwarded to the consumption
- ✓ The energy output of the PV panels (not absorbed by the consumption-energy surplus) is stored at the batteries via the charge controller
- ✓ The battery is used to cover the energy deficit via the charge controller and the DC/AC inverter

For estimating the appropriate configuration of the proposed PV-diesel hybrid system, three governing parameters should be defined: the peak power "N_o" of the PV generator used (or equivalently the number "z" of the panels required, $N_o=z.N^+$), the battery maximum necessary capacity "Q_{max}" and the annual diesel-oil consumption "M_f".

As already mentioned, the present study is concentrated initially on investigating the energy needs of the remote Greek telecommunication stations, while emphasis is given on recording the corresponding energy consumption profile, see also figure (4). Accordingly, taking into account the available solar irradiance as well as the corresponding ambient temperature, one may calculate the optimum PV generator peak power and the battery capacity required in order to minimize the imported oil consumption or the life cycle operational cost of the entire installation. For this purpose the well established[5][6] numerical code "PHOTOV-III" is extended to include the contribution of a small diesel-electric generator. This new numerical code "PV-DIESEL II" is used in order to simulate the energy balance of the proposed hybrid PV-battery-diesel generator based stand-alone installation.

The analysis undertaken, for every selected combination of PV generator peak power and battery energy storage capacity, calculates the corresponding oil consumption as well as the corresponding energy generation of the PV generator. This new numerical code "PV-DIESEL II" can be equally well used to carry out an appropriate parametrical analysis on an hourly energy production-demand basis. In this context, if the annual permitted oil consumption "M_f" is given, the number of PV panels required "z" and the corresponding battery capacity "Q_{max}" may be estimated. More specifically, given the "M_f" value for each "z" and "Q_{max}" pair, the "PV-DIESEL II" algorithm is executed for the entire time-period selected (e.g. one month, six-months, one year or even for three years), while emphasis is laid on obtaining zero-load rejection operation. After calculating the appropriate (M_f, z, Q_{max}) combinations that guarantee the stand-alone system energy autonomy, one may proceed to analyze the proposed PV-diesel hybrid installation energy balance in detail.

The main steps of the "PV-DIESEL II" algorithm are:

i. For every "M_f" value analysed, select a number of "z" panels.
ii. Accordingly select a "Q_{max}" value.
iii. For every time point of a given time period (with a specific time step) estimate the energy produced "N_{PV}" by the photovoltaic generator, taking into account the existing solar radiation, the ambient temperature and the selected photovoltaic panel power curve.
iv. Compare the energy production with the isolated consumer energy demand "N_D". If any energy surplus occurs ($N_{PV}>N_D$), the energy is stored to the battery bank and a new time point is examined (i.e. proceed to step vi). Otherwise, proceed to step (v).
v. The energy deficit (N_D-N_{PV}) is covered by the energy storage system, only if the battery is not near the lower limit ($Q>Q_{min}$). Accordingly proceed to step (vi). In cases that the battery is practically empty ($Q\leq Q_{min}$), the load is covered by the diesel-electric generator and the algorithm continues to step (vi). If the available diesel-oil quantity has been already consumed the battery size is increased (by a given quantity) and the complete analysis is repeated, starting from step (ii).
vi. If the time period analyzed is terminated proceed to step (i), increasing the number of PV panels (z). Otherwise proceed to step (iii).

Following the integration of the energy balance analysis, a (z-Q^*) curve is predicted under a given diesel-oil quantity "M_f". To get an unambiguous picture, keep in mind that for every pair of (z-Q^*) the stand-alone hybrid photovoltaic-based system is energy autonomous for the period investigated, using however a predefined diesel-oil quantity "M_f". Finally, the optimum pair may be selected from every (z-Q^*) curve, on the basis of a specific optimization criterion.

4. Energy Balance Calculation Results

The proposed solution is accordingly applied to the typical T/C station of figure (4) which is located in the Rhodes island. The area solar potential is quite high, especially during the summer period, where the solar energy available at the horizontal plane is higher than 220kWh/mo.m^2, see also figure (6). On the contrary, during winter the values observed are less than 70kWh/mo.m^2.

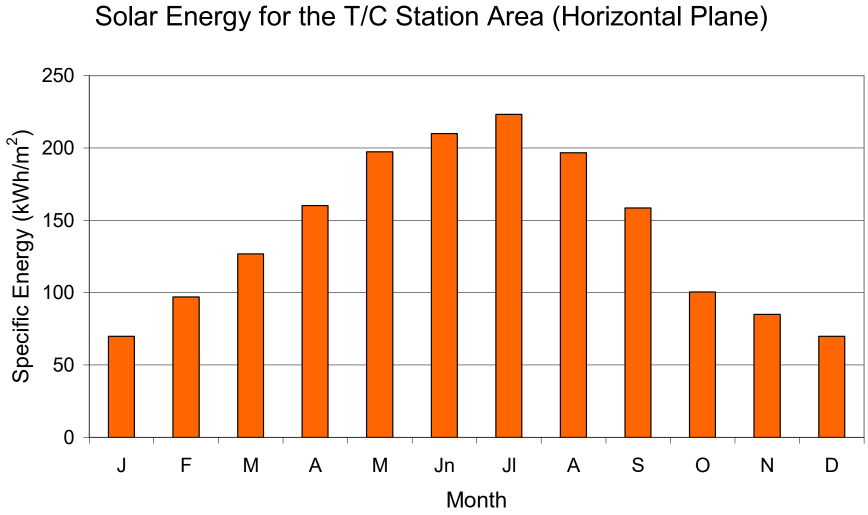

Figure 6: Available solar potential

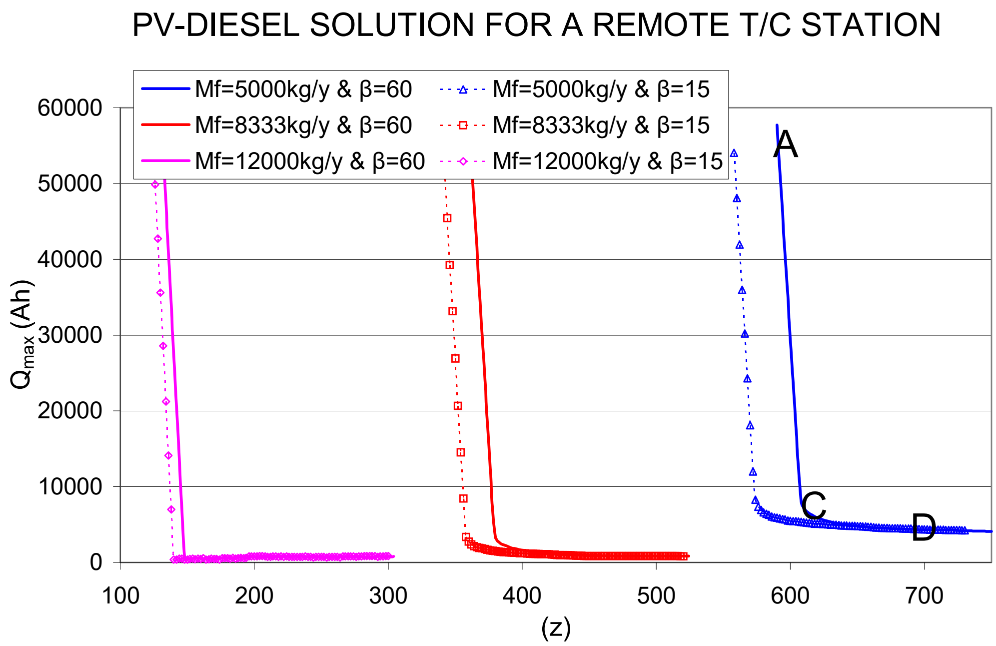

Figure 7: Proposed PV-based solutions

For the current analysis one may use polycrystalline panels of 51Wp, with open circuit voltage equal to 21.5Volt and short circuit current 3.3A respectively, at 1000W/m^2 solar irradiance. For the energy storage process one may use heavy duty lead-acid batteries of 24Volt and DOD_L=75%, while the nominal power of the diesel-electric generator is 15kW and the corresponding minimum specific consumption value approaches 0.300kg/kWh.

Using the calculation results of figure (7) one may find the (Q_{max}-z) curves which under given annual fuel quantity (i.e. M_f=ct) guarantee the energy autonomy of the remote T/C station. For comparison purposes, for each M_f=ct value one may find two curves, one for low panels' tilt angle (β=15°) and one for high panels' tilt angle (β=60°). Taking a closer look at the energy autonomy curves of figure

(7) one may distinguish three separate sub regions. More specifically, in the first part of each (Q_{max}-z) curve one may see a significant battery capacity reduction as the number of PV panels (z) increases (e.g. point A). Accordingly, in the second part of each (Q_{max}-z) curve the battery capacity reduction with the "z" increase is decelerated, thus a reasonable "Q_{max}" decline is encountered as the PV panels number increases (e.g. point C). Finally, in the last part of the (Q_{max}-z) curve the required battery size remains almost constant, independent from the considerable "z" augmentation, e.g. point D.

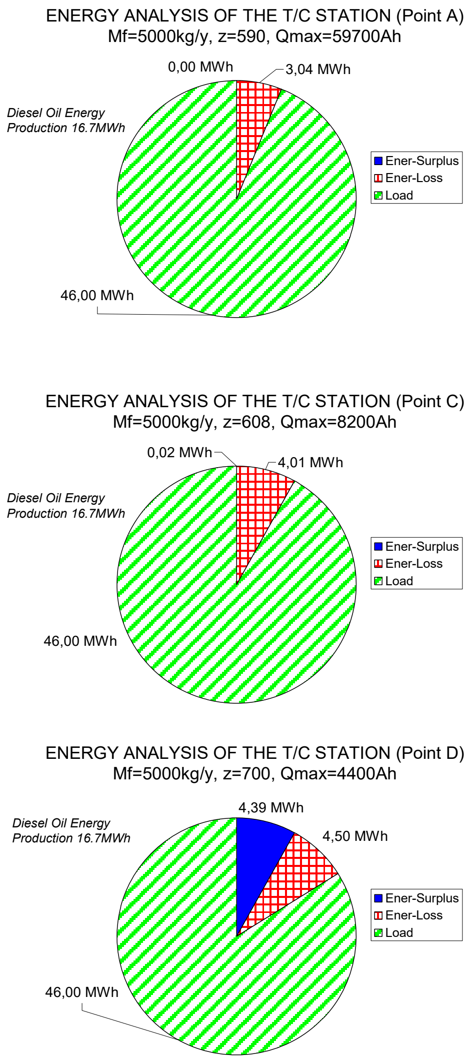

Figure 8: Energy balance analysis

Another important conclusion results by the gradual increase of the available fuel oil quantity. Actually, as "M_f" increases the number of PV-panels required is considerably decreasing, while a remarkable battery capacity reduction is also observed. Besides, for high fuel quantities available the slope of the (Q_{max}-z) curve becomes more abrupt, underlining the limited role of the PV panels on the system energy demand fulfilment. Finally, it is also interesting to mention the impact of the PV-panels tilt angle "β" on the solutions obtained. On the basis of our calculation results one may note that the number of the PV-panels required to cover the energy demand of the T/C station under investigation is remarkably reduced (for constant battery capacity and annual fuel quantity) when "β" takes relatively low values ("β=15°", i.e. near the horizontal plane) in comparison with the "β=60°" solution. This conclusion is in contradiction with the analysis of a PV-battery stand-alone system[5], implemented without the existence of a diesel-electric generator. In fact, in our previous study the optimum panels tilt angle was near the 60°, for the same area investigated. However, this contradiction is not irrational, since in the stand-alone case one seeks the optimum angle for energy autonomy of the system during the winter period, while in the current analysis the existence of the diesel-electric generator (operating as a backup power device during the low solar irradiance periods) leads to solutions producing the maximum energy output, therefore presenting the best operation during summer.

Proceeding now to the energy balance analysis of the proposed solution one may compare in figure (8) the corresponding energy balance results for three representative points (A,C and D) of the proposed solution, see also figure (7). In this context, the solution "A" uses the minimum PV-panels number (z=590) but quite huge lead-acid batteries. As a result there is almost no energy surplus, i.e. the PV-generator and the diesel-electric generator hardly cover the T/C station load demand, while the corresponding system loss is approximately 3MWh. Next, by slightly increasing the number of PV panels (point C, z=608) a considerable battery capacity reduction is encountered. More precisely, for this case the annual photovoltaic production is increased by 1MWh, which is however finally transformed to system loss. As in the previous case, the energy surplus of the system is almost zero. Finally, for the last point "D" examined here, the "z" value is significantly increased, while the battery capacity is fairly reduced. Due to the greater number of PV panels used, the energy production of the system not only covers the T/C station energy requirements and the corresponding system loss but also produces a significant energy surplus that approaches 4.4MWh/year.

Considering the energy balance analysis undertaken, the optimum system dimensions should be expected near the point C area (for a given annual fuel quantity). This estimation is quite rational, since the battery capacity of point C is considerable less than the one of point A and because for point C there is almost zero energy surplus, which is not the case for point D (due to the grater number of PV panels required). As it is obvious, for the optimum sizing of a similar PV-based solution one needs a complete life cycle cost-benefit analysis, taking also into consideration the annual fuel cost, which however is the subject of a forthcoming study.

5. Conclusions

An integrated method, able to define the appropriate dimensions of a hybrid photovoltaic-diesel-battery power station, which is used to guarantee the energy autonomy of a typical T/C station on annual basis, is presented. The results obtained are based on experimental long-term measurements and operational characteristics provided by the proposed system components manufacturers. Accordingly, an extensive energy balance analysis is carried out for several hybrid PV-based configurations and variable annual fuel quantities available. According to the results obtained, the majority of the electricity demand may be covered by the photovoltaic generator energy yield, while the system components energy loss represents 7%-10% in the system energy balance. Finally, the impact of the PV panels tilt angle on the system dimensions is also investigated.

Recapitulating, according to the results obtained the proposed configuration is expected to present not only considerable environmental but also financial benefits and may be an attractive solution for the energy support of remote telecommunication stations, providing also increased reliability and low maintenance needs.

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EXPERIMENTAL ANALYSIS OF THE AIR POLLUTION IMPACT ON PHOTOVOLTAIC PANELS' ENERGY YIELD

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Abstract

Electricity production using photovoltaic (PV) generators is based on a well established technology that can be easily adjusted at existing buildings, thus an increased interest on the application of PV systems in urban areas has been encountered during the last ten years. On the other hand, the atmosphere quality of most Greek cities presents serious problems due to the significant amounts of air pollutants emitted. One of the negative effects of this increased air pollution is the impact noted on the available solar irradiance. The main target of the present paper is to experimentally determine how air pollution affects the energy performance of photovoltaics. For this purpose a systematic and detailed series of measurements, carried out under variable solar irradiance and ambient temperature conditions, utilizes two -statistically checked- identical PV panels located in the same area. More precisely, the current set of measurements is implemented under strictly controlled and forced conditions, in order to relate the amount of the dust existing on the PV panels with the corresponding energy yield. According to the results obtained, one may state that the solid particles existing in the atmosphere of heavy polluted urban areas negatively affect the PV panels' energy production, even leading to up to 30% lower power outputs.

Keywords: Urban Areas; Energy Performance; Solar Irradiance; Controlled Experimental Conditions

1. Introduction

Electricity production using photovoltaic (PV) generators is based on a well established technology that may significantly contribute in covering the continuously increasing electricity demand worldwide[1][2]. Additionally, the electricity produced from PV systems may also contribute to face the peak load demand during midday, especially during the summer. Finally, taking into consideration the minimum maintenance needs and environmental impacts of PV panels as well as the fact that commercial panels can be easily adjusted at existing buildings, an increased interest on the application of PV systems in urban areas has been encountered during the last ten years[3]. More precisely, for high solar radiation areas small PV generators are characterized as economically attractive investments[3][4], especially if the subsidization opportunities by local authorities are taken into consideration.

On the other hand, the atmosphere quality of most Greek cities presents serious problems due to the significant amounts of air pollutants emitted. Actually, the greater Athens area, like most metropolitan areas in the world, presents significant air pollution problems. These problems are the result of high population density and the accumulation of major economic activities in the region, while the intense sunshine contributes to the measured increased levels of photochemical air pollution, especially during the summer months. The air pollution problems are often exacerbated by factors that favor the accumulation of air pollutants over the city, such as topography (basin surrounded by mountains), narrow and deep street canyons. The main characteristics of air pollution in Athens can be summarized as follows: Examination of the temporal variation of the measured air pollutant concentrations in the greater Athens area, since 1984, shows a general decline of the concentrations of certain air pollutants. This decrease is mainly observed in the concentrations of the primary air pollutants, such as Black Smoke (BS). Such a decline is noteworthy, given the increase in population and economic activity that have occurred in the area during the considered time period. Higher concentration values of BS are measured at the downtown monitoring sites[5][6]. Moreover, since 2001, particulate matter with aerodynamic diameter less than 10 μm (PM_{10}) also show high concentrations[7]. One of the negative effects of this increased air pollution is the impact noted on the available solar irradiance[8].

Besides, a remarkable climate change of most densely populated areas has been encountered due to urbanization and industrialization. This change in the city's microclimate may affect the PVs' performance[9]. Note that the performance and the efficiency of the PV panels are strongly related to the available solar irradiance at the panels' surface[10]. According to the existing published work, the decrease of the descending solar irradiance on a PV panel depends on the amount of air pollutants[9]. Based on the above mentioned research, a strong indication that the power output may be lower for PV panels placed in urban areas than for those placed in the rural environment is made, as a result of the sunlight spectral difference caused by the air pollution.

In this context, according to Papayannis et al.[11] the relation between air pollution and solar irradiance at ground level is verified. Furthermore, the authors report that the reduction of solar irradiance reaching the ground can be up to 40% due to the increased air pollution levels and the existing aerosols.

Another climate parameter that affects particle deposition on the PV surface is humidity. As shown in a study by Elminir et al.[12], humidity causes the formation of a dew layer on the cover of the PV panel, thus implying higher levels of adhesion for the dust being deposited on the PV panels.

2. Position of the Problem

According to the research available, a remarkable impact of air pollution on the PV panels' and solar collectors' normal operation is reported during the last years. More specifically, a study concerning the reliability of solar water heating systems indicates that dust and dirt on the solar collector's surface are, in a great matter, the reason for the systems' performance reduction[13]. The relation of dirt on transparent covers of flat-plate collectors was studied initially by Garg[14]. The main results were an exponential relation between dirt and transparency as a function of time as well as the rapid transparency decrease for inclinations less than 30°.

The degradation of PV cells under solid micro-particle influence was investigated by Letin et al.[15]. The equivalent shunt and series resistances of a PV cell are strongly influenced under the impact of degradation, this leading to the reduction of the PV panel's Fill Factor (FF)[16]. In relation to the microparticle structure and the effect of degradation, the decrease of the shunt-series resistances varies[15]. Accordingly, the efficiency of the PV cell is also affected.

In an attempt to simulate the solid particles' impact on the efficiency of existing PV panels, El-Shobokshy and Hussein[17] performed experiments, under strictly controlled and forced conditions, to relate the amount of dust laid on the PV panel to its efficiency. Their main result was that the carbon based dust had a severe impact on the PV panel's efficiency decrease. The results pointed that particles with a diameter of 80μm can reduce the PV panel's short circuit current nearly to 82% when the deposition density is almost 250gr/m^2.

Next, Kappos et al.[18] investigated the relation of natural particle deposition on the PV panel surface to the corresponding voltage output, under various inclinations of the PV panel. They showed that the particle deposition is directly analogue to the inclination of the PV panel. When the PV panel's tilt angle is high, less dust is positioned on the panel surface, leading to a limited decrease rate of the PV power output. The mean decrease percentage of the PV voltage output after three months of observation was 5% for the vertically placed panels in contrast to the 20% of the PV modules placed horizontally.

Recapitulating, according to the available published information, the air pollution impact becomes severe in the urban environment, where human activities enforce the already occurring natural phenomena. More precisely, the dust and solid particles deposition on the PV panels' front side, resulting from the fossil fuel consumption and the construction related activities, may seriously affect the portion of solar energy finally absorbed by the PV cells. Thus, a significant change of the PV panels' current and voltage output should be expected, this leading to a remarkable energy generation decrease and a possible failure of the PV generator sizing.

Figure 1: Experimental photovoltaic installation

The main target of the present study is to experimentally determine how air pollution affects the energy performance of photovoltaics. For this purpose a systematic and detailed series of measurements, carried out under variable solar irradiance and ambient temperature conditions, utilizes two -statistically checked- identical PV panels located in the same area, figure (1). During the experiments, the solar radiation and the ambient parameters along with the PV panels' current, the voltage output and the panels' tilt angle, have all been recorded. From the results obtained one may estimate the power output of the two PV micro-generators.

More precisely, the current set of measurements is implemented under strictly controlled and forced conditions, in order to relate the amount of the dust existing on the PV panels with the corresponding energy yield. During the experiments several types of representative solid particles have been utilized, i.e. carbon, red-soil and limestone based particles.

3. Experimental Procedure

As already mentioned, the basic concept of the experimental procedure is to compare, on a real time basis, the performance variation of two identical PV panels, one artificially polluted with a selected polluter and the other kept clear from any external pollutant. For this purpose, at first, both of the PV panels are cleaned very carefully to remove any dust. Then, the first PV panel is polluted uniformly by spraying water containing the selected polluter. In order for the PV panels to operate at identical environmental conditions, sufficient time is required in order for the sprayed water to evaporate and the PVs' operational temperature to become the same.

Accordingly, measurements of the PVs operational voltage and current are collected along with the solar irradiance both at horizontal plane and at the panels' level. When a significant number of measurements are recorded, the dust deposited on the polluted PV panel is collected in order to weigh it and estimate the mgr of polluter deposited per cm^2 of PV surface "A_c".

Next, the surface of the PV panel is wiped with cotton pieces, which have been previously wet with water, until all of the polluter's mass is removed from the artificially polluted PV panel. Prior to this, the cotton pieces are placed in a paper envelope, and then placed together in a dehumidifier for 24 hours in order for the former to dry out. After the dehumidification procedure, the envelopes containing the cotton pieces are weighed using a precision balance with a minimum of measurable weight of 0.1mgr.

After the collection of the polluter mass by the cotton pieces, the cotton pieces are placed in the envelope, dehumidified for 24 hours and then weighed for a second time. The difference between the initial and final weight "δM" leads to the net weight of the polluter mass.

4. Discussion of Experimental Results

Applying the above described experimental procedure for several limestone specific mass depositions ($\delta m=\delta M/A_c$) one may get the results of figures (2) to (4). More precisely, in figure (2) one may observe the relatively slight power decrease of the artificially polluted panel (δm_1=0.038mgr/cm^2) in comparison with the clean one. Actually, the corresponding power difference is approximately 5W, representing almost 5% of the respective clean panel output.

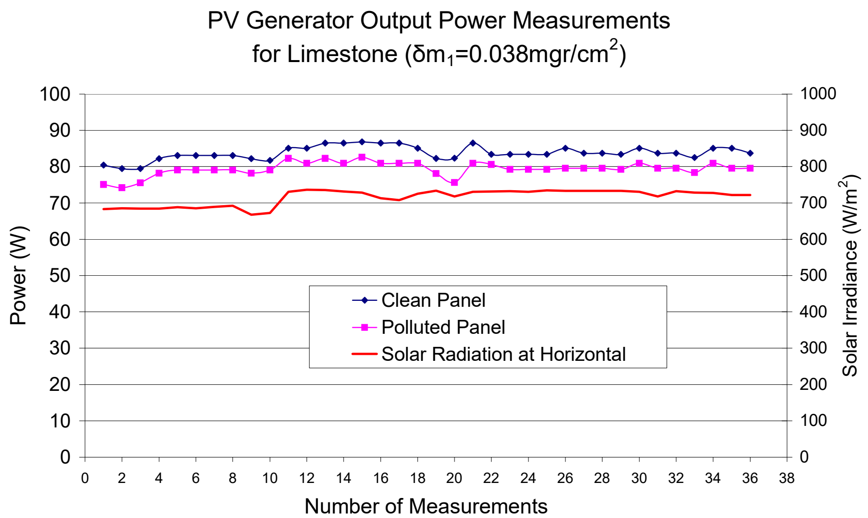

Figure 2: Experimental data for low air-pollution

By doubling the limestone mass deposition, i.e. δm_2=0.076mgr/cm^2, the power output of the artificially polluted PV panel presents almost the same output reduction with the previous case, although somewhat higher, figure (3). At this point it is important to mention that the accuracy of the experimental power measurements is of the order of 1W, hence in order to describe differences of this order of magnitude one may need a more accurate measurement apparatus. In any case, using the experimental values of figures (2) and (3) one may state that even a relatively small air pollution deposition on the PV panels' surface induces approximately 5% reduction of their power output.

In order to examine the impact of additional air pollutant mass deposition one may increase the corresponding specific mass by one order of magnitude, i.e. δm_3=10.δm_1, δm_3=0.380mgr/cm^2. In this extreme case much greater power output changes may be encountered (figure (4)), even exceeding 20W. More precisely, the corresponding output power decrease of the air polluted panel is almost 30% of the corresponding clean one. Another aspect of this last experiment is the almost constant output of the air polluted panel although the corresponding solar radiation presents a remarkable variation ±50W/m^2.

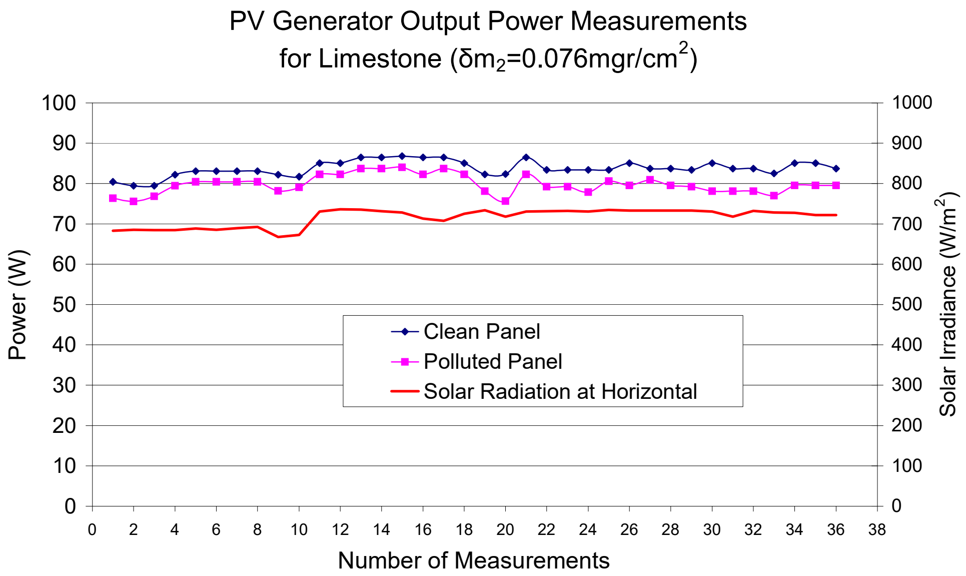

Figure 3: Experimental data for medium air-pollution

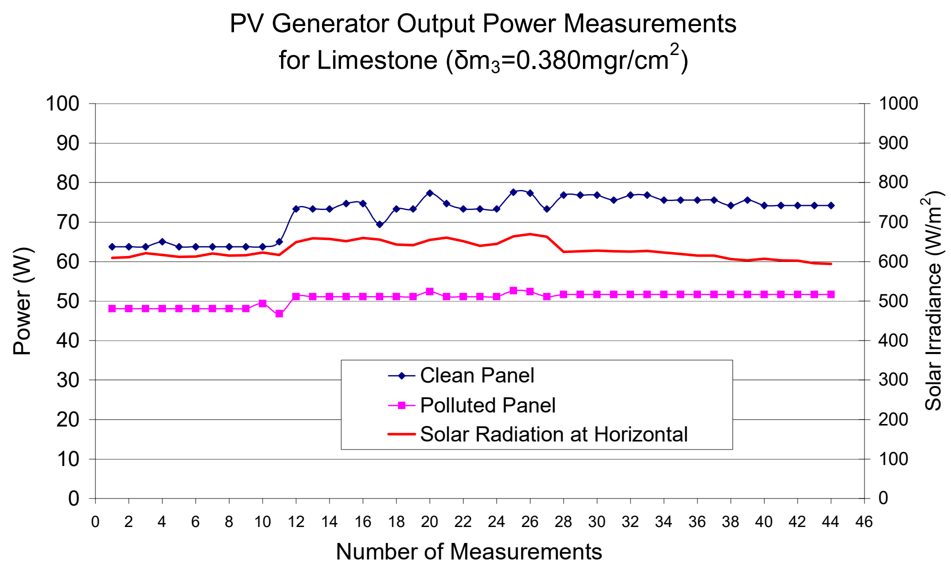

Figure 4: Experimental data for high air-pollution

In the last figure (5) included in the current analysis one may find the efficiency difference "δη" between the polluted and the clean (almost identical and nearby located at the same tilt angle) PV panels defined as:

$$\delta\eta = \eta_{cl} - \eta_{pol} \tag{1}$$

where the efficiency of the panels used is estimated[19] as:

$$\eta = \frac{P}{A_c \cdot G_T} = \frac{U \cdot I}{A_c \cdot G_T} \tag{2}$$

with "P" being the output power of each panel calculated as the product of its current "I" and its voltage "U", while "A_c" is the corresponding panel surface and "G_T" is the total solar irradiance at the panel's surface level.

According to the analysis of the available results one may conclude that there is a remarkable efficiency drop of the air polluted PV panels (in comparison with the clean ones), which normally varies between 0.5% and 1% in absolute figures. However, in extreme air pollution cases the corresponding efficiency decrease may approach 3%, i.e. from 11% down to 8%.

5. Conclusions

A detailed experimental study was carried out in order to investigate the air pollution impact on existing PV installations. For this purpose, one has used almost identical PV panels operating in the same area under the same operational conditions. During the analysis, special emphasis is given in order to estimate the PV panels power output and efficiency. In this context, extensive comparisons between clean and air polluted panels were carried out.

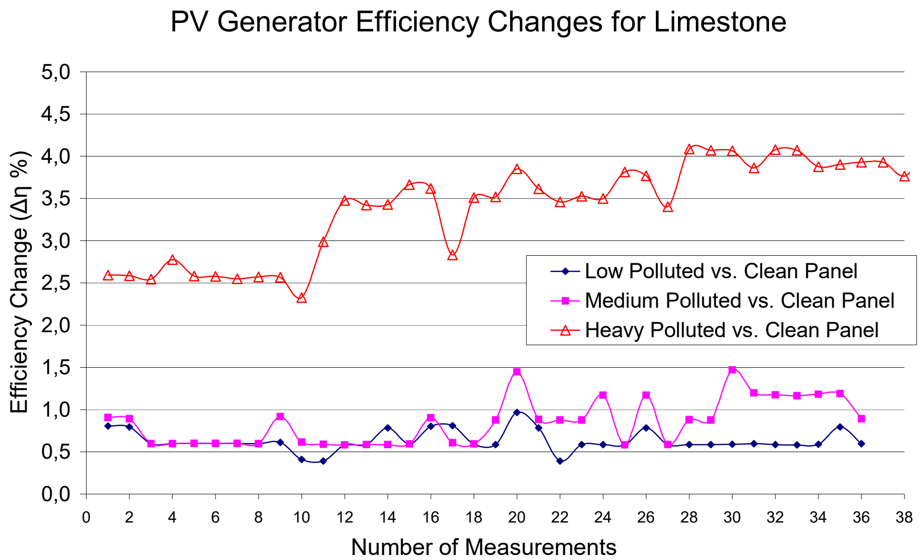

Figure 5: Experimental data for the air pollution impact of the PV panels' efficiency

According to the results obtained, one may state that the solid particles existing in the atmosphere of heavy polluted urban areas negatively affect the PV panels' energy production, even leading to up to 30% lower power outputs. However, in most cases the power drop is around 5%, while the corresponding efficiency decrease approaches 1%.

Finally, additional research is recommended in order to investigate the influence of the panels' tilt angle on the real energy output of PV generators operating in a heavy polluted urban environment as well as the effects of different types of air pollutants on the photovoltaic generator energy yield.

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PART FOUR

RENEWABLE AND FOSSIL FUELS

REVIEW AND FUTURE PROSPECTS OF LIGNITE-BASED ELECTRICITY GENERATION IN GREECE

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Abstract

In the present study, a review of the lignite based electricity generation in Greece is presented. By using real, long-term data concerning the national electricity generation and an appropriate mathematical model developed from first principles, it is expected that the lignite's depletion time shall vary from 25 to 50 years. Acknowledging its finite character, an investigation is carried out in order to assess the future prospects of lignite in the national electricity status. For this purpose, emphasis is also given on the impacts entailed by the former exploitation for electricity purposes on both the local environment and the national economy.

Keywords: Lignite; Electricity Generation; Depletion Time; Mathematical Model; Sensitivity Analysis

1. Introduction

The Greek Electricity Generation System (EGS) divided in two discrete sub-sectors, i.e. the interconnected mainland electricity production network and the corresponding non-interconnected Aegean Archipelago islands, not only demonstrates a geographical demarcation to account, but also supports the parallel operation of two entirely different electrical systems to be considered. With regards to the Archipelago region, the approximately 250 thermal power units[1] comprise 13 Autonomous and 19 Local Power Stations on top of the Crete island autonomous power network[2], all operating on the basis of imported amounts of diesel and heavy oil.

On the other hand, the mainland's electrical grid is mainly supported by 15 major thermal power stations (TPSs) rated at 8200 MW, with 13 of them owned by the Greek PPC (Public Power Corporation), see also figure (1). The existing electricity generation units are mainly based on the local lignite reserves -eight (8) power stations with 5300 MW of installed capacity- while the corresponding capacity share for the oil and natural gas along with the combined cycle stations operating reaches 2900 MW. More specifically, the lignite based power stations include the TPS of Agios Dimitrios (5 units) 1600MW, the TPS of Kardia (4 units) 1200MW, the TPS of Aminteo (2 units) 600MW, the TPS of Ptolemaida (4 units) 850MW, the TPS of Megalopolis (4 units) 850MW and the more recent one of Florina (1 unit) 330MW.

In the interconnected electrical system one may also find fifteen (15) large hydropower stations in conjunction with several (50) other small ones with total capacity 3100 MW[3]. Apart from the hydro power units, additional RES contribution ascribed to the mainland's grid derives either from the more mature wind power generation or from biomass, supported by approximately 580 MW and 25 MW of installed power respectively[4][5].

In figure (2a), one may configure the increasing rate of national electricity consumption demand during a 45 years time period, also involving the first stage of domestic electrification. Meanwhile, the electrical demand time evolution described by a mean annual increase rate of 4.0%, well represents the last 25 years under study. The corresponding percentage for the coming decade is estimated at an annual increase of 2% to 3%[4][6], although the authors expect a slightly higher value (≈ 3.5%). This continuously increasing electricity consumption is divided almost equivalently between the domestic sector (32.7%), the industrial sector (28.0%) and the commercial use (28.9%), see also figure (2b)[7].

During the same period of time (1960-2005), the local lignite's electricity generation contribution identifies its leading role in the national electricity system development, strongly supporting the significant progress noted in every aspect of every day living as well. More specifically, for the overall period examined, a mean contribution share of 55% is to be considered, while, when accounting for the years since 1980, the corresponding value is estimated at 66%. Note finally that the current lignite-based and RES-based electricity generation represents almost 65% of the total national consumption. On the other hand, the contribution of imported natural gas and oil is almost 30%, while the net electricity imports from the neighbor countries vary between 3% and 5%.

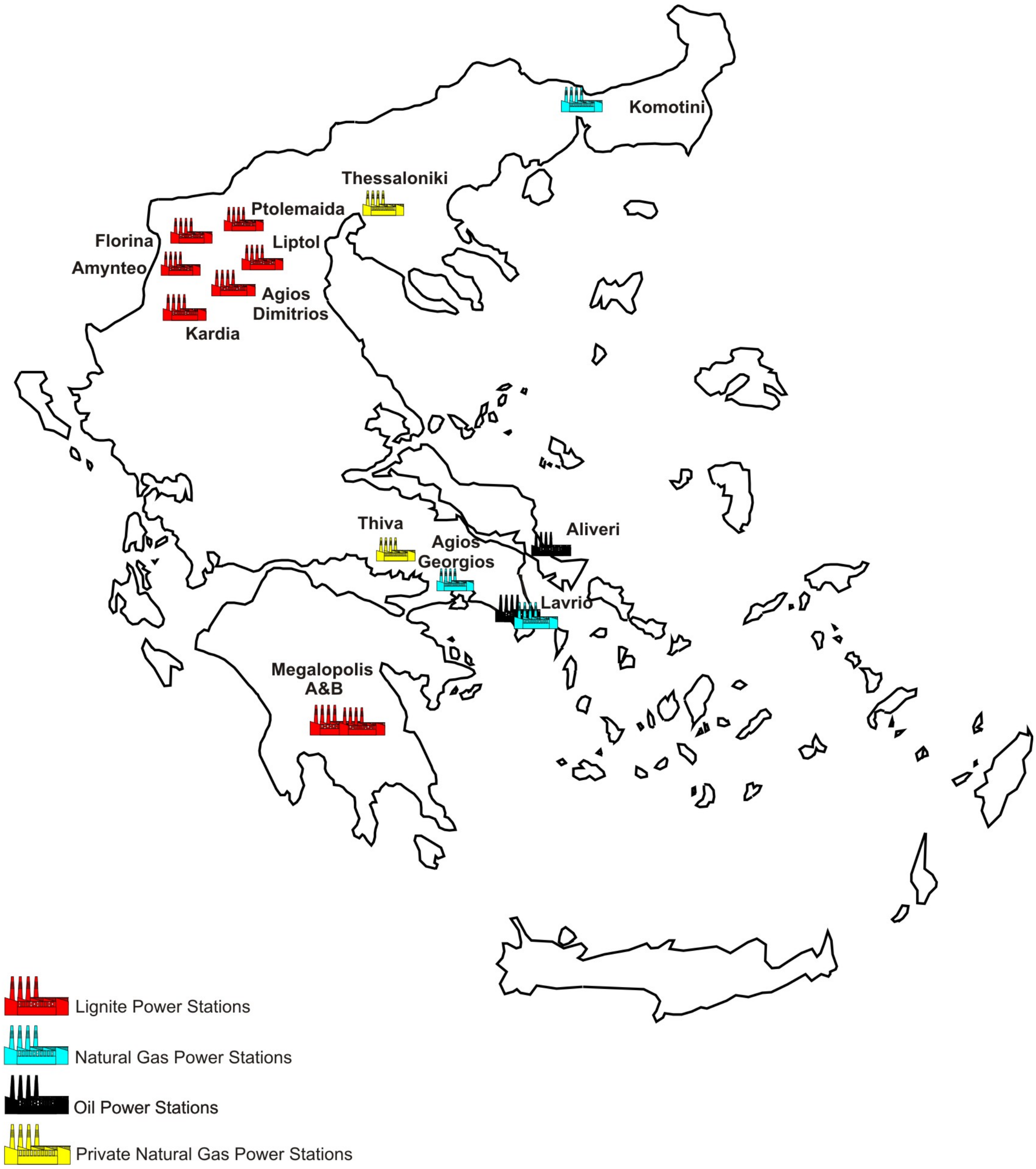

Figure 1: Major thermal power stations operating in Greek mainland

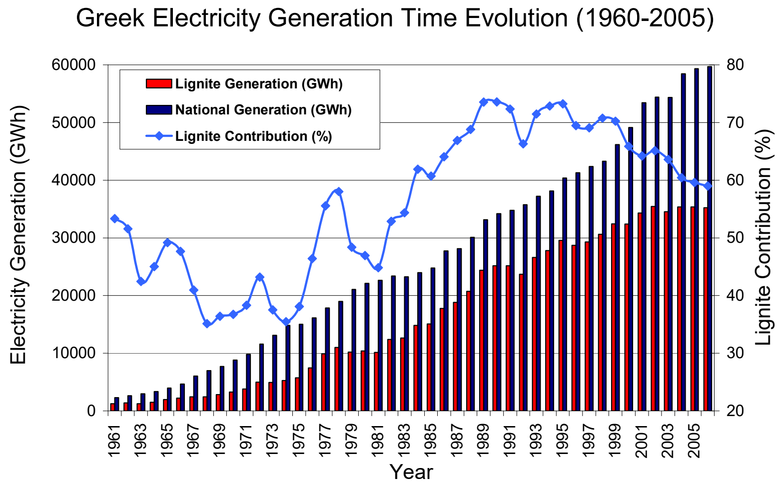

Figure 2a: Greek electricity generation time evolution

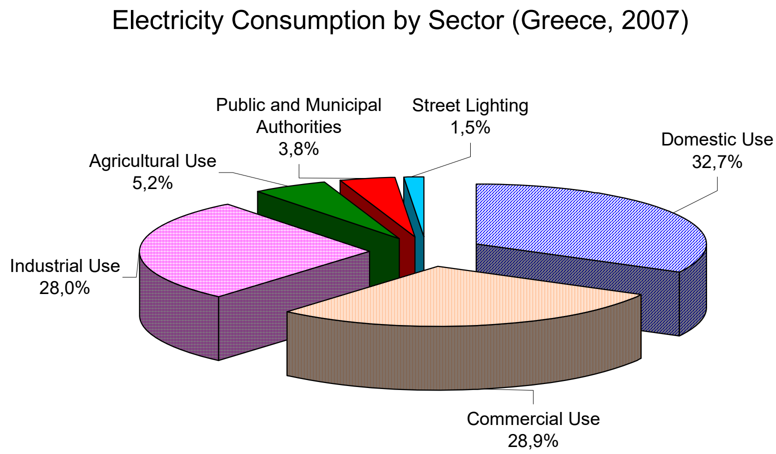

Figure 2b: Greek electricity consumption analysis by sector based on [7]

Emphasizing on the important role of lignite in the course of time, the current study aims to underline the urgency of adopting certain strategies so as to ensure the local reserves' depletion-time extension. Consequently, the need for maintaining the national energy reserves that should meanwhile be supported by a corresponding rational exploitation is thought to be of primary concern for the country's best interest. For this reason, in the present study, a recording of the proved and potential national lignite reserves along with the presentation of a depletion time-model considering different application scenarios, are both available. A presentation of the Greek lignite characteristics involving an analysis concerning the environmental impacts caused by the lignite usage and a discussion whether lignite suggests a financially beneficial energy source for the national economy is also provided (i.e. examination of the macroeconomic cost, the real energy price, the cost of enhancing the lignite technology and the cost of substituting lignite).

2. Greek Lignite Characteristics

Presently, the proven national reserves' estimations support the existence of almost 5 billion tones of lignite scattered in the entire Greek region[8]. However, according to the nowadays techno-economical status, the potential quantity of lignite to be exploited is equal to 3.2 billion tones[9], 63% of which exclusive rights have been accorded to the Greek P.P.C. The main deposits (figure (3)) are located in the areas of Ptolemaida, Amynteo and Florina (West Macedonia) with a total of 1.9 billion tones, while the corresponding deposits of Drama and Elassona have a content of 900 and 170 million tones respectively. Additionally, in the Megalopoli area in Peloponnesus, the amount of the existing lignite reaches 240 million tones. In 2005, Greece, being the second biggest producer of lignite in the EU and sixth worldwide, extracted almost 70 million tones of lignite leading to the country's ranking at the tenth place concerning the lignite electricity contribution share[10]. Meanwhile, the up to now national cumulative lignite production represents approximately 1/3 of the total proven reserves.

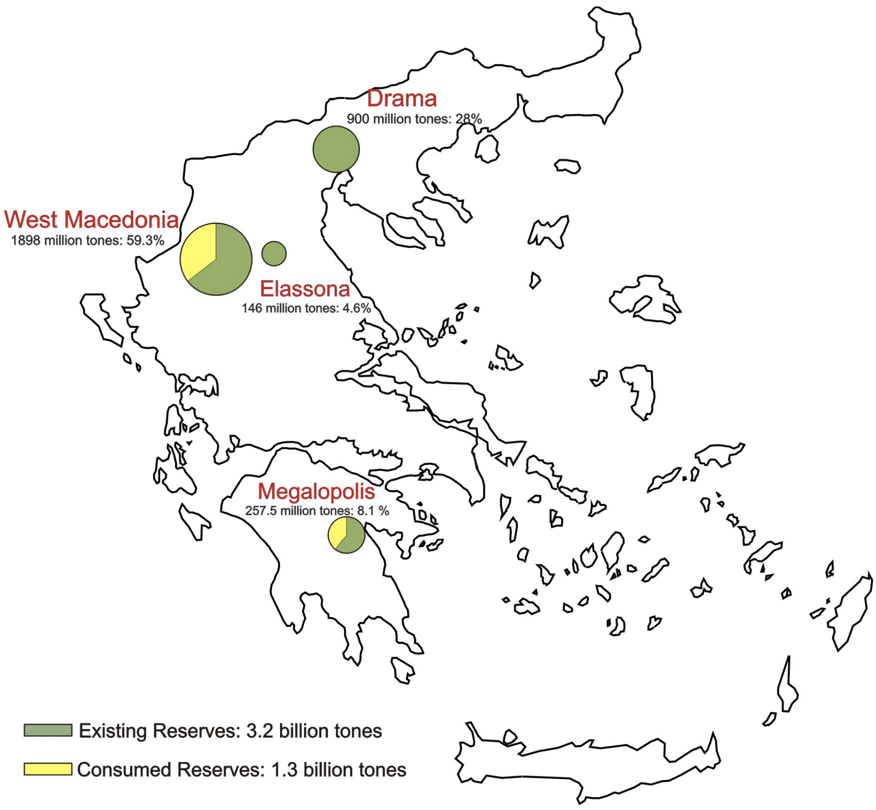

Figure 3: Lignite national reserves[9]

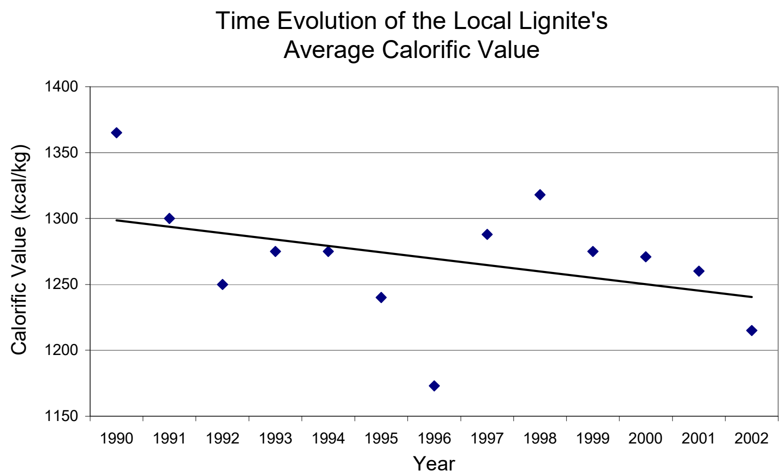

Figure 4: Time variation of the local lignite's average calorific value

As far as the local lignite's quality characteristics are concerned, the calorific value is kept quite low, ranging from 900 – 1,100 kcal/kg in the areas of Megalopoli, Amynteo, and Drama, to 1,800 - 2,300 kcal/kg in Florina and Elassona with the Ptolemaida lignite presenting calorific values between 1,250 and 1,350 kcal/kg. Meanwhile, the average calorific value time evolution (figure (4)) demonstrates the local reserves' gradual degradation[11]. An example encounters the West Macedonia case in which regional reserves tend to present a degradation of 100kcal/kg (from an average of 1,200-1,300 to a corresponding 1,100-1,200 kcal/kg). The potential operation of new mines on the other hand (Drama, Elassona) may promise for the slight improvement of the local lignite's energy content[12].

Another factor describing the quality of existing reserves is the moisture content. A wide range of moisture content values, depending on the area of extraction, varies from 9% to 66% and gives a sample average of 38%. Besides, the corresponding ash range may be defined by a mean percentage of 22% for 14 areas considered[13-15]. On the other hand, the low sulphur content, comprising one of the local lignite's environmental advantages[16], varies from 1% to 6.4% with Megalopoli giving the greatest analogy in volatile sulphur (greater than 86%) and the Ptolemaida-Amynteo basin presenting the corresponding lowest.

To have a direct comparison of the Greek lignite's main quality characteristics against the corresponding values describing the reserves found in different areas worldwide the following qualitative figure (5), based on information given in Kavouridis et al.[17], may be presented. As it may be easily configured, the two major providers of the local lignite reserves, i.e. Ptolemaida and Megalopoli, demonstrate high moisture contents, low calorific values and moderate ash contents. Concerning the Aliveri (Euboea) lignite, the latter seems to be the most attractive version of the local coal to keep in mind, however the corresponding reserves have already been exploited.

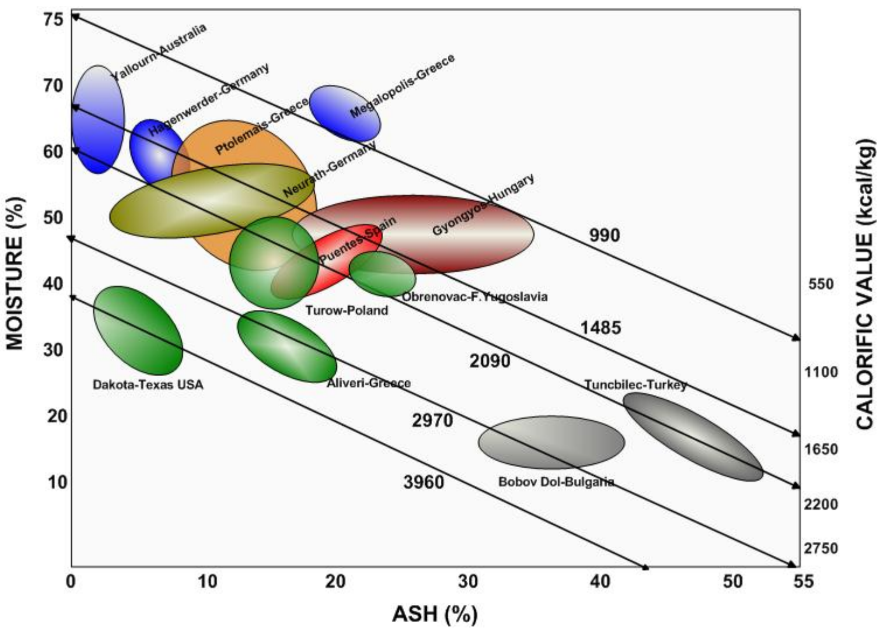

Figure 5: Main characteristics of lignite samples across the world, based on [17]

3. Pros and Cons of Local Lignite Utilization

The advantages accompanying the Greek lignite's electricity generation are mainly ascribed to the latter indigenous character, decreasing several of the externalities' impact and having up to now resulted in ensuring a quite attractive and steady price per kWh of electricity provided to the final consumption (52% less than the average EU-15 retail price)[18]. Moreover, the technological background established in the meantime also suggests a significant parameter for the lignite's prominence. With regards to the above, by exploiting the local lignite reserves, the macroeconomic cost (exchange loss, political dependency, etc.) being attributed on imported fuels is currently zeroed. According to studies conducted[19] and realizing a comparison among different countries and sources of electricity generation, the social-environmental cost is thought to be the local lignite's Achille's heel (especially when compared with its present market competitor, i.e. natural gas). The minimum risk of supplying electricity along with the regional development encountered in the areas of exploitation - both briefly analyzed in the next paragraphs- have partly compensated for the impacts affecting the local environment. Concerning the latter, an integrated life cycle (LC) approach should suggest the recording of impacts into every stage of the production chain (extraction-refining, transportation, plant operation, wastes disposal, construction and decommissioning of the plant).

3.1 Major Environmental Impacts

The impacts acknowledged for the lignite's utilization imply air emissions production, water resource use, hot water discharges, solid waste generation and land resource use. Actually, when lignite is burned, remarkable quantities of carbon dioxide, sulphur dioxide, nitrogen oxides, and TSP are released[16][20-22]. Additionally, the chemical and mineralogical composition of the fly ash reveal properties of environmental and health concern[23-25] that suggest the adoption of appropriate treatment actions[26], also promising for better combustibility characteristics[27]. Transport activities (conveyor bets, trucks, power plant constructive materials) as well as the loading and unloading procedure of the lignite fuel cycle also constitute a source of airborne emissions[28]. Concerning water resource use, considerable water quantities necessary for the purification of lignite after its extraction, as well as for steam and cooling generation, serve for the power plants' needs. In addition, if the water used is discharged back into the environment, the lignite's mining may cause the contamination of water quantities with heavy metals. Next, the hot water wastes produced from power plants and afterwards deposited, disturb the local environment's stability. The production of solid wastes involves ash generation and bulk inert materials contained in the lignite while the land use encounters the contamination of soil, the area disturbance due to surface and underground mining, and finally the lowering of groundwater tables[28].

To be more explicit, as far as the air emissions are considered, 1 tonne of CO_2[20] is the expected amount for the production of 1 MWh_e coming from the lignite's combustion while at the same time, for the same electricity output, the corresponding amount produced from natural gas is approximately 490 kg of CO_2 per MWh_e. Less incriminatory data are attributed to the SO_2 and NOx emissions, still however showing the comparatively more "hostile" character of lignite against the local environment.

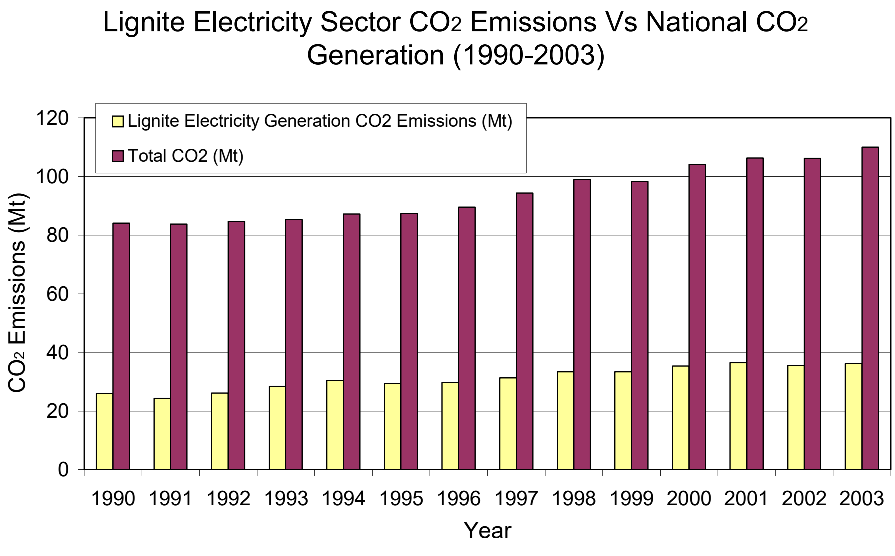

Figure 6: The contribution of lignite in the national carbon dioxide emission

In this context, it is important to mention that electricity generation is found responsible for almost 55% of the national CO_2 production, with approximately 60% of the former referring to lignite (see also figure (6)). Therefore, unless radical changes take place as far as the Greek electricity fuel mix is concerned, one may easily conclude that no CO_2 increase deceleration is to be noted, this entailing some serious worry concerning the compliance with the national Kyoto commitments. In fact, the

+25% emissions' target set for the period 2008-2012, always with regards to the 1990 levels, is currently expected to finally reach the levels of 40% during the remaining time.
In addition, the major contribution of lignite-fired power stations to the electricity generation in Greece together with the high sulphur content of the locally extracted fuel, especially in South Greece, also indicate that the electricity sector is the main responsible for the SO_2 emissions[16]. Note that the range of the SO_2 emission factor is quite broad with the highest of values determining the operation of South Greece power stations (Megalopolis) lacking integrated anti-pollution measures, even achieving values equal to 50kg/MWh. Unless the appropriate desulphurization equipment is installed in certain lignite power stations[29] the amount of annual SO_2 emissions, remaining relatively stable over the last years at 350ktons (approximately 280ktons due to lignite, see also figure (7)) and representing 80% of the corresponding national releases, is not expected to be reduced.

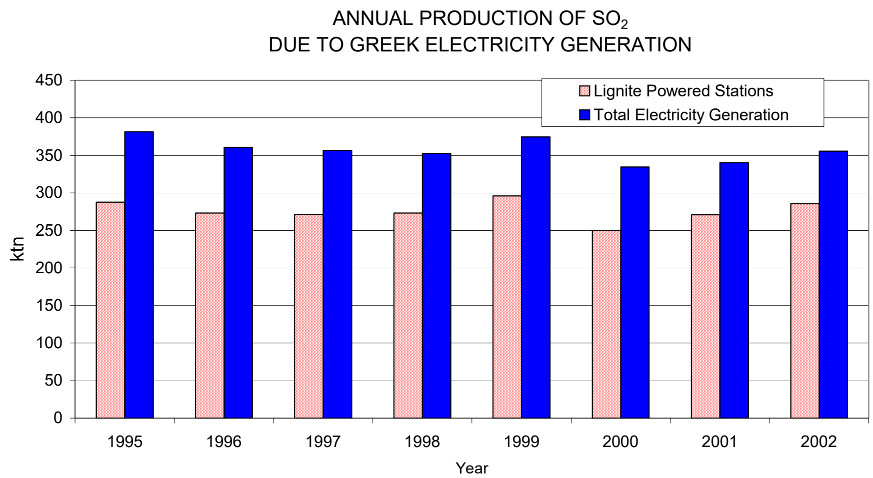

Figure 7: The contribution of lignite in the national sulphur dioxide emission

Furthermore, despite the introduction of natural gas in the local electricity market, the NOx emissions are gradually increasing with time[21]. More specifically, the annual NOx production by the Greek electricity generation system exceeded 70 ktn during the period from 2000 to 2002, marginally violating the emissions ceilings of both 88/609 and 2001/80 EU Directives. Given that over 90% of the national electricity production is based on carbon containing fuels, a continuous effort on diminishing the release of nitrogen oxides should be made, so that local electricity generation sector may accomplish the Large Combustion Plants Directive (2001/80/EC).

Finally, despite the fact that most of the Greek power plants are equipped with high retention efficiency electrostatic precipitators, fly ash particles are still emitted in the atmosphere due to the high rates of lignite consumption and the operation of low-efficiency precipitators. Thus, fly ash emission remains one of the most important environmental impacts of local lignite utilization. According to the most recent available information approximately 13Mtons of fly ash are produced annually in Greece[30][31], while the contribution of the Ptolemaida lignite field approaches 8Mtons/year. At this point it is important to mention that fly-ash particles are considered by many experts[23-25][32] as extremely contaminating, being also associated with respiratory and cardiovascular diseases[33]. In fact, according to the results of Sichletidis et al.[34], a high prevalence of rhinitis and infectious bronchitis of children residing in Western Macedonia were attributed to the heavy environmental pollution. Additionally, fly ash may also contain considerable levels of radioactivity, this suggesting high health hazards, especially for the power plants personnel[35]. As far as the utilization or disposal of fly ash is concerned, fly ash utilization worldwide is only slightly above 30%[36], while the remainder is disposed in landfills and fly ash basins or in extreme cases dumped at sea. Regarding the fly ash produced from Greek power stations, the relatively high uptake abilities and the low mobility of toxic elements[37] allow the use of fly ash in several applications such as adsorption materials, sewage treatment, land filling and cement and concrete production.

3.2 Major Macroeconomic Impacts

Beyond the quantification of the main environmental impacts, the investigation of financial damage and benefits deriving from the local lignite's usage is also necessary in order to get a clear picture concerning the presence of lignite in the national electricity generation scenery.

At first, emphasis should be laid on the European Union Emission Trading Scheme implying, apart from the environmental impacts caused by the use of lignite, serious financial surcharge. Actually, this damage is strongly depended on the rather unstable allowances price of CO_2 emissions even crashing down to 0.13€/t during June 2007, having peaked at 30€/t a year before. Nevertheless, estimations and forecasts[38] concerning the future CO_2 allowance price converge at a range of 20€/t -30€/t up to the year 2012 (signalling the end of the second trading period 2008-2012), thus sounding the alarm for the corresponding emissions' reduction.

In this context, many argue[39] that the price to pay for avoiding 1 tonne of CO_2 emitted by a conventional lignite station, among other solutions to undertake, strongly supports for the latter enhancement or even substitution by alternative thermal stations (such as combined cycle units operating on natural gas), with mechanisms for capturing CO_2 suggesting a cost of 25-40€/t of CO_2 avoided. On the other hand, the implementation of new renewable energy installations is described by rather higher corresponding costs. However in order for the Kyoto dictations to be satisfied the partial reduction of CO_2 emissions achieved by the use of more efficient measures concerning the existing power stations, although seeming to be more cost-effective, is not thought to be adequate. For this reason, more radical measures to be undertaken require the adoption of renewable energy technologies. In fact, according to Tsoutsos et al.[40], in order to achieve to a full extent the target up to 2010, an additional investment cost of some 1.6 billion € on RES projects is required. On the other hand, Tigas et al.[41] claim that to shoulder the responsibility of fulfilling the Kyoto commitments for the same time period, 2-2.5 billion € of investments are required in the field of RES, cogeneration and energy saving.

Another aspect of the discussion whether lignite should be considered as beneficial for the local electricity generation sector calls on the investigation of macroeconomic cost. The macroeconomic cost results if quantifying and accumulating parameters like the trade equilibrium burden, the country's dependence on other energy centres, the indigenous and global gradual depletion of the energy deposits, as well as the unemployment decrease and the gross domestic product increase. As already mentioned, since lignite comprises an indigenous energy resource, the arising macroeconomic advantages are more than evident and can only be displaced by the "infinite" renewable energy sources exploitation. For instance, if half the electricity generation ascribed to lignite (~17 TWh) was to be substituted by imported oil, some 5.5 to 6 Mtons necessary per annum would imply a national debt of around 2.2 billion € per year, currently being avoided. Similar are also the amounts of imported natural gas that may be alternatively avoided due to the systematic exploitation of local lignite reserves for electricity generation. In this context, in figures (8a) and (8b) one may encounter the avoided amount of both imported oil and natural gas over the last 25 years, and easily draw the corresponding financial benefit deriving from the utilization of local lignite. Besides, one should not disregard that apart from the cost deriving from net imports, the infrastructure necessary for the shift (new power plants, modification of already existing, pipelines, etc.) should be considered as well.

Another important macroeconomic topic is the cost of fly ash disposal, or in other cases the potential value of the fly ash used as raw material. Actually, the cost of fly ash disposal is directly related to the method adopted, while the transportation requirements should be considered as one of the major cost components[42]. In this context, since the disposal of fly ash as a by-product is becoming an increasing economic and environmental burden, the utilization of the former as a resource of value added products is of paramount importance[43]. More specifically, the utilization of fly-ash as a raw material in specific industrial sectors (like cement industry) illustrates how useful fly ash can be. Note that using published data from the cement industry the value of fly ash may be increased from effectively zero to $80 per tonne[44] (strongly depending on the current price of cement).

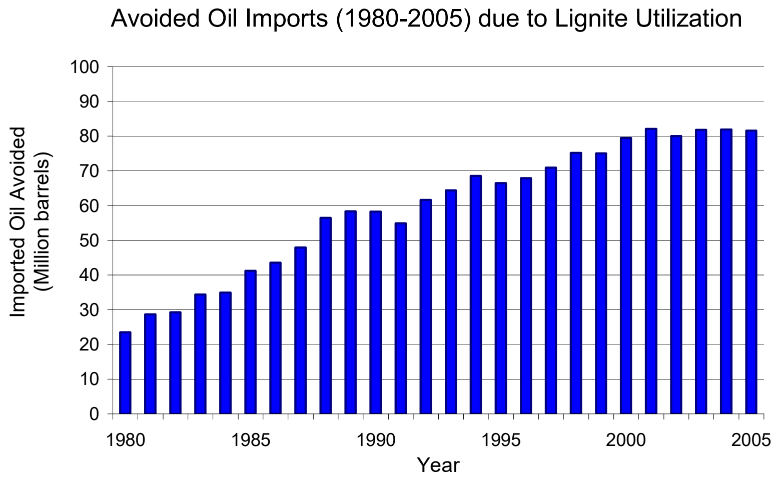

Figure 8a: Avoided oil imports due to the utilization of local lignite

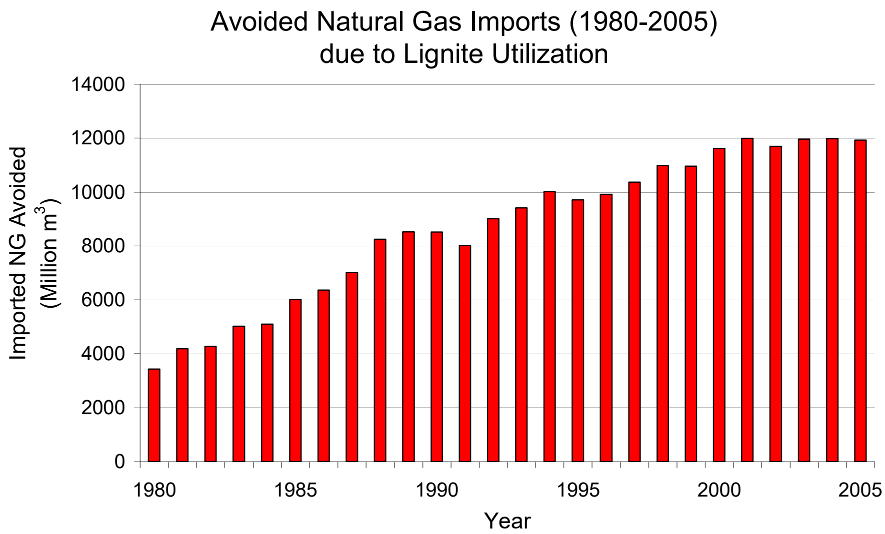

Figure 8b: Avoided natural gas imports due to the utilization of local lignite

Beyond these, the local societies' gaining from the operation of lignite power stations is another dimension, often obscured by issues dealing with environmental degradation. As Lalasidis[45] points out for example, the prefecture of Drama where high levels of unemployment may be encountered (~15%), could benefit from the exploitation of the local lignite deposits and the installation of a new 300 MW lignite fired power station, promising for the employment of approximately 1800 local habitants with the corresponding investments estimated to exceed 2 billion €. Potential attraction of industries exploiting the products and by-products of lignite utilization (ash exploitation, thermal energy recovery, etc.) may also be encountered in the broad area, this also leading to the local society development booming. Additionally, techniques concerned with the use of lignite for environmental purposes[46][47] and energy production methods that support the use of cleaner fuel mixtures[48] demonstrate the wide range of potential applications.

Accordingly, by also counting in the financial cost aspect involving the components of extraction stage, process to end-use, transportation, total procedure support and taxation, a comparison on a real energy price basis among the different energy sources shall designate lignite as the most cost-effective form of electricity production. This may justify the fact that although the shift towards natural gas and renewable energies in the electricity sector did led to the reduction of approximately 9000 kt of CO_2 in the period 1990-2002[49], the presence of lignite still remains strong. Nevertheless, if considering some of the major benefits and drawbacks previously discussed, one should see that the prescription of an energy planning that is flexible and still committed to both virtual and procedural national obligations demands for a more sceptical way in handling lignite's exploitation.

4. Lignite Consumption Time Evolution

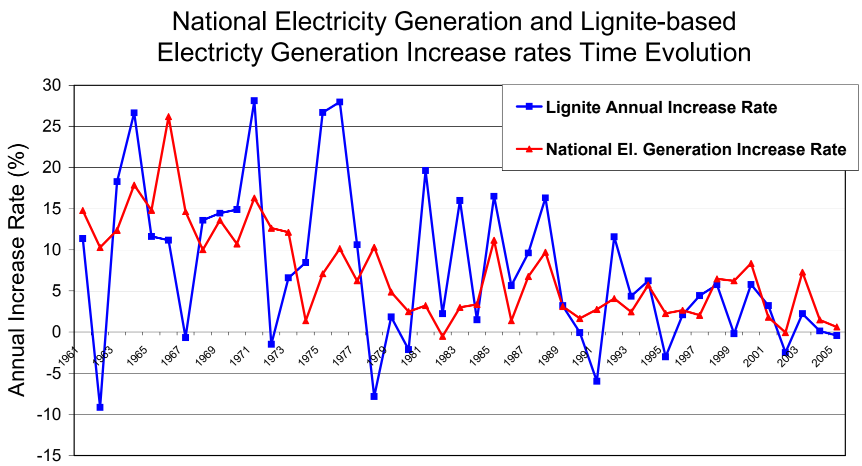

Figure 9: Annual increase-decrease rates of national electricity generation and lignite contribution

As already discussed in the introduction section, the national electricity demand is well described by an increasing rate of 4%, representing the period 1980-2005 and presenting a relative stability during the last years. The corresponding average mean annum increase of lignite during the same period is around 5.7%, however shifting to milder values (~3%) in the most recent years. In figure (9) one can notice the highly variable behaviour of both increase rates investigated in the course of time, i.e. annual lignite electricity generation and annual national electricity generation rates. As concluded from this figure, more intense fluctuations are to be considered for lignite in the early years of electrification, while a more mild variation trend is noted in the most recent period examined, during which the lignite rate seems more adjusted to the one describing the national electricity demand. It may also be configured that during the most recent years (since the nineties) a more flexible fuel mix to be considered has lead to the lignite's generation gradual stabilization, currently following a behaviour more close to the one of the national demand trend.

A more detailed investigation suggests the examination of the local lignite's contribution in terms of electricity production efficiency. More specifically, an efficiency coefficient "η_λ" describing the entire electricity production chain based on lignite may consider the two edges, i.e. the lignite quantity extracted "M_λ" and the corresponding net electricity provided "E_λ" to consumers. In order to calculate the above coefficient (tones/TWh) one should take into account the lignite production (extraction) rates and the corresponding values concerning the net electricity generation by lignite. The calculation period selected refers to the years from 1994 to 2005. Note that in 1994 the contribution of the lignite presented one of its peaks and since then a slight contribution decrease has been noted, mainly due to the natural gas entering the market during the same period (since 1996). A second reason for selecting the specific period is that it can be thought as quite recent, therefore considering both the quality degradation of the lignite reserves left and the technology progress encountered.

To illustrate the above, the following figure (10) has been created. As expected, there is a strong relevance between the time evolution of the reserves' calorific value and the corresponding electricity generation covering the proportion of demand ascribed to lignite. For greater calorific values given, a lower efficiency coefficient value is to expect and vice versa. A mean efficiency coefficient (lignite specific consumption) obtained assumes that for the generation of 1 TWh_e, an amount of 2.08 million tones of lignite is needed. Additionally, since no obvious influence seems to be noticed, what can be said in concern to the utilization of lignite for electricity generation is that during the recent years a significant technological development in the corresponding production sector should not be considered. On the contrary, a prospect of improving the efficiency of old lignite stations, currently described by an average 32%-33%, to a potential 40% exhibited by new technologies' incorporation, will, apart from a greater utilization rate of lignite, lead to the stabilization of the emissions' production rate[12].

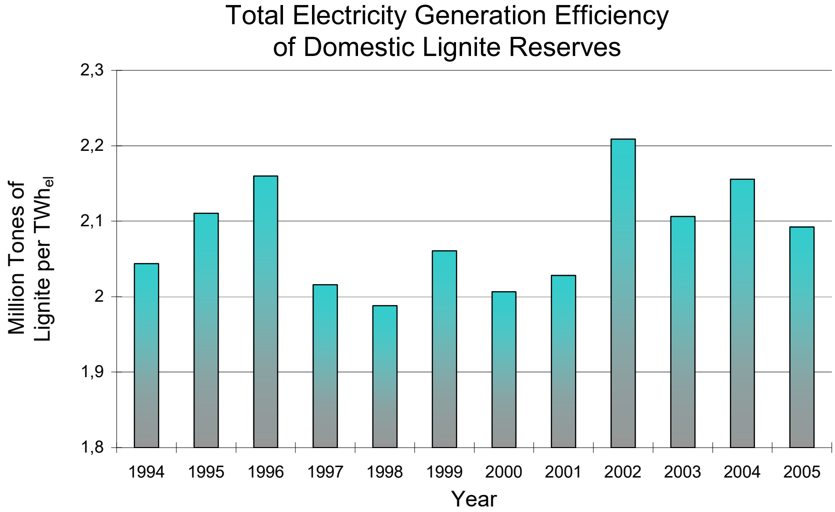

Figure 10: Lignite's electricity transformation specific consumption time evolution

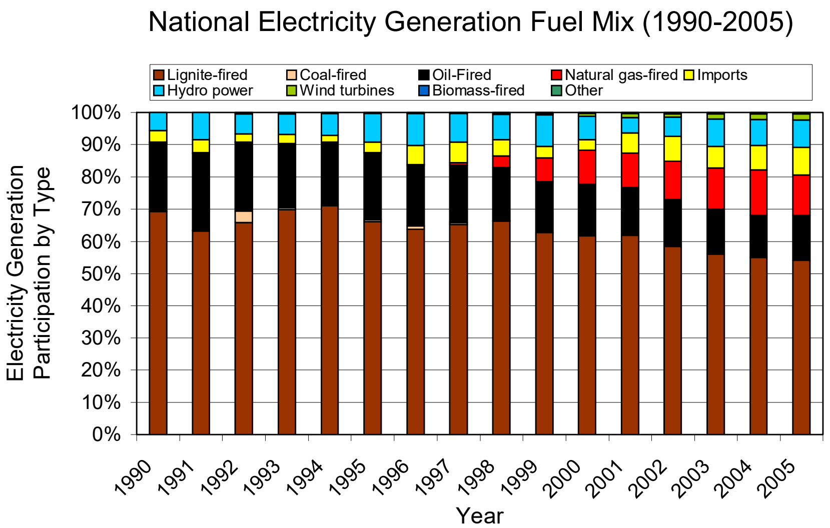

Figure 11: Greek electricity generation fuel mix

In respect of the above, the natural gas entering the market since 1996 has lead to a cut-back of the lignite's and oil's contribution shares in the national electricity fuel mix (figure (11)). Presently, the power share of natural gas units, including the combined cycle stations existing, reaches a total of nearly 2,140 MW. In accordance to the future national energy planning[6], the capacity of natural gas units to be employed (mainly combined cycle stations) may exceed 5,000 MW, therefore an estimated contribution of approximately 25% demand coverage deriving from the more expensive and imported natural gas quantities is the upper limit to keep in mind. A third side involved in the national electricity fuel mix, i.e. the RES generation sector development may also play a leading role in the electricity field. Since the new law enactment (law 3468/06)[50], the beneficial character of potential investments may be thought as established. The variable output of such power stations on the other hand comprises the restrictive factor of these specific technologies.

In conclusion, a sustainable national energy strategy in the view of the local market's liberalization, must confront the need of both retaining an indigenous character that is devoid of the warps entailed in greater dependency states and extend the national reserves' depletion-expectancy. In the following paragraphs, an effort to investigate the depletion scenarios of lignite aspires to designate certain proposals regarding the planning and administration of natural energy resources in Greece.

5. Lignite Reserves Depletion Model

To determine the depletion time of the local lignite reserves an appropriate model has been developed from first principles. The parameters taken into consideration are the proven lignite reserves' energy content "E_{tn}" expressed in terms of potential electricity generated, the national electricity demand "E_o" for a given base year and the coefficient "β" describing the participation of all the other energy sources (excluding lignite, i.e. lignite contribution equals (1-β)) on the domestic electricity production. Additionally, one should also introduce the coefficients "e_i" and "ξ_i", describing the annual (during the year "i") electricity generation increase (or decrease) and the annual lignite substitution rate from all other electrification sources (natural gas, wind energy, solar energy, etc.) respectively.

In this context, the national electricity generation share covered (during the reference year i=0) by lignite, i.e. "$E_{l(o)}$", is given as:

$$E_{l(o)} = E_o - \beta \cdot E_o \cdot = (1-\beta) \cdot E_o \tag{1}$$

Accordingly, by introducing the above mentioned annual electricity generation increase and lignite substitution rate coefficients (e_i, ξ_i), the corresponding share of lignite-based electricity generation concerning the year following, "$E_{l(1)}$ ", may be estimated:

$$E_{l(1)} = E_o \cdot (1+e_1) - \beta \cdot (1+e_1) \cdot (1+\xi_1) \cdot E_o \tag{2}$$

Similarly, the contribution of lignite in the national electricity demand for any given year (i=n), "$E_{l(n)}$", can be expressed as:

$$E_{l(n)} = E_o \cdot \prod_{i=1}^{i=n} (1+e_i) - \left[\beta \cdot E_o \cdot \left(\prod_{i=1}^{i=n} (1+e_i) \cdot (1+\xi_i) \right) \right] \tag{3}$$

Finally, in order to determine the cumulative consumption of lignite "E_{ln}" (including the reference year "o") in a n-years period, a summation of the examined years' annual consumption has to be realized, i.e.

$$E_{ln} = \sum_{j=0}^{j=n} E_{l(j)} = E_{l(o)} + E_{l(1)} + \ldots + E_{l(n)} \tag{4}$$

or equivalently:

$$E_{ln} = E_o \cdot \left\{ \left[1 + \sum_{j=1}^{j=n} \left(\prod_{i=1}^{i=n} (1+e_i) \right) \right] - \beta \cdot \left[1 + \sum_{j=1}^{j=n} \left(\prod_{i=1}^{i=n} (1+e_i) \cdot \prod_{i=1}^{i=n} (1+\xi_i) \right) \right] \right\} \tag{5}$$

By determining the expected depletion time of available lignite reserves, one can compare the result obtained from equation (5) with the corresponding proved (techno-economically feasible) national reserves' equivalent electricity generation content. In any case, a marginal exploitation coefficient (safety factor) "SF" implying the importance of certain strategic reserves to be preserved has to be introduced. Note that the safety factor "SF" expresses the need for sustaining strategic lignite stores that serve a twofold purpose within the limits of security of supply. More specifically, the strategic reserves are required in order to both meet an off-schedule demand (standby units are prerequisites) and deal with potential energy imports' supply interruptions resulting either from a supply failure or a purposeful reduction with political ends. Any case given, the existence of strategic lignite reserves provides the country with a certain level of independency, a respectable energy planning redefinition period and the potential to negotiate on a more disengaged basis. Finally, "SF" may equally well compensate for the possibility of an exaggerated lignite reserves' exploitation cost appearing due to the gradual quality degradation impact prohibiting (on techno-economic basis) the total reserves utilization. Consequently, the depletion time requested may be estimated using equation (6), i.e.

$$E_{ln} \le E_{tn} \cdot (1 - SF) \tag{6}$$

In order to also account for the fact that additional exploitable lignite reserves may be found in the Greek territory during the "n"-year period, one should introduce the coefficient "λ_j" describing during the year "j":

a. The annum rate of finding new deposits
b. The domestic lignite exploitation efficiency improvement
c. The electricity generation efficiency improvement for the lignite-fired power stations (including quality change -according to the law of gradual degradation for the natural resources' reserves-, technology improvements, loss decrease, etc.)

As a realistic case study one may introduce a yearly reduction rate "$\delta\lambda$" ascribed to "λ_j" (e.g. $\delta\lambda$=0.1%) and supporting the law of gradual degradation for the natural resources' reserves (first approximation). Accordingly one may write:

$$\lambda_j = \lambda_o - \delta\lambda \cdot (j-1) \qquad \text{if } \lambda_j \ge 0 \qquad \text{or} \qquad \lambda_j = 0 \tag{7}$$

Consequently, since accepting that the national lignite reserves cannot remain constant in a n-years period to investigate, the latter may be determined according to the following equation:

$$E_{tn} = E_{to} \cdot \prod_{i=1}^{n} (1 + \lambda_i) \tag{8}$$

with "E_{to}" representing the proven reserves' quantity at the year of reference "o".

The proposed model in its complete form can solve the general problem of lignite reserves depletion time once the time series of the parameters involved have been defined. However, in order to obtain a closed analytical solution and since one cannot easily forecast the time-series of the parameters "e_i" and "ξ_i" involved, a first approximation of the mean long-term annual values for these coefficients, i.e. $\bar{e}$ and $\bar{\xi}$ respectively, may be utilized, hence the final equation for the lignite's time of depletion is given[51] as:

$$E_o \cdot \left[\frac{(1+\bar{e})^{n+1} - 1}{\bar{e}} - \beta \cdot \frac{[(1+\bar{e}) \cdot (1+\bar{\xi})]^{n+1} - 1}{\bar{e} + \bar{\xi} \cdot (1+\bar{e})} \right] \le E_{to} \cdot \prod_{i=1}^{n} (1 + \lambda_i) \cdot (1 - SF) \tag{9}$$

It is important to mention that the solution of the above non-linear equation is derived by using an iterative algorithm and the appropriate numerical techniques on the basis of a trial and error approach.

6. Application Results and Sensitivity Analysis

To investigate the involved parameters' impact on the domestic lignite depletion time determination, representative values describing the national electricity scenery will be adopted. Consequently, a base scenario used as a yardstick will be introduced in the application model previously analyzed. More precisely, the values undertaken and describing the national electricity sector's status quo are cited in Table I. Accordingly, a sensitivity analysis investigating the impact of the above mentioned major variables will then be realized. In this context, the variables presently studied are the following:

- The mean annual escalation rate of national electricity generation "e"
- The mean annual rate of lignite's substitution by other energy sources "ξ"
- The mean annual rate of lignite's reserves electricity content increase "λ"
- The total base year lignite's proven reserves "E_{to}"

Table I. Base Scenario–Involved Parameters' Representative Values

Parameters	E_{to} (TWh)	E_o (TWh)	SF (%)	e (%)	ξ (%)	λ (%)	δλ (%)	β (%)
Central Value	1,923	57.8	20	3	1	3	0.1	34
Min Value				1	0	0		
Max Value				7	2	5		

Before proceeding to the analysis to be accomplished, a remark in concern to the energy content ascribed to the local lignite's proven reserves is thought to be necessary. More specifically, the proven reserves' value currently introduced supports the estimations for 5 billion tones of lignite existing. Therefore, by adopting the average lignite specific consumption coefficient already determined, i.e. 2.08 million tones/TWh_e, as well as the marginal exploitation coefficient (SF=0.2), the electrical energy content of the existing lignite deposits "E_{to}" may be defined, i.e. $E_{to} \approx 2000 TWh_e$, Table I.

6.1 Annual Escalation Rate of National Electricity Generation "e"

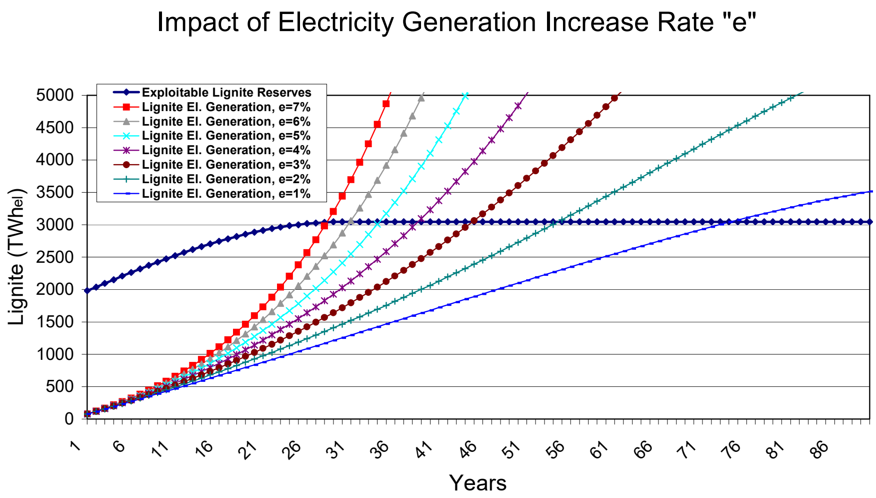

Figure 12: Effect of electricity generation escalation rate "e" on the lignite depletion time

In figure (12), one may observe the impact of a varying annual escalation electricity generation rate on the domestic lignite existing reserves depletion time. As expected, by increasing the value of "e", the depletion time of lignite decreases. For example, if a value of e=3% is assumed, then the estimated depletion time equals to 44.9 years. Moreover, by decreasing the rate of electricity demand, the depletion time extends significantly, i.e. if "e" becomes 1%, then the expected time for the lignite to last is 74.5 years. In conclusion, if a non-exhaustion perspective is to purchase, the annual rate of national electricity generation alone should be described by negative values only. Towards the direction of reducing "e", the implementation of energy saving policies and measures is essential. However directives such as 2000/55/EC, 2002/91/EC and 2006/32/EC are still only ostensibly applied in Greece.

6.2 Annual Rate of Lignite's Substitution "ξ"

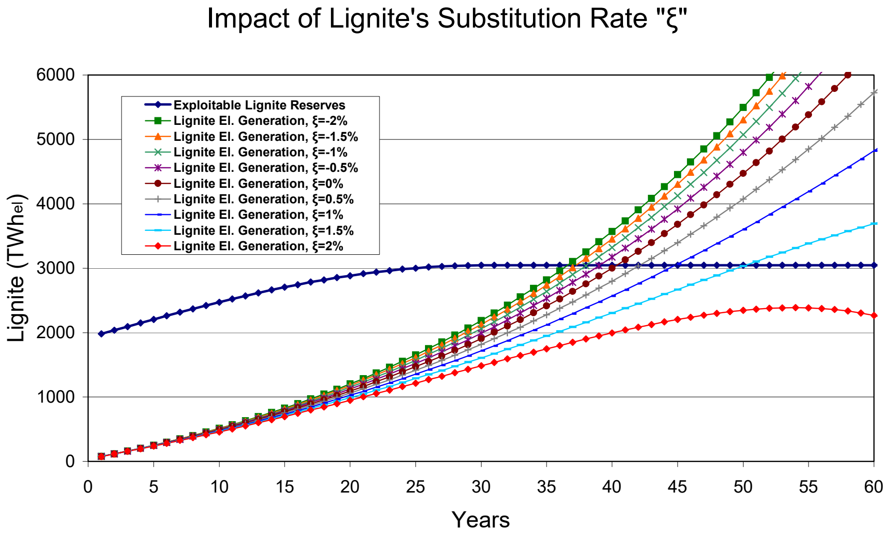

Figure 13: Effect of lignite's annual substitution rate "ξ" on the lignite depletion time

If discussing on the annual substitution rate of lignite in the electricity generation mix, a more mild variation range should be undertaken. Although the 2010 target did "dictate" the installation of approximately 7GW of cumulative RES power (mainly supported by wind energy and small hydro units, turnkey cost 700€/kW and 1200€/kW respectively), the required 9.5% annual increase of the RES share (base year 2005) in the national electricity generation with analogous "ξ" rates is not expected to be accomplished. On the other hand, considering the up to now situation, a substantial substitution may be mainly expected by the further promotion of natural gas in the years to come, not however diminishing a potential boom in the RES market as well. Any case given, the substitution rate is not expected to break a relatively narrow range of variation around the selected 1% per year. Besides, one should pay some attention on the cost issues as well. For example, for a 2% substitution of lignite electricity generation by wind farms the annual installation of 350MW of wind power suggests a cost of almost 250M€, showing the intensity of investments required. Currently, negative values of "ξ" demonstrating a decrease trend presume a countable national demand increase to mind and a contribution share of all other alternatives (natural gas, renewables) remaining relatively stable. As previously discussed, the contribution of RES-based electricity generation in the Greek electricity fuel mix comprises a typical example for this to realize[51]. The results obtained are well demonstrated in figure (13). In accordance to the range selected, one can clearly notice the rapid increase of depletion time for "ξ" values greater than 1.5%. In fact, if a substitution rate greater than 1.75% per annum is achieved, an important part of the local lignite reserves may be sustained in the course of time. In figure (14), values of "ξ" related to the electricity demand rate "e", under the hypothesis of zero new reserves' localization (λ=0%), suggest the lignite's depletion time upper limits. More specifically, by combining the resulting non-depletion critical points (combinations "ξ-e") the curve of sustainability for the local lignite reserves may arise. Consequently, the values on the right of this curve, clearly demonstrating considerable substitution of the lignite-based electricity generation from other energy sources, support the scenario of the national energy reserves' conservation.

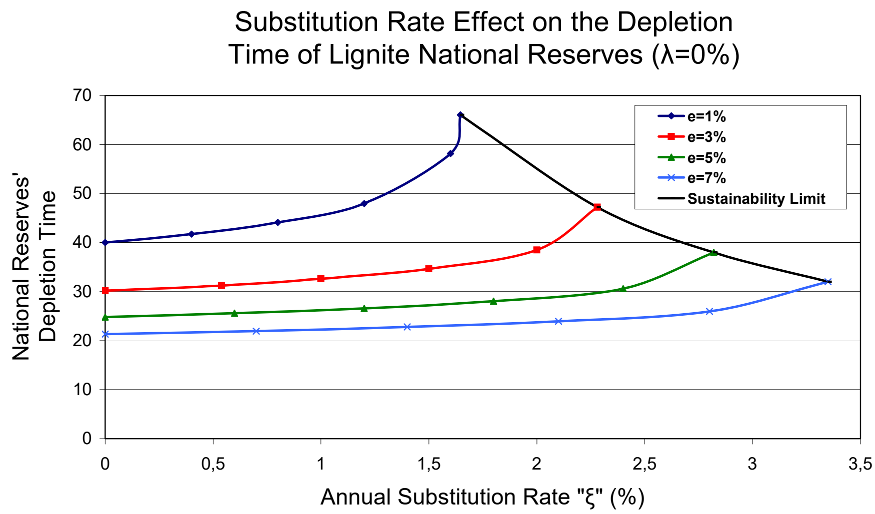

Figure 14: Effect of combined lignite substitution annual rate "ξ" and electricity demand annual escalation rate "e" on the domestic lignite depletion time

6.3 Annual Rate of Lignite's Reserves Electricity Content Increase "λ"

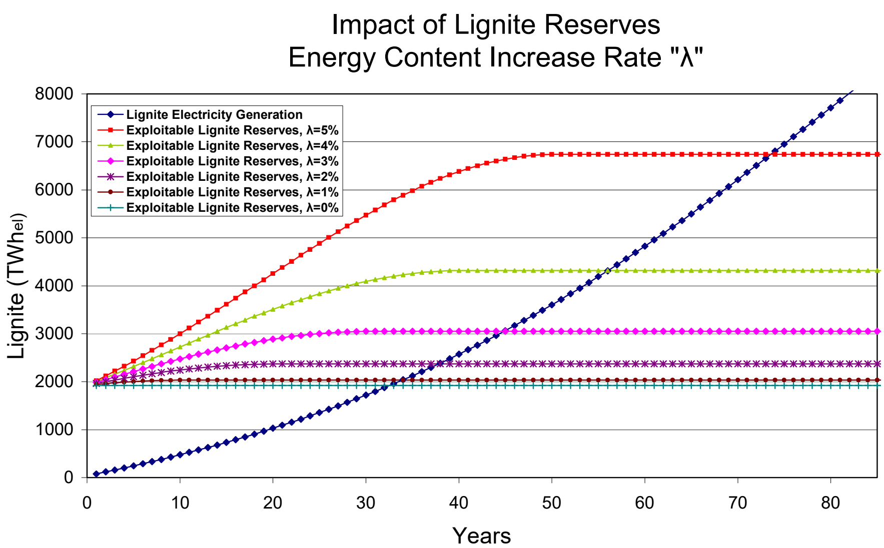

Figure 15: Effect of lignite reserves annual electricity content increase "λ" on the domestic lignite depletion time

In case that the "λ" coefficient representing the rate of domestic lignite's reserves electricity content increase (e.g. new reserves' localization, increase of lignite-based power station efficiency) on an annual basis becomes zero, i.e. the proven reserves of lignite energy content remains constant and equal to the one adopted during the reference year, the depletion time of lignite equals to 32.6 years. On the other hand, a 5% increase rate may significantly extend the lignite's life for more than 70 years (see figure (15)). Either way, although the impact of new reserves' localization does have an important influence on the lignite's depletion time, it is important to emphasize on the fact that the corresponding factor presents less options of "controlling". On the other hand, the parameter of substitution for example may derive as a result of a sophisticated energy planning and be afterwards adopted.

6.4 Total Base Year Proven Reserves "E_{to}"

Finally, it is interesting to investigate on the resulting time of depletion if a hypothetical variation of the total proven reserves is considered. Although such a scenario is only theoretical, given the case study used one may prove that the depletion time variation may be granted as practically independent (after a certain point of available reserves) from the lignite reserves being available. This theoretical approach introduces multiplication factors on the logarithmic scale of ten (x10, x100, x1,000 and x10,000 times). As expected, by increasing the existing proven reserves, the prolongation of the depletion time is de facto (figure (16)). However, after exceeding the $2 \cdot 10^6$ TWh_e of electrical energy content, the depletion time variation smoothes and tends to a more stable state. Even if the existing domestic lignite reserves were one thousand(!) times the up to now located ones, the corresponding depletion time would increase by only 200 years, figure (16). Although not describing a realistic scenario (especially in the highest of the multiplication scales selected), the impact of multiple proven reserves on the depletion time illustrates the greater importance ascribed to the impact of the rest parameters considered. More specifically, from the present analysis, the need for energy saving measures and for the lignite's gradual substitution acceleration, i.e. "e" reduction and "ξ" increase respectively, is becoming evident.

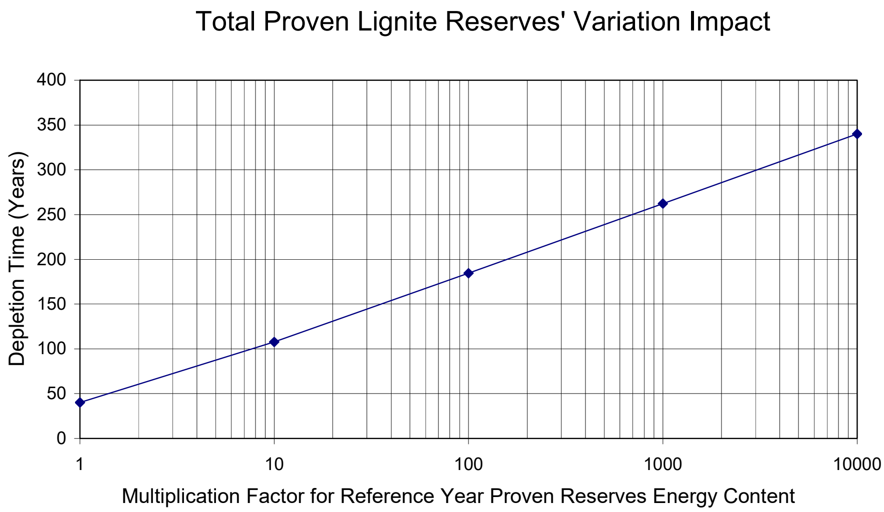

Figure 16: Effect of the base year proven reserves energy content "E_{to}" value on the domestic lignite depletion time

6.5 Sensitivity Analysis

In figure (17), the impact of all major parameters affecting the investigated problem is illustrated. Given a base scenario ("e"=3%, "β"=34%, "λ"=3% and "ξ"=1%) a sensitivity analysis deriving from the relative variation (Table I) of parameters selected (in relation with the base scenario) shall point out the magnitude of impact each of the parameters implies, always in concern to the depletion time of lignite, i.e. in what level does each of the parameters affect the depletion time under the condition of the same percentage variation. More specifically, the parameters of the annual electricity generation increase rate "e", the substitution rate of lignite-based electricity generation "ξ" and the lignite's reserves energy content increase rate "λ" are co-evaluated. As noted from this figure, the national electricity generation increase rate per annum along with the lignite reserves' energy content increase rate, comprise the two most influential parameters, described by an exactly converse behaviour. Concerning "e", if an increase is to be concerned, the acceleration of the lignite's reserves depletion is expected. On the other hand, an analogous increase for the "λ" value entails the exactly opposite result, i.e. the lignite's reserves life-expectancy prolongation. What must be underlined though is the narrow margin of control -mainly attributed to the parameter of "λ"- which depends on new reserves' localization or on technological improvements of the entire lignite exploitation process. On the contrary, the parameter of "e" may be influenced in a more decisive way under measures and policies supporting energy saving. Regarding the parameter of "ξ", presenting in most cases the mildest impact on the depletion time variation, it may comprise the result of a sophisticated national energy planning based on RES and natural gas faster penetration in the local market. More specifically, by adopting gradually increasing substitution rates, thought to suggest the most feasible of the potential mitigation scenarios, a considerable extension of the local lignite's' reserves may be encountered. Note that the non-depletion lignite reserves scenario may be realized in case that the "ξ" value increases by more than 75% in relation with the central value of Table I (see also figure (14)).

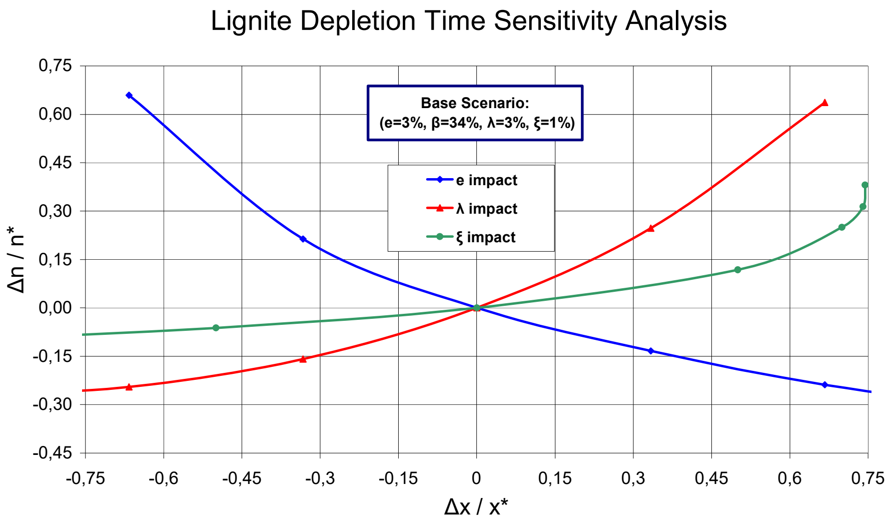

Figure 17: Lignite depletion time sensitivity analysis

7. Conclusions

Since having established the dominant role of lignite in the country's electrification as well as in the entire time evolution of the national electricity demand's satisfaction, in the present study, a retrospect of the up to now participation of lignite in the indigenous electricity generation along with a numerical analysis setting the future prospects ascribed to the latter, have both been set forth.

By investigating the characteristics of the local lignite, the positive impacts featuring the latter point out the significance of the lowest -among the EU-15- electricity price provided to final consumption (52% less than the European average kept at 14.3€/100kWh for domestic use in 2005), the circumvention of exchange losses (over 80 million oil barrels suggesting a 4.5 billion € exchange loss per annum), the development of local societies and the country's as a whole, and the acquisition of the technological knowledge regarding the corresponding production chain. On the other hand, the local lignite's utilization is accused of serious environmental damage caused by air emissions (over 35 Mtons of CO_2 and approximately 280 ktons of SO_2 annually), water and land resources use, water discharges and solid waste generation. The gradual degradation of reserves, the low efficiency rates presented by the power stations in operation and the appearing prospect of depletion in less than 30 years comprise additional drawbacks to mind.

The sensitivity analysis realized and studying the influence of certain major parameters' variation on the life-expectancy of the lignite's total reserves shows that the master catalysts affecting the time of depletion are the rate of annual electricity demand increase "e" and the lignite's reserves electricity content increase rate "λ". In concern to the parameter of lignite's substitution "ξ" and the hypothesis of the total proven reserves' variation, the former presented a more temperate impact to account while the latter, although not co-evaluated with the rest parameters, tended after a certain point to demonstrate a stabilizing behaviour. However, when "ξ" exceeds a specific numerical value -mainly depending on the corresponding "e" value- the sustainability of the local lignite reserves may be safeguarded. It is important to note that the future values of the "ξ" and "e" parameters may be decided by a sophisticated national energy planning supporting the application of appropriate energy management measures and policies, therefore serving the scope of the local reserves' sustainability.

In conclusion, if the terminus is to prolong the exploitation of lignite in the national electricity fuel mix and in parallel ensure the retaining of the national strategic reserves, the critical issue of configuring an energy policy prompting the decrease of the current electricity consumption rate and carefully examining the gradual substitution of lignite should be of paramount importance. Besides, in order to safeguard continuous life quality amelioration, one should take into consideration the issues of energy supply security, environmental protection, regional development and maximum permitted exploitation of indigenous resources. Finally, it is essential to state that any form of energy should neither be a priori rejected nor idealized.

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MODELLING, OPTIMIZATION AND LIFE CYCLE ANALYSIS OF BIOFUELS SUPPLY CHAIN

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Abstract

Continuous efforts towards the solution of the energy supply security problem and the environmental impacts caused by the transportation sector have led to the development, of the so called alternative fuels. Liquid biofuels, produced either from energy crops or from food processing residues can be used as transportation fuels in a large range of vehicles and blends and offer a real potential for development towards sustainable mobility with the involvement of the agricultural, energy and automotive sectors. The aim of this work is the development of a mathematical model for the optimisation of the biofuels supply chain, the value chain of which typically includes the feedstock production, the biofuel production, the blending (if applicable), the distribution and the consumption. The optimization results, which employ a wide range of critical parameters affecting the performance of the whole biofuels value chain system are identified and expressed quantitatively. Implementation of the model supports decision taking in various planning and operational issues such as infrastructure investments, the quantities of raw materials to be cultivated, the quantities of biofuels to be produced in the domestic market or to be imported. All these alternative scenarios can be evaluated with the support of the model, for the optimal planning and operation of the biofuels supply chain.

Keywords: Fuel Market; Energy Crops; Feedstock; Environmental Impacts

1. Introduction

A promising prospect in the critical issue of a country's fuel security / oil dependency, especially for the energy intensive transport sector, is the introduction of alternative fuels and especially of biofuels. Today, these fuels produced either from energy crops or from food processing residues, consist approximately 2% of the European fuel market, a rate that by 2020 is expected to reach the anticipated target of 10%[1].

Today, two primary biofuels are in wide spread, both of which can run in existing vehicles. Ethanol is currently blended with gasoline and biodiesel with petroleum-based diesel for use in conventional diesel-fuelled vehicles. With the main driving force being the obligation of the EU-Member States to adopt the directive 2003/30/EC and the forthcoming new RES directive[1], the introduction of biofuels in a country's energy balance, creates a wide and interesting area in terms of financial development.

At the moment, although a large number of feedstock and production technologies are available, the penetration of biofuels has not been the anticipated, due to their relative high production costs and the social opposition that they have been facing. Thus, in that research field, many studies have been conducted, trying to model and minimize all costs and parameters related with biofuels production, but not extended work has been done in the biofuels supply chain modelling. The aim of this work is the development of a mathematical model for the optimization of the biofuels' supply chain, the value chain of which typically includes the feedstock production, the biofuel production, the blending (if applicable), the distribution and the consumption.

Biofuels' production (chain) involves many sub-domains such as agriculture (energy crops, raw materials production), biofuels production procedure itself (transformation of already- existing plants or/and implementation of new ones) and of course it involves the integrated supply and trade network. Therefore biofuels' domain sets up an added value in the country's economical profile either from the raw materials' production or from the fuels production themselves. So, a country, proportionally to its production possibilities, can take advantage of the large extent of biofuels' domain in profit of its agricultural and industrial sector development. Biofuels supply chain usually incorporates the following activities-stages (figure (1)):

- Raw materials production (which is related to the land availability and suitability, soil's efficiency associated to different types of plants)
- Biofuels production (which refers to the transformation of raw materials through various processes into biofuels)
- Blending (in the case that biofuels are provided to the end consumers in mixed state)
- Biofuels' transportation and finally
- Consumption

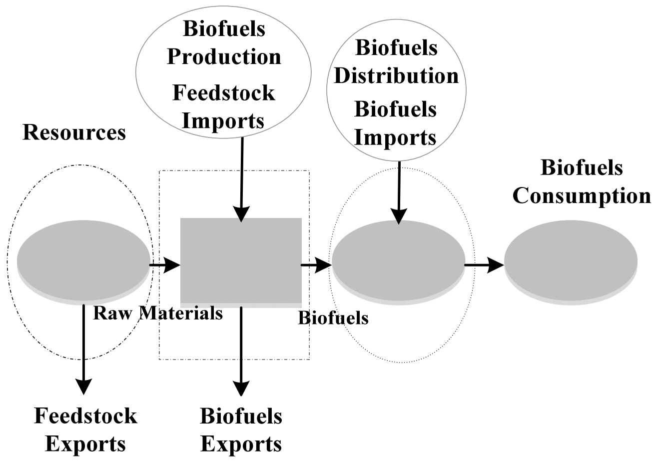

Figure 1: The biofuels' supply chain system

The development of the local market of biofuels, in the geographical area of a country has not any constraint on the origin of the raw materials or end products. As it is illustrated in figure (1), in any stage of the supply chain, there is the flexibility of importing the required quantities in case of not been locally produced.

Accordingly, it is possible in any stage of the supply chain sub-products to be exported due to over adequacy or economical profitability. The decision point, i.e. in which stage of the supply chain an investor is going to step in, is a strategic decision for the development of biofuels' market and it is determined by multiple technical and financial parameters. In any case it does not pose the question whether a country has the possibility in terms of financial and technical potentiality to become a biofuels producer or not, or it has to import the required quantities. The parameters that are compromised in this decision point implement firstly a techno-economical evaluation of the integrated biofuels production activity and a rational and structured appraisal method of different/alternative scenarios of decision making.

2. Life Cycle Analysis

A lot of discussion has recently been conducted concerning the overall benefits or disadvantages of biofuels' use, mainly compared to conventional-fossil fuels. To that effect, one of the tools that have been employed is Life Cycle Analysis (LCA), i.e. an integrated evaluation of the advantages and disadvantages of biofuels for their entire lifecycle.

However, it should be mentioned that the way LCA is defined and used, may result in different conclusions for exactly the same issue. Therefore, the objective of the current short notice is not to add one more approach to the biofuels' LCA bibliography, but rather to synthesize the main and most characteristic aspects concerning the debate that takes place as well as to point out the future prospects of this wondering.

Assigning a preliminary definition, according to the ISO 14040, in the general case LCA is a "systematic set of procedures for compiling and examining the inputs and outputs of materials and energy and the associated environmental impacts directly attributable to the functioning of a product or service system throughout its life cycle".

There are many indices describing the LCA aspects (net energy value, energy ratio), new theories (ecological energy balance) and novel considerations (carbon debt of land conversion). It is not the scope of the present work to review all these definitions; therefore in the table below only the basic ones along with their attributes are provided (Table I):

Table I: Dimensionless LCA indices with their attributes

Attribute	Index	Explanation
Energy	Energy Ratio (ER)	Energy outputs/Fossil energy inputs[2].
Environment	Proportion of GHG's emissions savings	Greenhouse gas emissions (including CO_2, CH_4, and others) avoided using biofuels, related to the amount and carbon intensity of the fossil fuel inputs needed to produce the biofuel, as well as to what fossil fuel is substituted by use of the biofuel[3].
Efficiency	Performance of end fuel (ratio and/ or proportion)	The net fraction of motor fuel (gasoline/diesel) that could be replaced with biofuel[4].

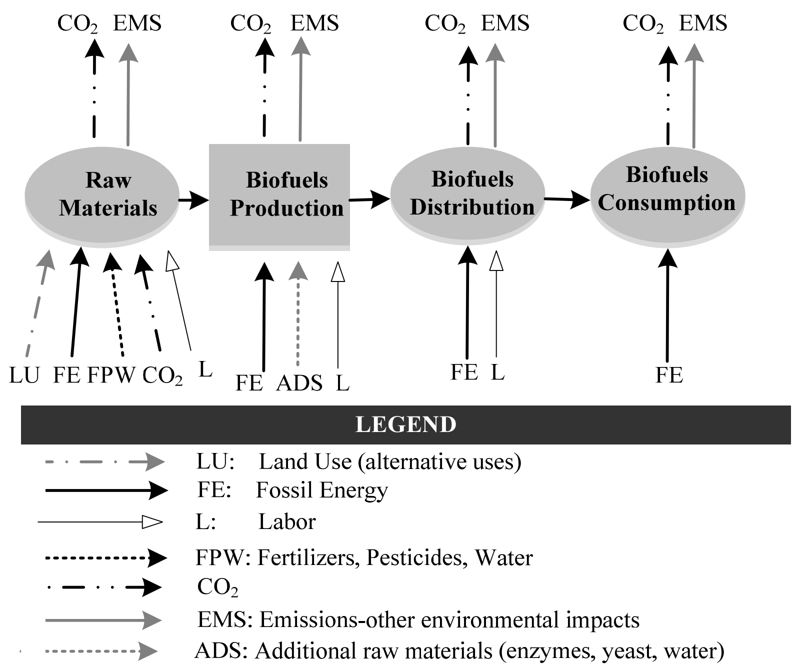

Figure 2: The biofuels' supply chain system from a LCA perspective

The basic LCA components of the biofuels' supply chain are the followings (figure (2)):

1. Raw materials cultivation: use of fertilizers (N, P, K), pesticides, soil emissions from that activity,

tractors energy consumption, emissions feedstock and also valorization of by-products
2. Biofuel processing: fossil energy and chemical consumption into the conversion processes (i.e. extraction, drying, refining, esterification, fermentation)
3. Biofuels distribution: fossil fuel consumption
4. End use: exhaust emissions from biofuels usage either blended, or in pure state, substituting fossil fuels

One should not miss in the above orientation to compromise the labor consumed (energy), as well as the land alteration issue- post land usage and the water utilization parameter (critical in areas with limited resources).

Thus, after the above contemplation one could point out the critical parameters affecting biofuels' life cycle assessment and the environmental impacts of each activity step (Tables II,III).

Table II: Parameters consideration into biofuels life cycle assessment

Parameters
Raw materials - feedstock type
Past land usage (forest, grassland or set- aside/ degraded land)
Climatic conditions (affects biomass availability & distribution)
Geographical location (associated with climate, temperature ranges, emission diffusion phenomena)
Technological process path followed and production patterns
The scale and mix of the technology (large or small)
Land availability (post land usage)
The usage / processing or not of by-products
The relative use of the end fuel either in mixed or in pure mode
The quality of the end fuel (relative to the vehicles efficiency determining the rate of exhaust emissions from consumption

Table III: Environmental effects/ impacts from each stage of the supply chain

Stage	**Environmental impact**
Raw materials /feedstock cultivation	Short – Medium term: - Soil Erosion - Nutrient Runoff - Pesticide Runoff - Land Use (Conversion) - GHG Emissions - Biodiversity Long term (mainly assigned to land's characteristics): -Acidification -Depletion of abiotic resources -Eutrophication -Land degradation -Ecological toxicity (soil, water)
Biofuels production	- Air Pollution - Water Pollution - GHG Emissions
Biofuels distribution	- Air Pollution - GHG Emissions
Biofuels consumption	- Displaced Air Pollution - Displaced GHG Emissions

It is believed that all this sudden and unforeseen debate on biofuels environmental performance and energy usage, assigning to them all the burden of food prices' skyrocketing, can be fairly explained by taking into consideration a nexus of factors with the most important being, the fallen world inventories (of rice), the geographical specific population increase, the amelioration of standard of living, the change of land use (industrial development) and/ or the profit seeking behavior of various actors.

Synopsizing one could say that Life Cycle Analyses might present biofuels as CO_2 beneficial, if not accounting for the carbon sequestration sacrificed by diverting land from its existing usages, or malignant if not utilizing and valorizing the derived by-products, or regarding bad farm practices. In the absence of a global land use model, (in order to estimate the greenhouse gas effect of the land use changes) multiple CO_2-equivalency factors can be per case assigned each one delivering a different result (figure (3)). Therefore, some criticism must lay down on the relative interpretation of these life cycles, before adopting them.

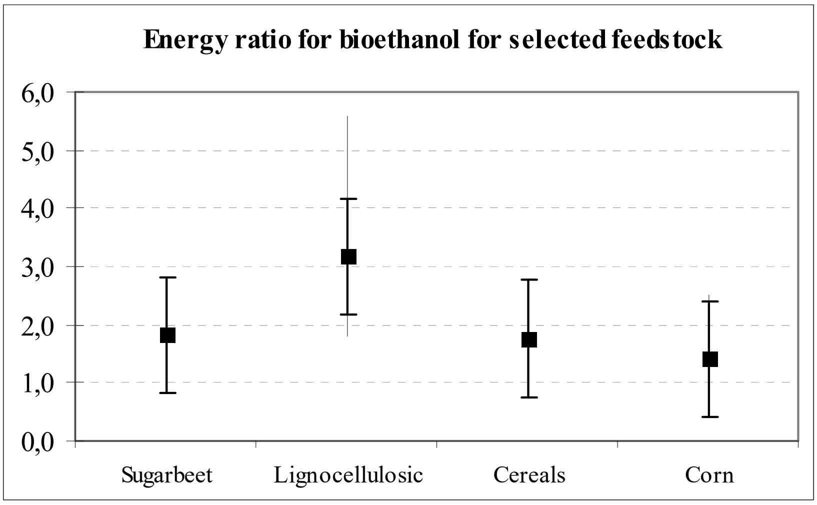

Figure 3: Energy ratios for selected bioethanol feedstock[6]

3. Biofuels supply chain modeling issues

The main contribution of developing a mathematical model for biofuels' supply chain optimization is that it helps primarily in the formulation of decisions that need to be undertaken and secondly selecting over different alternatives concerning the structure and operation of biofuels' supply chain such as:

- The extent of the cultivated land for specific raw materials
- The produced quantities of each specific raw material selected that could be used, resulting the corresponding area to be cultivated
- The decision of creating production infrastructure with the corresponding investments for biofuels production
- Raw material quantities that could or should be imported
- Biofuels quantities that should be produced from each selected raw material
- Quantities and types of biofuels that should be imported

The proposed mathematical model is generic and attempts to simulate and optimise the performance of the biofuels value chain under certain operational constraints. The model could be implemented locally, for a certain area or a certain configuration of the supply chain (raw materials-biofuels production-final consumption) or of a more extended range which presupposes the transportation of raw materials or/and biofuels and the corresponding costs.

In the general case, the characteristics of the model are illustrated bellow:

Definition of the system

Given:
- The geographical area under consideration
- The time horizon for the problem solution

Optimization criterion

- Maximization of the total value (profit or gain) deriving from biofuels supply chain= total profit (from biofuels, energy and the other co products)- Total Cost (from the raw materials as well as biofuels production, transportation) or
- Maximization of the local added value or
- Minimization of the total biofuels production cost or
- Minimization of imported raw materials or
- Minimization of imported biofuels or
- Minimization of environmental impacts deriving from the production of biofuels

Constraints

- Raw materials production capacity (usage, availability, land suitability). Raw materials production is totally depends on the land's yield.
- Conversion of raw material into biofuels. The delivered quantity of biofuels for each raw material is determined by the corresponding yield.
- Capacity of the biofuel production units. The delivered quantity of biofuels is determined by the capacity of the each production plant.
- Satisfying the market demands. The required biofuels quantity will be satisfied either from the inland production or from imports.
- The biofuels produced quantity that are not required for local consumption will be exported.
- The required and not domestically available raw material quantity for the production of biofuels will be imported.
- Mass balances considering yields in the production units.
- If the domestically produced biofuels quantity does not satisfy local demand, the missing quantity will be imported.

Problem parameters

- Soil's efficiency for each selected raw material
- Available land (in terms of extent and capacity) for each selected raw material
- Development/ production cost for each selected raw material
- Biofuel cost in the production plant
- Efficiency of biofuels production for each selected raw material
- Raw materials transportation cost
- Biofuels transportation cost
- Environmental (measurable) impacts for each of the selected methods

Problem variables

- Raw material quantity locally cultivated
- Raw material quantity which is turned into every type of biofuels
- Imported raw material quantity
- Biofuel quantity produced in each production plant
- Imported quantity of each type of biofuel
- Raw materials transported quantity (which brings up the corresponding transportation cost)
- Biofuels or raw materials transported quantity

In the objective function, in the term of total cost, the produced and sold quantities of biofuels are multiplied by the corresponding selling price. Therefore, in this way it is provided a possibility of analysing and appraising differential biofuels pricing politics as well as incentive actions.

4. Mathematical model development

The model to be developed should reflect the major considerations and operational constraints of the system, while, at the same time should not be extremely complex, in order to be easily solvable and provide valuable results to the users. As it includes a series of different time scale problems, the model could be used by different stakeholders and therefore be adjusted accordingly. In the present work a general framework for the model is proposed that will be refined at a later stage.

Index	Description
i	raw materials
j	Biofuels
t	Time
H	time horizon

Parameters

Name	Description
$A_i^{\max}$	Maximum land available for raw material i (in m^2)
e_i	Yield of land in raw material i (in tones of seed / m^2)
b_{ij}	Yield of raw material i for the production of biofuel j (in tones of raw material / tone of biofuel)
CAP_j	Capacity for production of biofuel j
DRM_i	Demand for raw material i for the biofuels to be produced
DB_j	Demand for biofuels to satisfy needs and legislation
C_j	Production cost for biofuel j locally produced (€/tn)
C_j^{imp}	Cost of imported biofuel (€/tn)
CR_i	Cost of production of raw material (€/tn)
CR_i^{imp}	Cost of imported raw material (€/tn)
$PR_i^{\exp}$	Price of exported raw material (€/tn)
P_j	Selling price of biofuel j locally produced and consumed (€/tn)
$P_j^{\exp}$	Selling price of biofuel j locally produced but exported (€/tn)

Variables

Name	Description
A_i	Area being cultivated for raw material i (in m^2)
X_i	Quantity of raw material i being locally cultivated in area A_i (in tn)
$X_i^{\exp}$	Quantity of raw material i that is exported (in tones, included in X_i)
X_i^{imp}	Quantity of raw material i being imported for domestic production of biofuels (in tn)
Y_j	Quantity of biofuel j being domestically produced (in tn)
$Y_j^{\exp}$	Quantity of biofuel j being exported (in tn)-(included in Y_j)
Y_j^{imp}	Quantity of biofuel j being imported to in order to satisfy demand (tn)

Other variables maybe considered at a later stage, such as:

Variables

Description	
w_k : (1,0)	Binary variables indicating decision on production technology (it affects costs, conversions, capacities etc)

For a certain time horizon H:

Raw materials requirement and production

$$A_i \times e_i = X_i \quad A_i \le A_i^{max} \quad \text{for each i}$$

This set of constraints is written for each raw material i taken into consideration. The raw materials that will be considered in each problem will be chosen at the beginning and will depend on the biofuel to be produced (design variables).

Biofuels production (for each j considered)

$$Y_j = \sum b_{ij} \times \left(X_i - X_i^{exp} + X_i^{imp}\right)$$

the sum is taken over all raw materials i that produce biofuel j

Biofuels' demand satisfaction

$$\left(Y_j - Y_j^{exp} + Y_j^{imp}\right) \ge DB_j$$

This set of constraints is written for all biofuels j that will be considered in the problem. It is emphasized that biofuels that will be considered in the problem are design variables and depend on the problem to be solved.

Capacity limitations

$$Y_j \le CAP_j \text{ for each j}$$

In case we consider the produced quantity of each plant rather than total, then the capacity constraint should be taken separately for each plant.

Optimization criterion:

Max (value) or Total System Performance = max (Σ(inflows) – Σ(outflows))-

- other costs (transportation , environmental etc)

$$\max = \left\{ \begin{array}{l} \sum_j \left(\begin{array}{l} p_j \times \left(Y_j - Y_j^{exp}\right) + P_j^{exp} \times Y_j^{exp} \\ - C_j^{imp} \times Y_j^{imp} - C_j \times Y_j \end{array} \right) \\ - \sum_i \left(\begin{array}{l} CR_i \times X_i + CR_i^{imp} \times X_i^{imp} - \\ PR_i^{exp} \times X_i^{exp} \end{array} \right) \end{array} \right\}$$

The resulting optimization model is an Linear Programming or, in case binary decision variables are included, a Mixed Linear Programming Problem optimization algorithms (GAMS, LINDO, etc.). The most difficult and crucial step is how to find valid values for all the aforementioned parameters. An indication of the values that are currently considered in the ongoing research being carried out are provided in Table IV:

Table IV: Illustration of indicative values for model-validation[6]

Raw material & Indicative values	e_i (tn/m^2)	b_{ij} (tn raw material / tn biofuel)
Rapeseed	3.5×10^{-4}	2.78
Sunflower	1.8×10^{-4}	2.50
Wheat	6.3×10^{-4}	3.58

Sugar beet	69.0x10^{-4}	12.53

5. Conclusions

Trying to answer to the biofuels' debate one could claim that there are two basic axes that should be compromised in theirs environmental – economical- energy performance assessment: (a) Best available practices for farming and production of (at least) fist generation biofuels and (b) Appropriate modeling and parameters contemplation in the entire biofuels' supply chain.

The implementation of the integrated biofuels supply chain model that has been developed in the present work can help substantially the optimization of the supply chain's operation in various issues, such as the selection of the cultivation areas, the design of biofuels production units, the biofuels quantities to be domestically produced and exported or imported, the pricing of the produced, exported and imported quantities, and, in general to evaluate different production and consumption supply chain configurations. In its progress the present research work will include the detailed quantification of the problem parameters for specific problems and the running of the model, in order to identify deficiencies and bottlenecks, as well as to reveal the main characteristics of these new complex supply chains.

Furthermore, the model can be extended to include various other possibilities such as production technologies selection, cultivation and production units sitting and structure of the distribution network for specific cases.

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OPTIMUM SIZING OF A HYDROGEN PRODUCTION INSTALLATION BASED ON RENEWABLE ENERGY SURPLUS

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Abstract

According to the most recent European Commission proposal, the renewable energy share in the European energy sector should reach 20% by the year 2020. Such a goal could be supported by the concept of coupling renewable energy installations with energy storage or clean fuel production systems (e.g. hydrogen) that will be able to exploit the maximum renewable energy produced. Such systems overcome the technological barriers of the weak electrical networks and promise high quality of electricity distribution. Additionally, the income loss of renewable energy investments (mainly wind parks), owed to the curtailments of significant renewable energy production by the specific electrical grids, may be remarkably ameliorated. An integrated algorithm, based on real renewable energy curtailments data and being able to estimate the optimum size of a hydrogen production installation cooperating with existing wind parks, is currently presented. The calculation results indicate that the optimum size of a hydrogen production plant can match the wind energy curtailments' profile, thus significantly increasing the renewable energy absorption by the local electrical grid and remarkably ameliorating the economic viability of the renewable energy investments.

Keywords: Hybrid Systems; Hydrogen; Integrated Renewable Energy Systems

1. Introduction

According to the 2001/77 Directive[1], Greece should cover -by the year 2010- 20.1% of its gross electricity consumption by Renewable Energy Sources (RES). Meanwhile, a new proposal recently published by the Commission[2] revises the targets concerned with the RES contribution in the EU total energy consumption, suggesting a share of 20% by the year 2020.

According to the most recent data (2005), the renewable energy sources' contribution to the electricity demand of Greece by a total of 10.7% is broken down to 2.1% of wind energy, 8.4% of hydro energy, 0.2% of biomass and less than 1% of solar energy. Given the fact that the most promising and aggressively growing renewable energy source is wind energy (figure 1)[3][4], more attention should be given in order to ensure both the maximum penetration and the economic viability of wind energy projects. Taking into consideration the installed capacity of wind turbines (890MW) and the corresponding wind energy released to the electricity network (1,699GWh), the overall capacity factor of wind energy in Greece, ranges between 22% and 23%.

On the other hand energy storage has become a mature technology, with great activity in the corresponding research area. In order for the targets set by the EU to be fulfilled, the required promotion of wind energy may be supported by the concept of coupling renewable energy installations with energy storage or clean fuel production systems (e.g. hydrogen), able to exploit the maximum renewable energy produced[5]. Such systems overcome the technological barriers of the weak electrical networks and promise high quality of electricity distribution.

Additionally, since hydrogen has been produced for years in order to serve various industrial purposes, a great experience in the field of hydrogen production may be noted. The idea of storing excessive wind energy which cannot be absorbed by the local grid by producing hydrogen comprises a concept

Kavadias K.A., Zafirakis D.P., Rozakeas K., Kaldellis J.K., 2008, "Optimum Sizing of a Hydrogen Production Installation Based on Renewable Energy Surplus", X^{th} World Renewable Energy Congress, July 2008, Glasgow-Scotland, UK.

that has been under investigation for a long time, however not yet implemented to such an extent. The main advantage of the hydrogen is its mobility (it can be consumed elsewhere from the place that it is produced), and the fact that it can be stored for long periods of time.

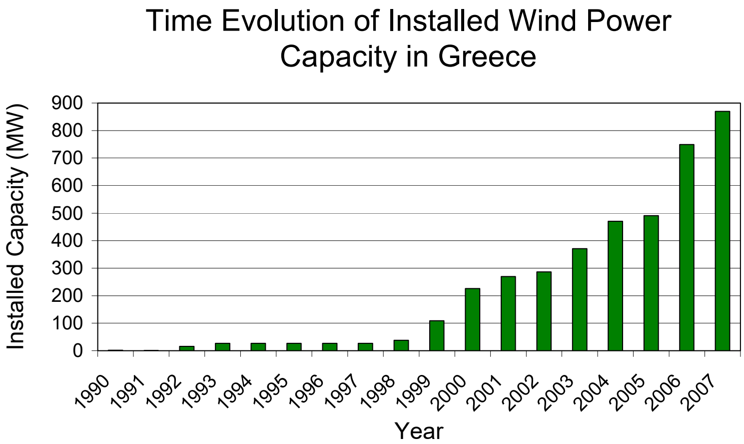

Figure 1: Time evolution of wind parks installation in Greece

Based on a developed algorithm, the aim of the proposed work is to estimate the optimum size of a hydrogen production plant, used in order to absorb the renewable energy surplus deriving from the existing wind parks of an autonomous electrical network. For this purpose, a three-year period hourly data of wind energy curtailments, recorded from selected wind parks installed on the Island of Crete, are currently used, while it is important to note that the proposed analysis may be equally well applied to the entire island wind parks' curtailments.

Using long-term energy curtailments data, the developed algorithm could be used in any existing renewable energy installation that faces grid energy curtailments. Besides, in order to achieve optimum sizing of the hydrogen production plant, all the operational factors of the commercial electrolysis devices should be considered.

2. Problem Definition

In many Greek regions and more precisely in the Greek islands, although the local renewable potential is often significantly high, the local autonomous electrical networks are unable to absorb the renewable energy produced[6]. Other barriers against renewable energy penetration are caused mainly by the significant gap between energy production and demand[7]. This is particularly observed in the case of wind energy and is due to the stochastic variability of the wind speed. As a result, significant amounts of renewable energy are rejected by the local grids[8].

In this context, apart from the unreliability concerned with the wind energy absorption, the deriving income loss of renewable energy investments (mainly wind parks), owed to the curtailments of significant renewable energy production by the specific electrical grids, should be remarkably ameliorated.

Besides, one shouldn't neglect the cost of electricity production[9], mainly at the autonomous electrical grids (e.g. Aegean Sea Islands), where in most cases the electricity production cost is even four times the selling price. The Aegean Sea Islands have excellent wind potential[10] but the weakness of the electrical grid keeps the renewable energy penetration limits rather low. In such cases there are significant quantities of energy which are not absorbed by the grid.

By storing the excess wind energy and use it in peak load demands, i.e. when there isn't any wind available, the renewable energy penetration limits may be by-passed and the disturbance of the local grid's stability may be avoided. The use of the stored energy at peak demand can also ameliorate the operation of the autonomous power stations and lower their operational cost.

3. Proposed Solution

In order to minimize the problem arising by the mismatch between demand and intermittent wind energy production, the current work investigates the performance of a combined wind park installation and a hydrogen production unit. According to the proposed solution, during low consumption periods, excess wind energy can be used to produce hydrogen via electrolysis.

More precisely, the proposed configuration (figure 2) consists of an existing wind park, a water purification unit in order to improve the quality of the water, a water storage tank to ensure that the process has adequate water in storage in case the water system is interrupted, the electrolyte solution (in alkaline systems) and the hydrogen generation unit. The latter consists of the electrolysis stack, the gas purification module, the dryer and the heat removal system. In the proposed analysis, hydrogen compression unit is not included as it is assumed that hydrogen is fed directly into a pipeline.

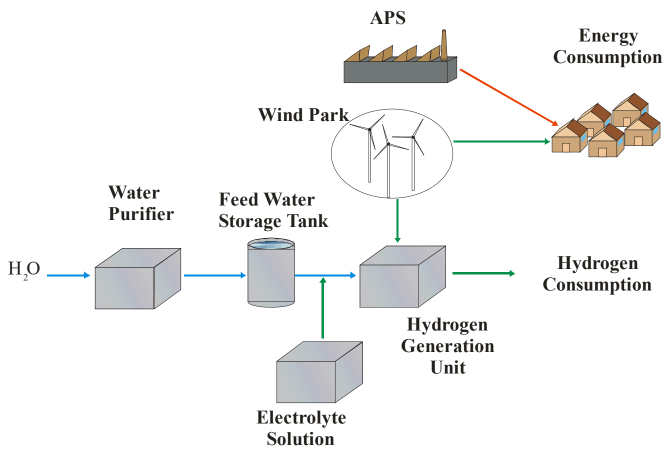

Figure 2: Integrated Wind-Hydrogen production installation

During the operation of the proposed Wind-Hydrogen energy production installation, the following situations may appear:

a. The wind park's power surplus is higher or equal to the power capacity of the hydrogen production unit. The hydrogen production unit absorbs only the power capacity that it needs, and the energy surplus is transferred to low priority loads.
b. The wind park's power surplus is between the lower and maximum limit of the power capacity of the hydrogen production unit. The hydrogen production unit absorbs the wind energy surplus.
c. The wind park's power surplus is lower than the minimum power required for the operation of the hydrogen production unit. The wind energy surplus is transferred to low priority loads.

4. Sizing Methodology

The proposed analysis is based on real operational data from existing wind parks which are located on the Island of Crete. According to authors' previous work[6], the specific wind parks have faced significant curtailments from the local grid (figure (3)).

The current work is targeting on defining the size of the hydrogen production unit which could be installed on the island in order to absorb the wind energy excess. The optimum sizing solution is estimated on the basis of maximum wind energy penetration and maximum economic efficiency.

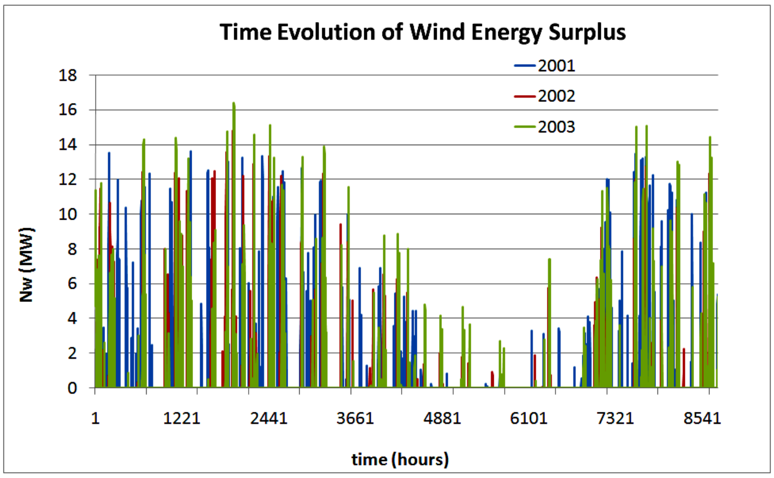

Figure 3: Excess wind power time variation

The quantity of hydrogen produced by the electrolysis depends on the available excess wind energy and the performance of the electrolyzer. Thus, the quantity "H" of hydrogen produced is calculated by equation (1):

$$H = \frac{E_w}{e} \tag{1}$$

where "E_w" is the available wind energy in kWh and "e" is the amount of energy needed for the production of hydrogen (kWh/kg).

Note that as already mentioned, the operation limits of the hydrogen production installation determining the final energy "E_w" exploited by the hydrogen unit have been taken into account.

For the estimation of the economic feasibility of the hydrogen installation, all the necessary economic factors have been taken into consideration, (e.g. initial investment cost of the electrolysis, the annual mean capital cost of the local market, the annual fixed maintenance and operating cost, the variable maintenance and operating cost etc)

More precisely, the net present value "NPV" of the installation can be calculated by equation (2):

$$NPV = R_H + R_O + Y_n - (1-\gamma)IC_o - FC - VC - WC - EC \tag{2}$$

where "R_H" is the revenues from the hydrogen sales, "R_O" is the income from the sale of the produced oxygen, "Y_n" is the residual value of the plant after "n" years of operation, "γ" is the subsidy of the initial cost "IC_o", "FC" and "VC" are the corresponding fixed and variable maintenance and operational costs, "WC" is the cost of the water volume required and "EC" is the cost of energy input in case of purchasing the wind energy.

The internal rate of return (IRR) is the corresponding capital cost for which net present value equals to zero.

5. Application Results

Three year wind energy curtailments were used by the developed algorithm in order to simulate the operation of different sizes of hydrogen production plants. According to the available excess wind energy, the electrolysis power varies between 1MW and 14MW (figure (4))

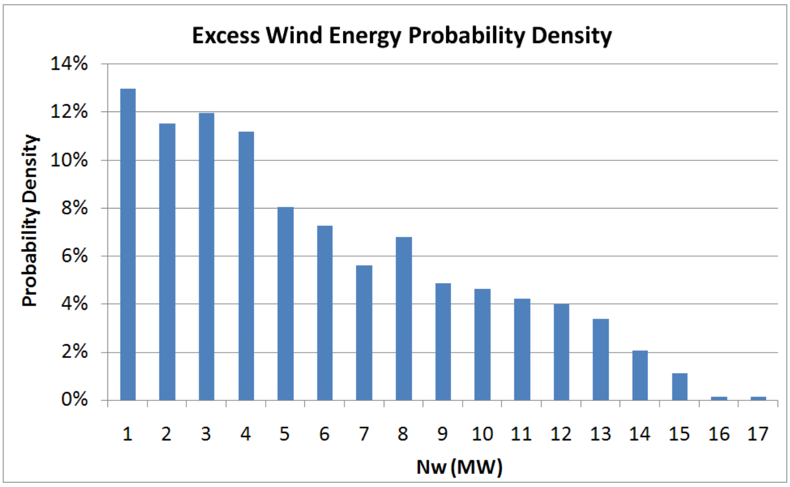

Figure 4: 3-year excess wind power probability density

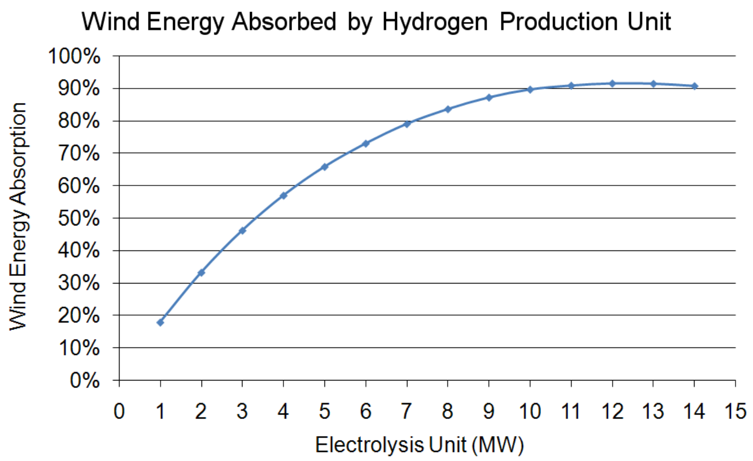

Figure 5: Wind energy absorbance for different electrolysis units

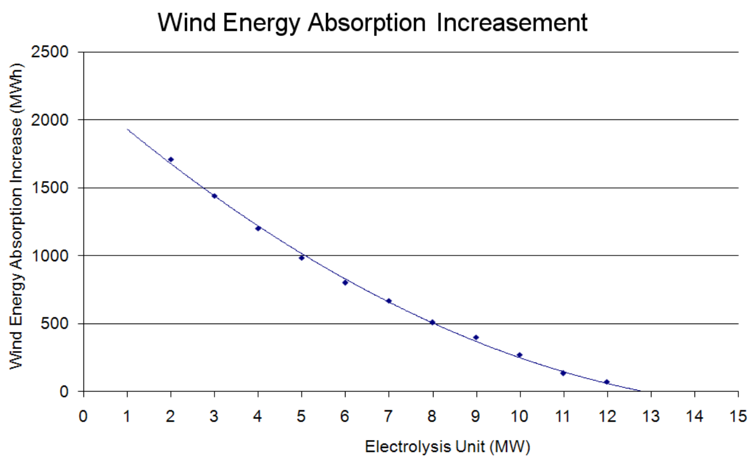

Figure 6: Wind energy absorbance deceleration

According to the results, there is a 10% possibility to obtain excess wind energy by the wind park, which would be available for hydrogen production. The wind energy absorption by the hydrogen production unit could reach 90% for a 10MW electrolysis unit (figure (5)). Additionally, one may also conclude that the absorbance of the wind energy surplus is gradually decelerated, see figure (6).

Considering the best size of the hydrogen production unit, based on the latter economic efficiency, figure (7) presents the net present value variation for a 10 years' period of plant operation. The best NPV value is obtained for the 4MW installation, i.e. when the net present value of the plant reaches 710,000Euro. Although it is a significant amount, it represents only 25% of the plant's initial cost. In order to obtain positive values of net present value, the size of the electrolysis unit should be lower than 9MW. In the case of the 4MW plant, the absorbed wind energy is 57%.

Figure (8) presents the internal rate of return variation for the different electrolysis' sizes under investigation. According to the results, the IRR value for the 4MW unit is approximately 13% while the corresponding value for the 10MW unit is 5%. In order to achieve IRR values higher than 10%, the hydrogen production unit should be up to 5MW, i.e. the point that the obtainable wind energy surplus absorption reaches the value of 70%.

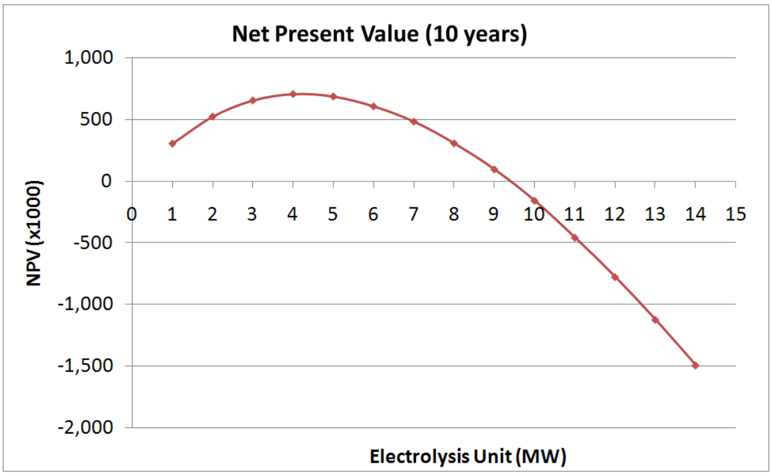

Figure 7: 10-year net present values for different installations

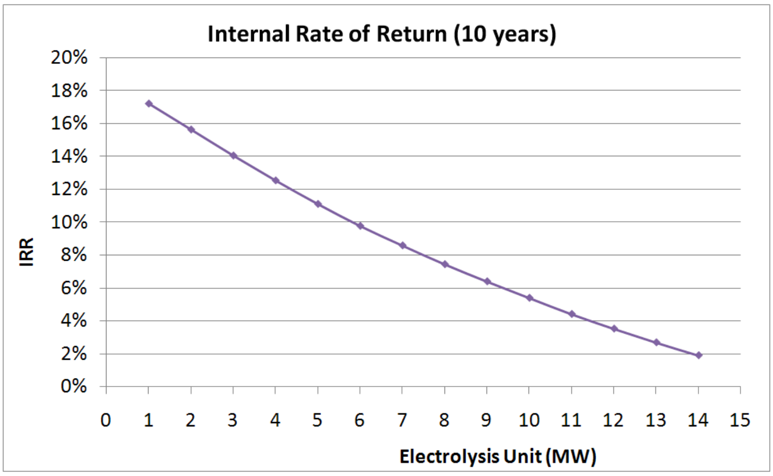

Figure 8: 10-year internal rate of return values

6. Conclusions

According to the results obtained, the optimum size of a hydrogen production installation strongly depends on the proportion as well as on the time-scattering of the renewable energy being rejected.

Taking into account the minimum energy needs of the hydrogen plant along with the installation and operational costs, there is a contradiction between the optimum size of the plant for maximum renewable energy absorption and the optimum size of the plant for best economic performance. One of the main parameters affecting the optimum solution is the hydrogen market price. In this context, in order to give motivations to investors for investing on installations with maximum renewable energy absorption, the cost difference between the two optimum size solutions may be subsidized for a selected time period.

An integrated algorithm, based on real renewable energy curtailments data and being able to estimate the optimum size of a hydrogen production installation cooperating with existing wind parks, is currently presented. The calculation results indicate that the optimum size of a hydrogen production plant can match the wind energy curtailments' profile, thus significantly increasing the renewable energy absorption by the local electrical grid and remarkably ameliorating the economic viability of the renewable energy investments.

In view of the goals of the renewable energy penetration in the European energy network and the uncertain future of the oil prices worldwide, such hybrid power stations, based on renewable energy plants and environmental friendly hydrogen production installations, will progressively take on.

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DESIGN AND FEASIBILITY ANALYSIS OF A NEW BIODIESEL PLANT IN GREECE

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Abstract

There is a continuously interest concerning the Biofuel implementation in Europe, mainly because of environmental protection and energy supply reasons. In this context the European Union (EU) strongly encourages the use of Biofuels through a number of Directives. The Directive 2003/30/EC of the EU sets up the targets of biofuels on the EU transport fuel market setting the reference value to 5.75% of all gasoline and diesel used in transport by the end of 2010. Amongst different biofuels pathways available, biodiesel from agriculture derived feedstock appears to be the feasible, ready to market option in Greece. The objective of the present work is to make a detailed analysis of a biodiesel production plant design characteristics in Greece, considering that the raw materials will also be locally produced. Furthermore, the feasibility of such a plant is evaluated and useful conclusions are drawn in respect to the unit production cost and various other technical and economical parameters.

Keywords: Biodiesel; Greece; Production Units; Biodiesel Plant Design and Feasibility Analysis

1. Introduction

During the past three decades the need to establish national energy-self reliance and to develop alternatives to limited fossil fuels resources have resulted in the development of alternative fuel technologies based on the use of agriculture feedstock for the production of liquid biofuels. Biodiesel continues to be the biofuel that EU prefers representing 81.5% of total biofuel production in EU for the year 2005. The time evolution of biodiesel production in EU is shown in Figure 1.

In 2010 the EU-25 energy consumption for transport purposes is estimated to be around 390 Mtoe[2]. Reaching the 2003/30/EC Directive target requires to bring around 22.4 Mtoe (5.75%) on biofuels. With the current production of 3,184,000 tones of biodiesel, EU can not satisfy these needs. Therefore, the two directions to be followed are: the increase of the domestic production within EU boundaries and/or the biofuels imports from other countries[3].

2. Biodiesel characteristics

Biodiesel is an alternative fuel for diesel engines that is produced by the chemical reaction of a vegetable oil or animal fat with an alcohol such as methanol. The reaction requires the presence of a catalyst, usually a strong base, such as sodium or potassium hydroxide, and produces new chemical compounds called methyl-esters. It is these esters that have come to be known as biodiesel. The whole process is known as transesterification[4]. Transesterification is considered today to be the most efficient process to produce biodiesel[5], for several reasons including:

- Low temperature (65º C) and pressure (20 psi) of the process,
- High conversion (98 %) with minimal side reactions and reaction time,
- Direct conversion to methyl ester with no intermediate steps,
- No need of special construction materials

3. Design analysis

3.1 Production process description

Biodiesel is the product obtained when a vegetable oil or animal fat is chemically reacted with an alcohol to produce fatty acid alkyl esters. A catalyst such as sodium or potassium hydroxide is required. Glycerol is produced as a co-product[6]. The approximate proportions of the reaction are:
1000 Kg of oil + 110 Kg of methanol → 1000 Kg of biodiesel + 110 Kg of glycerol Catalyst usually requires a quantity equal to 1.5% of the oil quantity. Based on several researches for each tonne of biodiesel produced an average electrical energy input of approximately 60kWh is required. Biodiesel production plant operation usually uses natural gas to generate process steam for the evaporation and distillation processes. Normally, for each tonne of biodiesel produced an average natural gas supply of approximately 440kWh is required. Water requirements of a biodiesel production plant include process water, steam water and cooling water, approximately 1,28 tonnes of water for each tonne of biodiesel produced. Finally modern biodiesel production plants should produce (by recycling and reuse) no more of 2 tonnes of waste water for each tonne of biodiesel produced[7]. The typical input-output balance of biodiesel production through transesterification process is shown in Figure 2.

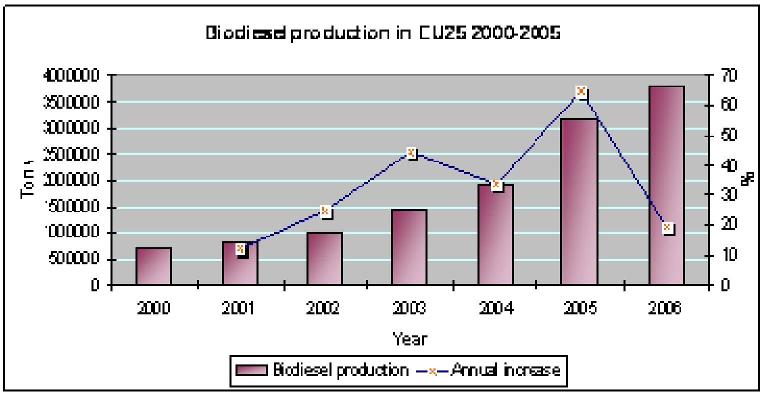

Figure 1: Biodiesel production in EU 2000-2005[1]

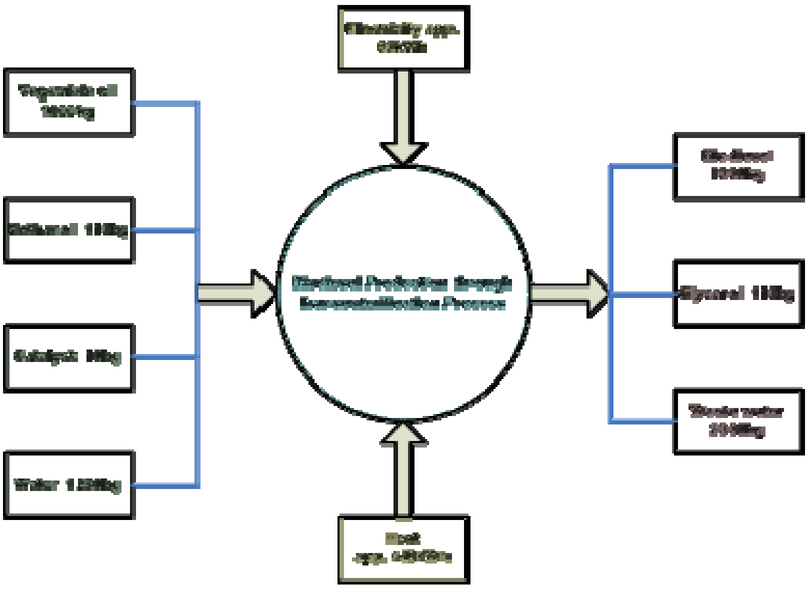

Figure 2: Input-output balance of biodiesel production through transesterification process

3.2 Capacity of the plant

The first decision point for the design of a production unit is its capacity. For the purpose of the plant, i.e. whether it will cover only domestic needs or exports or both, as well as according to feasibility considerations. For that reason it is necessary to take a look at the current status of biodiesel production in Greece. In 2004, Greece submitted a very extensive and complete 1st national report under Directive 2003/30. This 1st report estimated that 148,000 tonnes of biodiesel would be needed to fulfil the 5.75% target by the end of 2010[8].

The distribution of biodiesel in Greece started in December 2005 when the first batches were distributed to refineries by Hellenic Biopetroleum S.A. The blend of 2% biodiesel by volume in automotive diesel has been distributed to all final consumers since February 2006 and continues to be distributed smoothly. This percentage was raised to 3.5 % by volume (71,851 tonnes) by about the end of 2006, and reach 5% (97,695 tonnes) in 2007[9]. Currently 9 biodiesel plants with a total capacity of 440,000 tons/year are operational in Greece as set out in the Table I[10].

Table I: Biodiesel production plants in Greece[8]

Company	Annual Capacity (tonnes)	Location
Ekkokistiria-klostiria Voreiou	20,000	Komotini
Paylos N.Pettas	60,000	Patra
Biodiesel LTD	20,000	Thessaloniki
VertOil SA	30,000	Kilkis
Agroinvest SA	200,000	Achladi
Staff Colour Energy	15,000	Larissa
ELVI	35,000	Kilkis
ELIN Biofuels SA	40,000	Volos
Vioenergeia Papantoniou SA	20,000	Chalkidiki
TOTAL	**440,000**	

According to currently available data, a further eight biodiesel production units are at the initial stages of design and construction: four with a capacity of 5,000 tonnes, two with a capacity of 11,000 tonnes, one with a capacity of 22,000 tonnes and one with a capacity of 100,000 tonnes, (plant to start in the end of 2007)[9]. Taking into consideration that the domestic biodiesel production is expected to reach the 600,000 tons/year by the end of 2010 and that 148,000 tonnes of biodiesel would be needed to fulfil the 5,75% target by the end of 2010, the existing biodiesel capacity would already allow Greece to fulfil its 5,75% target by 2010. If running at full capacity, Greece could even export about 50% of its domestic biodiesel. Another parameter that must be taken into consideration is that most of biodiesel raw materials (70%) are imported by Greek producers (mostly rapeseed and soybean oils). The remaining 30% is domestically produced: cotton-seed, sunflower and used cooking oils[10].

Summarizing all the above parameters, current domestic biodiesel production, national biodiesel targets and raw material availability, one may clearly state that the construction of a new small-size biodiesel production unit with an annual capacity of 4,000~5,000 tons will be a reasonable choice as it will be able to cover a share of the domestic market needs, it will have availability for exports and its raw material needs will be covered by the domestically produced raw materials. Furthermore the selection of the above capacity for the purposes of the current study is convenient, since it results in a moderate investment (small to medium scale), a reasonable and feasible operational cost (already it needs about 2.7~3.5 million € for raw material and labour, as it will be analyzed below) and there is equipment available in the market for this size of the plant. In our case study we choose the design and cost analysis of a biodiesel production plant with an annual capacity of 4,000 tons.

3.3 Production cost analysis

The cost parameters of a biodiesel production plant can be split up into the annual biodiesel production costs and the investment costs. As investment costs can be characterized the capital costs for the purchasing of the production equipment, the land acquisition assets and the associated infrastructure labor costs. As annual biodiesel production costs can be characterized the production inputs/output costs and the maintenance and operation costs.

Currently in Greece nine (9) biodiesel production plants are currently operating. The production processes of these plants rely on a quite recent and efficient engineering technology, since most of them are built quite recently, between 2006 and 2007. All of them use the transestererification process for biodiesel production. Since this technology is now mature in Greece, it is believed that a new biodiesel production unit must follow this process. Based on the aforementioned requirements, the production inputs and outputs for a biodiesel production plant with an annual capacity of 4,000 tonnes as well as the annual cost analysis of these inputs are presented in Table II. For the purpose of this study unit costs have been obtained from HBI & Oleoline.com[11] and the Invest in Greece Agency Organization[12].

According to Table II, the crucial parameter that affects the production cost is the vegetable oil price. The identification of the various cost components of the production of biofuels will help to find optimal and practical promotion measures in order to increase the industry's competitiveness and expand its commercial availability. In addition to this, the cost analysis also helps producers to identify areas that can be improved in order to obtain significant cost reductions.

Table II: Biodiesel production inputs & outputs costs analysis

Production Inputs	Annual Use	Unitary Cost	Annual Cost (€)
Vegetable Oils (tons/y)	4,000	500~700 E/ton	2,000,000~2,800,000
Methanol (tons/y)	440	~ 410 E/ton	180,400
Catalyst (tons/y)	40	~ 700 E/ton	28,000
Water (tons/y)	5,120	~ 0.93 E/ton	4,760
Electricity (kWh/y)	240,000	~0.065 E/kWh	15,600
Natural Gas (kWh/y)	1,760,000	~0.044 E/kWh	77,400
			2,306,200~3,106,200
Production Outputs			
Glycerin (tons/y)	440	~120 E/ton	52,800
Waste water (tons/y)	8,000	~1 E/ton	8,000
Biodiesel (tons/y)	**4,000**		**2,262,200~3,061,400**

3.4 Equipment cost analysis

A provision of the biodiesel production process is provided here. A simplified block flow diagram of biodiesel production is shown below in Figure 3.

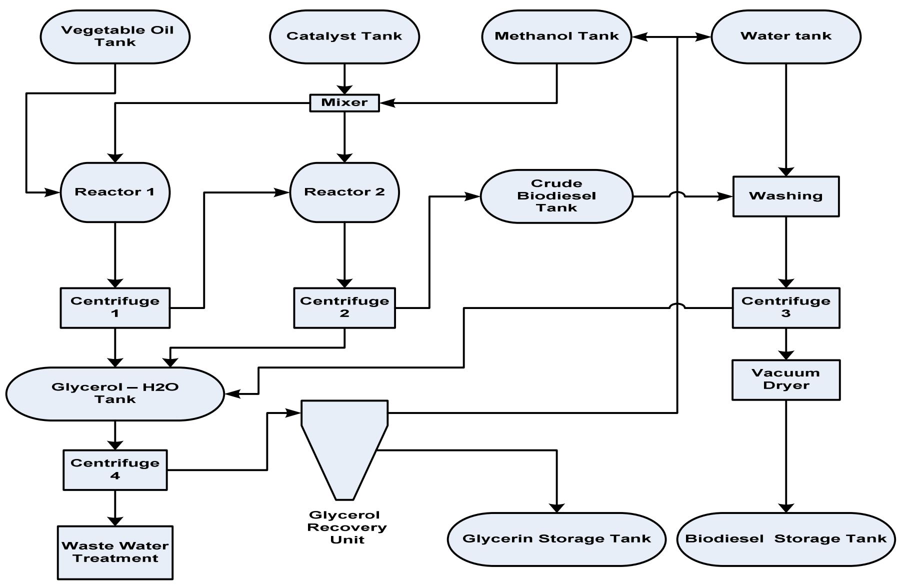

Figure 3: Flow sheet for the production of biodiesel from vegetable oil

The design of a pilot biodiesel production unit consists of three processing sections:

1. A transesterification unit where the vegetable oil is subject to chemical transesterification in order to produce fatty acid methyl esters (biodiesel) and co-product glycerol,
2. A biodiesel purification section where the methyl esters are refined to meet the biodiesel specifications, and
3. A glycerol recovery section

The objective of this chapter is to discuss the principles behind the primary plant equipment that would be used in a biodiesel production facility. A detailed analysis of reactors, storage tanks, centrifuges, and distillation columns will be included. There will also be additional equipment in the plant such as pumps, mixers, piping, heat and electricity distribution systems etc., since that account as a percentage of the four major pre-mentioned categories[13].The plant design is based on two sequential transesterification reactions are modelled. Glycerol, a co-product of acylglycerol transesterification, separates from the oil phase, the crude methyl ester stream is washed with water to neutralize the catalyst and convert any soaps to free fatty acids. Centrifugation is then employed to separate the biodiesel from the aqueous phase. The latter is cycled to the glycerol recovery section to be purified. The crude, washed methyl ester product may contain several percent of water that is then removed in a vacuum dryer[14][15].

Based on production processes shown in Figure 3 and using current best values for equipment costs, estimated equipment costs are presented in Table III.

Table III: Equipment cost analysis of a 4,000ton/year biodiesel plant[16]

Item	***Cost(€)***
Working supply capacity	
Vegetable oil storage tank	61812
Methanol storage tank	612
Catalyst storage tank	6120
Glycerin storage tank	6120
Water storage tank	78940
Biodiesel storage tank	61812
Total supply storage	**215,416**
Transesterification process	
Methanol storage tank	265
Vegetable oil storage tank	2448
Catalyst storage tank	25
Crude Biodiesel storage tank	2448
Reactor #1	27000
Reactor #2	27000
Catalyst & methanol mixer	56000
Centrifuge #1	46800
Centrifuge #2	46800
Subtotal transesterification process	**206,338**
Methyl-ester purification process	
Water storage tank	3060
Centrifuge #3	46800
Vacuum dryer	15290
Subtotal methyl-ester process	**65,150**
Glycerin recovery process	
Glycerol – H20 storage tank	612

Item	***Cost(€)***
Centrifuge #4	46800
Crude glycerol distillation system	220000
Subtotal glycerin recovery process	**267,412**
Total process equipment	**538,900**
Utility equipment (15% of the total process equipment)	**80,835**
Total equipment cost	**835,151**
Installation and transport (100%of the total equipment cost)	**835,151**
Total cost	**1,670,300**

Details of the facility specification are available in[16]. The cost has been estimated according to a variety of assumptions and calculations such as:

- The budget for different plant sizes provided by manufactures
- The choice of construction materials and equipment items
- An average price of available domestic market options

Table III presents the most crucial equipment items cost. The estimated total capital cost was approximately 1,670,300 €. One half of this was for the hardware, while the other half was based on our assumption of a construction cost roughly equal to equipment cost. Of the equipment cost nearly one half is for product storage tanks. These were modeled at a 25 day working supply capacity. It is also assumed that utility equipment costs (cooling tower system, electrical and heat distribution system, pumps, valves and piping) was at 15% of the total equipment costs and that the installation and transport costs of the plant was equal at the 100% of the of the total equipment cost.

3.5 Land acquisition & infrastructure cost analysis

The criteria for a good biodiesel plant site encompass many factors such as feedstock proximity, good road and rail access and access to required utilities such as electricity, natural gas and water supply. The proximity of feedstock is a crucial component of the site evaluation and feasibility for the biodiesel plant. Thus the site selection is chosen to be near agricultural areas where the appropriate vegetable oils for the production of biodiesel are available. Another parameter that cannot be ignored is that most of the domestically used biodiesel raw materials (70%) are imported by Greek producers (mostly rapeseed and soybean oils). In the plant discussion most of the raw material would need to be imported if no alternatives to the necessary plant feedstock may be supplied by neighbouring countries, under the condition that transport costs remain low.

Regions that fulfil these criteria are Macedonia and Thrace, according to values that were obtained from Invest in Greece Agency Organization[12], the land acquisition cost in these selected areas is priced between 10,000~35,000 €/1,000m^2. The land requirements for plants with a capacity of 4000tons/year is estimated to consist of 5,000~7,000m^2, including the production facilities, electricity, natural gas and waste water facilities, a tank yard allowing raw materials and products storage, offices facilities, highway access and loading/unloading facilities and the prospect of a future plant capacity expansion[17]. Working capital, construction and site preparation costs, building construction costs, site preparation costs, and permits/misc. are estimated to be equal at 100% of the land acquisition cost. The analysis of the land acquisition and infrastructure analysis is shown on Table IV.

Table IV: Land requirement costs of a 4,000ton/year biodiesel producing plant

Category	**Cost(€)**
Land acquisition	50,000~245,000
Other costs (100% of the land acquisition cost)	100,000~490,00
Total cost	**150,000~735,000**

3.6 Maintenance and operation cost analysis

A 4,000ton/year biodiesel plant is estimated to require 20 employees, the exact number of employees can vary depending upon the plant design and operating plan. The area within 50km of the site should be easily able to supply the labour for the biodiesel plant operations, specialty positions such as the plant manager or lab supervisor may have to be recruited from greater distances, Table V below presents a proposal concerning the personnel requirements of the plant.

The plant is expected to operate at three shifts per day for 330days per year, according to Invest in Greece Agency[12]. The average monthly labor cost in the industrial sector in Greece is estimated to be almost 1,100€/month.The maintenance cost of the plant is assumed to be equal to10% of the total equipment cost. Table VI presents the maintenance and operation cost of the plant.

Table V: Personnel requirements for the 4,000ton/year biodiesel plant

Employees	***Number***
Administration/Management personnel	
Plant manager	1
Quality control manager	1
Administrative assistant	1
Production personnel	
Lab technician	1
Shift team leader	3
Shift operators	6
Yard/commodities personnel	3
Maintenance personnel	
Maintenance worker	1
Electrician	1
Instrument technician	1
Raw material & storage personnel	1
Total number of employees	**20**

Table VI: M&O cost analysis of a 4,000ton/year biodiesel plant

Category	**Cost(€)**
Employee annual labour	286,000
Maintenance cost (10% of the total equipment cost)	167,030
Total Maintenance and Operational Cost	**453,000**

3.7 Summary of the costs

The total cost parameters analysis of a new biodiesel production plant, including annual biodiesel production cost and investment cost are shown in Table VII. The analysis calculated a final biodiesel production cost of 0.598~0.773€/lt. These values are consistent with the results of other analyses of the cost of biodiesel production from vegetable oils[5][6][18][19].

Raw materials costs constitute the greatest component of overall production costs (84~88%), and of those the cost of the vegetable oil feedstock is the largest contributing factor, almost 75~80% of the overall production cost. These values are consistent with the results of other vegetable oil biodiesel production cost analyses[6-14].

Table VII: Total cost analysis of a of a 4,000ton/year biodiesel producing plant

Category	***Cost (€)***
Annual biodiesel production cost	
Production inputs & output costs	**2,262,200~3,061,400**
Maintenance & Operation cost	**453,000**
Total annual biodiesel production cost	**2,715,200~3,514,400**

Category	*Cost (€)*
Biodiesel production cost/ kg	**0.679~0.879**
Biodiesel production cost/ lt	**0.598~0.773**
Investment cost	
Equipment cost	**1,670,300**
Land acquisition & infrastructure labour cost	**150,000~735,000**
Total investment cost	**1,820,300~2,405,300**

The large contribution of feedstock cost to the cost of biodiesel highlight the potential value of low cost vegetable oil alternatives to the improvement of the biodiesel plant economic viability. Income from the sale of the glycerol co-product resulted in an estimated 1.5~1.9% reduction in production cost. As biodiesel production volumes increase in the future it is expected that the concomitant increase in glycerol supplies will reduce its market value. Concerning the investment cost the analysis resulted in a final investment cost of 455,000~602,000/1000t of capacity. Equipment cost constitutes a 69~92% of the total investment cost, of these the cost of storage tanks is the biggest contributing factor, itself constituting a 42% of the overall equipment cost. These were modelled at a 25 day working supply capacity. In the choice of construction materials the most average economical of available options were chosen. Thus for example the storage tanks were specified to be constructed of stainless steel, the selection of carbon steel storage tanks which are costing less would have had a significance impact on the investment cost. Substantial savings would be achieved from reducing the storage capacity, as in the case plant sitting next to a vegetable oil extraction site or accepting smaller inventory holding capabilities. It should be noted that the total investment cost has been found similar to several other design studies[19].

4. Feasibility Analysis

The feasibility analysis of the investment is based on two different scenarios:

1. A low cost value scenario, where as parameters were chosen the minimum costs of investment and annual operation, and
2. A high cost value scenario, where as parameters were chosen the maximum costs of investment and annual operation.

The life cycle of the investment was chosen to be 20 years and the method we used for the evaluation was the Net Present Value Method (NPV) with a discount rate of 8%.It was assumed that each five operational years of the plant, there will be a 5% increase in the production costs as well as in the biodiesel selling price. The biodiesel selling prices calculated in the feasibility analysis were 0.638€/lt in the low cost value scenario and 0.839€/lt in the high cost value scenario during the first year of the plant operation. These prices occurred taking into consideration the annual biodiesel production cost for the two different scenarios (high and low biodiesel production cost). Various values have been given to biodiesel selling prices, in order to investigate the behavior of NPV. Certainly only the ones resulting to NPV>0 have been kept and one is shown below. In all scenarios, it was estimated that the project will start to give a net profit after the first 8 operational years. The whole set of the scenarios parameters and the results of the analysis are presented in Table VIII, and Figures 4 and 5 below.

Table VIII: Feasibility analysis of the project (*an increase of 5% every five years has been assumed)

Costs/Revenues	Low cost value scenario	High cost value scenario
Investment Cost	1,820,300 €	2,405,300 €
M&O Cost*	453,000 €	453,000 €
Production Cost*	2,226,200 €	3,061,400 €
Annual Cost*	2,679,200 €	3,514,400 €
Biodiesel Price*	0.638 €	0.839 €
Annual Biodiesel Production*	4,545,454 lt	4,545,454 lt
Revenues*	2,900,000 €	3,813,636 €

Discount rate	8%	8%
NPV	428,893€	638,325 €

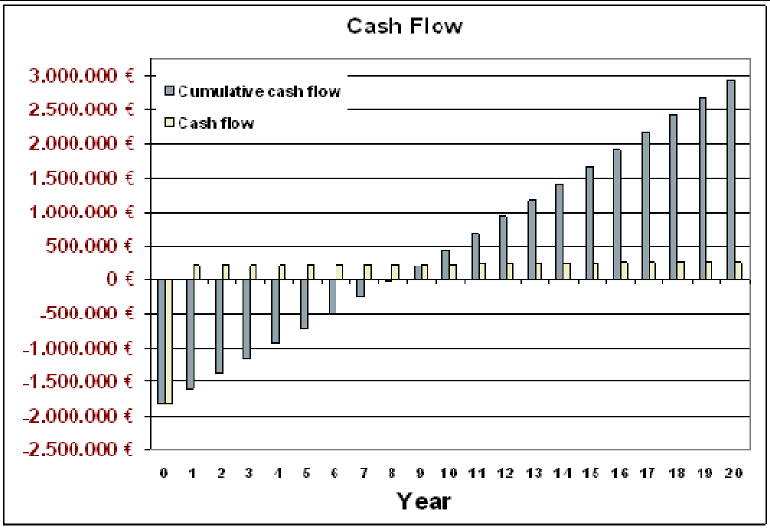

Figure 4: Low cost scenario cash flow analysis

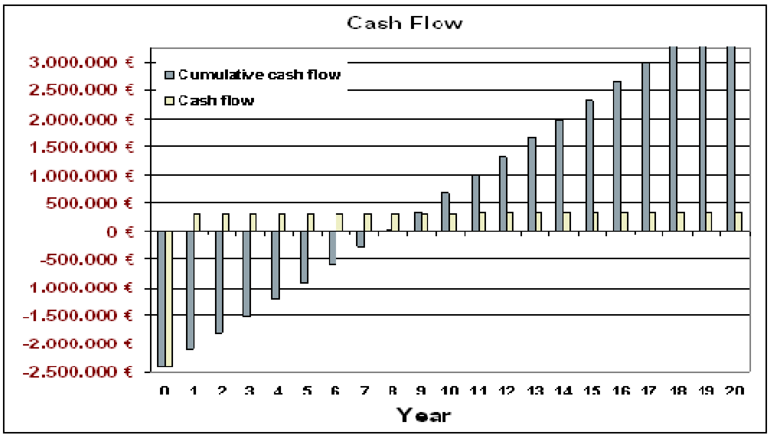

Figure 5: High cost scenario cash flow analysis

5. Conclusions

The present work has led to some interesting results concerning the prospects of a small scale (4,000tons/year) biodiesel production unit in Greece. In conclusion, one may state that the feasibility and the financial efficiency of the project depend on two main parameters: the raw materials cost and the biodiesel selling price. More specifically:

- The life cycle of the project has been chosen to be 20 years and the method we used for the evaluation was the Net Present Value Method (NPV) with a discount rate of 8%. It was assumed that each five operational years of the plant, there will be a 5% increase in the production costs as well as in the biodiesel selling price.
- The investment cost for the construction of a small size biodiesel production unit was estimated to be 455,000~602,000/1000t of capacity. Facility construction costs were calculated to be 1.82~2.40million€.
- Equipment cost constitutes a 69~92% of the total investment cost. The storage tanks cost is the biggest contributing factor (42% of the overall equipment cost).
- The analysis resulted in a final biodiesel production cost of 0.558~0.773 €/lt.
- Raw materials costs constitute the greatest component of overall production costs (84~88%) and the cost of the vegetable oil feedstock contributes almost 75~80% in the overall production cost.

- The biodiesel selling prices calculated in the feasibility analysis were 0.638€/lt in the low cost value scenario and 0.839€/lt in the high cost value scenario during the first year of the plant operation. Various values have been assigned to biodiesel selling prices, in order to investigate the behavior of NPV
- Any reduction effort in the total investment cost should focus on the equipment cost and especially in the storage tanks
- The large contribution of feedstock cost to the cost of biodiesel highlights the importance of low cost raw materials in improving the economic viability of the project.

When reviewing the design and feasibility analysis of biodiesel production plant, it quickly becomes apparent that it is difficult to standardise the total investment and production cost, since its main characteristics (feedstocks, final products, the equipment items cost, land acquisition) are subject to market price fluctuations. Also, the cost of conventional diesel fuel, which is directly related to the price of crude oil, is subject to similar fluctuations, creating uncertainty in targets for biodiesel production cost/selling price. For this reason, the authors highlight the most costly parameters in a proposed production plant, allowing the cost reduction efforts to focus where they might have the greatest impact improving the economic viability of the project.

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PART FIVE

WIND ENERGY APPLICATIONS RELATED TOPICS

ANALYZING THE PUBLIC OPINION TOWARDS WIND ENERGY APPLICATIONS IN GREECE

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Abstract

During the last years, wind energy is established as a mature electricity production technology. In Greece the installed wind capacity slightly exceeds the 850MW, despite the excellent wind potential of the area and the fact that requests for new wind parks above 13000MW exist in the Ministry of Development. The insufficient infrastructure is only partially responsible for this irrational evolution, since in many regions serious local population reactions have been encountered, which in some cases lead even to the complete wind power project cancellation. In this context, an extensive study is conducted during the last five years, concerning the public attitude towards wind energy applications, in several island and mainland Greek territories possessing high wind potential and investment interest. One of the major targets of the present analysis is to explain the inconsistency encountered between the firm social acceptance of wind energy applications and the remarkable visual and noise annoyance reported from existing wind turbines. Among the primary conclusions drawn, one may underline the necessity of additional public information about wind energy sector, the additional attention required during the local energy planning procedures and the need of wind power stations to be good neighbors to the nearby communities.

Keywords: Opinion Survey; Environmental Impacts; Macroeconomic Impacts; NIMBY

1. Introduction

During the last years, wind energy is established as a mature electricity production technology, constituting not only an economically attractive option to contribute in fulfilling the worldwide constantly increasing energy demand, but also a sustainable energy solution for global development[1][2][3].

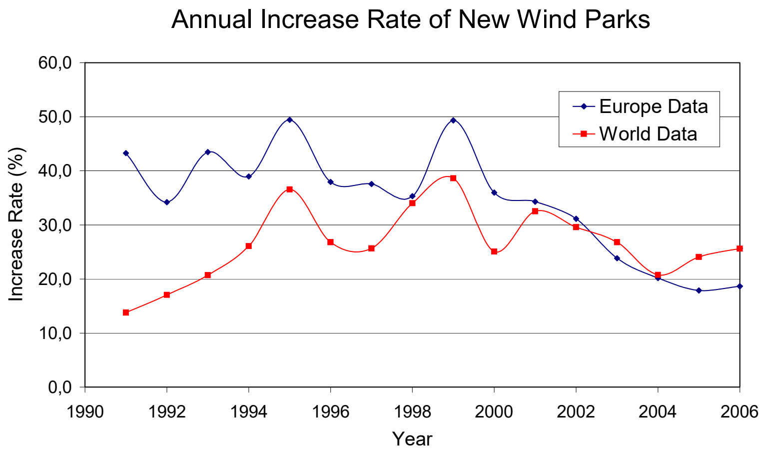

Figure 1: Annual increase rate of installed wind power in Europe and the World

In this context, wind energy has been the galloping energy sector for electricity production in various European countries, since the corresponding development rate of installed capacity for the last decade exceeds 20% on an annual basis, figure (1). Thus, at the end of 2007, the total wind capacity in Europe[1] exceeds 56000MW, producing more than 120TWh/year, equivalent to the annual electricity consumption of 80 million typical consumers.

However, the increased number of wind parks throughout Europe (more than 150,000 wind turbines have been installed since 1980) and the considerable size[2][4] of the contemporary wind converters, their rotor diameter exceeding 120m, create a remarkable concern of local people about the existence of such huge installations in their area[5][6][7][8]. The result of this situation is a considerable number of negative reactions of local communities against the development of new wind parks, despite the favorable techno-economic conditions available.

2. Position of the Problem

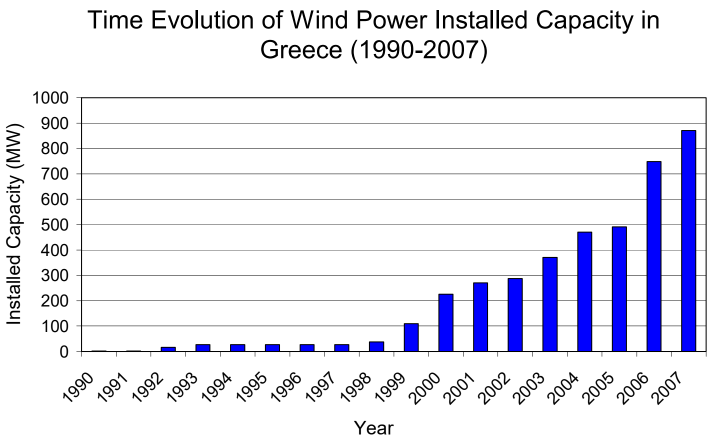

Figure 2: Installed wind power time evolution in Greece

In Greece, after several years of instability (figure (2)) the installed wind capacity slightly exceeds 850MW, despite the excellent wind potential of the area and the fact that requests for new wind parks over 13000MW exist in the Ministry of Development[9][10]. As a result the wind energy contribution in the local electricity market is less than 3%, while the entire RES-based electricity generation (including the large hydro) is approximately 10%, considerably lower than the White Paper target of 20.1% by the end of 2010.

The insufficient infrastructure is only partially responsible for this irrational evolution, since in many regions serious local population reactions have been encountered, which in some cases lead even to the complete cancellation of wind power projects. Actually, more than 50 new projects face serious legal contradictions[11], resulting from the actions of local citizens against their implementation, thus delaying the contribution of additional $800MW_e$ to the national electricity balance.

In this context, an extensive study is conducted during the last five years[12][13][13][15], concerning the public attitude towards wind energy applications, in several island and mainland Greek territories possessing high wind potential and investing interest. One of the most important issues to be solved was the selection of the areas where the public survey should be carried out. Thus, during the planning phase of this survey[12] several geographical regions have been proposed, including the Crete island, S. Peloponnesus, S. Euboea, the islands of Chios and Samos as well as the islands of central Aegean. Generally, speaking the majority of the public attitude seems to be in favor[14] of new wind parks of medium size, however the concentration of huge installations based on numerous and large scale wind turbines is not always welcome[15].

Recapitulating, the present work investigates the social approval of existing wind parks by the nearby communities according to the opinion of people living in their proximity. For this purpose, the complete results of the public opinion survey carried out all over Greece during the last five years, concerning the local habitants' attitude towards existing wind parks, is presented for a representative area. This specific area has been selected in view of the wind turbines' limited acceptability by the local habitants[13].

3. Public Opinion Survey Presentation

In order to systematically investigate the public attitude towards wind energy applications in Greece, the Soft Energy Applications and Environmental Protection Laboratory of TEI Piraeus has first scheduled and subsequently conducted[12][14] a systematic public survey in several representative Greek territories, presenting wind energy development interest. During the entire investigation, emphasis is laid on the following topics:

- ✓ Part A: The degree of public knowledge on wind energy applications (questions 1 and 2)
- ✓ Part B: The public awareness about the environmental and macro-economic impacts of wind energy (questions 3, 4 and 5)
- ✓ Part C: The public attitude towards existing and new wind parks (questions 6, 7 and 8)

In an attempt to encourage the public contribution in this quite unusual (for the common people) research, the number of questions set is eight, thus less than ten minutes are normally required in order to fill the corresponding questionnaire. Besides, for increasing reliability and due to the country idiosyncrasy, the technique based on personal named or unnamed interviews was selected. More specifically, during this survey the questionnaires were completed in the interviewer's sight, while most respondents filled in their name and phone. It is also important to note that all the respondents were living near the existing wind parks (maximum distance 20km) and they belonged to groups of various professions and educational status, while the majority (55%) of them were women. The acceptance of our effort was quite encouraging, since almost one out of two of the persons asked answered the questions eagerly.

The next point to be arranged was the number of interviews needed to draw safe conclusions[16]. As it is obvious, the reliability of the results derived is strongly dependent on the size of the approved sample used, since the outcome uncertainty is normally decreasing with the square root of the sample size[17]. Due to the geographical diversity of the study and the manpower needed to implement the personal interviews all around Greece, a sample number in the range of 100 to 150 questionnaires was assumed acceptable, while 50 interviews were set as the lower limit, especially for small wind parks located in remote islands.

For the preparation of the questionnaire a large number of scientists have collaborated, including statistics experts, sociologists and market survey experts. The questions relative to the subject investigated are summarized in (Table I), along with the possible answers. The first two introductory questions (Part A) asked, guarantee that the people being interviewed are familiar with the subject examined. According to the entire sample analyzed (665 questionnaires), 96% of the people interviewed are familiar with the basic wind energy principles. Recapitulating, one may clearly state that the samples used have the necessary size to be statistically sound and credible, hence only 4% is excluded from further analysis.

In the second part (Part B) of the proposed questionnaire, emphasis is set in investigating the public opinion on the macroeconomic and environmental impact of existing wind power stations in representative Greek locations[18].

In the last part (Part C) of this investigation emphasis is primarily laid on the analysis of public attitude towards existing and operating wind parks, while the last question discusses the possibility of the local people participation in wind park development activities.

Table I: Questionnaire Used

Q-1	**What do you know about wind energy?**	
Possible Answers	a	It is obtained from the waves of the sea
	b	It is used in the solar heaters
	c	It is obtained from the wind
	d	It is obtained from nuclear plants
	e	I do not know
Q-2	**The wind converters or wind turbines are usually used:**	
Possible Answers	a	in producing electric energy
	b	in marking regions
	c	for aesthetic reasons
	d	for televising purposes
	e	for other reasons
Q-3	**The wind converters or wind turbines:**	
Possible Answers	a	protect the environment and reduce the quantity of imported oil
	b	destroy the environment
	c	consume large quantities of fuel
	d	worsen the environment but economize on energy
	e	I am not aware of their effect on the environment and the oil import
Q-4	**The wind converters or wind turbines of your territory:**	
Possible Answers	a	▪ are visually annoying
	b	have no visual impact on me
	c	are not aesthetically right
	d	I have no opinion on their aesthetic impact
	e	make the area attractive
Q-5	**The noise of the wind turbines in your territory:**	
Possible Answers	a	is too loud
	b	is too annoying
	c	does not actually disturb me
	d	is covered by the surroundings
	e	is pleasantly heard, in relation to their valuable energy
Q-6	**Do you actually agree with the installation of Wind Turbines in your territory?**	
Possible Answers	a	YES, I do
	b	NO, I don't
	c	I would agree if only I had proof of their usefulness
	d	I am not interested in this matter
	e	I have no formed opinion
Q-7	**In case of a new Wind Park installation in your territory:**	
Possible Answers	a	I would not care
	b	I would react on this installation
	c	I might agree, after examining all available data
	d	I have no formed opinion
	e	I would happily agree, being aware of their effectiveness
Q-8	**In case of a new Wind Park installation in your territory:**	
Possible Answers	a	I would not wish to participate, even when it is financially profitable
	b	I would not wish to participate, as I hear it is financially unprofitable
	c	I would ask for further financial data regarding this project
	d	I would wish to participate at any rate, realizing all financial benefits
	e	I am not interested in this matter

4. Results Presentation and Discussion

As already mentioned, one of the major targets of the present analysis is to relate the general positive public attitude[14] towards wind energy applications with the reaction encountered against new installations on the basis of the reported remarkable visual and noise annoyance caused by existing wind turbines.

Figure 3: General view of Marmari-Euboea wind park (17x300kW)

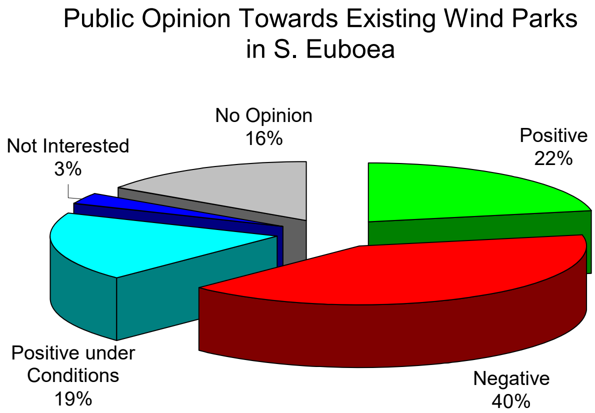

Figure 4: Public opinion towards wind parks

For this purpose, the area selected to be analyzed in the current paper is the S. Euboea island, where in the past serious conflicts between the wind park developers and the local citizens have been encountered[11]. The sample used includes 128 respondents, while the survey was carried out in three separate-independent phases, starting from 2001. Note that Euboea is a windy island, the second biggest of Greek islands after Crete, located nearby Athens. The east and south east parts of the island possess very good wind potential, thus Greek PPC installed at the early nineties[19] the first large-scale (for that time period) wind park of 5.1MW near Marmari, figure (3). However, this first wind park suffered from serious blade failures due to the extremely high wind speed values and high turbulence intensity of the area, leading to the complete replacement of the rotor blades for the 17 wind turbines of the wind park. Unfortunately, the electrical network of the area is not very strong, thus the maximum wind power to be transferred is only 150MW, seriously limiting the opportunities of building additional wind parks in the area. The result of this insufficient infrastructure was a very hard competition between the potential investors, in matters of land usage and priority in grid connection. This aggressive behavior of the wind parks' developers affects negatively the local communities[11].

More precisely, according to the results obtained for the S. Euboea case (Q-6), the public opinion is actually divided, figure (4). Thus, almost 4 out of 10 (40%) of the respondents clearly disagree with the operation of the wind parks in their region, while 22% definitely accept the wind turbines in their neighborhood. An extra 19% of the habitants tolerate them under the precondition of their proved usefulness. A sound explanation of the public attitude towards wind turbines encountered in S. Euboea may be the remarkable concentration (≈150MW) of numerous large wind converters, in a relatively short time.

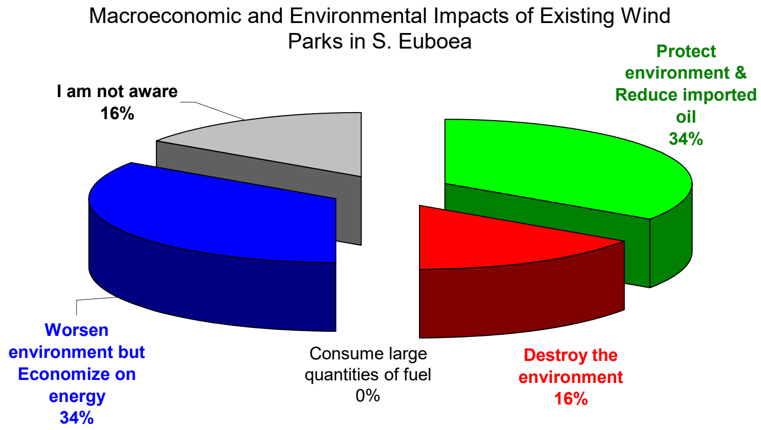

Figure 5: Macroeconomic and environmental impacts of wind parks, the public opinion

This general social attitude of local people towads existing wind parks in S. Euboea is also supported by the answers given in the first question (Q-3) of Part B concerning the macroeconomic and environmental impact of the corresponding wind energy applications. As it is obvious from figure (5), almost 50% of the respondents mention negative impact of the wind parks on the local environment. However, more than one third of them (34% of the total sample) accept the contribution of wind turbines to fossil fuel saving. In fact, almost seven out of ten (34%+34%) of the local habitants mention that wind energy reduces the oil imports, thus contributing in the national energy supply security and on exchange saving.

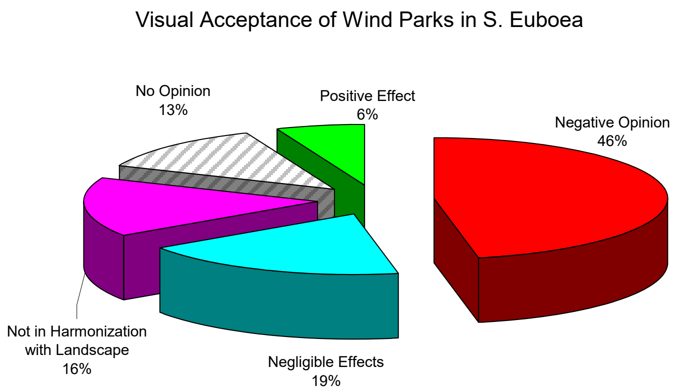

Figure 6: Wind turbines visual impact, the public opinion

It is also worthwhile to mention that according to the results of the current public survey (Q-4) the majority (46%) of the inhabitants express negative visual impact of wind turbines, while another 16% believe that the existing machines are not in harmony with the landscape, figure (6). On the other hand, only 6% likes the sight of these machines whereas 19% do not mention any visual intrusion.

Subsequently, it is interesting to mention that the portion of the respondents supporting that the noise of the wind turbines (Q-5) is either too loud or too annoying is 25%, while one should not disregard that almost 30% of the sample (figure (7)) declares that any wind turbine noise is covered by the surroundings.

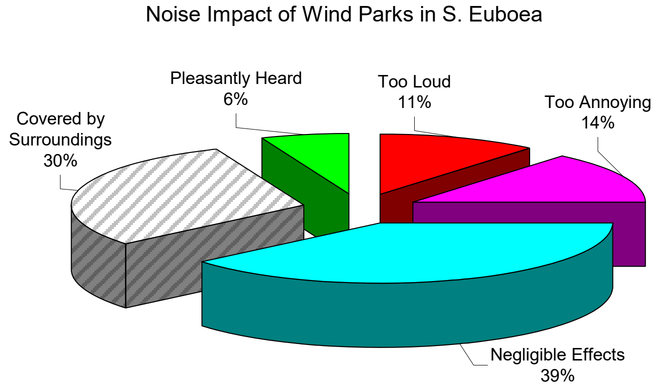

Figure 7: Wind turbines noise impact, the public opinion

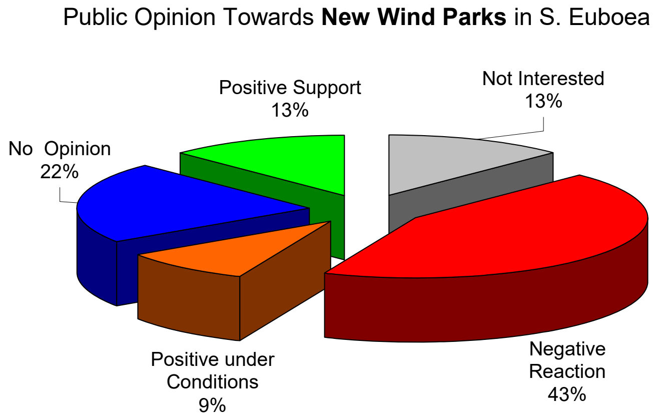

Figure 8: Public opinion towards wind parks

The situation is even less positive in case that new wind parks are scheduled (figure (8)), since only 13% of the respondents (Q-7) express positive opinion and another 9% declare positive only after examining all available information. Keep in mind that the majority of the local people (43%) remain negative opposing to any wind energy exploitation activity, while 22% of the sample expressing no opinion may be finally persuaded by the shaped majority.

This problematic situation is fully supported by the analysis outcome of the answers concerning the last question (Q-8) asked (figure (9)). According to the assessed results only 16% of the respondents are eager to participate in new wind energy projects due to expected monetary gains. Almost one out of three (28%) of the local people require more information about the financial behavior of similar projects, since in several cases the implementation risk mentioned[20] is quite high. People disliking wind turbines in their area represent 40% of the sample, while the vast majority (8/10) of them does not want to participate in new wind parks even under proved financial benefits conditions. Lastly, almost one out of six is not interested to participate in new wind power investments.

Summarizing the analysis of the current public opinion survey, focused on one of the most negatively reacting areas towards wind energy applications in Greece, the results obtained declare marginal acceptance for the existing wind parks. The public opinion is however less supportive in cases of new installations. In fact, even in this really "hostile" area analyzed, the general public attitude is not unreasonably against the new wind parks, since the local habitants do not disregard the positive environmental and macroeconomic impact of wind power installations on the national electricity generation status.

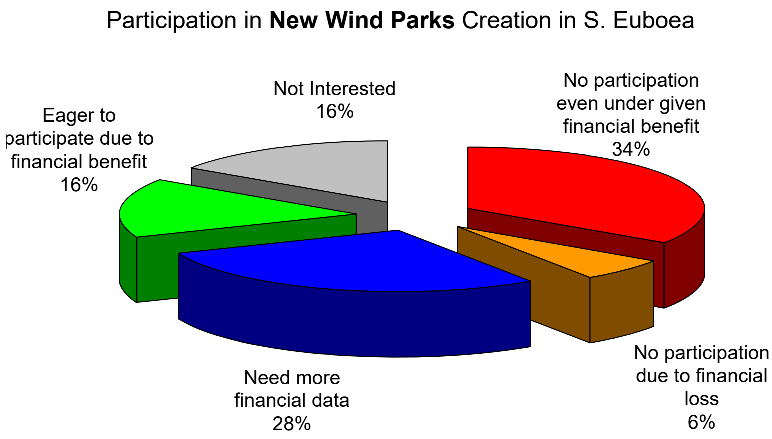

Figure 9: Public opinion towards wind parks

On the other hand, the most troublesome outcome of this survey is the existence of a specific minority that is strongly against wind energy applications, disregarding any financial benefits. Bear in mind that legal actions can be induced even by a single person.

5. Conclusions

An extensive study is conducted concerning the public attitude towards wind energy applications in several Greek territories possessing high wind potential and investing interest. This public opinion survey is based on a well elaborated questionnaire, carefully prepared by an appropriate expert group. The current paper is focused on analyzing the results for one of the most negatively reacting areas towards wind energy applications in Greece.

According to the data analyzed there is a serious contradiction between the general belief of positive macroeconomic and environmental impacts of wind parks and the increased visual intrusion and noise pollution mentioned. In the S. Euboea case one of the major problems encountered concerns the conflict about the ownership of land occupied by the wind parks. For this reason, although local people may accept the operation of the existing wind parks in their locality, they are firmly against new wind power stations despite the possibility of financial gains.

In order to face this serious problem, i.e. increase the public acceptance of wind energy applications, according to the authors' opinion wind industry should continue placing the same effort on reducing the environmental impacts of new wind power installations while at the same time remaining techno-economically attractive. Actually, among the primary conclusions drawn, one may underline the necessity for additional public information concerning the wind energy sector and additional attention required during the local energy planning procedures. Overall, the requirement for wind power stations to comprise electricity generation solutions that are compatible with nearby communities is illustrated.

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WIND ENERGY BASED DESALINATION PROCESSES AND PLANTS

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Abstract

Water is a valuable natural resource and its shortage is a serious problem being faced by many areas of the planet. Solution of the water supply problem includes technical and economic evaluation of various alternatives, taking into account the urgent character of the problem and the need for its sustainable solution. Desalination of brackish and sea water has become one of the most widely applicable methods to meet water demand in areas with limited water resources. The most promising desalination method is based on reverse osmosis phenomenon. One of the critical issues in water desalination is the high energy demand and, more specifically, electricity for RO desalination units. The use of renewable energy sources for the operation of desalination plants is a feasible and environmentally compatible solution in areas with significant RES potential. Especially for the Greek islands, where there is water and energy shortage and, at the same time a high RES potential, the wind based desalination plants comprise a promising technically feasible and financially attractive solution. The objective of the present work is to analyze the current status and the prospects of the wind based desalination plants. To that effect, the paper includes a concise review of the recent RO desalination processes advancements and the experience that has been acquired from the existing wind based desalination units worldwide and, more specifically in the islands. Furthermore, the present work highlights the main design and operation features of these units, as well as the difficulties and critical factors in their implementation.

Keywords: Greek Islands; Desalination Technology; Energy Issues; Environmental Impacts; Cost Analysis

1. Introduction

Water is a valuable natural resource and its shortage is a serious problem being faced by many areas of the planet. Decision making on the water supply method includes technical and economic evaluation of various alternatives, taking into account the urgent character of the problem and the need for its sustainable solution.

Desalination of brackish[1] and sea water[2] has become one of the most widely applicable methods to meet water demand and it is today widely applied in areas with limited water resources. One of the most promising desalination methods is based on reverse osmosis (RO) phenomenon. A critical issue in water desalination is the high energy demand and, more specifically, electricity for RO desalination units. RO is the desalination process with quite low energy requirements. Therefore, it was expectable that significant efforts would be taken to implement widely available and environmentally compatible energy sources for the desalination process.

The objective of the present work is to analyze the current status and the prospects of the wind based desalination plants and to highlight the main design and operation features of these units, as well as the difficulties and critical factors in their implementation.

2. RES based Desalination Processes

The use of renewable energy sources for the operation of desalination plants is a feasible and environmentally compatible solution in areas with significant RES potential.
The main driving forces for applying RES in desalination plants are the seasonal variability in water (and energy) demand, usually occuring when renewable energy availability is high, the limited availability of conventional energy supply in remote areas, the sufficiency of RES in islands, the technological advancements being achieved in desalination systems, the limitation of environmental impacts of conventional desalination systems and the relative easiness of the plant's operation and maintenance compared to conventional energy ones.

Especially for the Greek islands, where there is water and energy shortage and, at the same time a high RES potential, the RES based desalination plants comprise a promising technically feasible and financially attractive solution.

To that end, a lot of research and development work has been carried out and the problem of the optimal configuration / combination of a RES energy source with a desalination plant attracts the interest of many researchers and construction and engineering companies[3][4][5][6].

The best coupling of RES to desalination systems is determined from various criteria, such as the system's efficiency, the investment and operational cost, availability of operational personnel, the suitability of the system to the characteristics of the location, the possibility for future increase of the system capacity, etc[3]).

The selection of the appropriate RES desalination technology depends on a number of factors, including:

- required quantity of potable water (plant capacity),
- feed water salinity,
- remoteness,
- availability of grid electricity,
- technical infrastructure,
- type and potential of the local renewable energy resource.

Various combinations of RES and desalination systems have been proposed and implemented, each one with its own characteristics and suitability under certain criteria[4][5][7]. Desalination systems driven by wind power are the most frequent renewable energy desalination plants (figure (1)).

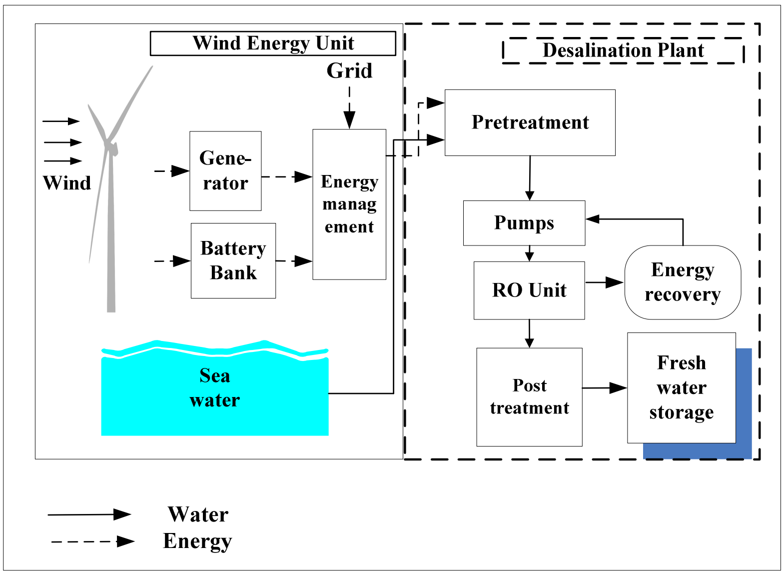

Figure 1: Structure of a wind based RO desalination plant

Coastal areas have a high availability of wind power resources, and wind power is the most competitive renewable energy technology in power generation. Therefore, wind powered desalination is a promising alternative. The idea to use wind power as an energy source for desalination is not new. Wind conditions, for example, in coastal areas are often in favor of this desalination system.

More specifically, wind energy can be used efficiently on condition that the average wind velocity is above 5 m/s. This makes wind-powered desalination a particularly interesting option for windy islands, both for the solution of their energy supply problem and for the operation of sea water desalination plants.

The new generation of small and medium-sized wind turbines that has been developed in the past years offers a high amount of reliability in service combined with low investment costs.

Two types of applications are usually referred as wind energy and desalination couplings. The first type concerns the coupling of the wind generator and the desalination plant on a small size autonomous electricity grid. The second concerns the direct coupling of these two for the sole purpose of production of water.

Desalination plants using membrane technologies are available in a wide range of capacities. As far as the recommended RES – desalination combinations are concerned, it is considered that wind desalination is most suitable for small (1-50 m^3/day) and medium (50-250 m^3/day) scale plants[7].

3. Energy Issues in Desalination Plants

All desalination systems use energy and, in fact, the energy consumption is one of the most important elements in determining water costs. About 0.7 kWh/m^3 is theoretically the minimum energy required to obtain fresh water from seawater[5]. For RO systems the energy consumption is in the range of 5-10 kWh/m^3 without energy recovery (large production plants), and 3-4 kWh/m^3 with energy recovery[7].

Recent developments in wind turbine technology mean that wind power can now be regarded as a reliable and cost-effective power source for many areas of the world[8].

Wind turbines may be classified depending on their nominal power "N_o" as very small (N_o<10 kW), small (N_o<100 kW), medium sized (N_o<0.5 MW) and large (N_o>0.5 MW) ones. All are based on mature technologies and they are commercially available except for the very large power systems, which still require several adjustments.

The basic assumptions for the required calculations concerning the energy efficiency of the wind turbines with or without an energy storage system may be considered as following:

For a wind turbine with a nominal power of N_o kW, we expect an energy production "E" in the order of magnitude of "$E=CF.N_o.8760$" kWh/year. Note that the installation capacity factor "CF" usually varies between 20% and 30%. Depending on the type of desalination plant, the required amount of energy per m^3 of potable water will also be given. Therefore, we may have a series of alternatives concerning the installed power of the wind turbine and the combined capacity of the desalination plant. Many other parameters should be taken into account in this design issues, such as the possible losses of an energy storage system or the availability of a water storage system[9][10].

The variable nature of wind power is not a problem as afar as water availability is concerned, because water can be stored inexpensively even for long periods of time without deterioration. With a plant that is dimensioned according to the local wind conditions, water becomes available any time.

However, variable wind power may cause operational problems in the system's operation and this is one of the most serious issues to be resolved in the design and implementation of this type of projects.

4. Environmental Impacts of RES Based Desalination Plants

Desalination plants cover the needs of remote areas in water. Usually they are implemented as a result of an analysis and alternative solutions evaluation amongst various possible solutions for water supply. For example, on several Greek islands, fresh water requirements are covered by the construction of large dams or ground reservoirs of desalination plants. In smaller islands, the only available solution is the transport of fresh water by ship, with high costs and improper hygienic conditions[11]. All these water supply methods cause a spectrum of environmental impacts, more or less serious depending on the type of the project, its location and scale.

The main environmental impacts of an RO desalination plant are the following:

- Noise disturbance
- Optical disturbance
- Land use
- Interference with public access in the coast
- Abstraction of brackish groundwater
- Discharge of brine - a concentrated salt solution that may be hot and may contain various chemicals on coastal or marine eco-systems or, in the case of inland brackish water desalination, on rivers and aquifers.
- The emission of greenhouse gases in the production of electricity and steam needed to power the desalination plants in case the energy provided is from the grid and fossil fuels are used to generate it.

The main positive environmental impact from desalination is that it reduces the pressure on conventional water resources. In particular, seawater desalination can help to relieve the pressure on overexploited coastal aquifiers[12].

In case that it is decided also to built a RES unit, either to cover only desalination unit's needs or to cover also energy demand of the area[10], then a strategic environmental assessment is needed that will evaluate in a integrated manner the impacts of all major projects being included.

5. Wind Based Desalination – Operational Issues

One of the problems of utilising wind power in process applications is the variable nature of the resource. While the wind is relatively predictable it is seldom constant and there will be periods when there will be none at all. The storage of wind energy in the form of electrical power is really only practical when small amounts are involved[13]. Storage batteries increase the total investment cost therefore, to run a process of any magnitude on stored electrical energy is not a practical proposition.
However if the product of the process can be stored inexpensively then it may be practical to oversize the process equipment to allow for downtime. Water can be stored for long periods of time without deterioration and the storage vessels are relatively cheap.

Variable power input force the desalination plant to operate in non-optimal conditions and may cause operational problems. To avoid the fluctuations inherent in renewable energies, different energy storage systems may be used[14].

The only matters that would require some careful design would be the relative sizes of the wind turbine and the RO plant and the cut-in and cut-out criteria for the RO plant to avoid excessive startup and shutdown cycles.

The intermediate energy storage system would be necessary, but it would reduce the available energy and would increase the cost of the plant.

The main drawback of RO in remote areas is the complex pre-treatment, the requirement of skilled workers, chemicals and membrane replacement.
For the operation of a wind-powered desalination plant, it is most important to have a plant that is insensitive to repeated start-up and shutdown cycles caused by sometimes rapidly changing wind conditions. Reverse osmosis is, with regard to pretreatment, membrane fouling, after-treatment and efficiency of the high pressure pumps, a process that is rather sensitive to a stop and start operation. In order to stand the discontinuous mode of operation, a new reverse osmosis membrane was developed, incorporating advantages of both spiral wound and plate and frame designs[15].

6. Wind Based Desalination – Design Issues

The main design variables that affect the design of an wind - RO system are:

- the water demand and, therefore, the RO plant's capacity
- the location that the wind turbine and the desalination plant will be installed (required sitting, altitude etc.)
- the feed water salinity
- the wind speed distribution
- the configuration of the energy system
- the water storage capacity
- the available power distribution
- desalination unit energy consumption
- the salt rejection
- the operating pressure
- the permeate flux, both in terms of overall product rate and specific rate (per unit membrane area).

The various alternative wind-RO configuration possibilities are the following[16]:

Systems with back up (diesel/grid)
In these systems, an additional energy source is provided (a diesel-powered generator or even the local grid) so that the power supplied to the RO is constant. The back-up generation complements the power generated from the wind turbine to match the RO unit power consumption. The main benefit of these systems, as in any hybrid wind-diesel configuration is the achievement of fuel savings, which may increase the generator availability and reduce overall energy costs.

Systems without back up
Systems without an external energy source can be divided into two categories, with emphasis on the RO unit operation: systems which run under approximately constant operating conditions; and those that experience variable operational conditions.

Near constant operating conditions
In this case an attempt is made to operate the RO unit with approximately constant operating conditions

Use of an energy storage device
Energy storage devices are employed to accumulate energy surplus during periods when the power generated by the wind turbine is greater than the load demand from the desalination unit. This surplus would then be used later when the generated power is insufficient to meet the load demand.

One common way of storing the surplus energy is by using batteries[10] or water pumping systems[17]. Storage sizing should be considered in the design stage. In addition, capital and maintenance costs should carefully be assessed.

7. Cost Analysis of Wind Based Desalination

The most promising potential market for wind powered RO is in present or potential future island tourist developments in places such as the Mediterranean islands, the Pacific Islands etc. Generally, if wind powered electricity generation is an economic proposition in any of these places and water is scarce (which it usually is), then wind powered reverse osmosis should also be economic. It is unlikely that energy storage would prove economical in these larger systems, although energy recovery for seawater plants would almost certainly be so.

In general, the cost reduction of renewable energy systems has been significant during the last decades. Therefore, future reductions as well as the rise of fossil fuel prices could make possible the competitiveness of seawater desalination driven by renewable energies.

For a given wind farm installed capacity (with a particular type of wind-turbine) and a given wind regime, there exists, from an economics point of view, an optimum nominal production capacity for each plant, that needs to be specified in each case under consideration. In this context, a wind farm with a nominal power of 460 kW and a wind regime (in the area of Pozo Izquierdo, proposed for its installation in Gran Canaria) with an annual average speed of 7.9 m/sec 10 m above ground level, would give rise to an optimum number of RO plants of 11, each with a capacity of 100 m^3/d. However, for technical and economical reasons the decision was made to use eight RO plants, each with a capacity of 25 m^3/d[15]. The average installed costs of seawater RO plants are in the range of $1,000 to $1,500 per cubic meter per day capacity.

The economics[18] of a combination of a wind turbine with an RO plant is helped by the fact that water is a storable commodity.

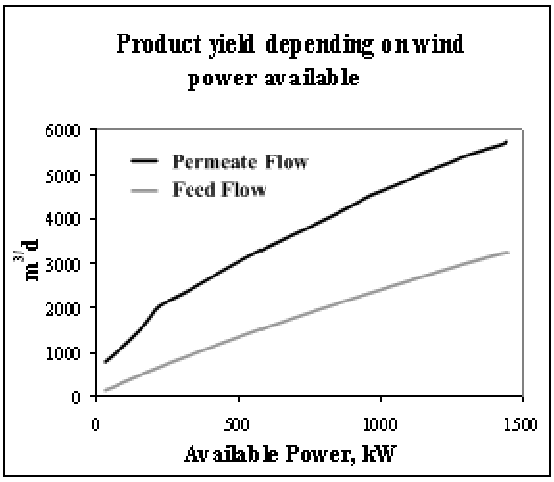

Figure 2: Product yield depending on wind power available[19]

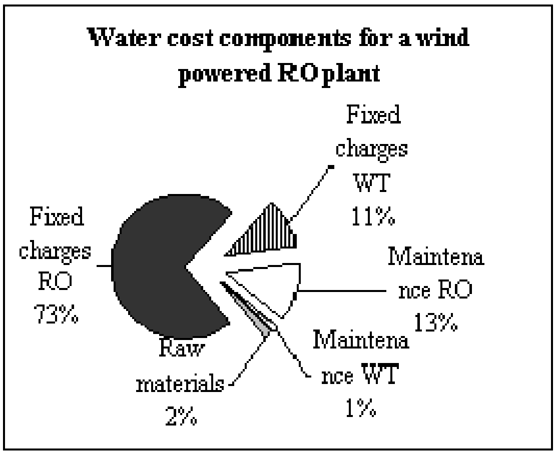

Figure 3: Water cost components for a wind powered RO plant[19]

Factors affecting water production cost in wind based desalination plants are shown in the following Table I[6][20][21][22].

Table I: Cost items of a wind based desalination plant

Direct Capital Cost	
	Cost of land
	Cost of Wind turbine
	Cost of energy storage systems

	Cost of the RO plant components
Annual Operating Cost	
	Electricity cost
	Manpower cost
	Maintenance and spares cost
	Chemicals cost
	Membranes replacement

The water cost of a wind brackish water reverse osmosis unit (large system, about 250 m^3/day) is of the order of 2 Euro/m^3. The implemented in Tenerife, Spain included for a 200 kW wind turbine, which would operate on average wind velocity 7,5 m/s, with an expected yearly energy yield around 600 MWh. This amount of energy is capable of producing over 200 m^3/d water[15].

8. Wind Based Desalination – Implementation Issues

The practical experience on wind powered RO systems has been with relatively small capacity systems. There have been a number of attempts to combine wind energy with RO. A number of plants have actually been operated. However, most of them were of small size, mainly for research purposes. Therefore not many conclusions have been reached in terms of expertise and know how. It is still difficult to control the usage of wind in a cost effective way. Coupling of a variable energy supply system, as mentioned earlier, to a desalination unit requires either power or demand management, and there is not much experience on it. However, the prospects of this combination are high mainly due to the low cost of wind energy.

The operational experience from early demonstration units is expected to contribute to improved designs and a large number commercial systems are expected to be implemented.

In this section we will describe two examples of wind based desalination units installed and operating in the Greek islands.

i) Milos Desalination Plant

In a Greek island called Milos and belonging in the Cyclades complex, a wind based desalination unit has recently been installed and operates since summer 2007. The unit has a capacity of 3000m^3/day. At the moment it operates in a daily production of 2000m^3 of potable water. This is a private investment that has been subsidized by the state. The water is sold to the municipality of Milos, in a continuous effort to solve the urgent water shortage problem, especially during the summer months. The contract that has been signed between the private company and Milos Municipality refers to a selling price of the water almost 1,8 euros/m^3.

The entire plant includes:

- The desalination plant
- A wind turbine of 600 kW
- The storage tanks (capacity 3000m^3)
- The remote control system

Before the installation of the unit, water was transported from Athens at a very high cost and very poor quality[11]. The implementation of this novel project has improved the quality of life of the island in many respects.

The sitting of the unit in a very touristic island as Milos could be a major problem, mainly because of the optical and noise disturbance. Therefore, the unit has been located on a hill that is not apparent from the most island villages.

ii) A Floating Wind Turbine/ Desalination Plant[23]

The first floating wind turbine/desalination plant in the world has been developed by a number of scientists / engineers with an academic and professional origin and lead by the University of the Aegean. Two of the most pressing environmental chal-lenges of today—energy production and water supply—have been met with an innovative and practical solution to meet the water needs of Greek islands.

The Floating Autonomous Environmental Friendly and Efficient Desalination Unit (FAEFEDU) is designed to produce potable water from sea water and do so by generating its own power through wind turbines on board.

The unit sits on a special floating 20 X 20 meter platform with a height of 8 meters for a cylinder and a 22-meter tower and can adapt to any weather conditions. Water production is more than 70 cubic meters per day—enough for the needs of about 300 people.

In order to achieve the largest possible energy and desalination production, scientists focused on minimizing the scale and polluting effects on the central unit, increasing the energy efficiency of the cycle.

In addition, because the unit is autonomous, it is not required to be connected to the national electrical grid. Since the unit is portable, it can be stationed away from populated centres and be placed wherever needed, on a seasonal basis for instance, to service the needs of islands that have an enlarged population during summer months. In addition, the unit can be repositioned to take advantage of changing weather conditions.

Figure 4: Floating Desalination Unit in Heraklia's harbour

FAEFEDU is fully autonomous, has an advanced automatic control system, operates unmanned and can be tele-operated and monitored remotely. The innovative system also eliminates any destructive land-based environmental interventions, since no roads or land construction are needed and no waste is produced. It is currently installed in the harbour of a small island called Heraklia (figure (4)) in order to cover the water needs of the village.

The Greek research community was heavily involved in the project, coordinating various disciplines to

fulfil the diverse needs of the unit. In addition, the Greek shipbuilding sector contributed with its vast know-how to produce the project at an attractive cost. Equipment providers from Germany, Sweden, and other European countries also participated.
The unit, the first of its kind in the world, was included in the "Natural Environment and Sustainable Development" section of the Operational Competitiveness Programme of the Greek state and was co-financed by the European Fund for Regional Development and domestic Hellenic sources.

9. Conclusions and Significance

The reverse osmosis technique is the most suitable for use in stand-alone wind- powered desalination systems. These systems are very valuable for regions like the Mediterranean islands, usually facing scarcity of potable water and lack of conventional energy sources, but do have at their disposal exploitable wind energy resources.

The financial performance of wind-powered desalination is also favourable. The costs are similar with what is expected for a conventional desalination system, proving to be particularly cost-competitive in areas with good wind resources that have high costs of energy. It can be concluded that wind-powered desalination can be competitive with other desalination systems, providing safe and clean drinking water efficiently in an environmentally responsible manner. Now that significantly larger and more reliable wind turbines have become available, wind powered desalination is poised to make the breakthrough into commercial applications.

The actual ratio of wind turbine size to RO plant sire that might be used in any instance should result from an optimisation making use of data that will be site specific for both the wind turbine and for the RO plant.

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INVESTIGATING THE RELATION BETWEEN THE RELIABILITY AND THE TECHNICAL AVAILABILITY OF WIND ENERGY APPLICATIONS

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Abstract

Wind energy is an established electricity production option worldwide. Taking into consideration that most wind turbines operate under unfavorable conditions, it is obvious that the success of a wind energy project heavily depends on the reliability of the equipment used. The reliability of a wind turbine depends on the design and construction of the model, on the material quality and classification as well as on the operating environment. In this context, this investigation focuses on the collection and analysis of data concerning the operation of installed wind turbines, in order to estimate their productivity and downtime period. Next, the technical availability of the existing wind parks is also calculated. For this purpose, available historical data are analyzed.

Keywords: Wind Turbine; Service Period; Energy Yield; Failure; Maintenance Cost

1. Introduction

Wind energy is an established electricity production option worldwide, contributing to the reduction of environmental pollutants generated by the operation of thermal power units. Actually, during the last years a considerable installed wind power increase has been encountered, thus the currently installed wind power (figure (1)) exceeds 90GW[1][2]. The situation in Greece, despite the excellent wind potential available, presents serious problems which restrict the installed wind power[3] at the 900MW level. One of the most influential evolutions that hinder the expected wind power penetration is the fair reliability and technical availability of the early installed wind turbines. Unfortunately, during the 90's remarkable wind turbine failures have been reported in several wind parks in Greece, defaming the wind energy applications[4]. On the other hand one should recognize that wind turbines are machines operating continuously (sometimes for several days without interruption) in very unfavourable weather conditions and their operational status cannot be regulated since it is strongly dependent on uncontrolled parameters (wind speed, ambient conditions, grid status etc.). In this context, it is obvious that the success of a wind energy project heavily depends on the reliability of the equipment used.

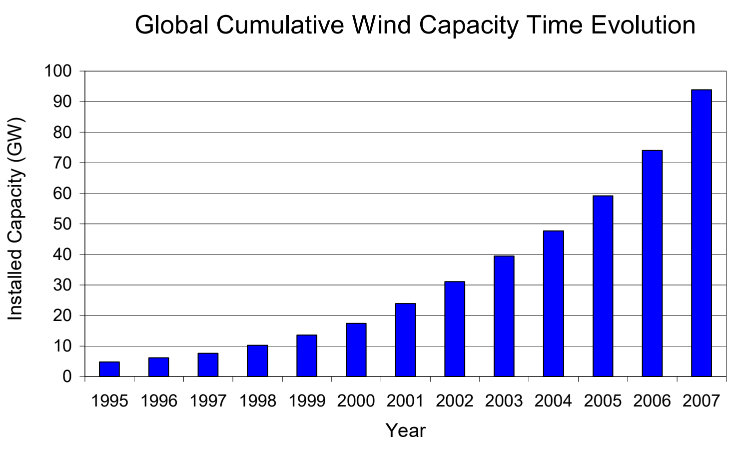

Figure 1: Global installed wind power (1995-2007)

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At this point it is important to note that a wind turbine's reliability greatly depends on the design and construction of the model under consideration as well as on its material quality and classification. The turbine's reliability also varies with the operating environment, stressing the need for careful selection of the appropriate turbine model for each specific location. On the other hand, poor reliability directly affects both the energy yield and the operation and maintenance requirements of the installation. For this purpose, the current investigation focuses on the collection and analysis of data concerning the operation of installed wind turbines in Greece and abroad, in order to estimate both their energy productivity and downtime period. The downtime period depends either on the unexpected malfunctions or on the scheduled maintenance works. On top of this, the technical availability of the existing wind parks is also calculated, while special attention is paid on establishing a quantitative relation between reliability and availability of the turbines under investigation. For this purpose, available historical data are analyzed and an attempt is made to locate the most common malfunctions that appear during the operation of the wind turbines.

However, for a complete analysis the maintenance and operation costs should also be estimated using a financial model which takes into account not only the cost of the scheduled service but also the additional cost of the most common malfunctions that arise during the operation years of a commercial wind turbine. In this analysis the lost revenues due to the missed energy production, caused by the downtime of the turbines, should be also included.

2. Position of the Problem

As already mentioned the reliability of a wind power installation influences both the energy production and the maintenance and operation (M&O) cost of the power station under investigation. This is reasonable, since the system reliability decreases as the downtime period of the machine increases. In most cases the reported downtime cases are caused by both regular maintenance and unforeseen malfunctions. As a result the operational period of the machine is reduced, while additional money is needed in order to face the downtime causes.

In this context, one should first determine the main reasons leading to low reliability of existing wind turbines (WTs). Using the experience gathered from various available sources, including published scientific papers, technical reports, on-field data and data based on personal communication with the appropriate service support stuff, the main reasons affecting the reliability of a WT include:

i. Scheduled maintenance
ii. Electrical grid problems
iii. Service problems
iv. Wrong/False failure announcement
v. Material failure
vi. Extreme weather conditions
vii. Corrosion problems in island environment
viii. Force Majeure problems
ix. Various/Miscellaneous

Facing the specific problems may in some cases (e.g. grid problems, normal service activities and false failure announcements) require no additional expenses. However in most cases, increase of the M&O cost is induced. On top of this, during the time that the WT is out of operation, analogous wind energy production loss may be encountered, mainly dependenting on the available wind potential during the specific time period. Following, a short reference[5][6] on the main downtime causes is undertaken in order to estimate both the time expected for dealing with each arising problem and the corresponding cost implied.

The regular maintenance of a wind park, including normal service activities and depending on the schedule provided by the manufacturer is executed between two and four times per year. Besides, scheduled/regular maintenance lasts for a given time period (5-20 hours, depending on the severity of the scheduled maintenance task) and is executed by a service crew of at least two technicians. To moderate the wind energy production losses of the installation, it is preferable for the maintenance tasks to be executed during the calm spells' periods, while during the windy periods any maintenance tasks should be avoided for safety reasons.

Nevertheless, the problems met in local electricity grids are possibly the main downtime cause, especially for isolated island networks[7][8]. The most common problems include considerable voltage variation (voltage sags and swells), phase asymmetry due to faults appearing either in the operation of network transformers or in the respective of wind turbines' compensation capacitors, phase discrepancy (normally following the network restoration), frequency deviations, as well as complete collapse of the local system (black out). In the majority of the above mentioned cases, the arising malfunctions are automatically repaired within a few minutes' time (10min up to one hour), while during certain times, the intervention of the machine operator through the use of a remote control system is necessary. Another severe problem, responsible for the restriction of the WTs' technical availability in island networks, not comprising a fault of either the equipment or the local electrical grid, is the curtailment-rejection of wind energy production during periods of low electricity demand[9], in order to protect the stability of the isolated electrical grid.

Furthermore, as far as the service problems are concerned, damages or unscheduled interruptions of operation, owed to the deficient maintenance of the equipment, should also be considered. In this category one may encounter the activation of aerodynamic brakes (due to the marginal adjustment of the respective mechanism) although there is no evidence showing an actual increase of the rotor's speed, the activation of overheating protection sensors, the overheating of moving shafts-bearings due to deficient lubrication (yaw mechanism, gear box bearings), etc. The specific problems may be gradually constrained as the maintenance personnel become more experienced and as the technology of the corresponding sensors is improved.

Concerning the wrong/false failure announcement faults, representing the majority of recorded problems for WTs during the past, they are usually dealt with through the use of remote control systems, not requiring any considerable cost and not implying a significant reduction of the turbine's energy production time. The cause of these problems may be ascribed to momentary fluctuations of the network parameters, to interactions among different signals and to deficient coordination of the turbine's operational parameters, as well as to deficient set-up of the controller algorithm.

The failure of materials and components comprises the most severe factor of unreliability for a WT, while the repair of these damages requires considerable time and additional expenses. Equipment failures may include the failure of small parts and the turbine's stop due to certain problems of the main components, i.e. blades, electrical generator, pitch mechanism, gearbox, yaw system, hydraulics, etc. In several cases, it is almost certain that one of the pre-mentioned main parts of the turbine should be replaced at least once within the service period of the WT. This considerable cost of replacement is separated from the corresponding fixed annual cost and is described[10] by the term of variable cost, while it may in certain cases lead to the abandonment of the turbine, especially if appearing close to the time of the expected service period of the installation. As it is definitely expected, less time is required for repairing the damage in case that permanent personnel is employed as well as in case that a stock of the appropriate spare parts is available (in respect of large scale wind parks) and the area of repair is easily accessed[11]. On the other hand, the problem becomes more difficult to solve in isolated small island areas, due to the fact that the arrival of an experienced and trained crew for the damage repair is much affected by the existing weather conditions. More specifically, in the area of the Aegean, the appearance of strong winds along with the insufficient transport networks between the islands may postpone the repair of any damage even for several weeks, hence constraining the energy production ability of the turbine as well.

Besides, the replacement cost is also affected by the weather conditions and the size of the wind park. In many cases, the mobilization-transition and accommodation expenses for the maintenance crew may even correspond to 50% of the total maintenance cost. Finally, the availability or not of spare parts along with the time efficiency of the respective supply chain are also critical for the financial evaluation of each damage.

Extreme weather conditions, often met in the area of the Aegean and especially in isolated and mountainous locations of wind parks' installations, are in many ways affecting the reliability of WTs. Some of the common problems encountered include the increased levels of moisture due to fog, with the former affecting the electrical and electronic parts of turbines, as well as the ice loading and the stand-still state for the anemometers and the wind direction systems, eventually leading to the stoppage of the entire WT. Additionally, both the moisture and the frost aggravate the operation of the blades and other mechanical parts of a WT, often causing increased loads (mainly fatigue) and leading to the acceleration of the equipment's wear. Extreme wind speed phenomena and lightning strokes, since classified in the category of "Force Majeure" problems are not currently examined. On the contrary, in the specific type of problems one may encounter the damages of the electrical and electronic equipment due to very high temperatures recorded in our country during the summer period.

Moreover, in island environments or in coastal areas, despite the careful design and the special manufacturing of the equipment, there are always some parts or sections that appear to be more sensitive in the corrosion caused by the nearby marine atmosphere. In several cases, minor problems due to corrosion or rust may lead to more accountable problems, like the blockade of the brake system and the electrical revolutions' reducer, as well as the complete destruction of the corresponding electrical motor.

The reliability problems owed to "Force Majeure" reasons include mainly destructions of equipment due to lightning strokes and extremely strong winds, while one should also consider destructions owed to fires, floods and considerable disturbances of the local electricity network. Note that in the Greek territory, lightning is recorded as one of the most severe problems, limiting the technical availability of the existing WTs. More specifically, lightning appearing may -according to the best case scenario- lead to the temporary interruption of the WT operation. In more severe cases, the destruction of certain electrical and electronic systems' parts (mainly the controller's) as well as the complete destruction of the rotor or even of the entire WT have also been encountered.

Finally, in the unclassified various problems one may include damages and problems owed to the wrong handling and operation of machinery and control systems by the personnel as well as to the destruction of cables and equipment parts caused by animals and third parties (the latter caused either on purpose or by mistake/accident).

3. Theoretical Model

The annual (8760hours) energy yield of a wind park of "z" wind turbines of rated power "N_o" is usually expressed as:

$$E = CF \cdot \left(z \cdot N_o\right) \cdot 8760 \tag{1}$$

where "CF" is the installation annual capacity factor given[10][12] as the product of the mean power coefficient "ω" with the technical availability "Δ" of the installation, i.e.:

$$CF = \omega \cdot \Delta \tag{2}$$

Using the annual energy yield of a wind park one can also estimate[10] the corresponding annual revenues "R" due to the energy production by the wind power station as:

$$R = E \cdot c \tag{3}$$

with "c" being the price of the wind energy sold to the local electrical grid.

According to previous studies[8-12], the mean power coefficient of a wind power installation depends on the wind potential and the ambient conditions of the installation, on the power curve of the turbines used and mainly on the collaboration between the wind turbine and the existing wind potential, i.e.:

$$\omega = \int_0^\infty \frac{N(V)}{N_o} \cdot f(V) \cdot dV = \int_{V_c}^{V_F} \frac{N(V)}{N_o} \cdot f(V) \cdot dV \tag{4}$$

where "f(V)" is the probability density function[4][8] describing the local wind potential and "N(V)" is the power curve of the wind turbine used versus wind speed "V". Taking into account the definition of "ω" it is obvious that its value is less than 1.0 due to the low ($0 \le V \le V_c$) and high ($V \ge V_F$) wind speed periods, as well as due to the wind turbine operation outside its rated power (i.e. $N(V) < N_o$).

On the other hand the technical availability of a WT depends on the technological status, the age and the location of the machine. In the present analysis the following expression is adopted[11][12] for the calculation of the technical availability of a wind turbine:

$$\Delta(t) = \Delta_o(t_o) \cdot \frac{\Delta_n}{\Delta_o}(\tau) \cdot \Delta_w \cdot \Delta_G \tag{5}$$

where "Δ_o" describes the technological status of a new-installed WT at the time "t_o", i.e. when the investment is realized. In the early 80's the technical availability of the first wind parks was approximately 60%, while at the beginning of the next decade the value of "Δ" outnumbered 90%. Nowadays, the wind energy technology has achieved such a level of quality, that new wind turbines obtain a technical availability of up to 99%.

The next term "Δ_w", takes into consideration the accessibility difficulties of the wind park under investigation. This parameter is of special interest for the remote Greek islands, especially during winter, due to bad weather conditions (high winds and huge waves suspend the ship department, thus preventing maintenance and repair of the existing wind turbines). For this purpose, an adapted form of the analysis by Van Bussel[13] may be used in order to simulate the "Δ_w" parameter of equation (5), (figure (2)).

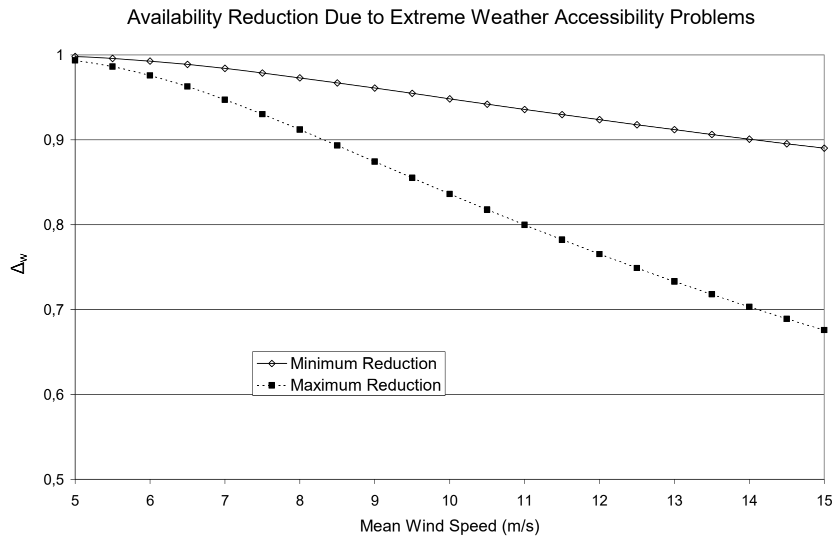

Figure 2: Reduction of Technical Availability values due to weather

Subsequently, in small autonomous grids one should take into account the actual upper limit for wind power penetration, in order to maintain the stability of these weak electrical grids. In similar cases the period of time "Δ_G" that wind energy is absorbed by the local grid is strongly decreased as the wind power penetration in the local grids is increased. In figure (3) one may find the maximum annual wind energy contribution in small island electrical systems as a function of the existing wind power penetration. However, detailed cost-benefit analyses and more recent calculations based on stochastic methods state[14][15] that the actual wind energy contribution without any energy storage devices is quite lower and rarely exceeds 10%.

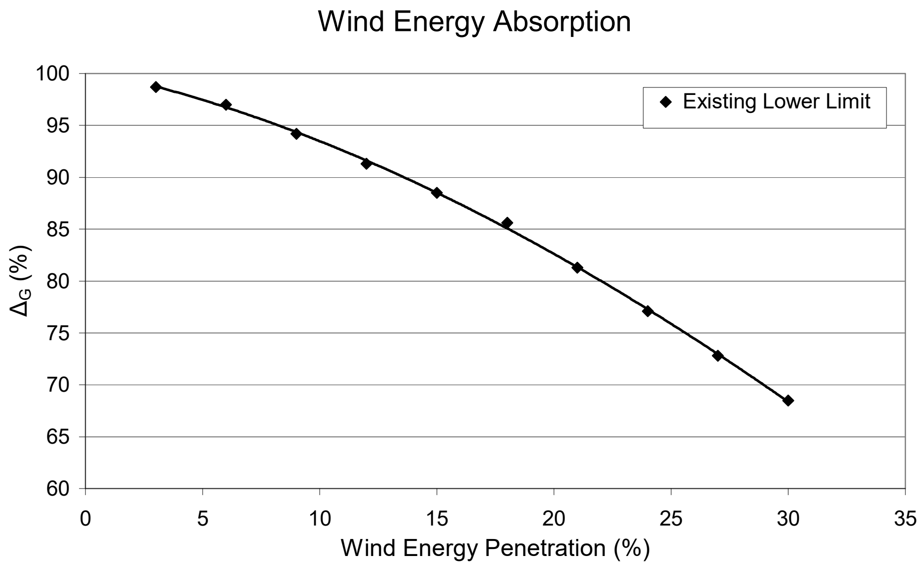

Figure 3: Minimum wind energy absorption by autonomous electrical grids

Finally, the most relative to the current analysis term is the term "$\Delta_n(\tau)/\Delta_o$", which expresses the technical availability changes during a wind turbine's operational life (τ). At this point it is important to mention that there are several "failure pattern distributions", i.e. from the well known "bathtub curve" and the "slow aging" one up to the "traditional view"[5][6]. Based on real data evaluations[16] it can be assumed that most wind turbines reliability is characterized by early failures until the third operational year. This phase is generally followed by a longer period (~10 years) of "random failures" before the failure rate through wear and damage accumulation "wear-out failures" increases with the operational age. In order to simulate the "$\Delta_n(\tau)/\Delta_o$" distribution the function "$\zeta=\zeta(\tau,z)$" is introduced, thus eq.(5) may be equally well written as:

$$\Delta(t) = \Delta_o(t_o) \cdot \Delta_w \cdot \Delta_G \cdot [[1-\zeta(\tau, z)]] \quad (6)$$

As it is rational, in cases of numerous wind turbines it is more possible for permanent service staff and for spare parts stock to exist. For this reason the operational time-dependent technical availability diminution "$\zeta(\tau,z)$" is lower for large wind parks ($z\approx 100$) than for individual wind converters, (figure (4)), see also [16] and [17].

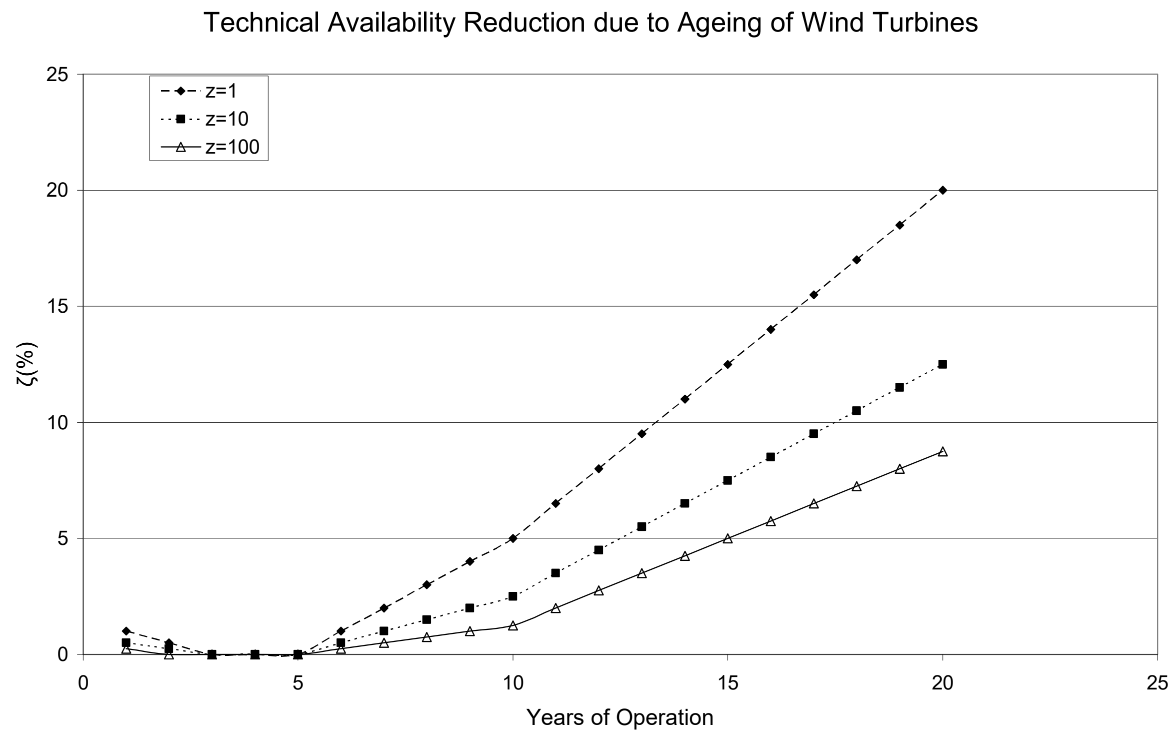

Figure 4: Technical availability reduction in the course of the operational time

On the other hand, the reduced reliability of a WT strongly influences the fixed and the variable maintenance and operation cost of the installation. In fact the M&O cost includes the normal service cost as well as the repairing of any system malfunctions and component failures. More precisely the additional M&O cost includes the service personnel transportation and accommodation cost, the labour cost, the necessary auxiliary equipment cost (e.g. cranes, platforms etc.), the spare and consumables utilized cost as well as engineering, consultation and staff insurance cost. Due to its significance, the financial evaluation of the M&O cost is not included in the present work, constituting the main subject of a parallel investigation.

4. Application Results

At this point it is important to note that there is a quite limited access on accurate data concerning the reliability of existing wind parks due to the definitely financial character of this information. On top of this, one needs long-term continuous data in order to obtain sound conclusions. For this purpose we present selected available data from a representative small wind park operating since 1991 in the Ikaria island. This wind park belongs to the former Public Power Corporation (PPC) and is no more in commercial operation. The results obtained are accordingly compared with available data concerning wind parks operating in Germany and India.

More specifically, the Ikaria wind park -erected by PPC in 1991- is one of the smallest Greek parks, consisting of seven old-fashioned (2nd generation) wind converters, i.e. 7 Windmatic 15S (or Aiolos-55) machines, rated power 7x55kW. Ikaria is a medium-sized island of the East Aegean Sea, situated 240km from Athens, nearby Samos, with the mean annual wind speed of the area exceeding 9m/s. The wind park under investigation is a typical example of the first wind parks installed by the PPC in remote Greek islands[4], using wind turbines of the 2nd and 3rd generation. According to the long-term annual energy yield analysis[4][12] of this wind power station there is a significant time-variation of the corresponding capacity factor taking values from 12% up to 35%. It is obvious that this strong wind energy generation variation cannot be attributed to the available wind potential variations and the corresponding "ω" value, thus the most reasonable explanation is the unsteady time evolution of the installation technical availability "Δ". In order to get a clear cut picture of the time evolution of the wind energy production, in figure (5) the energy production of the most representative wind turbine (i.e. WT-6) of the wind park under investigation is presented. According to the data available, the WT-6 was out of order during the second and third year of operation (from August 1992 up to March 1994), while remarkable downtime periods have been encountered during its entire 15-year service life.

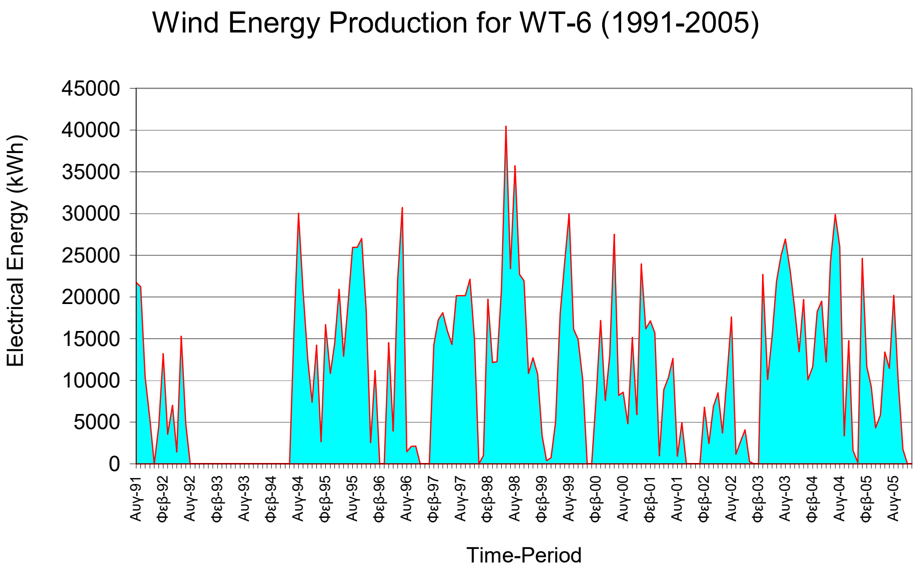

Figure 5: Wind energy production time-evolution

In an attempt to explain this quite unusual behavior of this WT, in figure (6) one may obtain the annual downtime of this wind turbine in the course of time. According to the data available, the long-term technical availability of the WT-6 is approximately 72.4%, this being a fair value for a very small and quite outmoded engine operating in the controversial environmental of the Aegean Sea. In the next figure (7) one may find the annual distribution of the total malfunctions of the WT, divided in three subcategories, i.e. electrical, electronic and mechanical malfunctions. As it results from this figure, the number of the annual malfunctions varies between a minimum value of five (5) and a maximum number of sixteen (16). Another interesting observation is that the number of failures decreases after the first ten years of operation. Finally, analyzing the data concerning the downtime related with each one of the above mentioned malfunction categories, using the records of the WT-6, one may find mechanical failures due to:

- loss of lubrication oil in the slide radial blocks
- hydraulic fluid leakage
- anemometer broken cups
- yaw system high temperature
- At the same time, the most important downtime is related with the wind turbine controller problems, attributed mainly to strong lightning and suspending the operation of the machine for more than 8000 hours in a fifteen year operational period. Finally, one should also mention that no serious electrical malfunctions have been encountered for the entire service life period of this WT. Summarizing, it is important to clarify that similar downtime behavior is presented by all the wind turbines of the Ikaria island wind park.

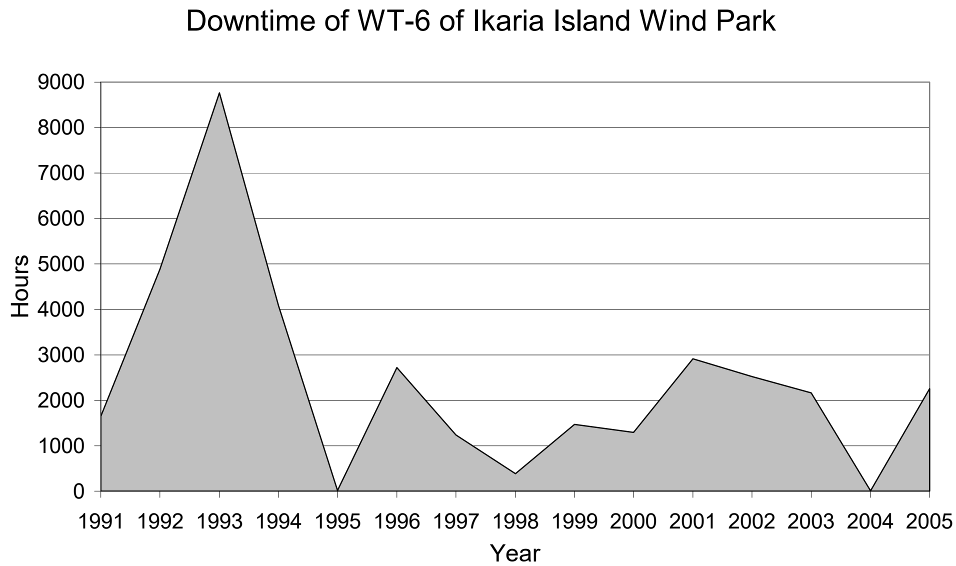

Figure 6: Downtime of a representative WT in the course of time

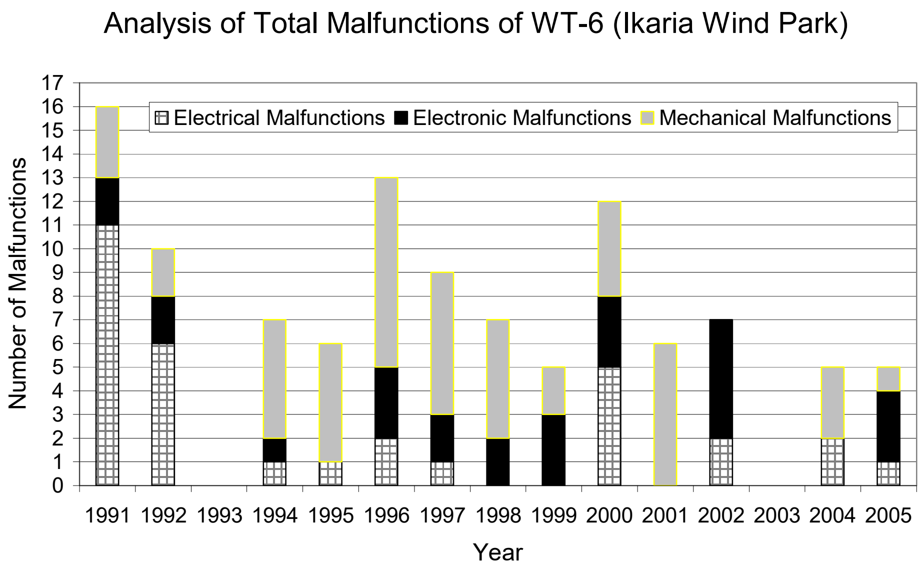

Figure 7: Fault analysis of a representative WT in the course of time

For comparison purposes, one may find in figure (8) the annual distribution of total failures for the German "250MW Wind Program"[18], including data of relatively small wind turbines (less than 500kW each) during almost the same time period. According to the published information the mechanical failures represent 48% of the total system malfunctions, while the electronics are assumed responsible for the respective 28%. Finally, the electrical system is responsible for the rest of malfunctions, i.e. 24%. On top of this, one may also examine the average annual failure rate of the small wind turbines of the program in the course of time. Comparing the data available it is obvious that the failure number of the Ikaria wind turbines is much higher than the number concerning the Germany wind program. Despite this difference in absolute numbers, it is important to mention that in both cases there is a continuously failure rate decrease during the first operational years of the wind turbines, attributed mainly to the increased experience of the service and operational personnel.

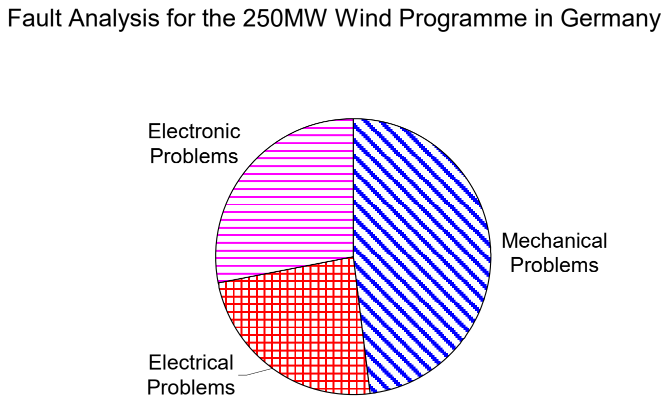

Figure 8: Fault analysis for the 250MW wind program in Germany

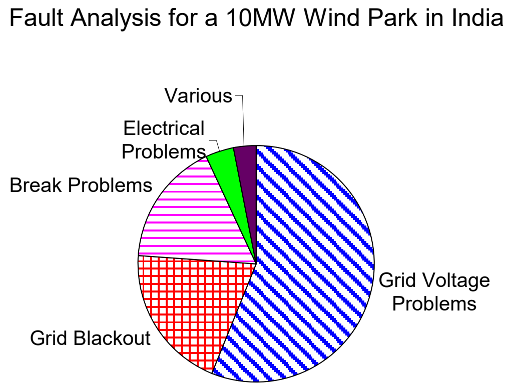

Figure 9: Fault analysis for the 10MW wind program in India

Similar results have been reported[19] for the operation of a quite large -for the time period- (10MW) wind park at Gujarat of India, where the overall technical availability is estimated at 80%. The wind park includes 50 wind turbines of 200kW rated power, while during the fault analysis almost thirty (30) major failures have been encountered. Opposite to the German Wind Program, the majority of the failures reported (figure (9)) are due to the electrical grid problems and problems of the electrical system of the machines, while no serious mechanical failures have been mentioned, excluding the brake problems representing less than 20% of the total problems.

5. Conclusions

In the current study, the reliability and the technical availability relation of contemporary wind energy applications is investigated. For this purpose the major malfunction problems of a typical wind park are first presented and categorized. Accordingly, an analytical model concerning the technical availability estimation of a commercial wind power station is presented, based on the experience gathered from various useful sources. Finally, detailed malfunction, downtime and energy production data of a selected small island wind park are analyzed in order to find the relation between all the parameters involved. In this context, the downtime is attributed to mechanical, electrical and electronic failures as well as to extreme weather and "Force Majeure" events (mainly lightning). The results obtained are compared with the results of published investigations concerning wind parks using wind turbines of similar age and technology in Germany and in India.

According to the results obtained, one may state that the failure number and the downtime of the remote island's wind park are quite higher than the corresponding values in Germany and in India. This is quite reasonable if one takes into account the transportation problems and the poor infrastructure situation in the Aegean Sea remote islands. On the other hand, the failure rate time evolution is in all cases examined following almost the same pattern, thus supporting the validity of the proposed analytical model. For the development of a complete technical availability-reliability model further work is under preparation using additional wind park reliability data and introducing the techno-economic evaluation of the operational behaviour of existing wind parks.

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A COMPUTATIONAL AERODYNAMICS SIMULATION OF THE NREL PHASE II ROTOR

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Abstract

The work presented in this article aims to the calculation of the aerodynamic characteristics of the NREL phase II rotor that is an horizontal axis downwind wind turbine rotor and which is assumed to stand isolated in the space. The Reynolds averaged Navier-Stokes equations combined with the Spalart-Allmaras turbulence model that describe the three dimensional steady state flow about the wind turbine rotor are solved with the aid of a commercial CFD code. A structured grid of approximately 3.3 million cells formulates the computational domain. The numerical results for the considered wind turbine rotor are benchmarked against wind tunnel measurements obtained at free stream velocity of 7.2m/s in the framework of VISCEL project. The comparisons show that the used CFD code can accurately predict the span-wise loading of the wind turbine rotor.

Keywords: Wind turbine; NREL Phase II rotor; VISCEL project; CFD

1. Introduction

With the experience of "oil shock" in the early 1970s and the environmental impact of burning fuels, energy policy has confirmed the improvement of the environmental sustainability of energy as a primary objective and the use of renewable sources[1]. Wind power generation is an environmentally friendly method of generating electric energy through the operation of a generator attached to the axis of a rotor blade that turns due to the rotational action of the resultant aerodynamic force generated by the change of wind momentum. Since wind energy is a low-density source of power, it is important to maximize the efficiency of wind machines. The prediction of the aerodynamic properties of wind turbines is more challenging in many ways than that of already complicated problems such us helicopter rotors and propellers.

The design of a wind turbine rotor requires accurate, reliable and robust numerical predictions. The literature reports various methods that compare numerical predictions to experiments. The methods vary from blade element momentum (BEM) theory[2], vortex lattice[3], coupled viscous/potential panel[4] to variants of Reynolds averaged Navier-Stokes (N-S)[5][6]. The computer related requirements which set in full N-S simulations[7][8][9] are overcome with hybrid N-S solver/free wake method. In this method, the computational domain is divided in N-S regions near the rotor blade and potential flow regions on outer field where free vortex methods are used to model the vortical flowfield[10][11][12].

BEM methods although based on a "two-dimensional" theory provide acceptable approximations to the axisymmetric distribution of inflow and loads found under conditions where the wind is normal to the plane of the rotor (i.e., the turbine is in zero yaw angle with respect to the oncoming wind), and there are no dynamic stall effects[13]. This explains their use in the preliminary studies concerning the performance of horizontal axis wind turbine (HAWT) rotors. A full aerodynamic analysis however should take into account important operational parameters like wind turbulence and shear. This can be accomplished with the full Navier-Stokes solvers. This class of methods have the potential to provide a consistent and physically realistic simulation of the turbine flow field. The field of CFD applied to rotating-blade problems is reviewed by McCroskey[14], Landgrebe[15], Hansen[16] et al and Hu et al[17].

The aim of the present work is to perform a 3-D flow analysis of a three-bladed small-sized rotor from the Viscous and Aerolastic Effects on Wind Turbine Blades – Phase II (VISCEL-II) project[18] with the aid of a commercially available CFD package. Several 2-D and 3-D simulations were carried out to yield information on the different involved aspects, ranging from aerodynamic calculations to wake development. The calculations are compared with experimental data for validation purposes.

2. Turbine Geometry

The National Renewable Energy Laboratory (NREL) phase-II rotor mounted on a downwind machine is a small three bladed HAWT rotor with 5.029m radius[19], as shown in figure (1). The blades of the phase-II rotor are non-twisted and non-tapered with a constant cord of 0.4572m. The NREL S809 airfoil series is used, except for the root. At 14.4% span the airfoil thickness is t/c=43% and decreases linearly to t/c=20.95% at 30% span, while outboard of 30%, thickness is constant at that value. The nominal rotation speed is 71.68 rpm and the pitch is 12 deg. This HAWT rotor was chosen to use data from the NREL phase-II experiment as reported in "IEA Annex XIV: Field Rotor Aerodynamics"[18] where also the geometry of the rotor is thoroughly described.

Figure1**:** Different views of the NREL Phase II Rotor

3. Description of the N-S Solver

The physico-mathematical modelling of the complicated HAWT rotor flow is provided by the steady, incompressible, isothermal Reynolds averaged Navier-Stokes (RANS) equations[20][21].

$$\nabla(u_i) = 0 \tag{1}$$

$$\rho \frac{\partial}{\partial x_j}\left(\overline{u}_i \overline{u}_j\right) = -\frac{\partial \overline{p}}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\tau_{ij} - \overline{\rho u_i u_j}\right) \tag{2}$$

combined with one of the existing options for turbulence modelling. The one-equation Spallart-Allmaras model[22][23] with standard wall functions ($y^+ \geq 30$) is proposed due to its efficiency in combining accuracy with low computing cost

$$\frac{\partial}{\partial t}(\rho\tilde{v}) + \frac{\partial}{\partial x_i}(\rho\tilde{v}u_i) = G_v + \frac{1}{\sigma_{\tilde{v}}}\left\{\frac{\partial}{\partial x_j}\left[(\mu + \rho\tilde{v})\frac{\partial \tilde{v}}{\partial x_j}\right] + C_{b2}\cdot\rho\left(\frac{\partial \tilde{v}}{\partial x_j}\right)^2\right\} - Y_v + S_{\tilde{v}} \tag{3}$$

where G_v is the production of turbulent viscosity, Y_v is the destruction of turbulent viscosity that occurs in the near-wall region due to wall blocking and viscous damping, v is the molecular kinematic viscosity, $\tilde{v}$ is identical to the turbulent kinematic viscosity except in the near-wall region, $\sigma_{\tilde{v}}$ and C_{b2} are constants and $S_{\tilde{v}}$ is a user defined source term.

The transport variable $\tilde{v}$ is related to the turbulent viscosity as follows

$$\mu_t = \rho\tilde{v}f_u \tag{4}$$

The viscous damping function f_u is given by

$$f_u = \frac{x^3}{x^3 + C_u^3} \tag{5}$$

where x relates the molecular velocity and the transport variable and is defined by the following equation

$$x \equiv \frac{\tilde{v}}{v} \tag{6}$$

The equations are solved by the commercial code Fluent[21] using the single reference frame (SRF) technique attached to the blades of the rotor. The non-linear system of equations implies the segregated solver, thus is solved sequentially. PRESTO and QUICK discretization schemes are used for the continuity and the momentum equations respectively. The PRESTO scheme[24] uses the discrete continuity balance for a "staggered" control volume about the face to compute the "staggered" pressure. QUICK-type schemes[25] are based on a weighted average of second-order-upwind and central interpolations of the variable. As the code solves the incompressible flow equations, no equation of state exist for the pressure, and the SIMPLE algorithm is used to enforce pressure-velocity coupling.

4. Computational Domain and Grid

In the current research work, the wind turbine tower and the ground are neglected, which is a fair approximation for HAWT rotor simulation. The computational domain is enclosed between a small inner cylinder and an outer cylinder with diameter equal to 6 times the rotor diameter, both axial centred. Thus, the region, which includes the hub of the rotor, is completely removed from the domain. The field is extended to 8 rotor diameters downwind of the turbine and 2 diameters upwind. Exploiting the 120 degrees periodicity of the three-bladed rotor, only one of the blades is explicitly modelled using the SRF technique as shown in figure (2).

The Fluent's pre-processor Gambit is used to create the volume mesh. It is a hexahedral mesh of approximately 3.3 million cells (145x135x167 cells in x, r and ϑ directions respectively). As shown in figure (3), the grid around the blade is H-type which is optimized to resolve the boundary layer for standard wall functions ($y^+ \geq 30$). All the calculations were carried out in an Intel Core 2 quad Extreme

QX6800 with 8Gb Ram. The number of iterations adjusted to reduce the scaled residual below the value of 10^{-5} which is the criterion of convergence. For each run, the observation of the static pressure, at a specific point in the free-stream behind the rotor and the value of the rotor power were appointed for the convergence of the solution. Aiming to smooth convergence, various runs were attempted by varying the under-relaxations factors. In that way a direct control regarding the update of computed variables through iterations, was achieved. Initializing with low values for the first iterations steps and observing the progress of the residuals, their values were modified for accelerating the convergence. For a typical run of a case the cpu time was approximately 20 days and the construction time of the domain grid was about a month. This is a factor that does not permit a grid independence task procedure.

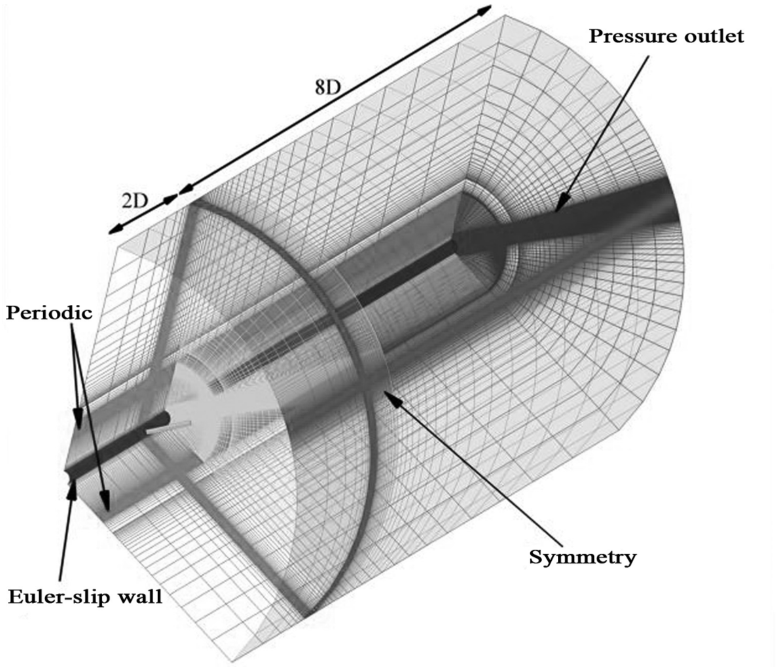

Figure 2: The control volume meshing in 120 degrees section and definition of the boundary conditions

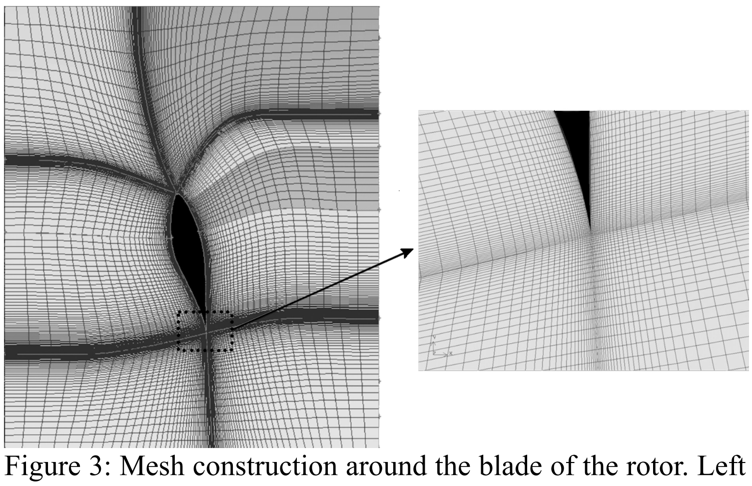

Figure 3: Mesh construction around the blade of the rotor. Left picture shows the mesh around the blade and the right picture shows detail of the mesh near the trailing edge of the blade

The working fluid for this analysis is the air with density equal to the reference value in the experimental data which is $0.997 kg/m^3$[18]. A uniform wind speed profile of 7.2m/s is assumed at the entrance of the domain as boundary condition with fixed turbulence intensity and turbulence viscosity ratio. The nominal rotation speed is 71.68 rpm. The boundary condition for the inner cylinder is Eulerslip and for the outer one is symmetry, as shown in figure (2). The no-slip wall condition is assigned to the rotor blade surface and the pressure outlet condition to the downwind extreme of the field.

5. Results

The commercial CFD code Fluent[21] is used for all the calculations presented. In order to validate the numerical results, experimental data are used from the 'IEA Annex XIV: Field Rotor Aerodynamics' report[19]. In figures (4a), (4b), (4c) and (4d), the numerical pressure coefficient distribution is presented and compared with experimental results for 30, 47, 63 and 80% spanwise locations, respectively. The calculated pressure coefficient follows the definition applied in experimental data for reasons of direct comparison. Therefore, the pressure coefficient is:

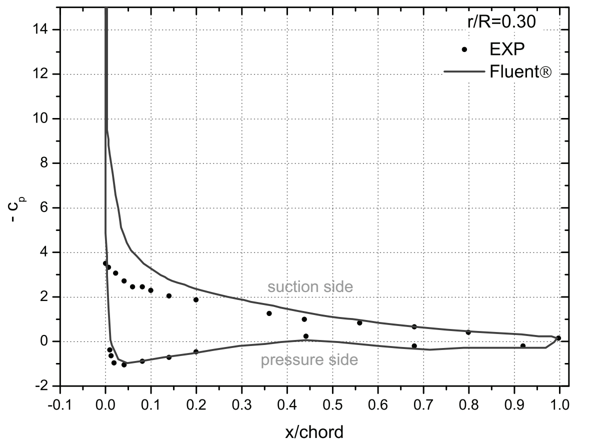

Figure 4a: Computed and experimental "EXP"[19] chord-wise pressure distributions at r/R=0.30 span-wise location

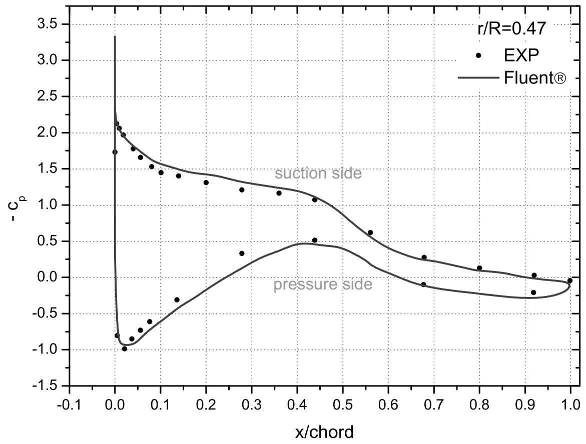

Figure 4b: Computed and experimental "EXP"[19] chord-wise pressure distributions at r/R=0.47 span-wise location

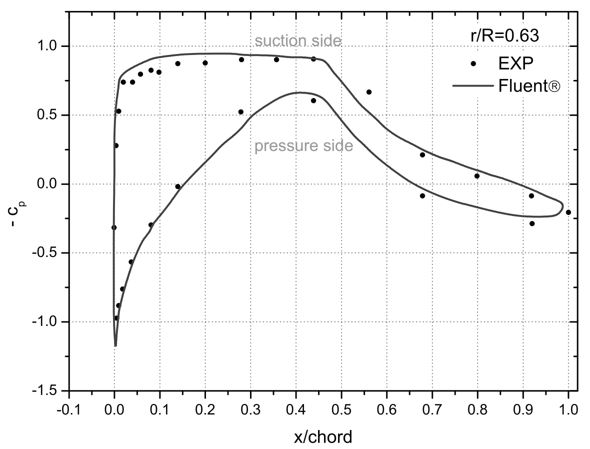

Figure 4c: Computed and experimental "EXP"[19] chord-wise pressure distributions at r/R=0.63 span-wise location

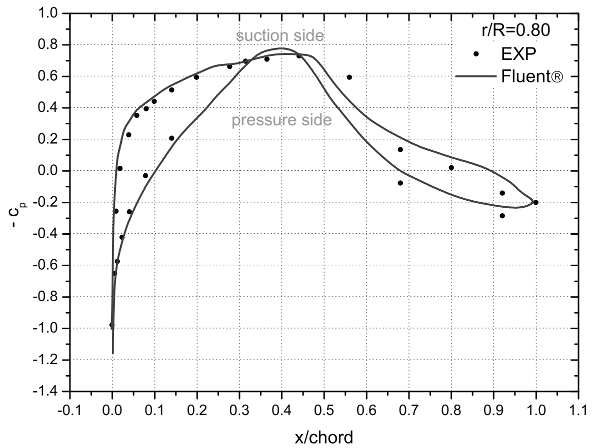

Figure 4d: Computed and experimental "EXP"[19] chord-wise pressure distributions at r/R=0.80 span-wise location

$$c_p = \frac{(p - p_{hub}) + p_{cent}}{q_{ref}^2} \tag{7}$$

where p is the local pressure on the blade surface, p_{hub} is the reference pressure on the hub of the rotor, $p_{cent}=0.5\rho(\Omega r)^2$ is the static pressure that accounts the centrifugal action of the flow and q_{ref} is the reference dynamic pressure in a distance of about half chord upstream of the blade in the corresponding radial position.

To minimize the influence of the tower on the experimental results instantaneous data at an azimuthal blade positions of 90 deg are used, i.e. when the blade is horizontal and moving down towards the tower. The comparison between the calculated pressure distribution and the experimental data is in satisfactory agreement. Some inaccuracies occur on the leading edge of the blade section and seem to increase at span-wise positions closer to the rotor hub.

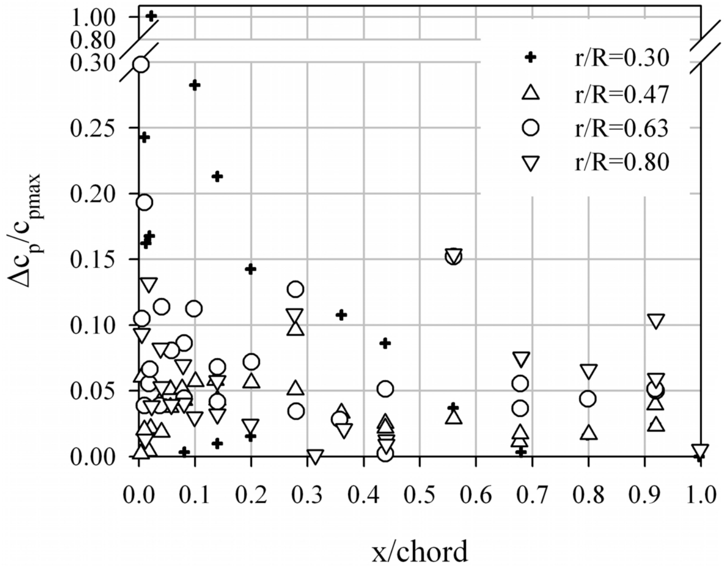

Figure 5: Deviation of the computed pressure coefficients from the corresponding experimental in the four sections examined alongside blade

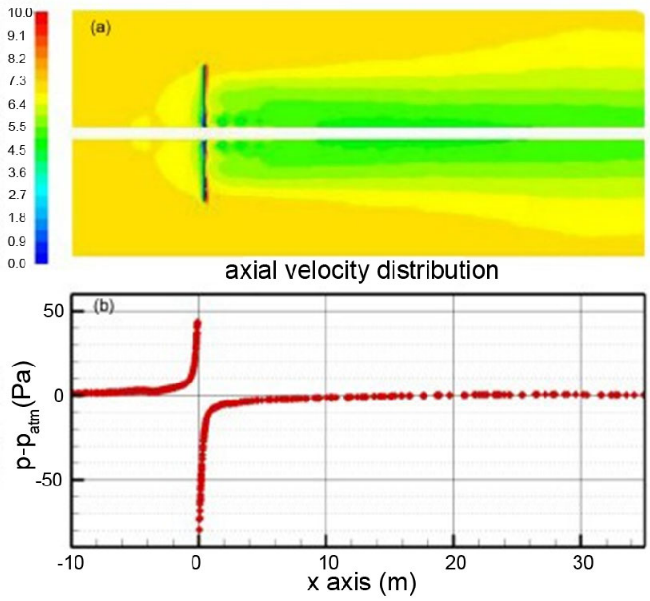

Figure 6: Near wake axial velocity distributions (a) and pressure distribution (b) along longitudinal axis of the NREL Phase II rotor at hub height

The accuracy of the computed pressure coefficients against the corresponding experimental values are checked in terms of their percentage deviation at the four spanwise examined stations, as shown in figure (5). The majority of the deviations are less than 6%. However, some important discrepancies are observed in the r/R=0.30 station near the blade root. The above observed discrepancies are probably due to the highly separated flow region which is not properly resolved with the RANS approximation.

The evolution of the produced wake from the rotor blade is depicted in the axial velocity contour plot which is shown in figure (6a). As expected, the cone shape of the wake evolution downward the rotor is clearly shown. Strong tip vortices are not clearly visible in this plot. In figure (6b), the relative to atmospheric static pressure variation along the longitudinal dimension of the field, it can be observed. The pressure increases gradually, approaching the rotor blade where a deep drop occurs, as expected, and after 1.5 rotor diameters downwind the pressure gradients diminish. The pressure rise before the rotor is in agreement with the theory, while the sudden pressure drop gradient is associated with the power extraction of the wind.

Theoretically, behind a HAWT rotor the generated wake central vortices develop near the blade root. This is represented in the latter contour plot and at the pathlines of figure (7), where the relative flowfield is shown near the blade root with strong three dimensional effects.

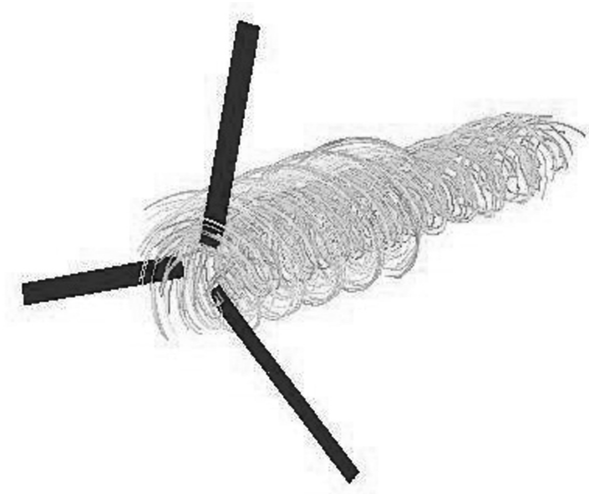

Figure 7: Pathlines at blade root

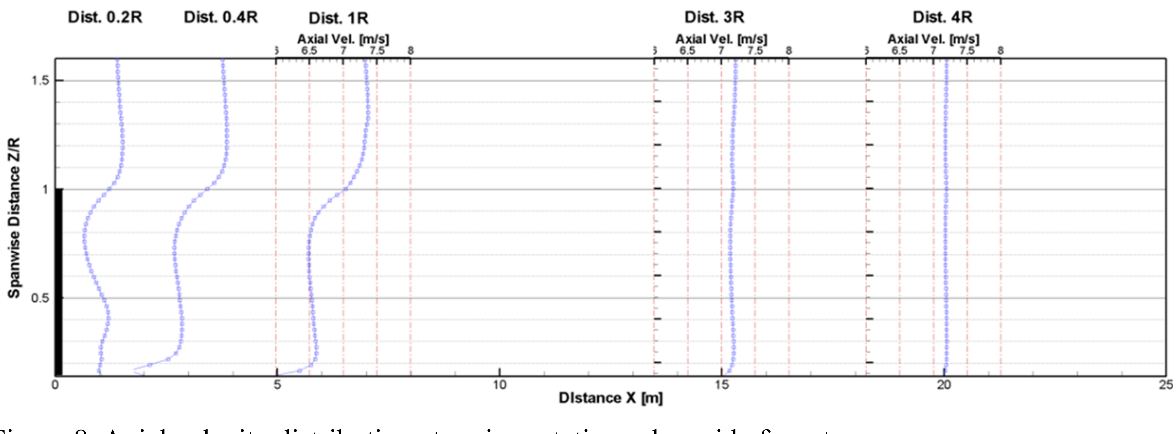

Figure 8: Axial velocity distribution at various stations alongside free stream

The development of the limiting streamlines (i.e. the curves whose directions coincide with that of the vanishing fluid velocity or the shear stress, at the surface) for both blade sides is shown in figure (9). It is clearly that near the root, strong 3D effects occur and the flow separates. The effect of rotation, which becomes more pronounced at inboard locations of the blade, is to suppress vortex shedding and the development of separation bubbles. When the flow separates, the Coriolis force acts as a favourable pressure gradient, causing the reattachment of the flow and the reduction of the separation bubble volume. The reduction of the bubble volume produces a pressure drop along the suction side of the airfoils increasing, thus, the blade loading.

The axial velocity distributions in the wake are observed in the axial velocity contour plots of the figure (11) and figure (8). It can be noticed that outside the wake shape downwind of the rotor, the axial velocity attains the free stream value. The deviation of the axial velocities from the free stream values is noticeable upwind the rotor and is further amplified after. Vortices are shed from the trailing edges of the blades which are diffusing in the far wake. These contours are used to identify the transition from the near to the far wake. In the near wake the shed vortices appear as distinct vortex spiral tubes as shown in figure (10). The involved vorticity strength decays in the downstream direction following the theoretical signature for such vorticity field structure.

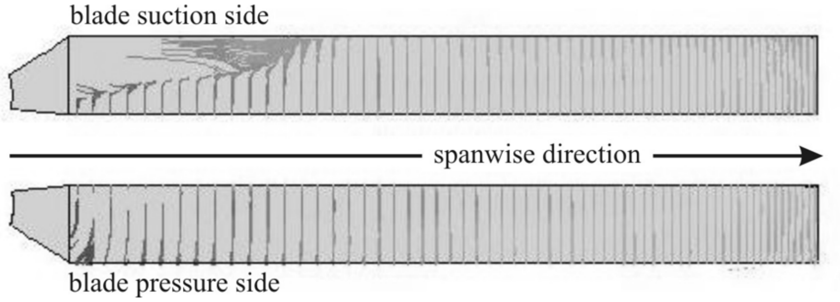

Figure 9: Development of the limiting streamlines for the NREL Viscel II rotor blade

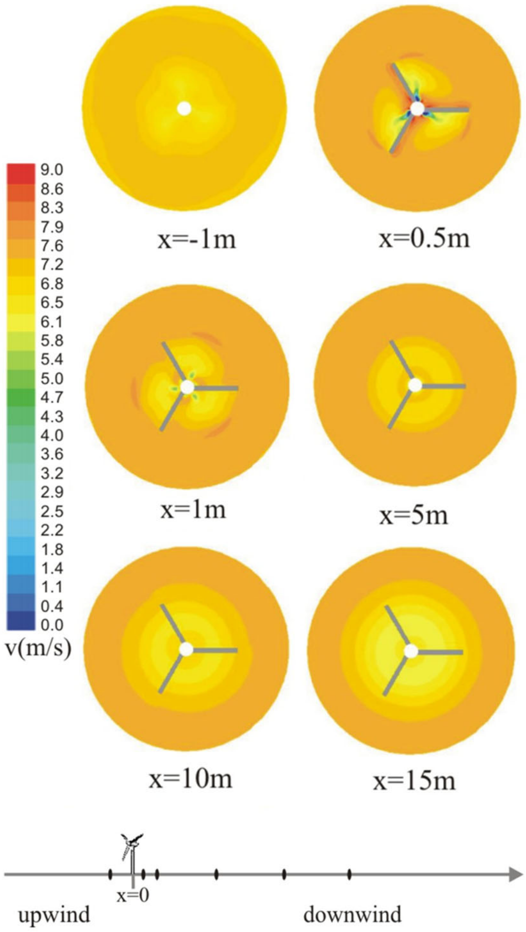

Figure 11: Calculation of the axial velocity contours at different positions upwind and downwind of the NREL Phase II rotor

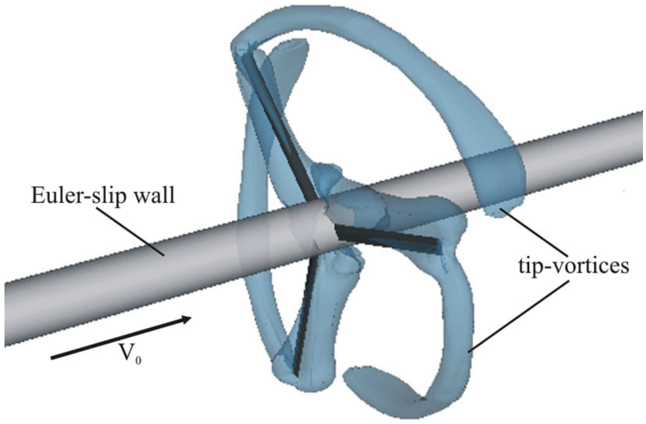

Figure 10: Vorticity iso-surface (U_0=7.2m/s)

6. Conclusions

The aerodynamic characteristics of a model HAWT are predicted by means of the commercial CFD code Fluent. Despite the evident simplicity of the wind turbine flowfield, there are three-dimensional effects, separated flows, wakes interactions and vortices which transform it to a complicated one.

The purpose of the current work is the numerical study on aerodynamic behaviour of HAWT rotor and the validation of the simulation with available experimental data. The numerical simulations allow also the prediction of the basic features of the wake development downwind the rotor. Different aspects of HAWT flow field are resolved with good accuracy, despite the different relevant scales involved. The simulations were validated and assessed against detailed wind turbine aerodynamic data. Nevertheless, the code and turbulence models tested failed to predict experimental power curves and further research is needed in that direction.

The study confirms that RANS simulations are capable to solve with a fair accuracy the different aspects involved in HAWT flow field, thus this confirms that nowadays CFD simulations can be the most important tool for analysis and design of wind turbine rotors.

Finally one of the future research directions will be the CFD simulation of the wind turbine flowfield with the detached-eddy simulation (DES) approach in order to understand better and fully simulate the complicated 3-d phenomena produced.

NOMENCLATURE

c_p	=	Pressure coefficient (dimensionless)
G_v	=	Production of turbulent viscosity
p	=	Pressure (Pa)
p_{atm}	=	Atmospheric pressure (Pa)
R	=	Radius of the wind turbine rotor (m)
SRF	=	Single Reference Frame Technique
t	=	Time (s)
u_i	=	Overall velocity component (m/s)
U_0	=	Free-stream velocity (m/s)
y^+	=	Dimensionless wall distance
Y_v	=	Destruction of turbulent viscosity

Greek Letters

μ_t	=	Turbulent viscosity (m^2/s)
v	=	Molecular kinematic viscosity (m^2/s)
$\tilde{v}$	=	Turbulent kinematic viscosity (m^2/s)
p	=	Density (kg/m^3)

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