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STAMOULIS
PUBLICATIONS

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Welcome to Soft Energy Applications & Environmental Protection Lab
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Καλώς ήρθατε στην Ιστοσελίδα του Εργαστηρίου Ήπιων Μορφών Ενέργειας & Προστασίας Περιβάλλοντος του Τ.Ε.Ι. ΠΕΙΡΑΙΑ

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The scientific team of **Soft Energy Applications & Environmental Protection Laboratory** has significant educational and research experience in the following fields:

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

Educational Activities

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2. *Lab of Renewable Energy Sources* (Lab of RES)	***5th 〃***
3. *Applications of Renewable Energy Sources* (RES II)	***6th 〃***
4. *Energy Mechanics & Management of Natural Sources* (EM-MNS)	***4th 〃***
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6. *Basic Principles of Ecology* (BPE)	***3rd 〃***
7. *Atmospheric Pollution – Antipollution Technologies* (AP-AT)	***4th 〃***
8. *Environmental Measurements Technology* (EMT)	***5th 〃***
9. *Waste Management Systems* (WMS)	***7th 〃***

Research Areas

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

Published Results:

- **Kaldellis J.K., 2002**, "Parametrical Investigation of the Wind-Hydro Electricity Production Solution for Aegean Archipelago", *Journal of Energy Conversion and Management*, vol.43/16, pp.2097-2113.
- **Kaldellis J.K., Kavadias K., Christinakis E., 2001**, "Evaluation of the Wind-Hydro Energy Solution for Remote Islands", *Journal of Energy Conversion and Management*, vol.42/9, pp.1105-1120.
- **Kaldellis J.K., Kavadias K.A., 2001**, "Optimal Wind-Hydro Solution for Aegean Sea Islands Electricity Demand Fulfillment", *Journal of Applied Energy*, vol.70, pp.333-354.

2. "Estimation of Social - Environmental Cost in the Energy Production Sector"

Published Results:

- **Kaldellis J.K., Keramaris K.G., Vlachou D.S, 2002**, "Estimating the Visual Impact of Wind Parks in Greece", 2002 Global Windpower, Conference Proceedings, Paper GWP_078, Paris, France.
- **Kaldellis J.K., Konstantinidis P., 2001**, "Renewable Energy Sources Versus Nuclear Power Plants Face the Urgent Electricity Demand of Aegean Sea Region", *Balkan Physics Letters Journal*, SI/2001, pp.169-180.
- **Marouli Chr., Kaldellis J.K., 2001**, "Risk in the Greek Electricity Production Sector", 7th International Conference on Environmental Science and Technology, Conference Proceedings, vol. C, pp.305-314, University of Aegean, Global-NEST, Syros, Greece.

3. "Technological Progress in Wind Energy Market"

Published Results:

- **Kaldellis J.K., Zervos A., 2002**, "Wind Power: A Sustainable Energy Solution for the World Development", Energy-2002 International Conference, June-2002, Athens, Greece.
- **Kaldellis J.K., 2002**, "Estimating the Optimum Size of Wind Power Applications in Greece", 2002 Global Windpower, Conference Proceedings, Paper GWP_077, Paris, France.
- **Kaldellis J.K., 2001**, "Evaluating the Maximum Wind Energy Penetration Limit for Weak Electrical Grids", European Wind Energy Conference, Conference Proceedings, pp.1215-1218, Bella Centre, Copenhagen.

4. "Technological Progress in Solar Energy Market"

Published Results:

- **Kaldellis J.K., Vlachou D.S., Koronakis P.S., Garofalakis J.E., 2001**, "Critical Evaluation of Solar Collector Market in Greece Using Long-Term Solar Intensity Measurements", *Balkan Physics Letters Journal*, SI/2001, pp.181-193.
- **Kaldellis J.K., Vlachou D., Kavadias K., 2001**, "An Integrated Renewable Energy Solution for Very Small Aegean Sea Islands", "Renewable Energies for Islands" International Conference, Conference Proceedings, Paper No 68, Chania, Crete, Greece.

5. "Flow Field Prediction for High Speed Turbomachines"

Published Results:

- **Chelmi Ef.V., Kaldellis J.K., 2002**, " A Reliable Numerical Algorithm Used to Predict the Optimum Operational Points of Contemporary Turbofan Engines", 4th GRACM Congress on Computational Mechanics, Conference Proceedings, Paper 2002_59, Patras, Greece.
- **Kaldellis J.K., 1998**, "Static Pressure Gradients inside the Shock-Shear Flow Interaction Region", *Technika Chronika, Scientific Journal of the Technical Chamber of Greece-IV*, vol18 (2), pp.19-33.
- **Kaldellis J., 1997**, "Aero-Thermodynamic Loss Analysis in Cases of Normal Shock Wave-Turbulent Shear Layer Interaction", published in ASME Transactions, *Journal of Fluids Engineering*, vol.119, pp.297-304.

6. "Techno-economic Evaluation of Renewable Energy Applications"

Published Results:

- **Kaldellis J.K., 2002**, "An Integrated Time-Depending Feasibility Analysis Model of Wind Energy Applications in Greece", *Energy Policy Journal* vol.30/4, pp.267-280.
- **Kaldellis J.K., 2002**, "Minimum Stand-Alone Wind Power System Cost Solution for Typical Aegean Sea Islands", *Wind Engineering Journal*, vol.26/4, pp.241-255.
- **Kaldellis J.K., Gavras T.J., 2000,** "The Economic Viability of Commercial Wind Plants in Greece. A Complete Sensitivity Analysis", *Energy Policy Journal*, vol.28, pp.509-517.

7. "Combined Wind-Photovoltaic Stand-Alone Applications"

Published Results:

- **Kaldellis J.K., 2002**, "Optimum Autonomous Wind Power System Sizing for Remote Consumers, Using Long-Term Wind Speed Data", *Journal of Applied Energy*, vol.71/3, pp.215-233.
- **Kaldellis J.K., Vlachos G. Th., Kavadias K.A., 2002**, "Optimum Sizing Basic Principles of a Combined Photovoltaic-Wind-Diesel Hybrid System for Isolated Consumers", EuroSun 2002 International Conference, Paper W141, Bologna, Italy.

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8. "Evaluation of Energy Storage Systems"

Published Results:

- **Kaldellis J.K., Kavadias K.A., 2001**, "Optimal Wind-Hydro Solution for Aegean Sea Islands Electricity Demand Fulfillment", *Journal of Applied Energy*, vol.70, pp.333-354.
- **Kavadias K., Komnimoglou A., Kaldellis J.K., 2001**, "Wind Energy Surplus Management for Remote Consumers Using a Water Pumping Storage System", European Wind Energy Conference, Conference Proceedings, pp.972-975, Bella Centre, Copenhagen.
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9. "Air Pollution Analysis"

Published Results:

- **Paliatsos A.G., Kaldellis J.K., Koronakis P.S., Garofalakis J.E., 2002**, "Fifteen Year Air Quality Trends Associated with the Vehicle Traffic in Athens, Greece" *Fresenius Environmental Bulletin*, vol.11/12b, pp.1119-1126.
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- **Kaldellis J. K., Konstantinidis P., Charalambidis P., 2001**, "The Impact of Automobile Catalytic Converters Degradation on Air Quality" International Conference on "Ecological Protection of the Planet Earth I", Conference Proceedings, vol. II, pp.633-641, Xanthi, Greece.

10. "Air Pollution Impact on Children and other Delicate Social Groups"

- **Koronakis P.S., Sfantos G.K., Paliatsos A.G., Kaldellis J.K., Garofalakis J.E., Koronaki I.P., 2002**, "Interrelations of UV-global/global/diffuse Solar Irradiance Components and UV-global Attenuation on Air Pollution Episode Days in Athens, Greece", *Atmospheric Environment*, 36/19, pp. 3173-3181, July.
- **Paliatsos A.G., Kaldellis J.K., Nastos P.Th., 2002**, "Assessment of Air Quality Spatial Distribution in the Greater Athens Area", International Conference, Protection and Restoration of the Environment VI, Conference Proceedings, pp. 1849-1853, Skiathos Island, Greece.

11. "Autocats Standardization and Recycling"

Published Results:

- **Paliatsos A.G., Kaldellis J.K., Viras L.G., 2001**, "The Management of Devaluated Autocats and Air Quality Variation in Athens", 7th International Conference on "Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes", Conference Proceedings, vol. A, pp.474-478, Belgirate-Italy.
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12. "RES Based Desalination"

Published Results:

- **Kaldellis J.K., Kavadias K., Vlachou D., 2000,** "Improving the Economic Viability of Desalination Plants", Mediterranean Conference on Policies and Strategies for Desalination and Renewable Energies, Santorini Island, Greece.
- **Kaldellis J.K., Kavadias K., Garofalakis J., 2000**, "Renewable Energy Solution for Clean Water Production in the Aegean Archipelago Islands", Mediterranean Conference on Policies and Strategies for Desalination and Renewable Energies, Santorini Island, Greece.

13. "Waste Management and Recycling Techniques"

Published Results:

- **Konstantinidis P., Skordilis A., Kaldellis J.K., 2001**, "Recycling of Electric and Electronic Waste in Greece: Possibilities and Prospects", 7th International Conference on Environmental Science and Technology, Conference Proceedings, Vol. A, pp.460-469, University of Aegean, Global-NEST, Syros, Greece.
- **Sakkas Th., Kaldellis J. K., 2001,** "Environmental Behavior of a Charcoal Gasification System. Experimental and Theoretical Investigation", International Conference on "Ecological Protection of the Planet Earth I", vol. II, pp.625-632, Xanthi, Greece.
- **Konstantinidis P., Spiropoulos V., Vamvakis A., Kaldellis J.K., 2000,** "Energy Savings and Cost Reduction by Recycling the Demolition-Construction Debris", International Conference, Protection & Restoration of the Environment V, pp.869-878, Thassos, Greece.

14. "Waste Water Treatment Applications"

Published Results:

- **Kondili E., Kaldellis J.K., 2002**, "Waste Minimization and Pollution Prevention by the Use of Production Planning Systems", International Conference, Protection and Restoration of the Environment VI, Conference Proceedings, pp.1277-1284, Skiathos Island, Greece.

- **Sigalas J.S., Kavadias K.A., Kaldellis J.K., 2000,** "An Autonomous Anaerobic Wastewater Treatment Plant Based on R.E.S. Theoretical and Experimental Approach", International Conference, Protection and Restoration of the Environment V, pp.735-743, Thassos Island, Greece.
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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", 6^{th} 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"

Published Results:

- **Kaldellis J. K., 2001**, "The NIMBY Syndrome in the Wind Energy Application Sector", International Conference on "Ecological Protection of the Planet Earth I", vol. II, pp.719-727, Xanthi, Greece.
- **Marouli Chr., Kaldellis J.K., 2001**, "Risk in the Greek Electricity Production Sector", 7th International Conference on Environmental Science and Technology, Conference Proceedings, vol. C, pp.305-314, University of Aegean, Global-NEST, Syros, Greece.
- **Kaldellis J.K., Keramaris K.G., Vlachou D.S, 2002**, "Estimating the Visual Impact of Wind Parks in Greece", 2002 Global Windpower, Conference Proceedings, Paper GWP_078, Paris, France.

Research Projects under Development

Participation in Research Programs (2001-2002A)

1. Hellenic/French Collaboration Research Program "Platon" entitled "***Advanced Techniques of Automation in Wastewater Treatment Plants***". (Accomplished)
2. "***Development of an Experimental Hybrid Plant based on a Wind Turbine - P/V Station Collaboration***", supported by T.E.I. of Piraeus (Accomplished)
3. "***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
4. Program "***RENES-Unet***", for the Diffusion of Renewable/Soft Energy Applications in Greece and European Union
5. "***Water Pumping Storage Systems for Crete Island***", in collaboration with the Technical University of Crete and the Enercon Hellas SA
6. "***NATURA-2000***", supported by the Greek Ministry of Environment, Physical Planning and Public Works
7. "***Natural Gas Cogeneration Opportunities in Urban Areas***", in collaboration with the Municipality of Nikaia
8. "***Energy Saving in TEI Buildings***", supported by TEI of Piraeus

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PART ONE

WIND ENERGY

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- Feasibility Evaluation
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AN INTEGRATED TIME-DEPENDING FEASIBILITY ANALYSIS MODEL OF WIND ENERGY APPLICATIONS IN GREECE

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Abstract

An integrated time-depending feasibility analysis is presented in order to improve the reliability of the computational methods to simulate the economic behaviour of commercial wind parks in Greece, in view of the continuous technological improvements of the sector and the important worldwide political and economic transformations. According to the proposed model, the time-dependency of the governing parameters is taken into account, based on almost twenty-years data from the local market records. Additionally, information concerning the technology depended parameters from several European and local wind parks is also incorporated. The application of the developed computational frame to several cases, concerning the economic behaviour of wind parks erected during 1985-95 in Greece, significantly improve the accuracy of predictions in comparison with the results based on time-mean values of the corresponding parameters. Finally, the proposed model satisfactorily explains the evolution of wind energy applications in Greece during the last fifteen years, on the basis of pure economic terms.

Keywords: Wind Energy; Time-Dependency; Feasibility Analysis; Cost to Benefit Ratio

1. Introduction

The continuous technological improvements, the important worldwide political and economic transformations along with the strong competitiveness among the main European manufacturers, significantly change the existing market opportunities in the area of wind energy applications all over Europe. For example, in Greece electricity market liberalization will start in February 2001, while a complete EU free electricity market is expected by 2005. At the same time, the Greek State integrated the new Renewable's legislative frame, based on the 2244/94 law. According to this frame, the electricity produced by renewable sources is sold to local utilities at a fixed percentage (e.g. 90% for the islands and 70% for the mainland) of the corresponding retail/market price.

In view of these fundamental changes and in order to improve the wind energy penetration by minimizing the uncertainties of the future investors, an integrated new feasibility analysis model is developed. According to this model, the time-dependency of the governing parameters -normally neglected for simplicity reasons- is taken into account. The vast majority of the calculations presented up to now are based on time-mean values, although it is common sense that our socio-economic environment is continuously changing.

The first attempt of the authors to face this simplification[1] led to remarkable differences between the pay-back period and the economic efficiency values calculated using the time-mean quantities in comparison with the values predicted via a time-depending numerical distribution of them. However, in this early publication the time-evolution of only two economic parameters (i.e. market inflation, fuel escalation rate) was taken into account, while the numerical values used were based on typical analytical functions (linear distribution, power law, sinusoidal profile etc.) with the same average value. On the contrary, the proposed model is based on real time-series of the governing parameters, while not only economic but also technological variables are included.

***Kaldellis J.K., 2002**, "An Integrated Time-Depending Feasibility Analysis Model of Wind Energy Applications in Greece", Energy Policy Jr, Vol. 30/4, pp.267–280.*

More precisely, in the following a complete theoretical frame concerning the cost-benefit analysis of wind energy applications is presented, time-dependency included. Accordingly, the evolution with time of the problem's main parameters is investigated, taking into account a twenty-years data from the local market as far as the economic and wind potential variables are concerned. Additionally, the distribution of the technology depended parameters data from the local and the European wind parks are also included. Finally, selected calculation results based on the proposed model, concerning the economic behavior of wind energy applications, are compared to more simple calculations results based on time-mean values.

2. Theoretical Model

The present study is based on an integrated cost benefit approach, using current values for all the quantities involved. As mentioned in previous works[1][2], the future value (after –n years of operation) of the investment cost "C_n" of a wind power installation consists of the initial installation cost "IC_o" (turn-on key value), as well as the maintenance and operation cost, "FC_n+VC_n". Therefore, one may write:

$$C_n = IC_o \cdot \left\{ \alpha \cdot \prod_{j=1}^{j=n} \left(1 + i_j\right) + \beta \cdot \prod_{j=1}^{j=n} \left(1 + i'_j\right) \right\} + FC_n + VC_n \qquad (1)$$

all quantities being functions of time.

More precisely, the initial cost "IC_o" includes the market price of the "z" machines used "$P_r \cdot N_t$" and the corresponding installation cost "$f(P_r \cdot N_t)$". Keep also in mind that "N_t" is the total nominal power of the wind farm, while the values of the specific ex-works price "P_r" and the installation cost factor "f" are analytically presented in Chapter 3, see also [3] and [4].

Table 1: Development Laws in Greece

Development Law	Validation Period	α	γ
1262/82	1982-90	≥15%	55%
1892/90	1990-94	≥25%	40%
2234/94	1994-98	≥30%	40%
2601/98	1998 up today	≥30%	40%

On top of that, the first term in the bracket of the RHS of equation (1) describes the invested capital "$\alpha \cdot IC_o$" future value (where "$i=i(t)$" is the return on investment index), while the second term expresses the corresponding cost ("i'" capital cost) of the loan capital "$\beta \cdot IC_o$". Besides, the following relation is valid:

$$\alpha + \beta = 1 - \gamma \qquad (2)$$

where "γ" is the subsidy percentage by the Greek State (Table 1), according to the existing development law for the renewable energy applications.

Subsequently, the maintenance and operation (M&O) cost can be split into the fixed maintenance cost "FC_n" and the variable one "VC_n". The annual fixed M&O cost may be estimated as a fraction "m" of the initial capital invested, taking also into account an annual increase of the cost equal to "g^{Σ}" (i.e. the M&O annual inflation rate). An additional increase of the M&O cost, related to the aging of wind converters, is expressed by the term "m_n/m_o". Summarizing, the fixed maintenance cost of the wind farm under investigation is given as:

$$FC_n = FC_{n-1} \cdot (1 + i_n) + (m \cdot IC_o) \cdot \prod_{j=1}^{j=n} \left(1 + g_j^{\Sigma}\right) \tag{3}$$

Finally, the variable maintenance and operation cost mainly depends on the replacement of "k_o" major parts of the installation, which have a shorter lifetime "n_k" than the complete installation. Using the symbol "r_k" for the replacement cost coefficient of each one of the "k_o" major parts (gear box, rotor blades etc), the "VC_n" term can be expressed using the following relation:

$$VC_n = IC_o \cdot \sum_{k=1}^{k=k_o} r_k \cdot \sum_{l=1}^{l=l_k} \left\{ \left[\prod_{j=1}^{j=l \cdot n_k} \left(1 + g_j^k\right) \cdot \left(1 - \rho_j^k\right) \right] \cdot \left[\prod_{j=l \cdot n_k}^{j=n} \left(1 + i_j\right) \right] \right\} \tag{4}$$

where "l_k" is the integer part of the following equation, i.e.:

$$l_k = \left[\frac{n-1}{n_k} \right] \tag{5}$$

Note that "g^k" and "ρ^k" describe the annual change of the price and the corresponding level of technological improvements for the "k-th" major component of a wind converter.

On the other hand, the annual savings "R_o" of a wind plant (consisting of z wind turbines of rated power "N_o", i.e. N_t=z·N_o) taking into account the numerical value of the corresponding parameters at the start of the power station operation can be expressed, according to equation (6) as:

$$R_o = 8760 \cdot \Delta_o \cdot \omega_o \cdot (z \cdot N_o) \cdot c_o \tag{6}$$

More precisely, "R_o" depends on the effective cost coefficient of the replaced conventional energy "c_o" at the beginning of the investment and on the corresponding technical availability "Δ_o", along with the mean power coefficient "ω_o" of the installation.

Consequently, the total (tax-free) savings over an n-year period "R_n", due to energy production by the wind power station, are given as:

$$R_n = R_{n-1}(1 + i_n) + R_o \cdot \frac{\omega_n \cdot \Delta_n}{\omega_o \cdot \Delta_o} \cdot \prod_{j=1}^{j=n} \left(1 + e_j\right) \tag{7}$$

where "e" is the electricity price escalation rate, defined as:

$$e_j = \frac{c_j}{c_{j-1}} - 1 \tag{8}$$

Subsequently, the wind power enterprise after tax (net) gains "G_n" can be predicted using the following expression:

$$G_n = R_n - C_n - \sum_{j=1}^{j=n} \Phi_{(j)} (1 + i)^{n-j} \tag{9}$$

where "$\Phi_{(j)}$" describes the tax paid during only the "j" year, mainly due to the revenue of the previous year.

According to the Greek tax-law, the "Φ_j" depends on the law-defined tax-coefficient (e.g. 33%), the net cash flow of the "j-1" year, the investment depreciations, as well as the financial obligations of the enterprise[5]. For simplicity reasons, the detailed impact of taxation will not be explicitly presented here. However, in all calculation results, the tax on profit is properly included.

Recapitulating, the exact value of the pay-back period of any wind power investment can be predicted, solving the break-even equation, thus:

$$G_n = 0 \quad for \quad n = n^* \tag{10}$$

Additionally, the economic attractiveness of such an investment is characterized by the economic efficiency "η^*" (or the benefit-cost ratio "BCR") of the wind plant, defined as:

$$\eta_n^* = \frac{\widetilde{G}_n}{IC_o \cdot (1-\gamma) - \widetilde{Y}_{(n)}} \tag{11}$$

or

$$BCR = \frac{\widetilde{G}_n}{IC_o \cdot (1-\gamma)} \tag{12}$$

where the symbol "~" is used to express constant values at the time point that the investment was accomplished, i.e.:

$$\widetilde{x}_j = \frac{x_j}{\prod_{k=1}^{k=j} (1+g_k)} \tag{13}$$

which is equivalent to the current value of a quantity, normally divided by the total inflation "g" (during an n-year period) of the economy. Finally, "$Y_{(n)}$" represents the residual value of the investment, mainly due to amounts recoverable at the "n" year of the project life (e.g. value of land or buildings, scrap or second hand value of equipment, etc.), along with the experience gained and the corresponding technological know-how.

3. Time-Evolution of the Governing Parameters

As previously mentioned, the governing parameters of any investment are strongly depended on its accomplishment time. In the proposed formulation, the time evolution is decomposed in two parts. The first part takes into account the time point "t_o" at which the wind power investment is taking place (t_o=0 for t=1990), while the second part is characterized by the life-period "τ" of the project undertaken.

More precisely, one may assume that:

$$t = t_o + \tau + 1990 \tag{14}$$

Therefore, any function of time f(t) can be decomposed in two parts, i.e. "f_o" and "f_n/f_o". According to this approach "f_o" depends exclusively on wind park installation time, while " f_n/f_o" is expressed as a function of the power station operational time, in an attempt to develop more generalized expressions for some parameters of the problem. Thus, f(t) is analyzed here as:

$$f(t) = f(t_o, \tau) = f_o(t_o) \cdot \frac{f_n}{f_o}(\tau) \tag{15}$$

Using this approach, the parameters "IC_o", "α", "β", "m_o", "r_k", "c_o", "ω_o" and "Δ_o" are by definition functions of the installation accomplishment time "t_o" only.

Similarly, the parameters "m_n/m_o", "Δ_n/Δ_o" can be expressed as functions of "τ", while the economic parameters "i", "i' ", "g^Σ", "g^k", "g", "ρ^k", "e" are generally functions of "t".

3.1 Market Price of the Wind Turbines

Using the results of an extensive (with time) market survey by the authors[2][4], the specific ex-works price "P_r" of a wind turbine -belonging in a wind farm of "z" machines- can be approached as a function of the machine rated power "N_o" in comparison with the optimum commercial value of that time period "$N_o^*(t_o)$", thus:

$$P_r(t_o) = \left[a \cdot (N_o - N_o^*) + b \cdot (N_o - N_o^*)^2 + c_\infty \cdot \left(1 + \varepsilon_1 \cdot e^{-\varepsilon_2 \cdot [t-1990]}\right)\right] \cdot \sigma_p(z) \tag{16}$$

In the proposed analysis the optimum size of the available -at every period- commercial wind converters is considered, i.e. $N_o = N_o^*$ and equations (16) reads:

$$P_r(t_o) = \left[c_\infty \cdot \left(1 + \varepsilon_1 \cdot e^{-\varepsilon_2 \cdot t_o}\right)\right] \cdot \sigma_p(z) \tag{17}$$

with c_∞=700Euro/kW, ε_1=0.7 and ε_2=0.125.

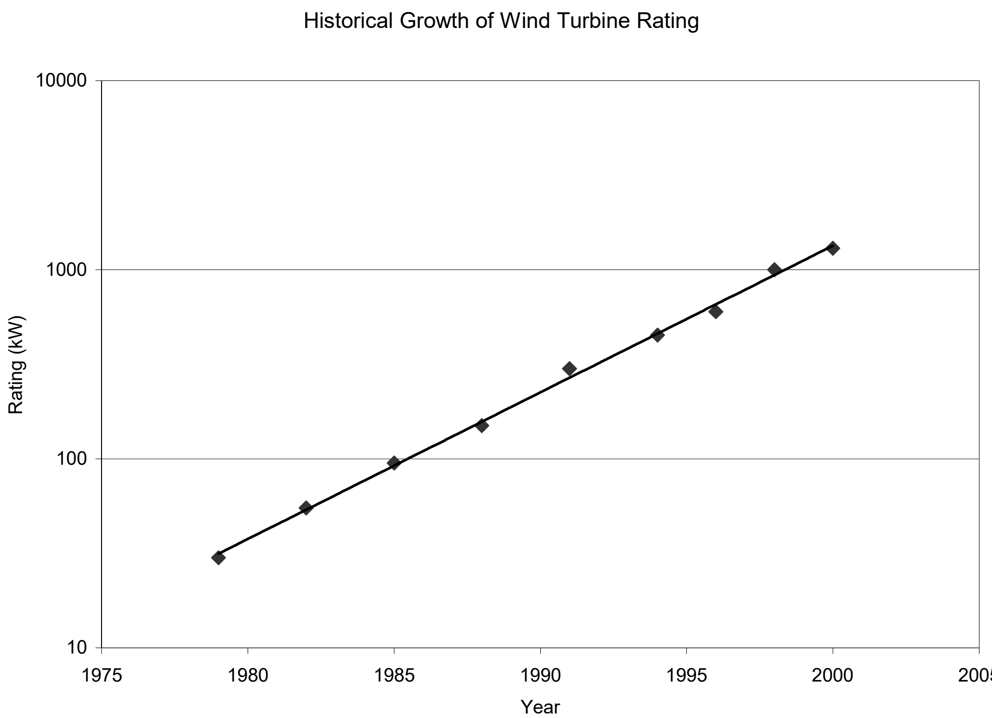

Figure 1: Time Evolution of Commercial Wind Turbine Size

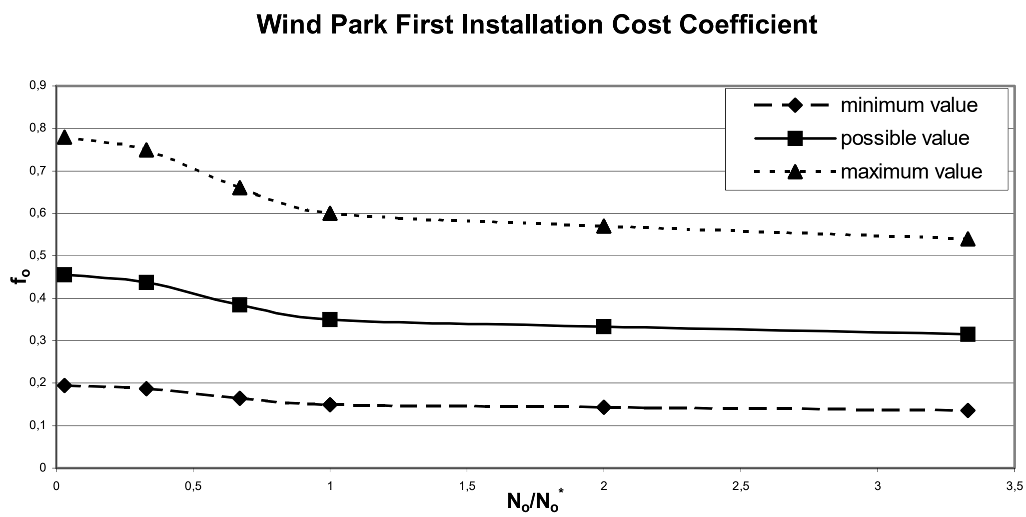

Figure 2: Installation Cost Coefficient

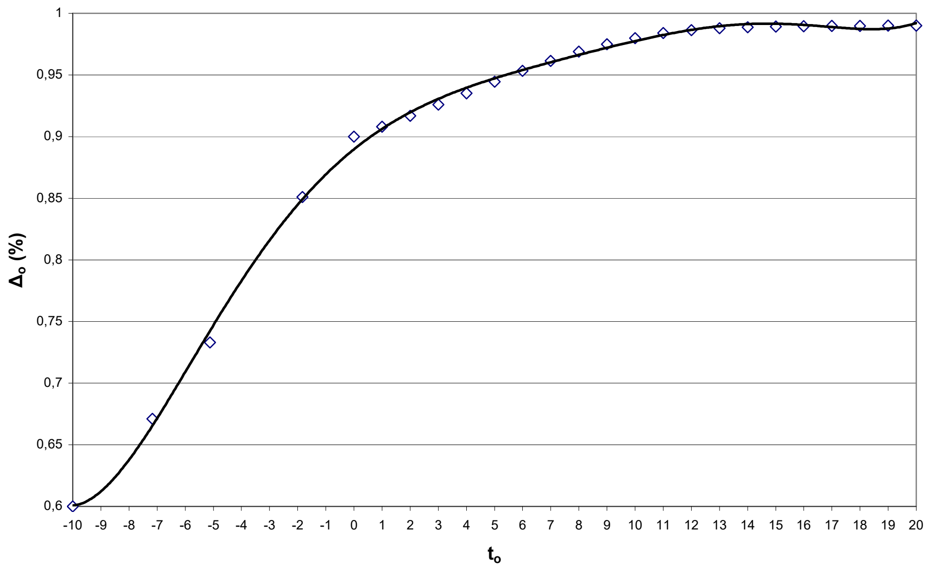

Figure 3: Initial Technical Availability Value

Keep in mind that $N_o^* = N_o^*(t_o)$ (see also figure (1)), while "$\sigma_p(z)$" takes into account the number of wind turbines "z" that constitute the wind farm under examination. In the present investigation a typical wind park containing z=10 machines is selected, thus $\sigma_p(z=10)=1.0$.

3.2 Balance of Plant Cost

The balance of plant cost includes foundation cost, electrical interconnection cost, land purchase, planning cost, approvals, infrastructure, management of the project and grid connection cost. Usually, the balance of plant cost is expressed as a fraction "f" of the wind turbines ex-works price. This additional cost depends on the number and size of machines in the wind park, along with the exact location of the wind power plant, i.e. "$f=f_o \cdot \sigma_f$".

For example, a number of items -like foundation cost, electrical interconnection cost, access tracks- decrease with the size or the number of the machines. Analytical studies[6] have revealed that the contribution of balance of plant cost to overall energy cost "f_o" can be reduced by approximately 25% by moving from 300kW machines to 1MW machines, (figure (2)). On top of that, in cases of large

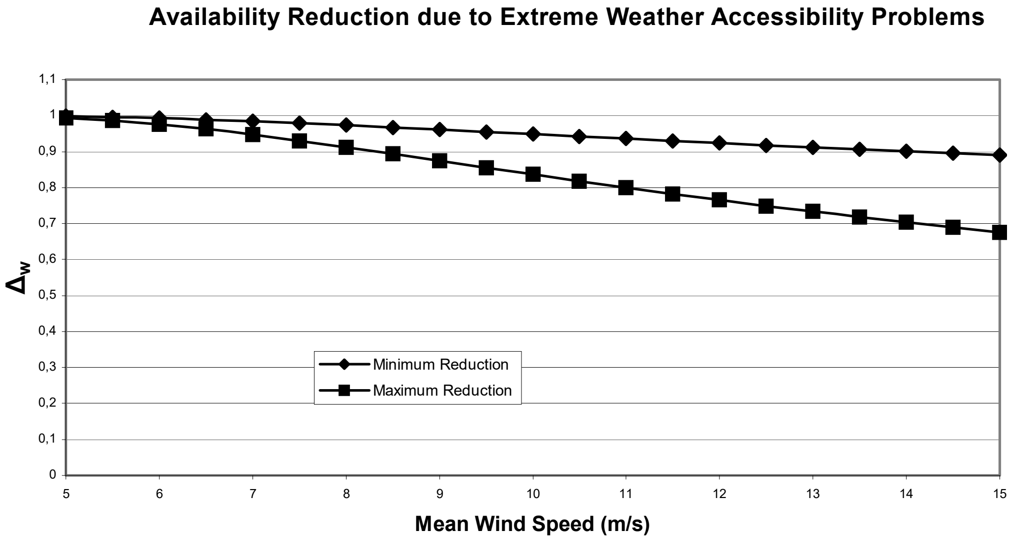

Figure 4: Reduction of Technical Availability Values due to Weather Limits

wind farms (z>10), the site infrastructure cost "σ_f" is spread over a bigger number of machines, reducing the unit cost. However, "σ_f" is taken equal to unity for z=10.

Using the above-presented analysis, the first installation cost expressed as:

$$IC_o = z \cdot P_r \cdot N_o + (\sigma_f \cdot f_o) \cdot (z \cdot P_r \cdot N_o) \tag{18}$$

is a function of "t_o", "N_o" and "z", also depending (see value scattering of figure (2)) on the selected wind park location.

3.3 Technical Availability Factor

Usually, wind turbines are constructed to operate for a period of at least 20 years. However, during their service-period these machines obtain a variable technical availability, depending on the technological status, the age and the location of the machine. The exact technical availability factor "Δ" is necessary for the calculation of the energy yield of the installation. In the present analysis the following expression is adopted:

$$\Delta(t) = \Delta_o(t_o) \cdot \frac{\Delta_n}{\Delta_o}(\tau) \cdot \Delta_w \cdot \Delta_G \tag{19}$$

Generally speaking, the "Δ_o" value mainly depends on the technological status at the time that the investment is realized. Early on 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 new wind energy technology has achieved such a level of quality, that wind turbines obtain a technical availability of 99%. Taking above information into consideration, "Δ_o" in the present analysis is well described by (figure (3)). However, one should also mention the accessibility difficulties of several 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[7] may be used in order to simulate the "Δ_w" function of equation (19), see (figure (4)).

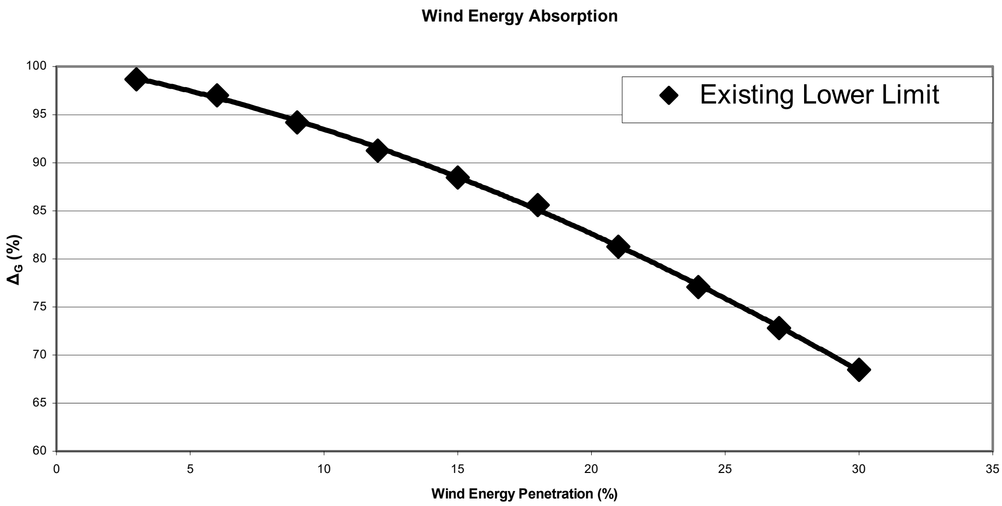

Figure 5: Minimum Wind Energy Absorption by Autonomous Electrical Grids

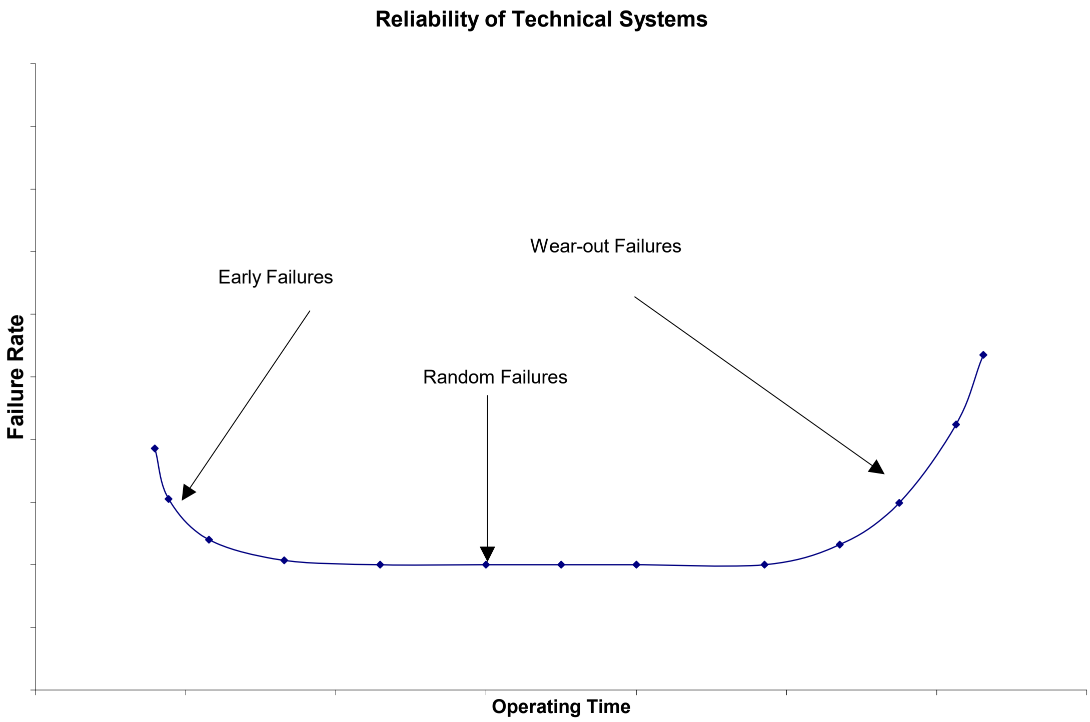

Figure 6: Wind Turbine Failure Rate versus Operating Time

On top of that, 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[8] as the wind power penetration in the local grids is increased, (figure (5)).

For the calculation of technical availability changes during a wind turbine's operational life, the so-called bathtub curve of (figure (6)) may be utilized. As in other technical areas, "early failures" often mark the operation[9]. Based on real data evaluations, 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 operational age, function "$\zeta=\zeta(\tau)$". Of course,

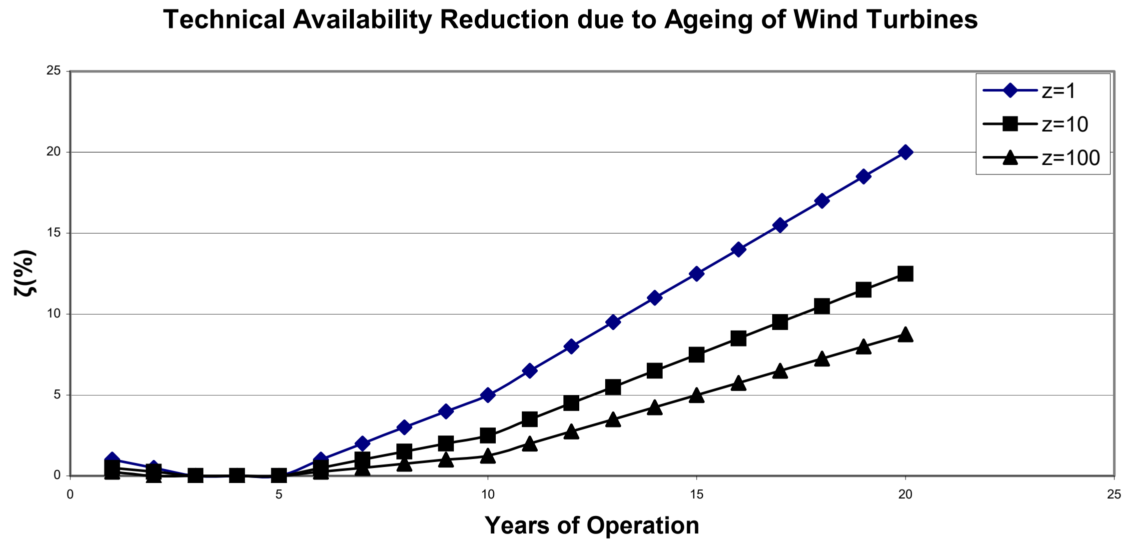

Figure 7: Technical Availability Reduction due to Wind Turbine Ageing

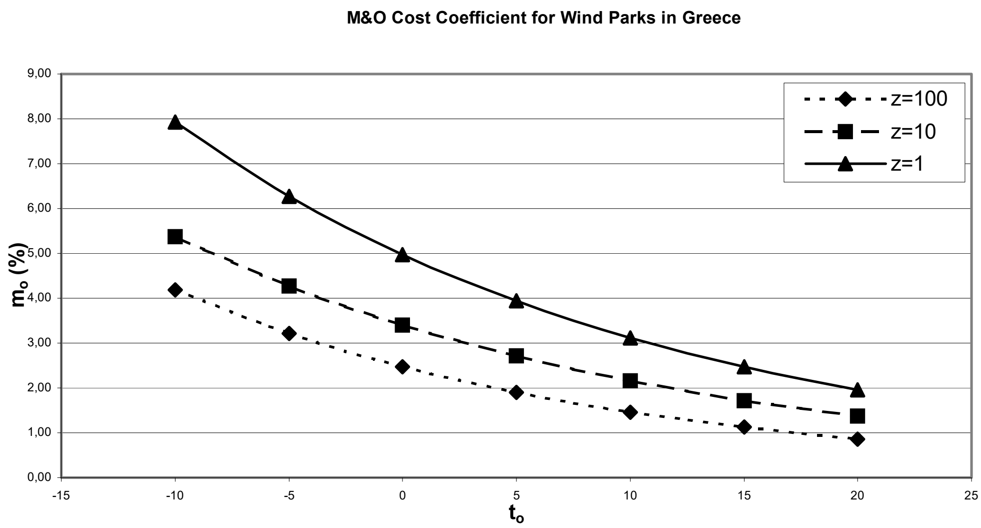

Figure 8: M&O Cost Coefficient Time Variation for Wind Parks in Greece

in cases of numerous wind turbines it is more possible for permanent service stuff as for spare parts stock to exist. For this reason the operational time-depended technical availability diminution "$\zeta(\tau,z)$" is less for large wind parks ($z\approx100$) than for individual wind converters[9][10][11], (figure (7)). Summarizing, one may write that:

$$\Delta(t) = \Delta_o(t_o) \cdot \Delta_w \cdot \Delta_G \cdot [1 - \zeta(\tau, z)] \tag{20}$$

3.4 Fixed Maintenance and Operation Cost

The main part of the wind energy production cost is due to the high initial invested capital for the wind farm erection. However, the cost related to maintenance, repairs, insurance, leases, management etc, also play an important role. The application of modern design and improved construction techniques along with the experience gained during the last twenty years leads to more efficient and reliable installations. The direct result of this evolution is a remarkable decrease of M&O cost, especially for medium and large-scale machines.

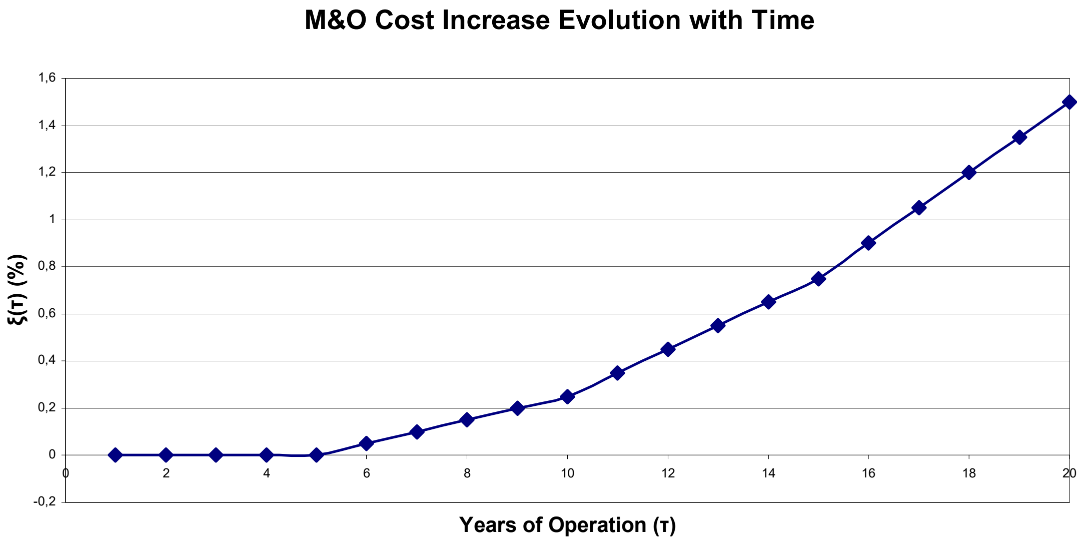

Figure 9: M&O Cost Coefficient Increase versus Operating Time

Using the work presented by many authors[3][10][12] the following expression is assumed valid:

$$m(t) = m_o(t_o, z) \cdot \frac{m_n}{m_o}(\tau) + \delta \tag{21}$$

where $m_o(t_o,z)$ depends on the technological status and the number of the wind turbines used (z is taken equal to 10 here), along with the accessibility of the wind park (distance, weather conditions, infrastructure, island/mainland etc.), (figure (8)). Accordingly, as indicated by various research groups gathered data, the time variation of "m" seems to a certain extent be determined by the age of the turbines. More precisely, during the first couple of years the warranty of the turbine manufacturer implies low-level expenses. After the 10^{th} year larger repairs start to come out, and this actually dominates the picture "ξ(τ)" during the last ten years of turbine life, see also (figure (9)).

Keep also in mind that "δ" corresponds to the insurance cost of the installation, being usually constant for a considerable part of the total wind turbine lifetime. The term "insurance" includes third part damage, machine damage and operation stoppage insurance. Applying the above analysis in equation (21), one gets:

$$m(t) = m_o(t_o, z) \cdot \left[1 + \frac{\xi(\tau)}{m_o}\right] + \delta \tag{22}$$

Summarizing, operation and maintenance (M&O) costs constitute a sizeable share of total annual costs of a wind power application. For a new turbine M&O costs contribute at 10÷15% to the total cost per kWh produced, increasing to at least 30÷40% at the end of the turbines lifetime.

3.5 Variable Maintenance and Operation Cost

Due to the fact, that the moving parts of a wind turbine (gear boxes, blades, electrical generator, yaw system etc) have usually shorter lifetime than the rest of the turbine, it is quite possible to replace one of these parts at least once during the service period of the machine. Statistically, depending also on the wind turbine type, some of the moving parts of a wind turbine have to be changed after 7 to 15 years[13]. The cost of replacement may considerably vary, compared to other normal repair cost,

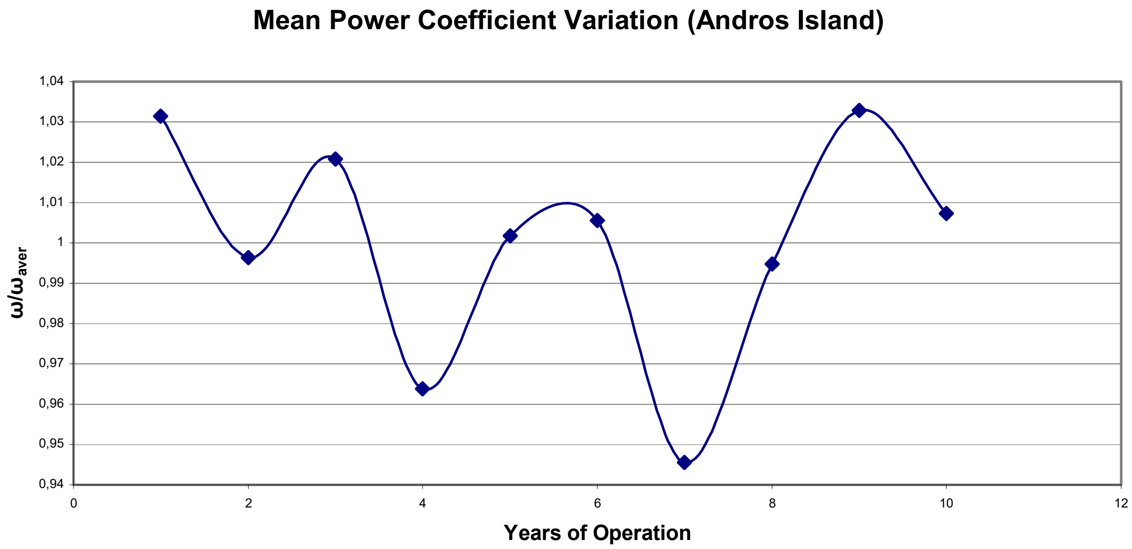

Figure 10: Mean Power Coefficient Values During a Ten Years Operation Period

imposing in some exceptional cases the abandoning of the whole project. This reinvestment is here attributed to the term variable M&O cost of the installation.

On the other hand, the technological improvements during the "n_k" years between two successive replacements of the "k-th" major component of a wind turbine (e.g. rotor blades) may significantly ameliorate (i.e. $\rho^k \approx 0.1 \div 0.3$) the operational behaviour of this component. In some cases, also, there is negative price inflation concerning the market price of a wind turbine's spare part, either due to economies of scale or due to technological improvements in the manufacturing process[14].

Generally speaking all replacement cost components tend to increase with the age of the turbine (time past "τ"), thus the necessary reinvestments start to dominate the total M&O cost during the last ten years of the turbine life.

4. Time Dependency of the Main Economic Parameters

According to previous sensitivity analysis[2], three are the main parameters, which mostly influence the economic viability of an investment in the wind power area, i.e. the mean power coefficient, the capital cost and the electricity (fuel) escalation rate.

However, the mean power coefficient depends[15] on the wind potential of the installation site and on the wind power curve of the machine[4], thus one may write:

$$\omega = \int_0^\infty \frac{N(V)}{N_o} \cdot f(V) \cdot dV \tag{23}$$

where "f(V)" is the probability density function describing the local wind potential and "N(V)" is the power curve of the wind turbines used versus wind speed "V". Taking into account the stochastic behaviour of the wind speed, a random variation of the mean power coefficient is expected, see for example (figure (10)). On top of that, a time depending efficiency degradation of the wind converter may also be included in a similar analysis.

On the contrary, the electricity price escalation rate and the capital cost are pure economic parameters; therefore their time evolution can be investigated by using historical data. More precisely, the capital cost depends on the investment opportunities, the timing of repayment, the risk of the investment and on any State or European subsidies. According to existing analysis[14] the capital cost is the sum of the inflation premium "g", the pure time-preference "i_b" and the risk premium "δi" depending on the risk "r" of the investment undertaken (e.g. $r=r_1$), thus:

$$i' = g + i_b + \delta i(r) \qquad (24)$$

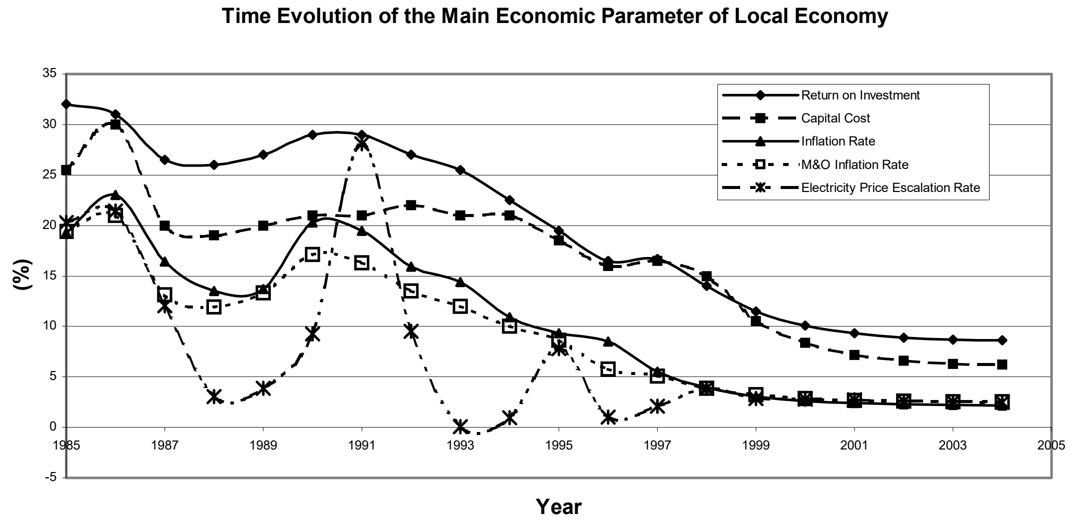

Figure 11: Time Evolution of the Main Economic Parameters of Local Economy

In cases of soft loans, e.g. State guarantee. $r_1 \rightarrow 0$. Additionally, the annual amount of money, which the investor demands in order to invest his own capital "i" is defined as the "return on investment" and is given by equation (24), too. This economic parameter depends on factors similar to the capital cost parameter, but it additionally reflects the expectancies of the single investor along with his own abilities and chances to invest money. For these reasons, it is assumed here that the variation of return on investment follows the capital cost, plus the risk premium "δi", defined according to the risk value "r" assumed by the single investor.

Accordingly, the inflation rate "g" expresses the tendency of everyday-life cost to increase and it is quantitatively approximated by the average rise in price levels. Similarly, the M&O cost inflation rate "g^{Σ}" describes the annual change (increase) of the M&O cost, taking into account the annual changes of labor cost and the corresponding spare parts.

Finally, the term "electricity price escalation rate", replacing here the more widely used term of "fuel escalation rate", describes the annual rate of change of the electric energy market price, since the wind energy produced by the wind power station under investigation is finally sold to the local PPC grid at a price directly related to the corresponding retail price. In general, the exact value of this parameter depends on various factors (e.g. dollar exchange rate, nature of the conventional energy to be replaced, the policy of the electrical utilities towards wind energy).

The evolution of all these parameters (i, i', g, g^{Σ}, e) is given in (figure (11)), for the period 1985-2000, based on the tracks of Greek economy. Expected -after 2000- values are presented, considering that Greece becomes a full member of E.U. financial market.

Recapitulating, the time variation of all necessary parameters of equations (10), (11) and (12) has been simulated. Thus, it is possible to accurately estimate the pay-back period and the economic efficiency or the benefit to cost ratio of any wind power investment in Greece, using the analysis of chapters 2 to 4.

5. Calculation Results

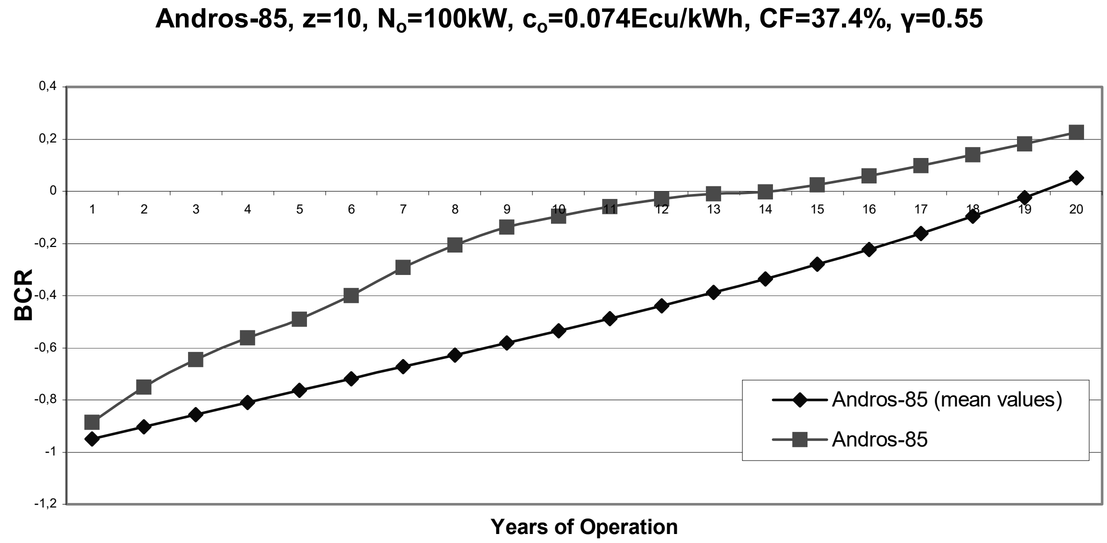

Figure 12: Comparison of Calculation Results Concerning the Island of Andros

In order to investigate the capabilities of the developed method, the calculation results concerning the economic behaviour of a typical wind park ($z=10$, $N_o=N_o^*$) in a windy area of Aegean Archipelago (island of Andros, annual mean wind speed at 10m height equal to 10.3m/s) are firstly presented. For this purpose the starting point of the two cases analyzed differ by five years, i.e. t=1985 (t_o=-5) and t=1990 (t_o=0), respectively.

More precisely, calculations for each wind park are carried out using either the time-depending values of all the necessary parameters or using their corresponding time-mean values. During the first test case, the investment under consideration includes ten wind turbines of nominal power of $N_o=N_o^*(1985)$=100kW, (figure (1)). The technical availability of the machines is estimated (figure (3)) equal to $\Delta_o(1985)=0.73$, which is subsequently decreased taking into account the bad weather influence (Δ_w, figure (4)) and the local grid stability limits (Δ_G, figure (5)). Keep in mind that in 1985 the local grid peak load was 7400kW, thus the proposed wind power penetration (1000kW) was approximately 13.5%. In 1985, the ex-work price of the wind converters was 1620Ecu (Euro)/kW, while the installation coefficient was assumed equal to 0.4 (figure (2)), due to the small size and the insufficient infrastructure of the island of Andros. Finally, the initial maintenance and operation cost factor of the installation is taken (figure (8)) equal to m_o=4.3%.

Using the available information concerning the wind potential of Andros[16] and selecting a representative (for 1985) wind turbine of 100kW the time-average value of the mean power coefficient (Eq.(23)) is $\omega_{aver} \approx 0.6$, thus the corresponding capacity factor ($CF=\Delta.\omega$) takes the value of 37.4%. Keep in mind that the excellent "ω" value (see also figure (10)) is not only due to the high wind potential of the area (mean wind speed ≈10.3m/s) but also due to the absence of other wind power installations (no wake effects), providing the investor with the ability to select the best site for his power station. As already mentioned the computational analysis is based on the real data distributions of the local economy (figure (11)), while for comparison purposes the calculations are also carried out using time-mean values of the necessary parameters, for the same time-period.

Thus in figure (12) the calculated BCR evolution with time is given for a wind park built in 1985 in Andros. As it is obvious, the calculation results based on real time-series data are quite different from the ones resulting from the time-mean values. More precisely, the investment is characterized as non-viable on the basis of the time-mean values, although the real data analysis estimates a break-even

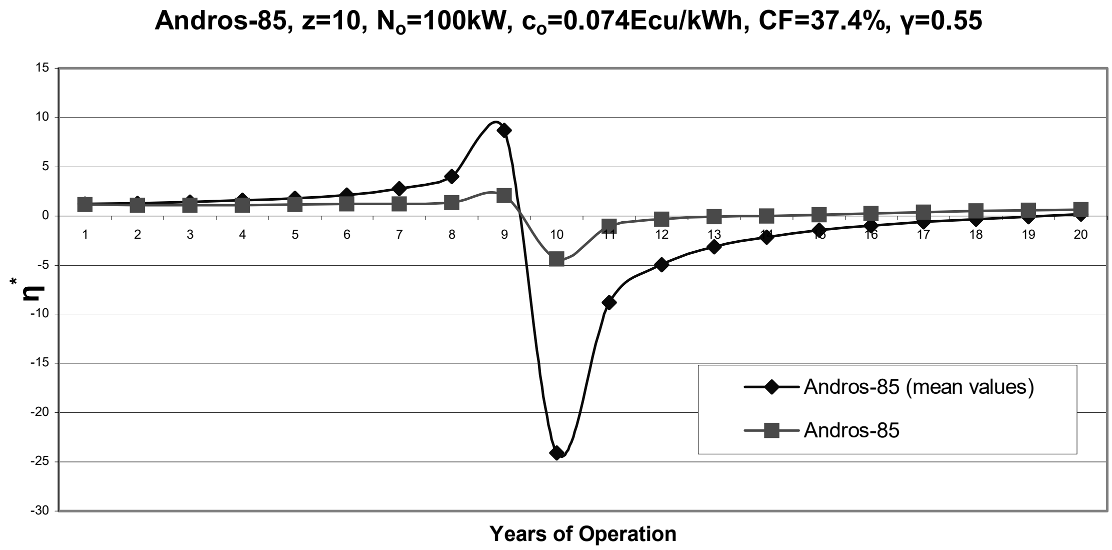

Figure 13: Time Evolution of Wind Park Economic Efficiency, Island of Andros, 1985

point at 14 years of operation. Additionally, the BCR value after 20 years of operation of the wind park is 22%, while the maximum difference between the calculation results of the methods compared appears between the 9th and the 10th year of operation of the power station. These discrepancies may be mainly attributed[17] to the distribution of electricity price escalation rate, see also figure (11), in comparison with the corresponding twenty-year time-average value ($\bar{e}$=6.9%). Thus taking into account that "e(t)" values are much higher than "$\bar{e}$", mainly during the first ten years of wind park operation, one may explain the growing calculation results discrepancy in the beginning and the declining one at the end of the examined period.

The conclusions already drawn are in accordance with the results of figure (13), where the economic efficiency profiles are shown as a function of time of the wind park operation. In this case, the current residual value of the investment is taken into account (equation (11)). Therefore, the positive values of "η*" during the initial phase of operation is the result of two negative numbers. More precisely, the net gains (Eq.10) of the investment (up to the break even point) are negative (figure (12)). However, negative is also the dominator of the efficiency, since the invested capital (excluding the State subsidization) is less than the residual value of the investment. Between operational years 9 and 10 the dominator of the investment zeros and then becomes positive, explaining in this way the non-continuous distribution of the "η*"-profiles of figure (13). At this point, it is important to mention that -according to the existing development law- there is no legal way to change the capital share of a State subsidized investment before the tenth year of operation, therefore the "η*" distribution becomes practically important after ten years of the investment functioning. According to the results of figure (13), there are remarkable differences between the calculation results of the two methods used, especially after the 14th year, where opposite sign of the investment economic efficiency is encountered.

Similar conclusions may be drawn from the application of the two methods under consideration, for a wind park consisting of 10x225kW wind turbines in Andros too. This wind park started its operation in 1990, therefore a considerable diminution (by almost 40%) of the pay-back period is predicted in comparison to 1985, (figure (14)). This significant modification is mainly due to the amelioration of the economical frame, the reduction of wind turbine specific price and the technological improvements realized by the corresponding industry. For this specific case study, it is interesting to mention that after 1990 the State owned Greek PPC almost freezes the corresponding electricity market prices, in an attempt to control the local inflation. For this reason, the long term (1990-2010) mean electricity price escalation rate ($\bar{e}$=4.5%) is initially lower (up to 1998) and accordingly higher (after 1998) of

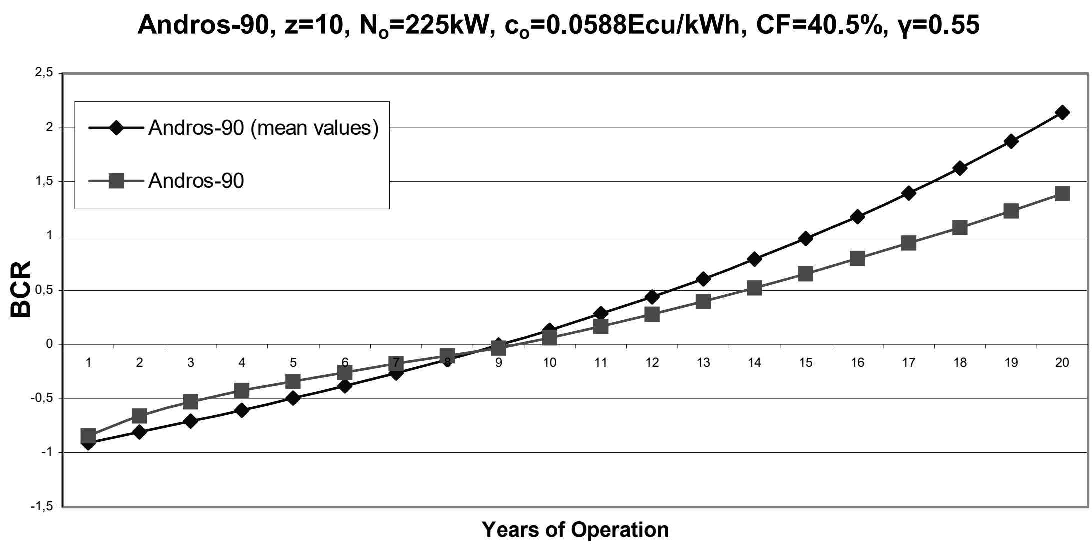

Figure 14: Comparison of Calculation Results Concerning the Island of Andros, 1990

the corresponding "e(t)" time evolution, explaining the "BCR" profiles differences between figure (12) and figure (14).

Both methods estimate the same break-even point, however the mean-values approximation overestimate by 60% the BCR value at the end of the 20-years operational period of the investment in comparison with the results of the time-depending data. The discrepancies between the two methods are more obvious in figure (15), where the time evolution of the investment economic efficiency is shown. It is also interesting to underline that the changes of the "η*" values are more mild when the real time depending data are used. On the contrary, if the corresponding mean values are utilized the efficiency changes are much more abrupt.

Summarizing the calculation results for the island of Andros, the time evolution of the BCR profiles for the two already analyzed wind parks (1985, 1990) along with the corresponding results (based on real time-series data) from a wind park (10x500kW) erected in 1995 are compared in figure (16). According to the results obtained, the pay-back period is remarkably decreased from 14 to 6.5 years between 1985 and 1995, while the expected economical gains are doubled between 1990 and 1995.

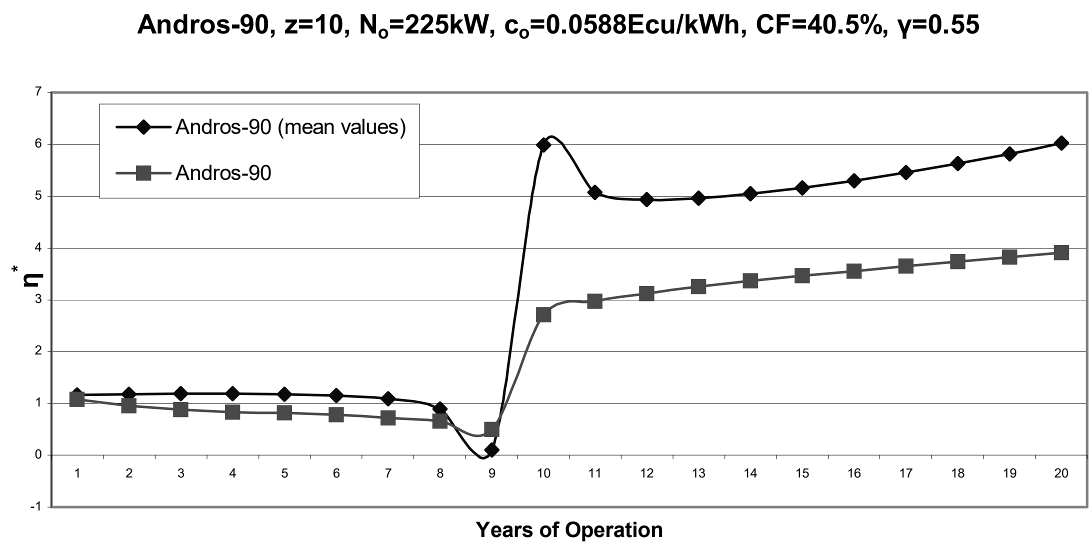

Figure 15: Time Evolution of Wind Park Economic Efficiency, Island of Andros, 1990

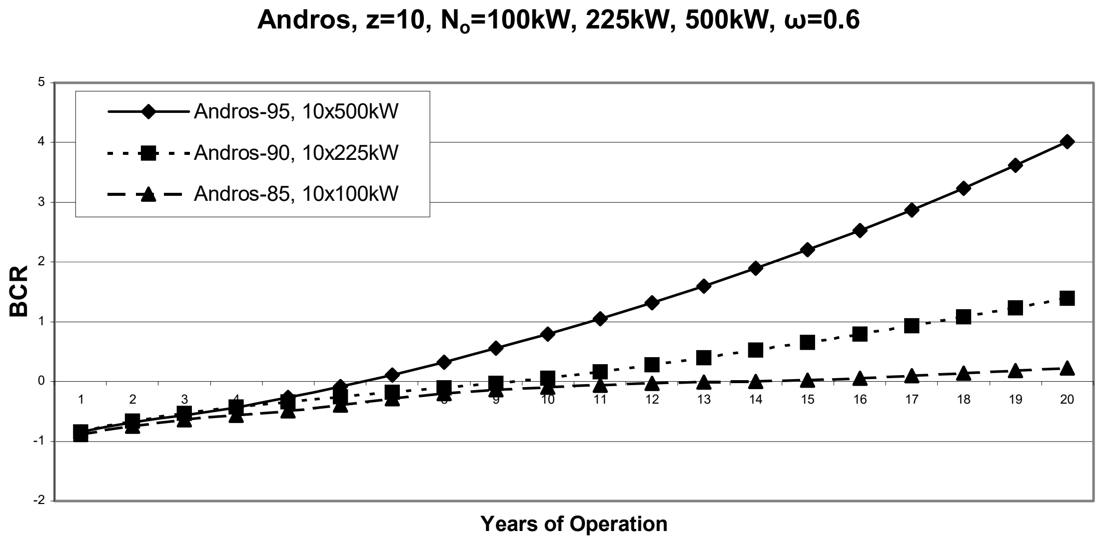

Figure 16: Economic Behaviour of Several Wind Parks Realized in different Time Points

These results underline the amelioration of the economic attractiveness of wind energy applications in Greece during the last ten years and are in accordance to the significant interest of several investors for the wind power sector during the last five years[11].

Accordingly, the present method is used to analyze the time-depending evolution of the economic behaviour of wind power applications in the mainland of our country. By comparing the available data, the wind potential in the mainland is not so high as in Aegean Archipelago, since only in selected sites the annual mean wind speed overpasses 8m/s. On the other hand, technical availability of mainland installations is more privileged than the island ones, not only due to mainland sites better accessibility ($\Delta_w \rightarrow 100\%$) but mainly due to full wind energy absorbency by the central electrical grid ($\Delta_G \rightarrow 1.0$). Of course, the wind-electricity price offered by Greek PPC is by almost 20% lower in the mainland than in the autonomous electrical grids, giving thus an economic advantage to island wind parks. Finally, according to the previous development laws the State subsidization percentage "γ" was higher for the islands ($\gamma \approx 55\%$) compared to the majority of mainland areas, where $\gamma \approx 30 \div 40\%$. However, according to the current development law (2601/98, Table 1), the State subsidization parameter is now the same (i.e. $\gamma=40\%$) for the whole country.

Taking into account this information, we proceed with the time evolution investigation of the economic behaviour of wind parks created in windy sites of South Peloponnessos, and more precisely in the region of Lakonia, during the period 1985÷1995. These wind parks characteristics are assumed similar to Andros Island corresponding ones, i.e. 10x100kW, 10x225kW and 10x500kW respectively, while the mean power coefficient is taken equal to 0.45. Keep in mind that the increase with time of the initial technical availability factor "Δ_o" ameliorates the wind parks annual energy production. This is not the case for the autonomous weak electrical grids, since the grid stability limit -in cases without additional energy storage systems[18]- drastically bounds the wind energy production absorbency.

The calculations results of the BCR distribution for various wind parks in Lakonia, started their operation in 1985, 1990 and 1995 respectively, are gathered in figure (17). According to the results obtained, the wind park created in 1985 is definitely not viable, while the wind park erected in 1990 is marginally viable, but in no case economically attractive (pay-back period almost 20 years). On the contrary, the economic behaviour of the wind power station started its operation in 1995 is very positive, being almost better than the corresponding wind park in the windy site of Andros island. This fact is mainly attributed to the total absorption of the produced wind-electrical energy by the central grid of PPC and to the lower first installation and M&O cost of the mainland wind parks, in comparison to a similar wind park in a small/medium sized island of Aegean Sea.

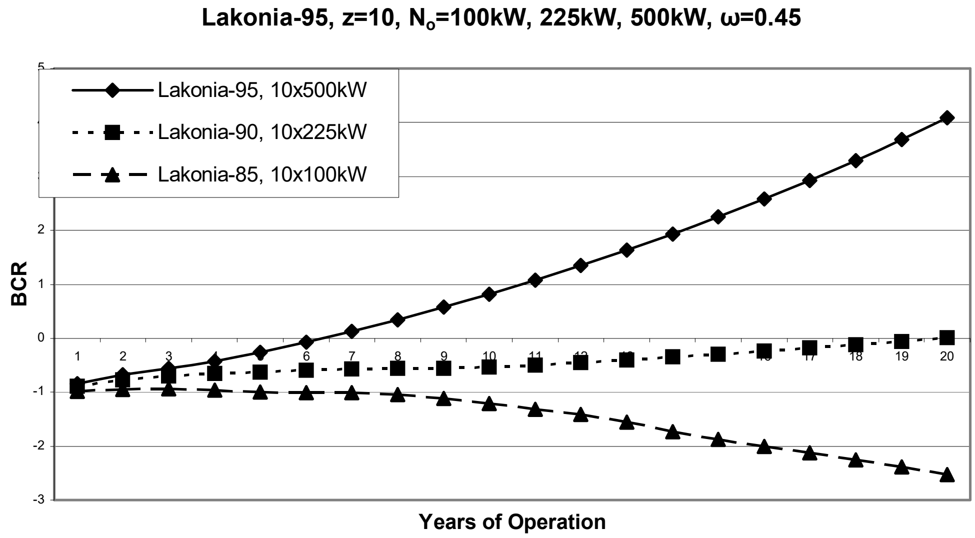

Figure 17: Economic Behaviour of Several Wind Parks Realized in different Time Points

All these computationally validated results are in full accordance with the existing situation of wind energy applications in Greece during the last 15 years. In fact, up to 1995, the local investors demonstrated no interest in wind parks construction even at windiest areas of S. Peloponnessos. However, during the last five years, a significant interest in erecting wind parks in Peloponnessos has emerged, therefore several new wind power stations of more than 100MW nominal power are under development all over the region.

6. Conclusions

An integrated time-depending feasibility analysis method is developed in order to improve the reliability of the calculation results concerning the economic behaviour of commercial wind parks in Greece. According to the proposed model, the time-dependency of the problem parameters is taken into account. Up to now the vast majority of the feasibility studies used neglect the time variation for simplicity reasons.

On the contrary, in the present analysis the evolution with time of the economic variables of the problem is included, taking into account twenty-years data from the local market records. Additionally, information concerning the technology depended parameters from several operated wind parks is also incorporated.

Applying the proposed model to several wind parks erected during the period 1985-95 in Greece, the significant differences between the calculation results based on time-series data of the main parameters and the corresponding results from their time-mean values are underlined. More precisely, in several cases wind energy investments are characterized as non-viable according to the long-term average approach, although the installation is found indeed viable using real data distributions. In other cases, the benefit to cost ratio or the investment economic efficiency profiles present opposite sings (negative instead of positive) if the simplified average approach is adopted. In view of such discrepancies, it is vital to incorporate the time-variation in the existing feasibility analysis methods so as to increase in predicting the reality.

Using the experience gained by the numerous case studies analyzed, the electricity price escalation rate and the capital cost-local economy inflation rate indexes are found the most influencing economic parameters of the feasibility analysis carried out. For this reason, their time-depending distribution is assumed necessary in order to obtain more accurate and realistic simulation results.

Subsequently, the above-described model can also be used to explain satisfactorily the evolution of the wind energy applications in Greece during the last fifteen years, on the basis of pure economic terms. Hence, the calculation results concerning both remote island and Greek mainland cases simulate realistically the local wind power investments economic behaviour, providing also some information for the future of wind energy in Greece.

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WIND POWER: A SUSTAINABLE ENERGY SOLUTION FOR THE WORLD DEVELOPMENT

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Abstract

Wind energy is now a mature electricity production technology, since wind energy has been the galloping energy sector for electricity production in various European countries. During the last five years, the development rate of installed capacity in individual countries varies between 15% and 75% per year; thus, the total wind capacity in Europe exceeds the 17300MW. However, the attempted European energy market "liberalization" disturbs the energy market equilibrium, threatening the future of wind power investments, in case that social and environmental benefit of renewable energy sources is disregarded. The present study is integrated with some interesting forecasts concerning the European wind power market evolution, along with some targets and proposals that -if realized- may facilitate and accelerate the wind energy penetration in most European markets, in favour of environmental protection and the desired sustainable development.

Keywords: Wind Power; Sustainable World Development; Energy

1. Introduction

Wind energy is now a mature electricity production technology, constituting not only an economically attractive solution for the constantly increasing energy demand worldwide, but also a sustainable energy solution for global development. In this context, wind energy has been the galloping energy sector for electricity production in various European countries. Three European countries -Germany, Spain and Denmark- are among the world leading nations in the field of wind energy applications[1].

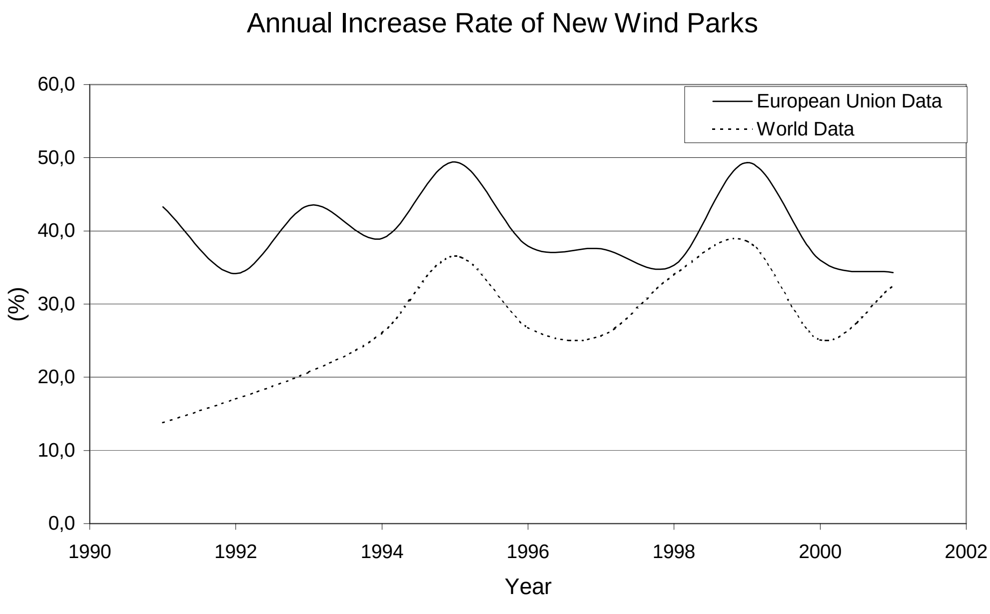

Figure 1: Annual Wind Power Change Rate

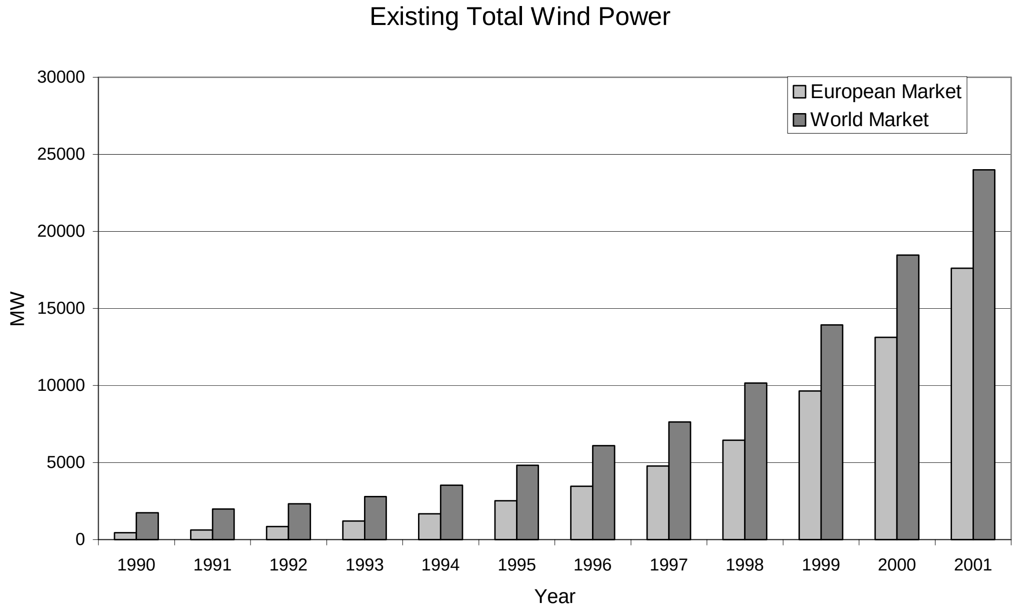

Figure 2: Wind Power Capacity, World Market

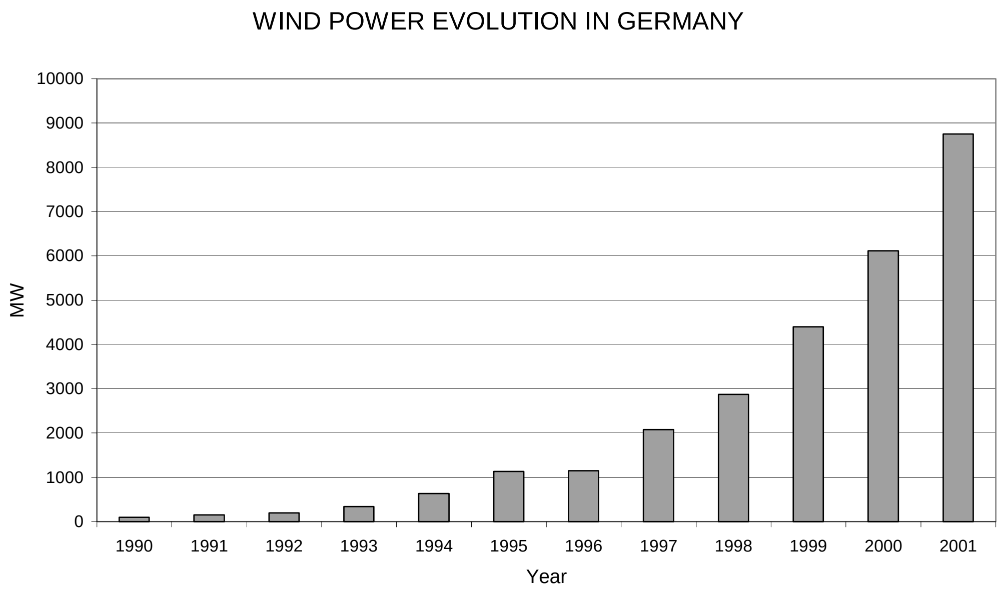

Figure 3: Wind Power Capacity in Germany

During the last five years, the development rate of installed capacity in individual countries varies between 15% and 75% per year; figure (1), while the corresponding E.U. mean value of the last decade exceeds the 40%. Thus, the original E.U. target for 4000MW of wind power by 2000 has been almost doubled, while the new European Wind Energy Association target attains 40000MW by 2010 and 100000MW by 2020. According to the official data[2], another 4500MW of wind capacity has been added up in Europe during 2001, being nearly 1000MW higher than 2000. Thus the total wind capacity in Europe exceeds the 17300MW, figure (2), producing almost 40TWh/year or equivalently the annual electricity consumption of 30 million typical consumers. For comparison purposes, less than 1750MW of new nuclear capacity was internationally grid integrated in 2001, as per the available records.

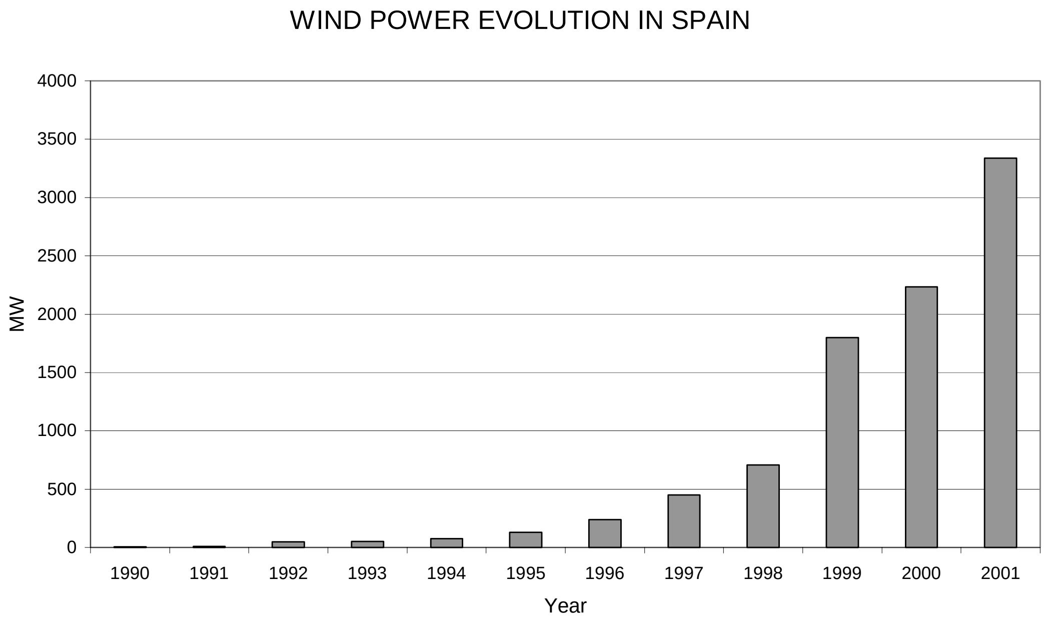

Figure 4: Wind Power Capacity in Spain

2. Major Wind Power Markets

According to the official data provided by EWEA, the total installed wind power capacity in Germany approaches the 8800MW, figure (3), hence wind power now accounts for almost 3.5% of German electricity consumption. The introduction of the new Renewable Energy Law during 2000 stimulates the financial interest on wind energy applications. More precisely, the new legislative frame is strongly supportive to the offshore wind parks, underlining the expectation that offshore installations will be playing an important role in the electricity production sector in the coming years.

Subsequently, Spain's installed capacity for 2001 surpasses the 1000MW, forming Spain the second largest European market for wind power in 2001. Therefore, totaling over 3300MW, Spain is now the second largest European market in terms of installed capacity; figure (4). Denmark is still one of the strongest wind energy markets, as the existing 2400MW of wind power contribute with more than 14% to the country annual electricity balance; figure (5). During the current year, the first 160MW offshore plant has been scheduled, while further offshore installations are expected at a rate of about 150MW per year. On top of that, new capacity is expected to be available by substituting old turbines (installed since 1980-85) with new larger ones.

Further European countries have also significantly increased their installed wind power, like Italy (60% increase during 2001), while UK and Sweden have correspondingly added 68MW and 59MW at the same time. France has introduced a fixed price program, re-establishing the old "Eole" program targeting 500MW by 2005, with a much more ambitious one of 5000MW by 2010.

A record installation of almost 1500MW has also been encountered in USA, figure (6), totaling the new world wind power sum during 2001 at 6000MW. The crucial issue in the US is the existing Production Tax Credit, as it offers a credit of almost 0.014€/kWh (adjusted for inflation) produced by a new wind plant during its first 10 years of operation. Canada, with an almost 150MW current level of operating wind farms, possesses an enormous unexploited wind potential.

In Asia, following a period of inactivity, India's government has introduced new financial incentives, hoping to offer in wind power development a real boost. At the same time, China's steps forward 1200MW by 2005 are relatively slow for the country's size, attributed mainly due to major administrative problems. Japan, whose total installed capacity approaches the 200MW, is expected to

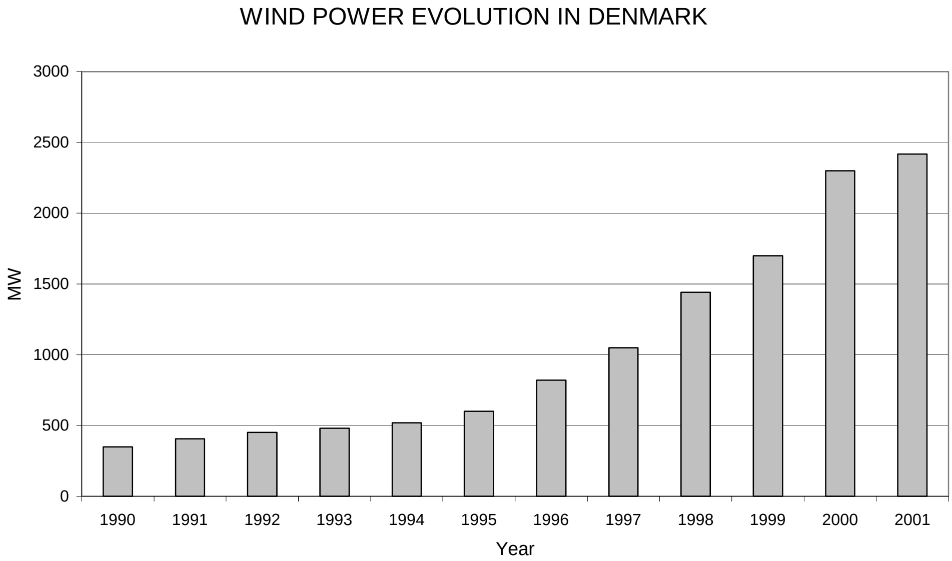

Figure 5: Wind Power Capacity in Denmark

develop wind power at a steady rate of approximately 100MW per year. Finally, the countries of the former Soviet Union generally have huge wind resources, which remain completely untapped either

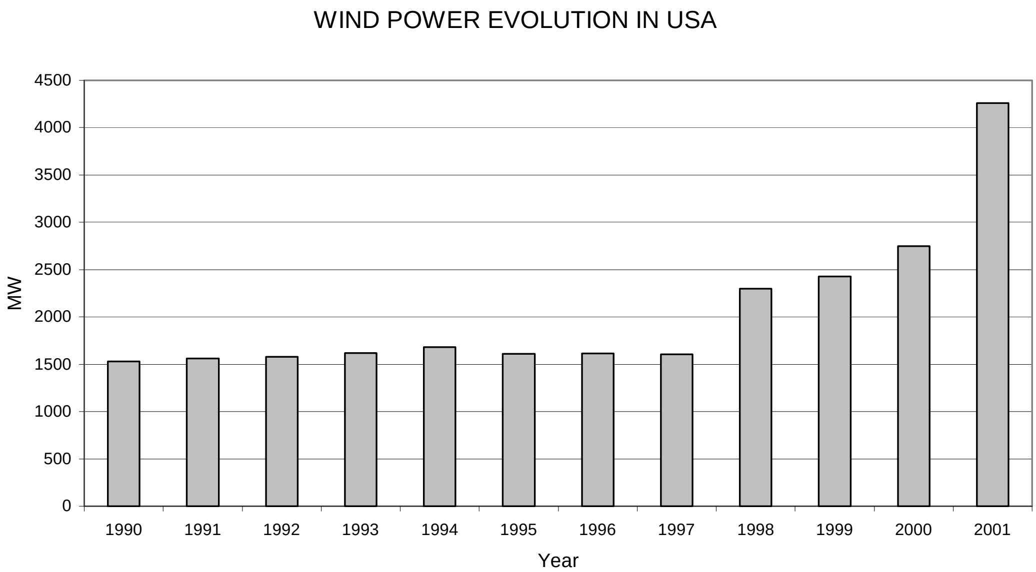

Figure 6: Wind Power Capacity in USA

due to insufficient investment capitals or due to plethora of oil and natural gas resources.

3. Manufacturers Activity

By early 1980's several large companies such as Boeing, Grumman, MAN, MBB and Westinghouse has attempted to enter the newborn wind turbine industry, based on their aerospace background. More or less all of these industries left the wind turbine business at the time when it was most turbulent and unsure[3]. This left the market place to small and medium sized companies looking for new niche markets related to their established skills. Since then, company development has been substantial and the ten largest European wind turbine manufacturers have now significant sales revenues of the order of 5 billion Euros.

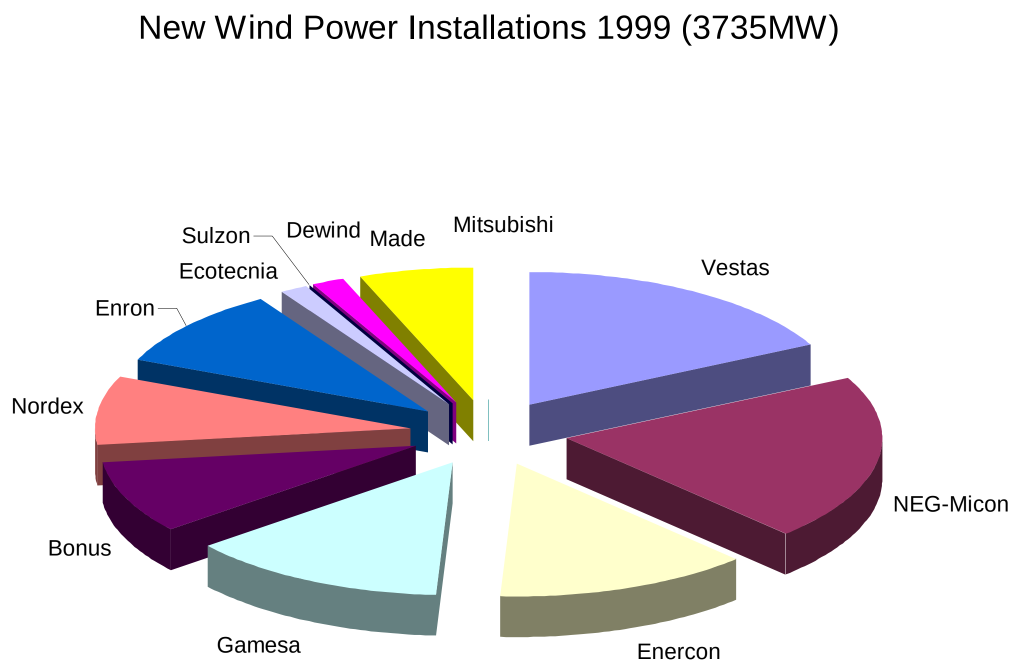

Figure 7a: Wind Power Market Shares, 1999

After thorough analysis of the available information, the world's "top 10" manufacturers, in terms of power installed, remain almost unchanged during the last years, figure (7), with some minor rearrangements. In this context, these ten companies possess more than 90% of the world market, while the Danish companies continue to lead the market. More specifically, the leaders are clearly Vestas, followed by NEG Micon, while Gamesa Eolica takes the third position from Enercon. Also Bonus, Nordex, Ecotecnia, Enron, Dewind and Sulzon, a new Indian manufacturer, constitute the "top 10", while in the next two positions there appear the Spanish Made and Mitsubishi Heavy Industries.

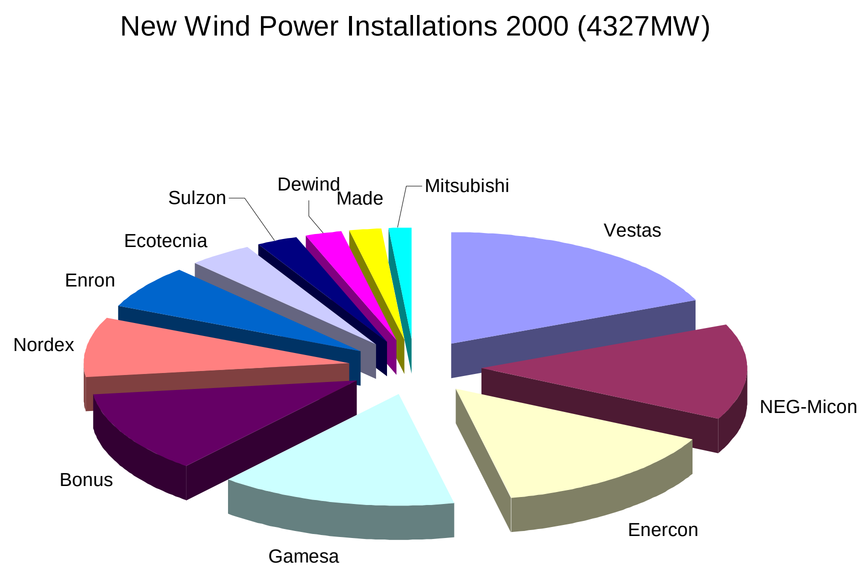

Figure 7b: Wind Power Market Shares, 2000

Finally, Danish companies continue to export a very large share of their production (e.g. Vestas exported the 86% of its annual production), while the German ones are mainly based on their large domestic market. Although this is the general trend, on the other side Enercon exported slightly over a quarter of its production, while Nordex-Bosig Energy GmbH is still defined as "Danish" company, even though it is 75% German-owned, and it has sold more to Germany than to Denmark during the last three years. Finally, the Spanish companies are now beginning to export seriously, while Gamesa and Made are expanded in oversea markets.

4. Technological Trends

In the early years, research institutions and universities have produced more knowledge than the wind industry could handle[4]. Nowadays, the situation is quite different, as up-scaling and offshore application of wind power raise more issues than the researchers can deal with. Among the main areas of concern are the primary energy conversion process (from wind to shaft power) and the overall system design. In this frame, the combination of increasing size and, at the same time, a change of concept from stall control (fixed rpm) to pitch control and variable rpm, is quite a challenge, as it requires a close collaboration between offshore and wind turbine technology. Up to now the stall regulated wind converters constitute the majority of the existing applications, figure (8), although the current trend is towards variable speed engines.

Similarly, the commercial converter dimensions have been increased by at least two orders of magnitude (25kW to 2.5MW) between 1981 and 2001[5]. This continuous size expansion (figure (9)) is dictated by the prospective positive scale economy effects especially for offshore applications, along with the difficulties in locating new wind park sites in most N. European countries. Finally, it is a common belief that by enlarging the rotor size and the corresponding hub height one may anticipate higher wind speed values, which may be not the case for high wind speed regions, like the ones existing in Greece[6].

Due to the continuously increasing rotor size, complicated phenomena like dynamic stall and yawed flow is not yet sufficiently understood, despite the usage of the most sophisticated numerical codes. Besides the increased machine dimensions amplified the aeroelasticity phenomena, like the lead/lag vibrations in blades. During a recent work by the authors, those upscaling effects were extensively analyzed. One of the major conclusions drawn[5] by this investigation is that, in case that no technological revolution will take place during the next five years, the established wind turbine size is not going to exceed the 3MW, while in any event, the 5MW should be the upper nominal power limit of the contemporary horizontal-axis wind turbines design philosophy.

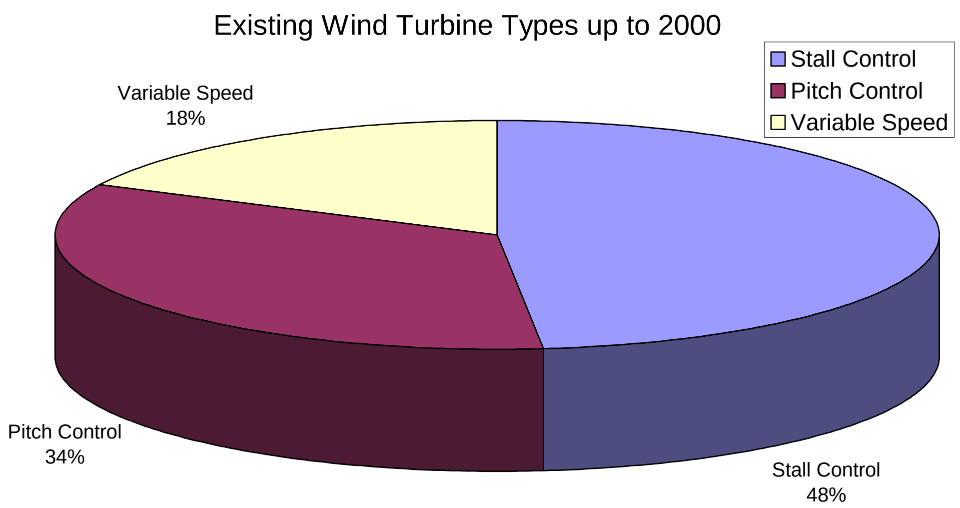

Figure 8: Wind Turbine Technology Used

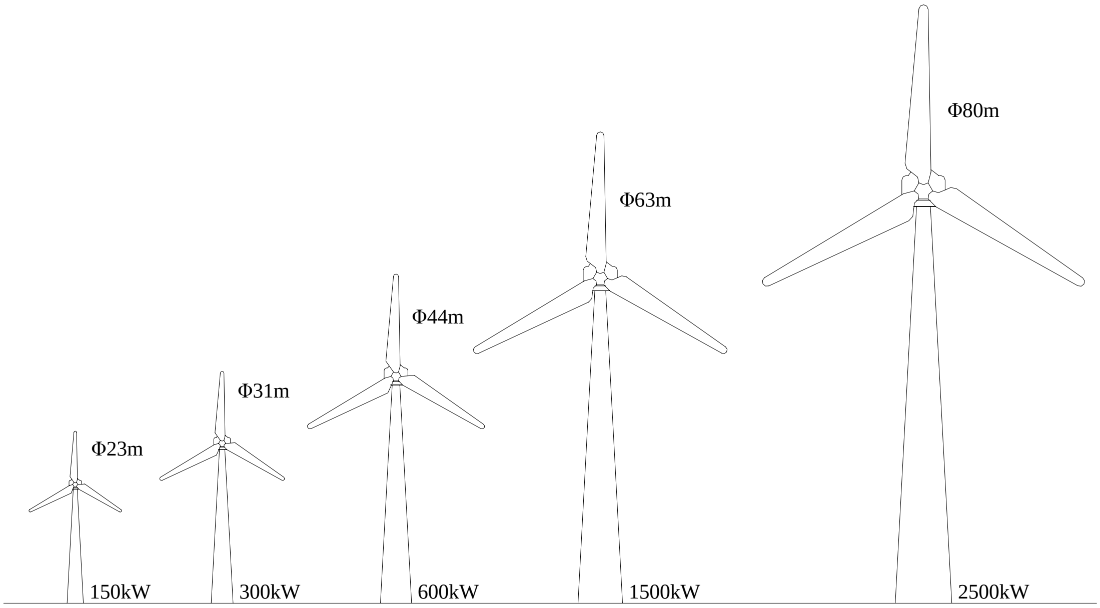

Figure 9: Commercial Wind Turbines Size Evolution

5. Economic Attractiveness of Wind Energy Investments

Wind power already competes with fossil fuel and nuclear power in many countries, especially if external-social costs are taken into consideration[7]. The generation cost of wind energy mainly depends[8] on total investment cost, operation and maintenance cost, available wind potential, availability of the installation and several other fiscal parameters like capital cost, operational life of the equipment, energy escalation rate etc.

Ex-works cost is estimated for commercially available wind turbines to be approximately 750-800€/kW of installed capacity or equivalently 320-360€/m^2 rotor swept area. According to recently published research by the authors[9] one may state:

a. There is a gradually decreasing price evolution of commercial wind turbines with time
b. The specific price distribution of commercial wind turbines presents a minimum at a given nominal

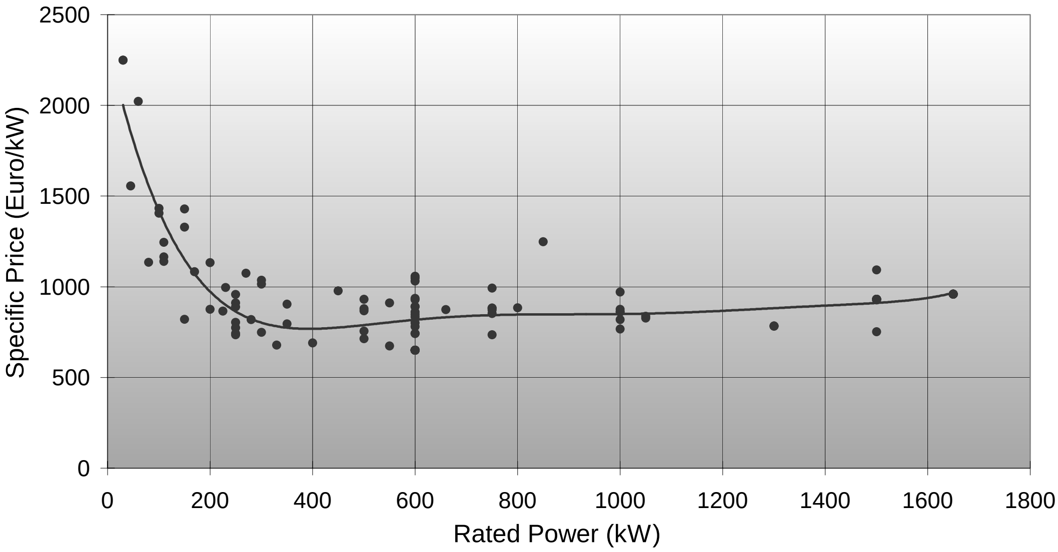

Figure 10: Wind Turbine Ex-Works Price

value, figure (10), varying every year. This minimum value results according to the mostly established wind power technology annually

c. There is a remarkable price diminution by increasing the number of machines used to create a wind power station

On the other side, the balance of the plant cost depends[3,10] on foundation cost, electrical interconnection cost, land purchase, planning cost, approvals, infrastructure, management of the project and grid connection cost, being also functions of wind turbines used relative size. According to detailed information, the major parameters affecting the above mentioned cost value is the area infrastructure situation and the number of wind turbines used.

Finally, operation and maintenance cost includes[9][11] service, consumables, repair, insurance, administration, lease of site etc. European experience indicate that annual M&O cost for relatively new grid-connected wind turbines is approximately 0.006-0.01€/kWh, almost half of which is attributed to insurance cost.

Recapitulating, one may state that wind based generated electricity production cost is almost equivalent to other fossil fuel technologies, especially in areas with good wind potential (i.e annual mean wind speed at hub height greater than 6.5m/s). However, the attempted European energy market "liberalization" disturbs the wind market equilibrium[12], threatening the future of wind power investments, in case that social and environmental benefit of renewable energy sources is disregarded.

In practice, wind energy development in the EU takes place within markets at various stages of liberalization, i.e. from completely open markets in Germany, Sweden and the UK, to markets with only a 23-26% market opening, as in Greece, France and Portugal. In this context, while liberalization improves the opportunities for wind energy development, such as through ensuring third part access to the grid, it is well recognized that market failure occurs in liberalized electricity markets, e.g. California crisis. Additionally, European wind farms compete against large, polluting, fossil fuel and nuclear power plants, which do not definitely charge the entire cost of the damage they cause. On top of that, almost all renewable energy technologies face severe competition by established firms and technologies, which introduced themselves and were developed under strictly monopoly market conditions.

The recently published European Community guidelines[13] on State Aid for Environmental Protection allow certain types and levels of support for renewables to be provided by EU member states. Besides, in March 2001, the European Court of Justice ruled that the German Feed-in Tariff does not constitute state aid, as no transfers from the public purse are involved. This decision provides clear assurance that obligations imposed alongside a minimum price guarantee can be in compliance with state aid rules. Finally, one cannot disregard the EU policy concerning the issue of security of energy supply. Thus, the corresponding "green paper" recognizes the potential benefits of wind energy in an attempt of EU to increase its energy self-sufficiency.

6. Environmental Benefits

Air pollutants are primarily emitted from the various energy transformation processes based on fossil fuels[14]. Today SO_2, NO_x, CO and volatile organic compounds (VOCs) are considered as the basic air pollutants along with the CO_2, resulting by using carbon as a fuel. These major pollutants may cause detriment at very different concentration levels, according to their toxicity factors. More specifically, according to recent research[15] and official data, every MWh of electricity consumed in Europe is considered responsible (Table I) for almost 4kgr of NO_x, 6kgr of SO_2 and 1000kg of CO_2. This significant environmental surcharge is directly connected to the continuous fossil fuel consumption in order to meet the amplified energy requirements of industrialized societies[16].

Table I: Specific Emissions (kg/MWh) from Fossil-Fuelled Electricity Plants versus Wind Parks

Air Pollutant	Netherlands	UK	Denmark	Greece	Wind Power
CO_2	872	936-1079	850	1054	7
SO_2	0.38	14.0-16.4	2.9	6.4	0.087
NO_x	0.89	2.5-5.3	2.6	4.3	0.036

Global warming due to anthropogenic emissions (e.g. CO_2 and CH_4) is now generally accepted as a fact; hence the IPCC (Intergovernmental Panel on Climate Change) scientists expect major ecological changes. In the EU, approximately one third of CO_2 emissions come from electrical power generation; thus for every 1% of conventional generation capacity displaced by renewables, a 0.3% reduction of total CO_2 emissions is being achieved.

Recapitulating, in Table II one may compare CO_2 emissions from a large variety of electricity generation technologies. Thus far, neither satisfactory nor commercially viable means of abating CO_2 emissions from fossil fuelled plants have been devised. Among the most commercially competitive technologies, wind energy and hydro power stations are assumed responsible for only 5-10kg CO_2 per MWh produced. On the other side, coal-fired stations produce more than 950kgr CO_2/MWh, while almost 730kgr CO_2/MWh is attributed to oil-fired installations.

Table II: CO_2 Emissions (kg/MWh) from Various Electricity Production Technologies[3]

Technology	Fuel Extraction	Construction	Operation	Total
Coal-fired	1	1	962	964
Oil-fired	-	-	726	726
Gas-fired	-	-	484	484
Nuclear	2	1	5	8
Geothermal	0.5	1	56	57.5
Wind	-	7	-	7
Small Hydro	-	10	-	10
Large Hydro	-	4	-	4
Solar Thermal	-	3	-	3
Photovoltaics	-	5	-	5
Wood	-1509	3	1346	-160

Finally, SO_2 and NO_x are the main -responsible for acidification- agents. The most important quantified effects of acid deposition are upon human health, building materials, historical monuments and commercial forestry. Furthermore, there are major impacts upon ecosystems, both terrestrial and aquatic, e.g. the lakes of Scandinavia. According to damage cost derived using previous estimates of acidification, an optimistic value may possibly be 6000Euro per tonne of either SO_2 or NO_x. Besides, impacts are non-localized, as they may be experienced hundreds or even thousands of kilometres from the initial emission point. Comparing for example the SO_2 and NO_x emissions from fossil-fuelled generating plants (Table I) with those produced by wind parks (i.e. 0.087kgrSO_2/MWh and 0.036kgrNO_x/MWh) on a wind turbine life cycle basis, one may state that the specific emissions from wind energy are a very small percentage respectively to those from fossil-fuelled plants.

According to the analysis presented, wind energy significantly contributes to ameliorating the environment quality in cases that they substitute fossil-fuelled power stations. However, in several cases encountered all over Europe, the establishment of new wind parks at certain places has been opposed by the local people[17], claiming important environmental impacts. According to several experts' opinion, unless this uncontrollable situation is properly analyzed and handled[18], the future of wind energy penetration might face serious contradictions.

7. Evaluation of Greek Wind Energy Market

According to extensive wind potential studies, Greece possesses one of the best wind potential of Europe, since the local average wind speeds (at hub height) may overpass the 8÷11m/s. More precisely, in the Aegean Archipelago there exist several islands, which, along with the mainland coasts, possess excellent wind potential. On the other hand, during the last two decades, the electricity demand in Greece increases by 4% per annum. This continuous electrical energy consumption acceleration has hitherto been primarily covered by either imported oil and natural gas or locally extracted lignite. Both electricity production solutions present remarkable environmental and macro-economic disadvantages, which should be counted in the electrical production market price[19]. At the same time, the financial electricity production cost for the majority of the remote Greek islands is extremely high, approaching the value of 0.25Euro/kWh, while the fuel cost is responsible for almost 50% of the above-mentioned value[20]. Additionally, Greek dependency on imported fuel (≈70% of its domestic energy consumption is imported) leads to a considerable exchange loss, especially with countries outside the E.U.

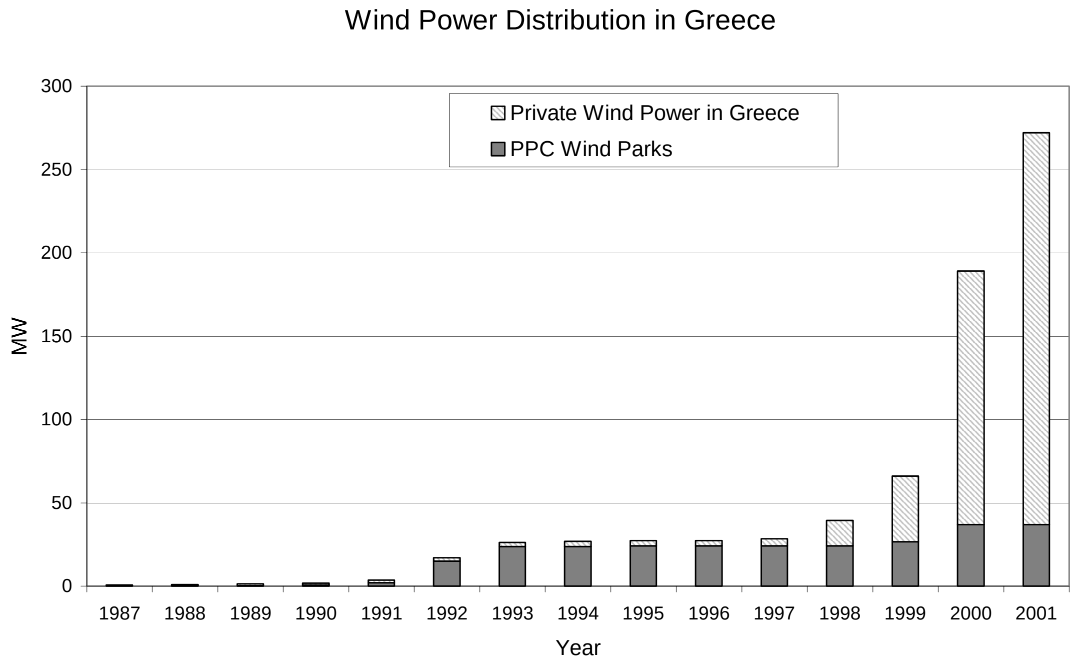

Figure 11: Wind Power Market Shares in Greece

For all these reasons, the Greek State has activated its renewable development program[21] since 1982, when the State owned PPC (Public Power Corporation) installed a 5x20kW pilot wind park on the island of Kithnos, using 2-bladed MAN (Aeroman) wind converters. These machines were subsequently replaced (1990) by 5x33kW wind turbines of the same manufacturer, operating during the last decade with variable energy production. Since the first pilot wind park of Kithnos was erected, a remarkable number of wind projects were realized, mainly during the 1990-93 and 1999-2001 periods.

It is important at this point to mention that PPC -the State owned electricity production and distribution company- has been monopolizing the Greek electricity market, theoretically up to 1994 (law 2244/94) and practically up to February 2001, when the local market liberalization (law 2773/99) officially came in force. In this context, up to mid-98 the vast majority of existing wind power belonged to PPC, figure (11), given that most of the 170 wind turbines operating in Greece belonged to PPC (142 machines).

However, once the major application problems related to the 2244/94 law for renewable energy sources installations were solved, the private wind parks capacity scaled[22] to 230MW, while at the same period PPC added only two new wind parks (10.5MW), totaling the wind power capacity of the company to 37MW only.

During the last years, the Greek State is strongly subsidizing private investments in the area of wind energy applications, either via the 2601/98-development law or the "Energy Operation or the Competitiveness Program" of the Ministry of Development. As a result, several requests for new wind parks of more than 10,000MW exist in the Ministry of Development, in an attempt to take advantage of the project total cost subsidization by 40%. On top of that, according to the existing Renewables' Law 2244/94, the national electrical grid owner is obliged to purchase electricity production by wind parks at 90% of the low voltage tariff on islands and 90% of the medium voltage price on the Greek mainland. In addition, ten-year electricity purchase contracts (open for a further ten year extension) are signed between PPC and the private investors of the wind energy sector.

A supplementary characteristic concerning the new wind parks installed has been their strict concentration in two geographical regions (i.e. East Crete and S. Euboea), while considerable new installations are being planned for the area of Peloponnesos This significant number of remarkably sized (500kW to 1MW) contemporary wind turbines, suddenly installed in those relatively restricted geographical areas, provoke serious local population reactions[23], which in some cases may even lead to cancellation of the complete wind power project, under the claim of important environmental impacts.

8. The Future of Wind Energy

Political interest in wind power comes –to a great extent- from its benefits in cutting greenhouse gas emissions. Thus, the economic viability of wind power is crucial, in order to become competitive and develop into the ideal mean of reducing emissions. For the realization of this target, many experts suggest[24] larger wind turbines, advanced siting knowledge and improved service and maintenance of the installations.

Additionally, one may state that there are two different market categories concerning the wind power applications. The first one includes the environmentally driven markets, while the second one contains the energy-driven economies. In these broad categories there belong the industrialized western countries (e.g. Germany, France, USA) and the developing countries (mainly in Asia) respectively. This division is not very accurate, since the need for energy is obvious in industrialized countries like Spain and in the western USA, while environmental concerns are starting to play a role in developing countries like China.

Subsequently, the financial mechanism used to encourage the introduction of wind power in a national market has substantial influence on the future of the sector. The four main models in use are:

- fixed-in tariffs (REFITS)
- renewable portfolio standard
- bidding processes
- price premium/energy tax and other tax-related benefits

Referring to the past experience, the most rapid development has been realized[12] in countries adopting the REFIT model, e.g. Denmark, Germany, Spain.

Finally, special attention should be paid at offshore development, started to take off in Europe. On the 86MW installed offshore since 1990, 54.5MW were installed in 2000, while there is a long list of projects under development to be realized up to 2005[25]. These projects are planned for Belgium, Denmark, Germany, Ireland, the Netherlands, Sweden and the UK, approaching 3100MW in total.

Even in case that all these projects are not going to come to fruition, one may estimate that a further 1500 to 2000 MW could be added in the near future.

Recapitulating, the wind power sector has to face serious challenges, like the upscaling and the improved dynamic control of the commercial engines, the cost efficiency integration of offshore installations, the forecasted reduction of electricity price and the worrying contradiction of local people in new installations at specific regions. If these subjects are properly treated, one may expect a constant medium-term growth rate in Europe, under the precondition that offshore development would take place. Additional new capacity is expected to result from the replacement of old turbines installed in the early 80's with new and larger ones. For the USA market the key issues are the duration of the Production Tax Credit and the contribution degree of the country to the climate change battle. Finally, in Asia markets only the reinforcement of China and India interest on wind power applications could really accelerate the steady but slow wind energy penetration on the Asiatic energy markets.

As a conclusion one should underline that European Wind Energy Association revised for second time its target for European installations in 2010 from 40000MW to 60000MW. In this way wind energy is expected to strongly contribute in achieving the EU target, i.e. to double the use of renewable energy by 2010, from 6% to 12%. Thus, there is a strong possibility for the White Paper assumption, that the electricity sector would be responsible for meeting two thirds of the target of 12% energy consumption from renewables, to be verified.

9. Conclusions and Proposals

It is well recognized that the global wind resource is plentiful. The main challenge for the contemporary technology is how this resource can be best exploited. Among the most important factors determining the success of this effort there are the cost reduction, the finding process of new sites, the complete system development, the reduction of environmental and social impacts and the implementation of national and international environmental and energy policies.

Thus far, the history of wind power development has been quite positive, as within only twenty years of evolution, electricity based on wind energy is almost fully competitive with other power generation technologies and may even be cheaper at selected sites, as fuel prices rise. Taking also into consideration the indisputable contribution of wind energy on environmental protection and restoration, one may clearly state that wind power is actually a sustainable energy solution for the world development during the next decades.

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EVALUATING THE MAXIMUM WIND ENERGY PENETRATION LIMIT FOR WEAK ELECTRICAL GRIDS

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Abstract

The remarkable fluctuations of daily and seasonal electricity consumption in almost all island grids impose serious limitations on wind energy application size, in order to guarantee the local grid stability. With the intention of maximizing the wind energy penetration in these autonomous electrical grids, an extensive study is carried out for several typical islands, concerning their electrical power demand during a long time-period. Using the official electricity consumption data, the typical hourly electricity demand profiles are estimated for every day of a week, either on a monthly or a seasonal basis. The peak and minimum electricity demand periods for every day of a month are also predicted, along with the corresponding possibility distribution. By combining the predicted electricity consumption profiles with the corresponding wind speed data, one has the ability to estimate a realistic penetration-contribution of the wind energy to the local grid.

Keywords: Electrical Load; Forecasts; Wind Energy Penetration

1. Introduction

The significant electricity production cost for all the Aegean Archipelago islands, due to the small and aged autonomous thermal power stations used, delays their development, deteriorating their habitants' living-quality. On the other hand, all these islands have very high wind potential[1], giving them the capability to cover an important part of their electricity demand by creating local wind parks[2]. However, the remarkable fluctuations of daily and seasonal electricity consumption in almost all island grids impose serious limitations on wind energy application size, in order to guarantee the local grid stability. Additional barriers against the penetration of the wind energy in these autonomous grids also result from the stochastic availability of the wind potential, leading often to an important disharmony between the wind energy production and the electricity demand.

In order to minimize such a serious problem and maximize the wind energy penetration in similar weak-autonomous electrical grids, an extensive study is carried out for several typical islands, in relation to their electrical power demand during a long time-period. More precisely, using the official electricity consumption data[3], the typical hourly electricity demand profiles are estimated for every day of a week, either on a monthly or a seasonal basis. The peak and minimum electricity demand periods for every day of a month are also predicted, along with the corresponding possibility distribution.

By combining the predicted electricity consumption profiles with the corresponding wind speed data and the wind turbine power curves of any wind park installed, one has the ability to estimate[4] a realistic penetration-contribution of the wind energy to the local grid, taking into account the necessary limits concerning the local grid stability. On top of that, in a liberalized free market, the electricity demand profiles may be used to determine the daily plan of local diesel engines operation and existing wind turbines, so as to maximize the clean energy production and minimize the fuel consumption along with the corresponding financial benefits, without jeopardizing the safety rules of the local grid[5].

***Kaldellis J.K., 2001**, "Evaluating the Maximum Wind Energy Penetration Limit for Weak Electrical Grids", European Wind Energy Conference, Conference Proceedings, pp.1215-1218, Bella Centre, Copenhagen.*

Finally, by accurately forecasting the hourly electricity demand during a whole year of an autonomous weak grid, one has the ability to estimate the maximum wind energy absorption of the local system and accordingly determine the optimum wind power-to-be- installed (no storage devices included) on a maximum benefit to cost basis[6].

2. Wind Turbines Influence on Weak Grids

It is so far a common belief that one of the major factors limiting the substantial wind power penetration in Greece is the weak existing PPC electricity network, especially in Aegean Archipelago islands, which possess excellent wind potential.

The main issues concerning the impact of wind turbines on autonomous weak electrical grids[7] include:

a. The influence of real and reactive power of wind parks on the network steady-state voltage value, especially for wind turbines using passive stall control systems.
b. The voltage step changes in relation to the starting or the generators changing of a wind turbine.
c. The "flicker" phenomenon due to the voltage fluctuations, caused by wind turbines real and reactive power variations. Flicker can be an important issue for weak grids, since consumers face a serious light intensity fluctuation. Contemporary, variable-speed wind turbines generally produce significantly lower flicker than outmoded fixed-speed stall control machines.
d. A remarkable level of harmonics (principally of 5^{th} and 7^{th} order), produced by the consumers' electronic equipment utilization and occasionally amplified by the wind converters operation.
e. Voltage unbalance, in case the customer single-phase loads are not correctly shared between the grid phases. Induction generators used by wind turbines interact with the system unbalance, leading to significant wind turbine downtime.

On the other side, the "embedded" generation (i.e. generators connected within the distribution system, close to consumption points) creates some remarkable benefits, like:

- ✓ Diminution of electricity transport loss
- ✓ Limited electrical transmission system capacity
- ✓ Reinforcement of the distribution system
- ✓ Improved reliability of electrical power supply

3. Wind Power Penetration Theoretical Limit

According to the above-presented information, it is clear that -despite the technological improvements by the contemporary wind turbine manufacturers- the existence of wind parks keeps on causing negative and positive effects on the local electrical grid. In fact, the induced perturbations are as important as the electrical network is weaker.

To face this problem, local electricity utilities set upper wind energy participation limits in the instantaneous electrical power demand management. In autonomous electrical grids of remote islands, based on internal combustion engines, Greek PPC permits the existing wind parks "N_{WT}" to contribute up to "λ%" of the instantaneous grid load "$N_G(t)$", i.e.:

$$N_{WT}(t) \leq \lambda \cdot N_G(t) \tag{1}$$

with "λ" taking values in the range of 30%.

This limit results from the selected operation point and the maximum permitted output of the local APS diesel engines[5], so as to undertake the total grid load in the minor case that the wind park unexpectedly zeroes its production. In cases that the local system includes gas, steam or hydro turbines, this limit "λ" should be reconsidered towards higher values. However, the utilization of gas turbines is quite expensive, thus it is often economically inappropriate to use them as stand by engines.

From the existing law-defined restrictions (8295/95), the maximum grid connected total wind power installed in an autonomous electrical system "N_{max}" is defined as "ε%" (e.g. ε=30%) of the peak load demand "N_p" of the grid under investigation during the previous year, i.e.

$$N_{max} \leq \varepsilon \cdot N_p \tag{2}$$

Therefore, one can calculate the maximum wind energy contribution in an autonomous electrical grid using the following relations. More precisely we define "Ψ" as:

$$\Psi = \frac{E_W}{E_G} = \frac{\int_o^T N_{WT}(t) \cdot dt}{\int_o^T N_G(t) \cdot dt} \tag{3}$$

Keep in mind that:

$$E_W = 8760 \cdot CF_w \cdot N_{max} \tag{4}$$

and

$$E_G = 8760 \cdot CF_G \cdot N_p \tag{5}$$

where "CF_w" and "CF_G" are the corresponding capacity factor values of the existing wind parks and the local electrical grid. Applying equations (4) and (5) to equation (3), taking also into account relation (2), one gets:

$$\Psi \leq \varepsilon \cdot \frac{CF_w}{CF_G} \tag{6}$$

According to previous authors work[8] the wind park capacity factor is the product of the technical availability "Δ(t)" with the mean power coefficient "ω(t)" of the installation, i.e.:

$$CF_w = \Delta \cdot \omega \tag{7}$$

More precisely, "ω" can be computed[8] as:

$$\omega = \int_0^\infty \frac{N(V)}{N_o} \cdot f(V) \cdot dV \tag{8}$$

with "V_c" and "V_F" the corresponding cut-in and cut-out wind speeds of the wind turbine analyzed, while "N(V)" is the corresponding power curve versus wind speed "V" and "f(V)" is the wind speed probability density function at hub height describing the local wind potential. Similarly the local grids capacity factor varies between 0.25 and 0.6 for the vast majority of the existing APS[9].

On the other side, by applying equation (3), in view of equation (1), it results:

$$\Psi \le \lambda \tag{9}$$

Thus, one may write:

$$\Psi_{max}^{th} = \min\left\{\lambda, \varepsilon \cdot \frac{CF_w}{CF_G}\right\} \tag{10}$$

4. Maximum Wind Power Penetration Target

As already mentioned the majority of Aegean Archipelago islands have an excellent wind potential, as in many regions the annual mean wind speed at 10m height exceeds 9m/s. However, the stochastic availability of wind energy, the limited local electrical network capacity and the daily and seasonal electricity demand fluctuations finally result in a serious restriction of the maximum wind power penetration, in order to maintain the local grid stability.

Taking these data into account, the authors assert that an energy storage system, when appropriately sized, is able to match a highly variable wind power production to a generally variable and unpredictable system demand, also contributing in energy production cost reduction.

According to previous research[5][10], the prospect of creating a combined wind-hydro energy production station (for medium sized islands) or an hybrid photovoltaic-wind power-battery station (for small islands) are the only available solutions, provided that the central target is to **maximize** the renewable energy sources penetration, under the precondition of rational electricity production cost. The main target of the proposed systems is to consistently cover the electricity requirements "N_G" of the local community on a regular basis, minimizing thus the oil consumption, given a first installation cost upper limit.

However, from an other point of view, by accurately forecasting the hourly electricity demand of an autonomous weak grid during a whole year, along with the corresponding wind speed of the area, one has the ability to estimate the maximum wind energy absorption by the local system and accordingly determine the optimum wind power-to-be-installed, in cases that no storage devices exist.

5. Remote Electrical Grid Analysis

In an attempt to maximize the wind energy penetration on an autonomous electrical grid one may express the definition of "Ψ" parameter according equation (3), as follows:

$$\Psi = \frac{\int_o^T N_{WT}(V(t)) \cdot \delta(t) \cdot dt}{\int_o^T N_G(t) \cdot dt} \tag{11}$$

where "δ(t)" is the well known Kronecker function taking values equal to either 1 (machine properly operating) or 0 (machine non available). In equation (11) the wind park output "N_{WT}" is mainly depended on the local area wind speed "V(t)" (air density and humidity also influence the wind turbines efficiency). Keep in mind that, during the last ten years, a significant number of high quality works were presented with reference to the short-term prediction of an area's wind speed.

In the following, the outcome of a serious effort to simulate the behaviour of the RHS dominator of equation (11) is described, concerning several typical Greek islands. This study is now under preparation, using the official electricity consumption data[3], while selected results will be presented. More precisely, during the first stage of this integrated research, the typical hourly electricity demand profiles are estimated for every day of a week, either on a monthly or a seasonal basis. The peak and minimum electricity demand periods for every day of a month are also predicted, along with the corresponding possibility distribution.

It is the authors' belief that, by combining the short-term wind speed forecasting and using the local grid expected electrical profiles, along with a semi-empirical (stochastic) model for the technical availability of the local wind park turbines, it is possible to significantly increase the wind power penetration, without jeopardizing the stability and safety rules of the local network.

In this case, the value of parameter "λ" is time depending (i.e. $\lambda=\lambda(t)$) and non-arbitrary defined. On the contrary, its exact value is the result of sequential mathematical calculations, based on the hitherto presented methodology. Similarly, the bylaw defined "ε" value should be readjusted, to permit the maximization of wind power penetration, based on a detailed cost-benefit analysis.

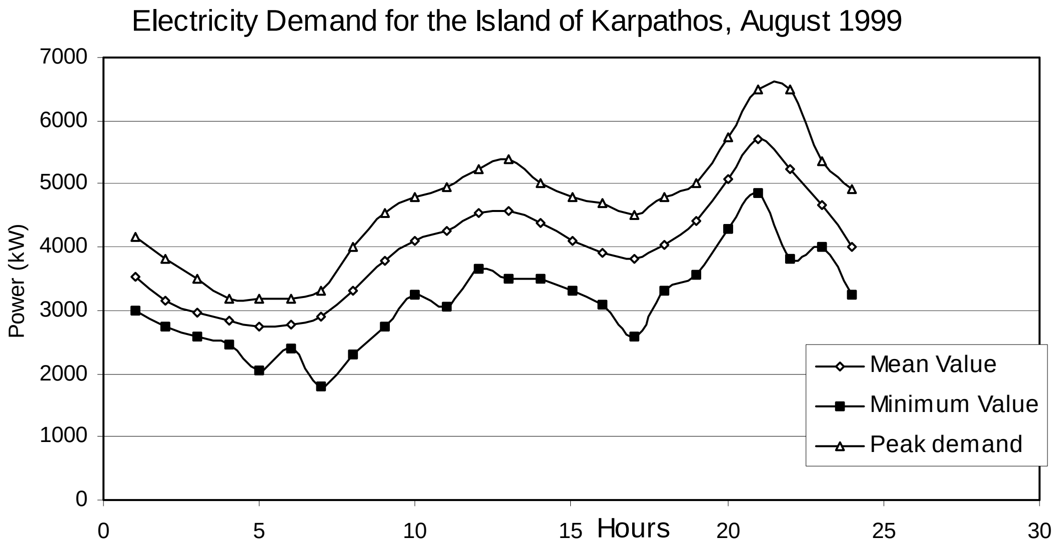

Figure 1: Typical Electricity Profiles for August 1999

6. Application Results

During the first phase of the present project, the electricity consumption profiles of Ikaria and Karpathos islands are examined, as their size and corresponding wind potential constitute them proper candidates for increased wind power penetration, either with additional energy storage systems or not. More precisely, the typical electricity demand profiles for these two islands are given (Figs 1 and 2) for August 1999. Keep in mind that the annual peak load demand appears during August for both islands for the entire recent five-year period analyzed. Another interesting result from these two figures is that the minimum value of the night maximum is clearly above the monthly averaged load demand.

Subsequently, according to information of Fig. 3, a remarkable increase of monthly energy consumption is encountered between 1997 and 1999 for Ikaria Island, leading to a mean annual electricity consumption increase of 8%.

In figure 4, the local grid capacity factor distribution for 1997, 1998 and 1999 is presented corresponding to the Ikarian network. Bear in mind that, during August, all the Greek autonomous systems present their maximum electricity demand. Thus, using the "CF_G" distribution of Fig. 4 and the corresponding "CF_w" values concerning a typical wind park of the same island, the maximum predicted "Ψ" value is inferior to 14%.

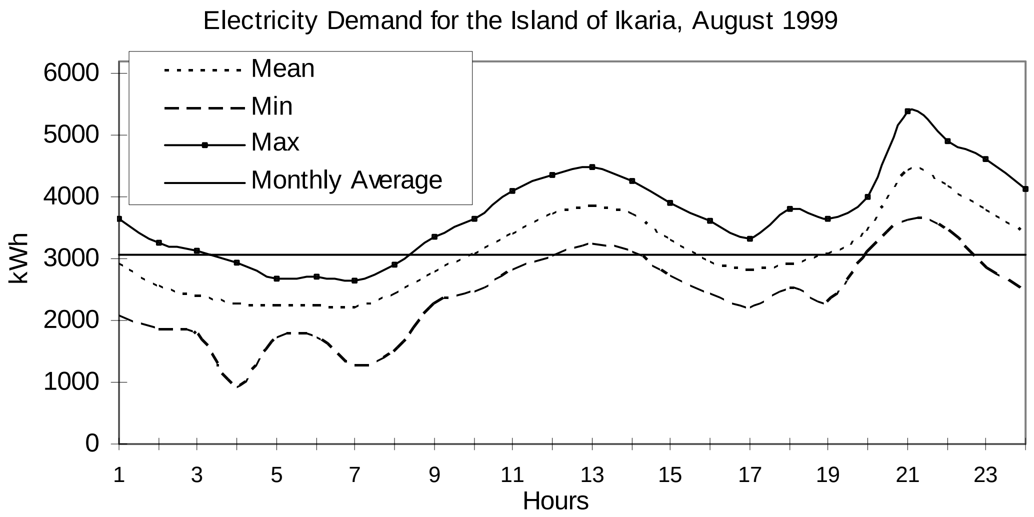

Figure 2: Typical Electricity Profiles for August 1999

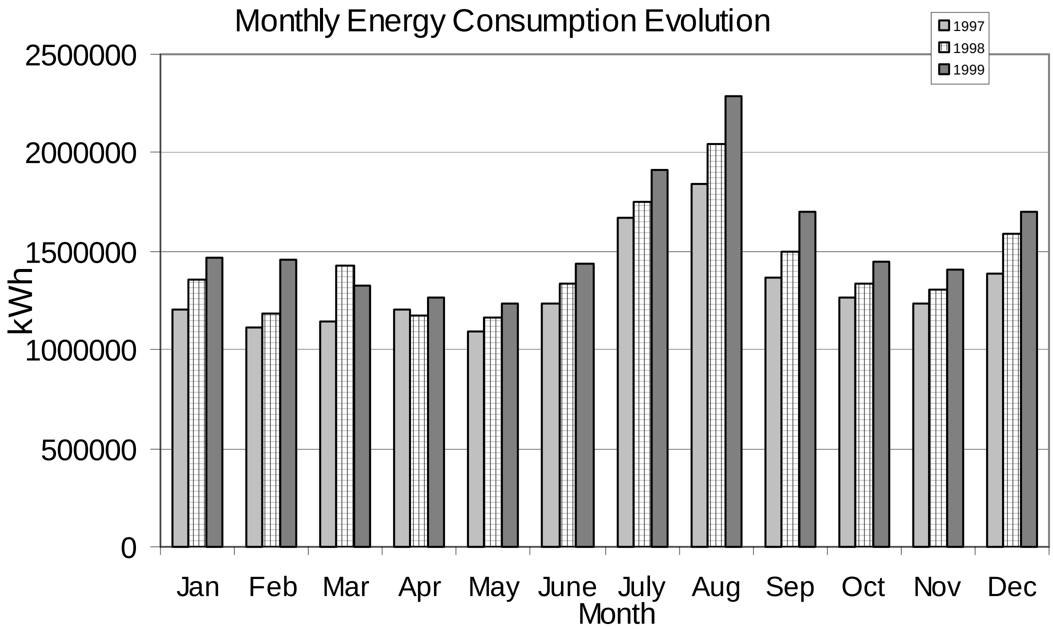

Figure 3: Monthly Electricity Consumption, Ikaria case

Accordingly, we estimate (Fig. 5) the typical daily profiles on a monthly basis, for each year examined. After extensive data analysis, the maximum load demand profiles appear on Saturday. More specifically, for Ikaria 1999, the electricity demand is never below 1200kW, while the peak load demand is over 5000kW, appearing between 21:00 and 22:00.

In the following (Figs 6 and 7), the mean seasonal load distribution (winter versus summer) is presented for the Saturday of 1997 to 1999 period. From both figures, it is clear that the mean load demand is continuously increasing with time, while even during winter the Saturday electricity consumption is quite high. Another interesting conclusion drawn from this extensive data analysis process leads (Fig. 8) to the possibility values of night maximum appearance during Saturday of 1999. According to the results obtained, the maximum summer demand takes place mainly between 21:00 and 22:00, while the corresponding winter values appear around 19:00 hours.

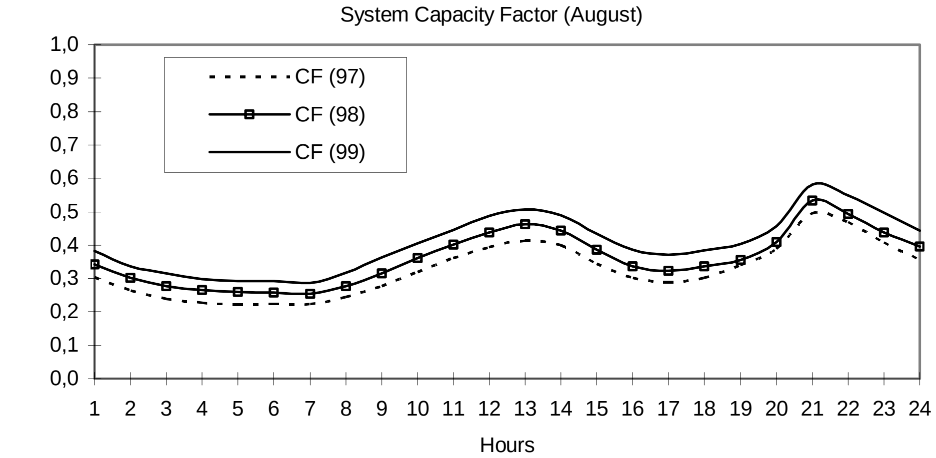

Figure 4: Capacity Factor Distribution, Ikaria case

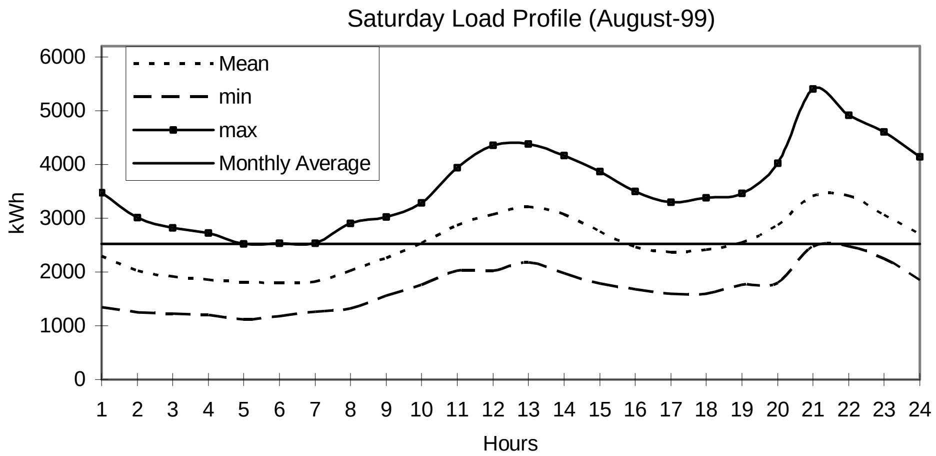

Figure 5: Saturday Load Profile, Ikaria Island

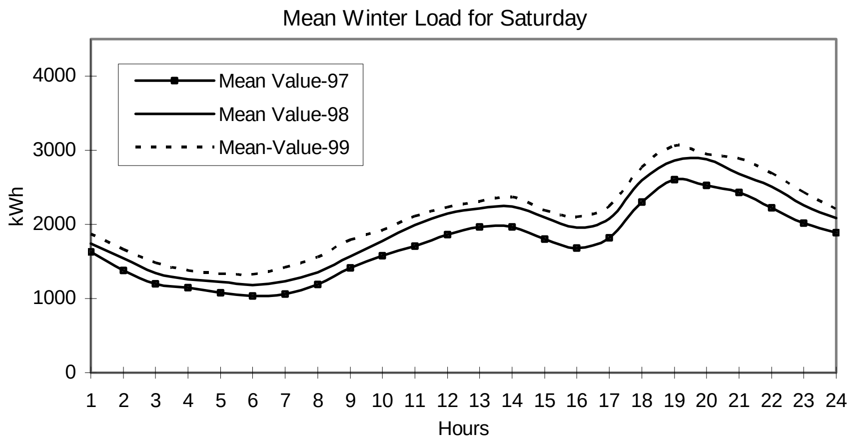

Figure 6: Saturday Mean Winter Load Profiles, Ikaria

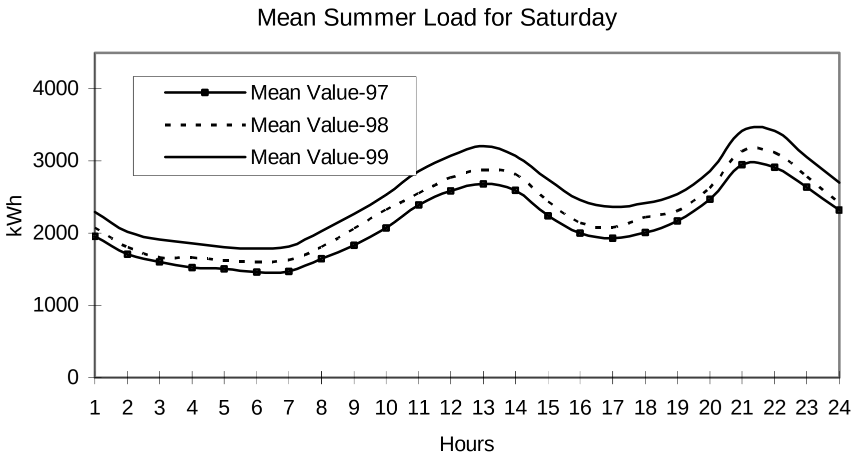

Figure 7: Saturday Mean Summer Load Profiles, Ikaria

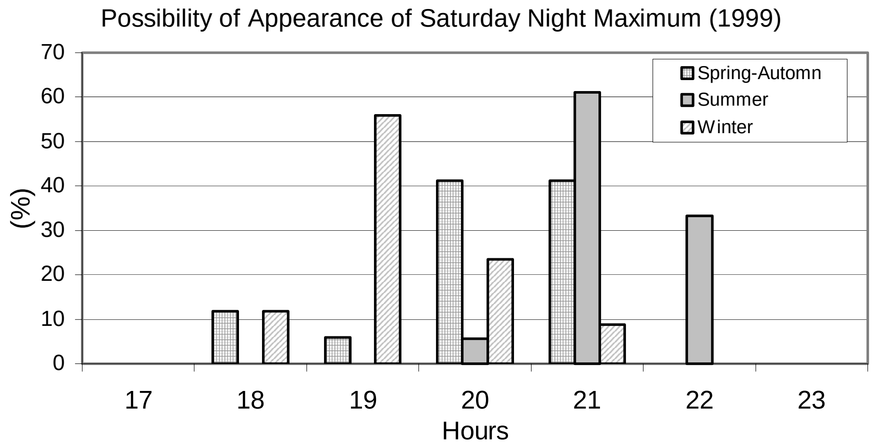

Figure 8: Night Maximum Appearance, Ikaria Island

7. Conclusions

An extensive study concerning the electricity consumption profiles for various remote islands electrical grid -for a considerable time- is under preparation. The primary outcome of the proposed study is to estimate the hourly electricity demand profiles during a whole year, while special emphasis is laid on predicting the maximum daily load value and possibility on a seasonal and monthly basis.

Accordingly, the main target of our effort is to maximize the wind energy penetration by combining the estimated electrical load profiles and the corresponding wind speed forecasts, without jeopardizing the local system quality and under a maximum installation cost constraint. In case this analysis is not taken into consideration, the following undesirable possibilities may occur:

✓ The total wind power installed approaches the PPC defined limit, i.e. 30% of previous year peak load. In this case, it is almost definite that the investment will not be viable, due to very low wind energy absorption by the local grid.

✓ The total wind power installed represents a small part of peak electricity demand (e.g. 10%). In this economically attractive case, the wind energy penetration is very low, despite the excellent local wind potential; therefore the maximum wind energy penetration target is abandoned.

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ESTIMATING THE OPTIMUM SIZE OF WIND POWER APPLICATIONS IN GREECE

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Abstract

Greece, and more precisely the Aegean Archipelago, has an excellent wind potential, while the widely ranging electricity-load of most Aegean islands is fulfilled by aged internal combustion engines using expensive imported oil. In order to accelerate the new wind park installations, the Greek State is strongly subsidizing private investments in the area of wind energy applications. As a result, requests for new wind parks of more than 11000MW exist in the Ministry of Development. However, the maximum wind power capacity is unfortunately limited by a variety of technical parameters. Besides, the expected financial results may be remarkably lower than the corresponding ones, in cases that the significant seasonal and daily electricity demand variations are not taken into account. Hence, an integrated analysis is carried out, concerning the optimum size of wind power applications in several Greek territories, in order to obtain a realistic evaluation of new wind parks requests. According to the existing electrical network and infrastructure situation, any substantial wind power addition is marginally attractive. Only in case that the local electricity network is strengthened and the wind-hydro solution is adopted, it is possible to substantially increase the wind power contribution to the local electricity demand.

Keywords: Optimum Size; Wind Power; Cost-Benefit Analysis; Size Constraints

1. Introduction

Greece, and more precisely the Aegean Archipelago, has an excellent wind potential, as in many regions, the annual mean wind speed at 10m heights exceeds the 10m/s. In addition, the widely ranging electricity load of most Aegean islands is fulfilled by aged internal combustion engines that use expensive imported oil. Thus the corresponding mean production cost approaches the 0.15Euro/kWh, while the corresponding low voltage electricity price is in the range of 0.08Euro/kWh.

Therefore, the possibility to establish a considerable number of wind power installations is widely acknowledged by many researchers[1,2,3] in an attempt to exploit the available wind potential and reduce the electricity production cost, along with the environmental pollution induced by thermal power plants.

Table I: New Wind Power Capacity Requests (R.A.E.)

Regions of Greece	**Requests (in MW)**	**Regions of Greece**	**Requests (in MW)**
N. Aegean	297	Peloponessos	3215
Dodekanessa	95	Macedonia	518
Crete	364	Ipiros	48
Cyclades	460	Central Greece	561
Attica	730	Euboea	2459

On top of that, the Greek State is strongly subsidizing private investments in the area of wind energy applications, either via the 2601/98-development law or the Operational Program "Competitiveness" of the Ministry of Development. As a result, requests for new wind parks of more than 11000MW (see Table I) exist in the Ministry of Development[4], so as to take advantage of the project total cost subsidization by 40%.

In view of the attempted electricity market liberalization, an extensive analysis -concerning the optimum wind power application size in several Greek territories- is carried out, in order to obtain a realistic evaluation of the new wind parks requests. This analysis is mainly focused on the Aegean Archipelago, since the best opportunities of important wind power penetration are gathered there. In this context, a large variety of existing constraints -limiting the maximum capacity of new wind parks- are taken into account, with the intention of estimating a realistic size for the economically viable new wind power installations in the Aegean Sea region.

2. Presentation of Main Limiting Factors

2.1 Electrical Network Constraints

One of the major factors limiting the substantial wind power penetration in Greece is the weak autonomous electricity network[2,5] in the Aegean Archipelago islands. More precisely, there is a law defined (8295/95) restriction "ε%" concerning the maximum grid-connected total wind-power installed in an autonomous electrical system. Hence, the maximum wind power penetration "N_{max}" is expressed as a function of the local peak load demand "N_p" during the previous year, i.e:

$$N_{max} \leq \varepsilon \cdot N_p \tag{1}$$

On top of that, local electricity utility (PPC) defines an upper wind energy participation limit "λ" in the instantaneous electrical power demand, to face undesirable local network problems. This limit is mainly empirically estimated, resulting by the existing internal combustion engines operational characteristics and the time-depending electricity load profile "$N_G(t)$". More precisely one may write:

$$N_{WT}(t) \leq \lambda \cdot N_G(t) \tag{2}$$

Thus, the corresponding annual yield "E_w" of the entire wind power stations of an autonomous electrical grid is given as:

$$E_w = \int_o^T N_{WT}(t) \cdot dt \leq \overline{\lambda} \cdot \int_o^T N_G(t) \cdot dt = \overline{\lambda} \cdot E_G \tag{3}$$

where " $\overline{\lambda}$ " is the time mean value of "λ", which is usually constant and T=1year.

By using the well known capacity factor definition both for wind parks and the local APS, i.e.:

$$E_W = 8760 \cdot CF_w \cdot N_{max} \tag{4}$$

and

$$E_G = 8760 \cdot CF_G \cdot N_p \tag{5}$$

equation (3) reads:

$$N_{max} \leq \overline{\lambda} \cdot \frac{CF_G}{CF_w} \cdot N_p \tag{6}$$

The upper value of "N_{max}" may be achieved only in the theoretical case that the wind energy production has exactly the same distribution with the corresponding load demand. Otherwise, a considerable portion of wind energy production should be aborted due to insufficient electricity demand. This phenomenon is very common for the existing APS, strongly affecting the economical behaviour of similar wind power investments.

Thus, by applying equations (1) and (6) one may estimate -in pure electricity management terms[5]- the maximum wind power penetration on a local autonomous grid, i.e.:

$$N_{max} = \min\left\{\varepsilon, \bar{\lambda} \cdot \frac{CF_G}{CF_W}\right\} \cdot N_p \quad (7)$$

Bear in mind that the above value (N_{max}) cannot be approached in cases that the feasible wind park sites are concentrated in a restricted region, where the local grid transferring capacity is limited. In such a case, either the maximum wind power to be installed should be decreased or the first installation cost is going to be increased due to the necessary infrastructure reinforcement[6].

2.2 Infrastructure-Available Area Restrictions

During the last ten years, the commercial wind turbine size has been exponential increased, as the current optimum wind turbine size for onshore installations is almost 2MW. However, although these installations appear economically attractive for European mainland, this is not the case for the small and medium sized islands of Aegean Sea[7]. Thus, in an attempt to confine the balance of the plant cost of a wind power station, there has been an upper size limit of the machines utilized. This limit depends on the local road network transferring capabilities, including also the necessary crane transportation procedure. Hence, the maximum rated power "N_{omax}" of the wind turbines used is confined according to the following relation:

$$W(N_o) \leq W_{max} \quad (8)$$

where "W_{max}" is estimated according to the existing transferring network abilities and "$W(N_o)$" is a semi-empirical function[1] relating to the maximum crane weight as a function of the wind turbine size. At this point it is important to clarify that equation (8) confines the size of an individual wind turbine and not the total wind power to be installed.

Accordingly, taking into account the minimum spacing restrictions $f(D(N_o))$ between wind turbines operating in the same region, an additional upper wind power limit may appear, due to the limited available area satisfying the corresponding preconditions (wind potential quality, distance from dwelling or electrical grid etc.). This restriction can be mathematically expressed as:

$$f(D(N_o)) \leq A_a \quad (9)$$

Finally, serious local population reactions against new wind parks are recently encountered[8] in some Greek territories, Aegean Sea islands not included. The common characteristic of similar situations is that a significant number of remarkably sized (500kW to 1MW) contemporary wind turbines are suddenly installed in these relatively restricted geographical areas, without the agreement of the local societies. Unfortunately, under specific circumstances these dynamic reactions may even lead to cancellation of the complete wind power project. According to the analysis by several researchers[9], it is concluded that local people oppose the foundation of new wind farms consisting of numerous sizeable wind turbines. Therefore, one may introduce an extra constraint concerning the number and size of the wind turbines to be installed in a specific area:

$$z^u \cdot N_o^y \leq \varepsilon_o \quad (10)$$

where "z" indicates the number of wind turbines to be installed in an area, while "u", "y", "ε_o" are semi-empirical coefficients depending on the particular location of the installation.

2.3 Cost Impact

The initial cost of a wind park "IC_o" is a function[10] of the wind turbines ex-works specific price "Pr" and the balance of the plant coefficient "f", i.e.:

$$IC_o = P_r \cdot z \cdot N_o \cdot (1 + f) \tag{11}$$

where:

$$P_r(t_o) = \left[f_N(\nu) + c_\infty \cdot \left(1 + \varepsilon_1 \cdot e^{-\varepsilon_2 \cdot t_o}\right)\right] \cdot \sigma_p(z) \tag{12}$$

with c_∞=700Euro/kW, ε_1=0.7 and ε_2=0.125. Besides, the relative size "ν" of the wind turbines used, in comparison with the optimum (best seller) wind turbine size for each year "$N_o^*(t_o)$", is defined as:

$$\nu = \frac{N_o}{N_o^*(t_o)} \tag{13}$$

where:

$$N_o^*(t_o) = A_N \cdot e^{B_N \cdot x} \tag{14}$$

with A_N=226.12, B_N=0.1786. Subsequently, "$\sigma_p(z)$" takes into account the number of wind turbines "z" constituting the wind farm under examination. Hence, the following relations are also valid for the European market[1]:

$$f_N = 566 \cdot e^{-\nu/0.35} - 132.5 + 100 \cdot \nu \tag{15}$$

$$\sigma_p(z) = 1.08 - 0.08 \log(z) \tag{16}$$

Similarly, the balance of the plant coefficient is expressed as:

$$f = f_o(\nu, q) \cdot \sigma_f(z) \tag{17}$$

where:

$$f_o = \alpha_1(q) \cdot e^{-\alpha_2(q) \cdot \nu} + \alpha_3(q) + \alpha_4(q) \cdot \nu \tag{18}$$

and

$$\sigma_f(z) = -0.075 \cdot (\log(z))^2 - 0.075 \cdot \log(z) + 1.15 \tag{19}$$

The exact value of parameters "α_i" is directly related to the infrastructure quality "q" of the wind park major area[6].

3. Economical Evaluation Model

For the economical analysis of a wind power investment, the theoretical model given by the authors[6,10] may be used. According to this model, one should estimate the expected pay-back period and the long-term efficiency of an investment. More precisely the pay-back period "n^*" can be predicted as:

$$G_n = R_n - C_n - \sum_{j=1}^{j=n} \Phi_{(j)} (1+i)^{n-j} = 0 \qquad \text{for } n=n^* \tag{20}$$

where "$\Phi_{(j)}$" describes the tax paid during only the "j" year, mainly due to the revenue of the previous year.

In equation (20) "C_n" describes the investment total cost after n-years of wind park operation, in current values. Thus one may write:

$$C_n = IC_o \cdot \left\{ \alpha \cdot \prod_{j=1}^{j=n} (1+i_j) + \beta \cdot \prod_{j=1}^{j=n} (1+i'_j) \right\} + FC_n + VC_n \tag{21}$$

where "FC_n" expresses the fixed and "VC_n" the variable maintenance-operation cost, not included explicitly in the present analysis. In equation (21), "$\alpha.IC_o$" describes the invested own capital, while the "$\beta.IC_o$" term expresses the loan capital, "$i'(t)$" being the capital cost index.

On the other hand, the investment revenue "R_n" after n-years of operation is given as:

$$R_n = R_{n-1}(1+i_n) + R_o \cdot \frac{CF_n}{CF_o} \cdot \prod_{j=1}^{j=n} (1+e_j) \tag{22}$$

where:

$$R_o = 8760 \cdot CF_o \cdot (z \cdot N_o) \cdot c_o \tag{23}$$

with:
i: return on investment index
e: electricity price escalation rate
c: effective cost coefficient of the conventional energy replaced by the wind park production

Keep in mind that the subscript "o" is used to express values at the accomplishment time "t_o" of the investment.

Consequently, for the calculation of investment revenue one needs the exact capacity factor distribution values versus time. According to authors previous work[11] the capacity factor is the product of the technical availability "$\Delta(t)$" with the mean power coefficient "$\omega(t)$" of the installation, i.e.:

$$CF = \Delta \cdot \omega \tag{24}$$

The technical availability factor appearing in equation (24) "$\Delta(t)$" can be expressed as:

$$\Delta(t) = \Delta^+(t_o) \cdot \frac{\Delta_n}{\Delta^+}(\tau, z) \cdot \Delta_w(t) \cdot \Delta_G(t) \cdot \frac{1}{\sigma_\Delta(\nu)} \tag{25}$$

Generally speaking, "$\Delta^+(t_o)$" mainly depends on the technological status during the period of time that the investment is realized ($x = t_o - 1990$), thus one may write:

$$\Delta^+(t_o) = 10^{-5} \cdot x^3 - 0.0009 \cdot x^2 + 0.0191 \cdot x + 0.8768 \tag{26}$$

However, it is also essential to mention the accessibility difficulties "Δ_w" -due to bad weather conditions- of almost all Greek islands, especially during the winter. For this purpose, "Δ_w" is a function of the mean wind speed at 10m height.

On top of that, an actual upper limit of wind power penetration is defined in the existing autonomous electrical grids, in an attempt to maintain grid stability. Therefore, the wind energy absorption by the local grid "Δ_G" is drastically falling[5] as the wind power penetration "y" in the local grid is increased, e.g.:

$$\Delta_G \geq 10^{-4} \cdot y^3 - 0.0229 \cdot y^2 - 0.4669 \cdot y + 100.37 \ (\%) \tag{27}$$

where:

$$y(t) = \frac{\text{Total Wind Power of the Grid}\,(t)}{\text{Peak Load of the Grid}\,(t)} \tag{28}$$

Subsequently, during service-period, wind turbines obtain a variable technical availability, depending on their technological status, age and location of the machine. Based on real data evaluations, one may simulate the reliability of most wind turbines by using an appropriate[6] function "$\Delta_n(\tau,z)/\Delta^+$".

Finally, the impact of wind turbines used relative size "ν" is expressed via "$\sigma_\Delta(\nu)$" coefficient, written as:

$$\sigma_\Delta = 0.9903 + \frac{0.24438}{(1 + 1.41611 \cdot \nu)^{3.676741}} \tag{29}$$

Similarly, the economic behaviour of a wind power installation can be also assessed using the economic efficiency "η^*" of the wind plant. Thus, using the definitions by the authors[6,10] one gets:

$$\eta_n^* = \tilde{G}_n / \left[IC_o \cdot (1 - \gamma) - \tilde{Y}_{(n)} \right] \tag{30}$$

where the symbol "~" is used to express constant values at the moment that the investment was accomplished. Besides, "$Y_{(n)}$" represents the residual value of the investment, mainly due to amounts recoverable at the "n" year of the project life.

Recapitulating, using the above theoretical model (presented in details in [6,10]) one has the opportunity to estimate the optimum wind power penetration in an autonomous electrical grid on a purely financial basis.

4. Applications Results

Aegean Archipelago is a remote Hellenic area, east of the mainland, including a large number of tiny, small and medium-sized scattered islands. More specifically, N. Aegean is one of the most underprivileged E.U. territories, distant from Athens; thus presenting major infrastructure deficit. The biggest islands of this area -Lesvos, Chios and Samos- possess their own electrical autonomous power stations (APS), while four supplementary small APS also exist in Ikaria, Limnos, Samothrace and Agios Efstratios islands.

In the following, the above-mentioned region is selected as an interesting example to check the applicability of the proposed analysis. One of the most remarkable characteristics of this area is its high wind potential, since in almost all islands the wind speed exceeds at several locations the 8.5m/s at 10m heights. Due to the available wind potential quality, a considerable number of wind turbines are operating since 1990 in all these islands. Using Table II information for the annual electricity parameters, along with equation (7), the maximum theoretical wind power penetration for each island is given in Table III.

Table II: Information about N. Aegean Remote Islands

Island	Peak Load (kW)	Elec. Cons. (MWh)	CF_G	Wind Power (kW)	CF_w	Area (km^2)
Lesvos	47000	217839	.529	2850	.370	1630
Chios	33300	149635	.513	5800	.255	843
Samos	24400	107338	.502	3900	.314	477
Limnos	12300	49321	.458	1140	.176	475
Ikaria	5860	20069	.391	385	.340	255
Samothrace	1560	2562	.187	220	.338	180
Ag. Efstratios	250	833	.380	150	.250	47

Table III: Wind Power Data for N. Aegean Islands

Island	Wind Power (kW)		Wind Turbine Size (kW)	
	Max	New	Max	Max(1)
Lesvos	14100	11250	1000	1500
Chios	9990	4190	1000	1000
Samos	7320	3420	750	1000
Limnos	3690	2550	500	600
Ikaria	1758	1373	500	600
Samothrace	260	40	-	-
Ag. Efstratios	75	0	-	-

From this preliminary investigation, the upper theoretical wind power penetration limit in N. Aegean Sea is 37MW; therefore the maximum new wind power supplement cannot exceed 23MW, as they already operate in the area 14MW of wind power, belonging almost exclusively to PPC.

Accordingly, by using equation (8) one may estimate the maximum wind turbine size capable of being installed in these islands, on the basis of available infrastructure. Subsequently, one may use equations (9) and (10) to estimate the necessary new wind parks area in each island, along with the corresponding wind turbines size and number. Considering these islands surface and high wind potential, one may easily conclude that there is no area depended limit for any new wind park establishment.

Similarly, due to the infrastructure limit and the maximum electrical power restriction, the number and size of wind turbines to be installed are not arising any significant annoyance on the local societies, which are generally in favor of such applications.

In order to estimate the suggested wind power penetration for each island, the economical model by the authors[6] is to be applied. Therefore, due to limited space, the application results concerning two representative islands are portrayed here. The islands analyzed is the biggest one (islands of Lesvos) and one of the small isles of the area, the island of Limnos.

Table IV: Numerical Values of the Main Economic Parameters

Capital Cost (i')	Return on Investment (i)	Inflation (g)	M&O Inflation (g^{Σ})	Energy Escal. Rate (e)
5-14%	6-15%	2-7%	2.5-4%	(-2)-7%

Limnos, is a small island of 13000 habitants and 475km^2 area. The wind potential of the area is very high, thus two small PPC wind parks operate in the island since 1992 (8x55kW and 7x100kW). According to Table III, the maximum wind turbine size that can be installed in the island is 500kW, while smaller engines rated between 200 and 300kW might be more appropriate for this specific region.

In this context, applying the economic model given by the authors for variable number (z=1 to 11) of 225kW wind turbines, the estimated payback period is presented in figure (1), under a pre-described number of economic scenarios (Table IV). According to the calculation results, the best wind turbine number is 4 to 6 (i.e. 900 to 1350kW), although in any case the new investment is hardly viable. This conclusion is clearly supported by the twenty-year financial efficiency of the investment (figure (2)).

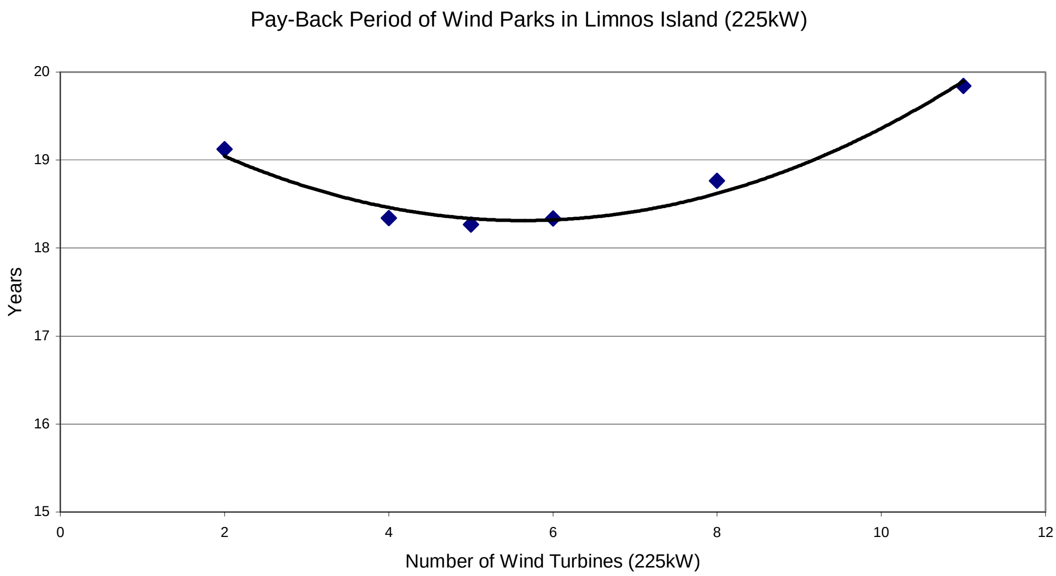

Figure 1: Pay-back Period of Wind Parks in Limnos

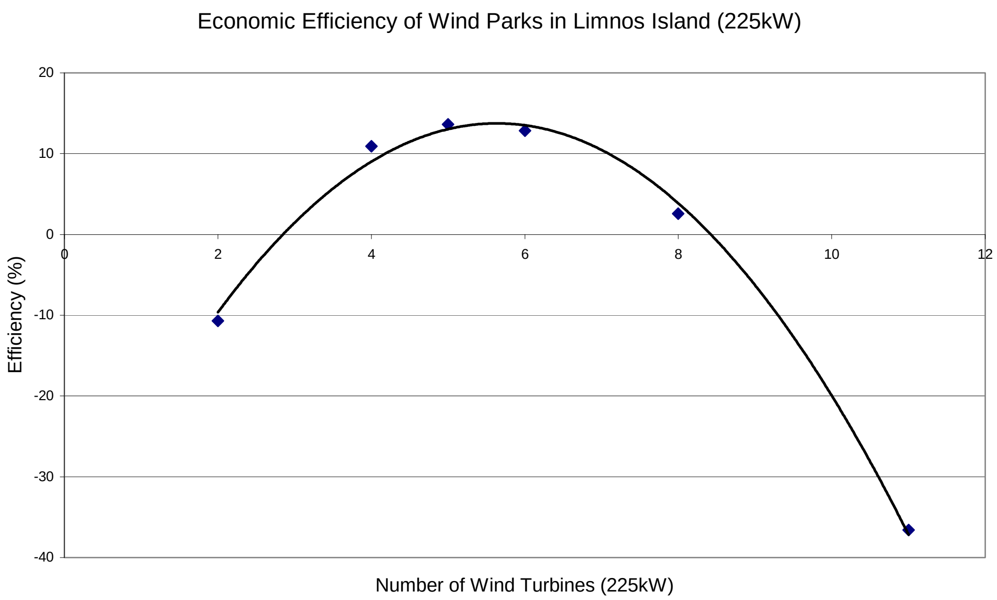

Figure 2: Economic Efficiency of Wind Parks in Limnos

The viability of new wind parks in Limnos island is fairly improved by using the 500kW turbines, figure (3). In this case the maximum long-term efficiency is 130%. Summarizing, one may conclude that despite the strong investment subsidization (40%) any wind power supplement in Limnos Island is marginally viable, while the maximum new wind power to be installed is less than 1500kW.

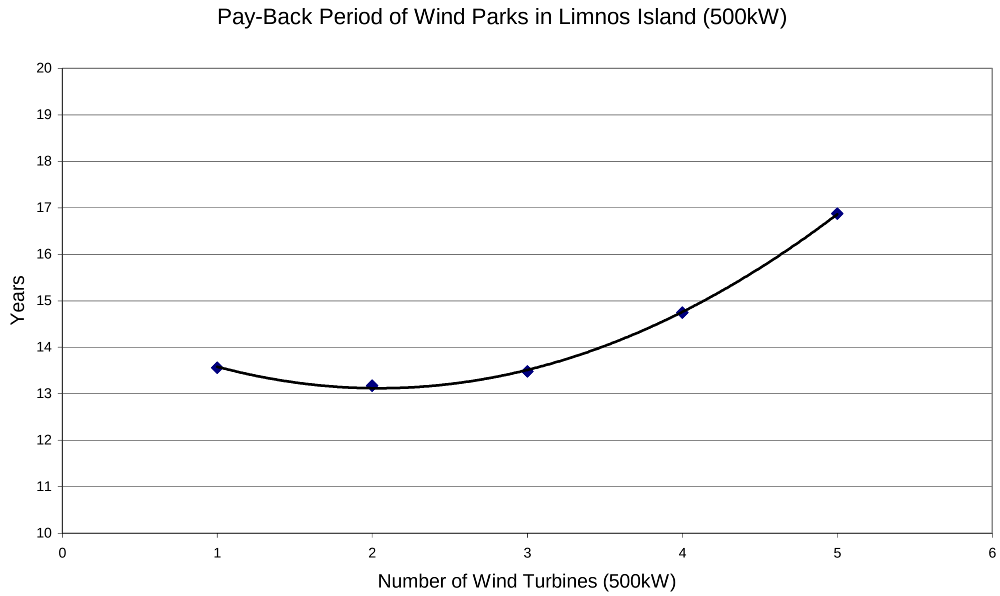

Figure 3: Pay-back Period of Wind Parks in Limnos

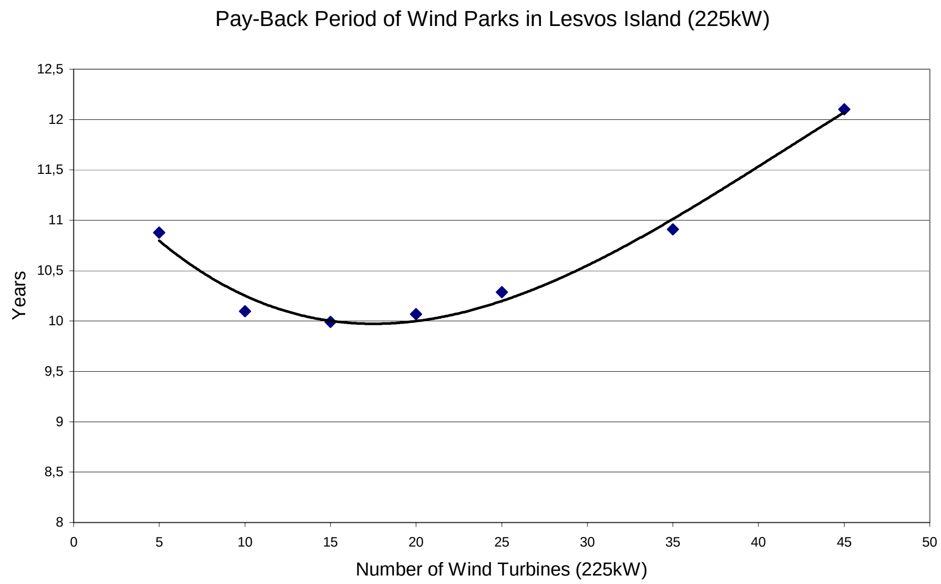

Figure 4: Pay-back Period of Wind Parks in Lesvos

Applying the same analysis for Lesvos Island, one may conclude that the maximum theoretical wind power penetration is 14100kW. Lesvos is the second -after Crete- biggest Greek island of Aegean Sea, possessing an excellent wind potential, as in several areas the local wind speed exceeds 8m/s. In the area two wind parks operate: one of 9x225kW by PPC and a smaller one of (2x300+225)kW by municipality of Mytilene. Hence, the maximum new wind power to be installed is approximately 11250kW.

Considering the local infrastructure status, one may state that the biggest wind turbine to be installed in the island -without any significant infrastructure reinforcement- is up to 1MW. In order to obtain an accurate picture of new wind farm possibilities, the authors analyzed three representative alternatives, i.e.:

a. 1 to 50 wind turbines of 225kW (similar to the ones already operating)
b. 1-18 wind converters of 600kW (the most reasonable solution according to the existing infrastructure status)
c. 1-11 wind turbines of 1MW (to take advantage of the scale economies and the current manufacturers trend)

According to the calculation results obtained for the 225kW solution (figure 4), the optimum economical behaviour is realized for z=15. Besides, for z>25 the wind power investment financial parameters are clearly worsening.

For the second wind turbine size (600kW) the general investment behaviour is remarkably ameliorated, since the minimum payback period predicted is 8.2 years and the corresponding long-term (20-year) economic efficiency is greater than 350%. However, for z>10 the financial characteristics of the investment are clearly depreciating, figure (5), while the maximum medium-term (10-years) efficiency and the minimum payback period is realized for z=7.

Subsequently, for the biggest wind turbines case the optimum wind turbine number is z=3 or 4 (figures 6 and 7). On the other side, for z>6 the new wind parks present negative financial performance. Summarizing, one may state that the maximum wind power supplement in Lesvos Island (beyond the two wind parks operating) is hardly 5MW (20x225kW or 8x600kW or 5x1MW). As far as the more attractive contribution is concerned, the biggest wind turbines present a relatively competitive advantage, although the 600kW alternative seems more practical.

Finally, the proposed wind turbines can be spread in one or two wind parks, not demanding significant area (less than 0.03% of island area) and not inducing any remarkable impact on local societies.

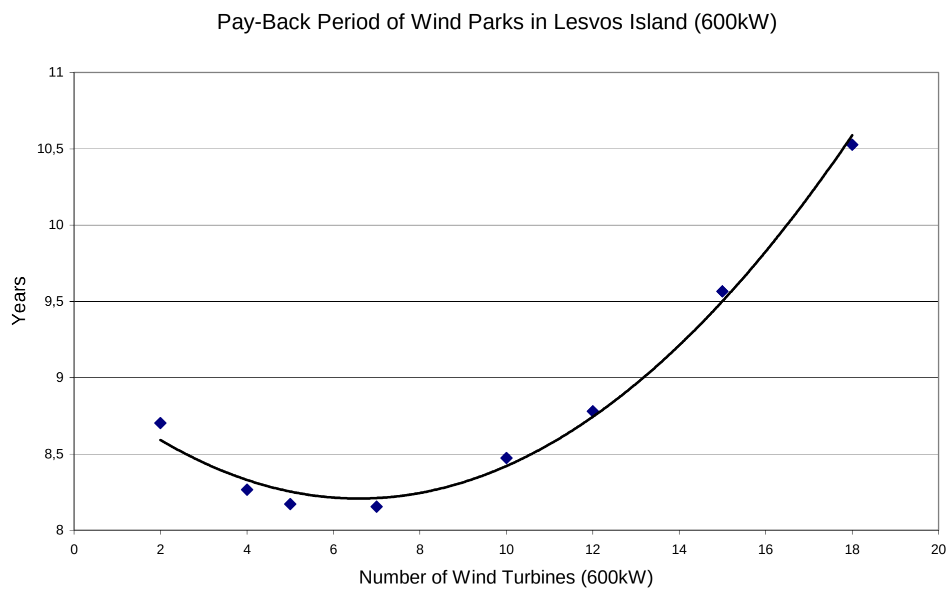

Figure 5: Pay-back Period of Wind Parks in Lesvos

5. Conclusions

An extensive study concerning the optimum wind power applications size in Greece is carried out, in order to obtain a realistic evaluation of the new wind park requests -over 11000MW- by various investors. The proposed analysis is mainly focused on the Aegean Archipelago region, since the best

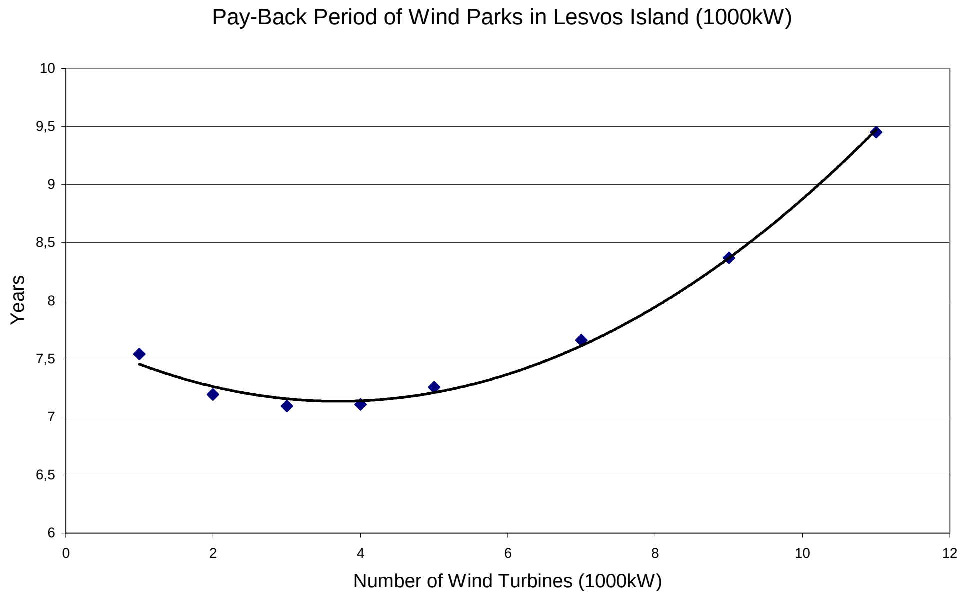

Figure 6: Pay-back Period of Wind Parks in Lesvos

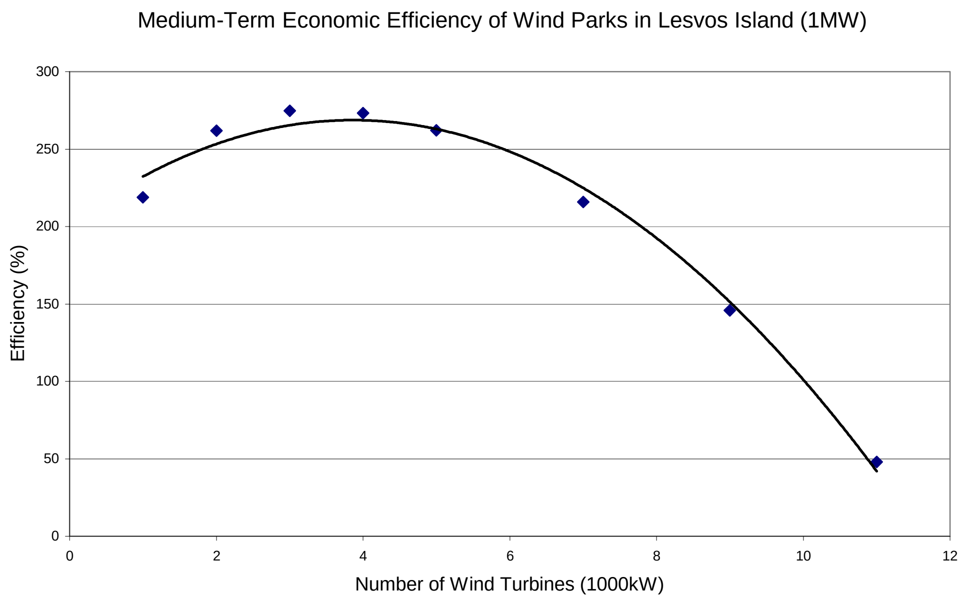

Figure 7: Economic Efficiency of Wind Parks in Lesvos

wind potential opportunities of important wind power penetration are gathered there. However, according to the existing electrical network and infrastructure situation, any substantial wind power supplement is marginally attractive, at least on the basis of the economic scenarios examined. Additionally, the maximum wind turbine size for Aegean Sea islands is hardly 1MW, while engines of 500-600kW are assumed more appropriate.

More specifically, for the N. Aegean Sea case, the economically viable wind power supplement is hardly 15MW, while in no case can this quantity exceed the 40MW, compared to the 297MW planned by interested investors. Only in case that the local electricity network is strengthened and the wind-hydro solution is adopted[12], it is possible to substantially increase the wind power contribution to the local electricity demand. In the opposite case the wind energy is not going to play an important role for the local economy improvement, despite the excellent wind potential of the area.

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A RELIABLE NUMERICAL ALGORITHM USED TO PREDICT THE OPTIMUM OPERATIONAL POINTS OF CONTEMPORARY TURBOFAN ENGINES

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Abstract

Due to the increased competitiveness among engine manufacturers, sophisticated engine monitoring systems have been developed during the last years. Similar investigations are directed towards minimizing the fuel consumption of the engine and reducing the maintenance cost through early fault identification, without jeopardizing the safety of the aircraft. The problem to be solved in the present study can be described as follows: "Given the flight conditions (i.e. aircraft velocity, wind speed, flight height, aircraft weight, ambient conditions and flight angle) estimate the optimum operational point of the aircraft engines -on the basis of thrust required- that fulfills the governing equations, under an optimization target (e.g. minimum fuel consumption or/and minimum HPT inlet temperature value)". In this context, a reliable numerical algorithm is developed in order to determine the necessary parameters values of a twin-spool turbofan engine, validating the governing equations of the problem, including energy, momentum and mass balance of the system. By applying the proposed algorithm, it is possible to adapt the engine operation on any runway or weather condition in an attempt to obtain a better performance operation. On top of that, special attention is paid to fulfill the flight requirements even during takeoff and landing procedures.

Keywords: Optimum Point; Turbofan Engine; Numerical Algorithm; Aircraft

1. Introduction

It is well known that the aircraft sector faces serious economical problems mainly due to the increased market competitiveness, leading several traditional firms one-step before bankruptcy. Among the reasons causing these serious economical problems, the high maintenance and operational cost -imposed by the extreme safety measures- has a dominant effect[1].

In an attempt to reduce the operational cost of an aircraft (e.g. reduction of fuel flow consumption and maintenance cost) and simultaneously increase the reliability of the transportation sector (e.g. early fault diagnosis) several interesting studies have been presented by various research groups[2][3][4].

In this context a new computational algorithm has been developed in order to predict the optimum operational point of a twin-spool turbofan engine, under given flight conditions. This research has been directed towards minimizing the fuel consumption of the aircraft engine and reducing the maintenance cost through early fault identification without jeopardizing the safety of the flight.

2. Position of the Problem

The problem to be solved in the present study can be described as follows: "*Given the flight conditions* (i.e. aircraft velocity, wind speed, flight height, aircraft weight, ambient conditions and flight angle) *estimate the optimum operational point of the aircraft engines* (on the basis of thrust required) *that fulfills the governing equations, under an optimization target* (e.g. minimum fuel consumption or/and minimum HPT inlet temperature value)".

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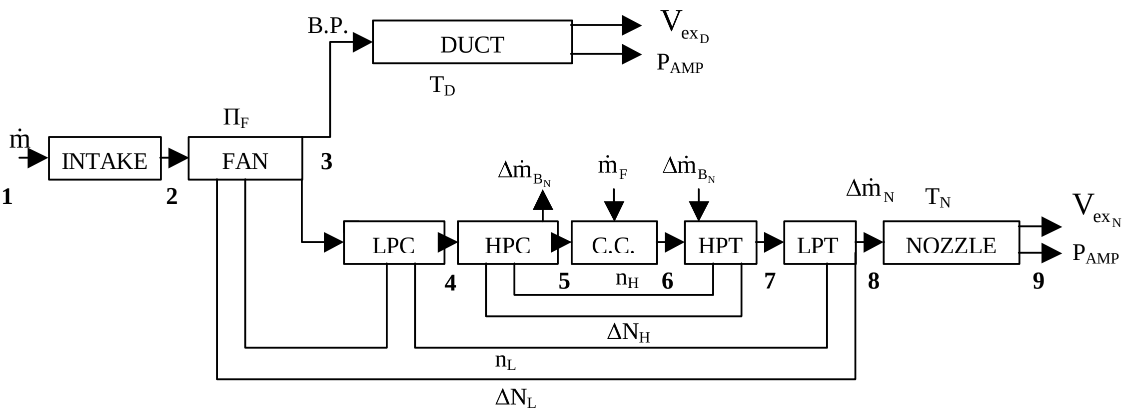

Figure 1: Schematic presentation of a twin spool turbofan engine

In order the proposed method to be applied in a specific engine (see also figure (1)), the operational maps of the engine components are required. On top of that, an attempt has been made to adapt typical engine maps[5] to an individual engine by using available test rig measurements, including aging effects.

Subsequently, the aircraft operational parameters (e.g. weight, wing area, lift and drag coefficients) as well as the flight conditions have been taken into consideration[6], since the engine thrust should validate the aircraft equation of motion.

Finally, in order to select the best operational point of the engine, under given flight conditions, several optimization targets have been set. The most widely used conditions/constraints include minimum specific fuel consumption, limited HPT inlet gas temperature and low noise emission level. Keep in mind that the importance (weight factor) of each restriction is normally set by the aircraft company[7].

3. Proposed Solution

For the analysis of a twin spool turbofan engine the following equations[8][9] should be taken into account:

a) High-speed shaft power balance
b) Low speed shaft power balance
c) Mass flow conservation at the hot nozzle inlet
d) Mass flow conservation through the engine duct
e) Combustion chamber energy conservation
f) Mass flow conservation through combustion chamber
g) Mass continuity through the engine (i.e. the mass flow rate at the inlet of the engine’s component equals to the mass flow rate at the outlet of the preceding component minus or plus any bleeding)
h) Aircraft lift requirement equation
i) Aircraft thrust requirement equation
j) Engine’s by pass ratio definition
k) Equation of engine thrust calculation

Using the above equations one may calculate the following engine parameters:

1) Engine thrust (T)
2) Mass fuel flow (m_f)

3) Mass airflow (m)
4) Low speed shaft rotational speed (n_L)
5) High speed shaft rotational speed (n_H)
6) Engine by-pass ratio (BP)
7) Hot nozzle exit velocity (Vex_n)
8) Duct exit velocity (Vex_D)
9) HPT inlet temperature (T_{tHPT}^{in})
10) Aircraft lift (L)
11) LPT pressure ratio (Π_{LPT})
12) HPT pressure ratio (Π_{HPT})
13) FAN pressure ratio (Π_{FAN})

In order to calculate the engine parameters the above-mentioned equations have been divided in two subgroups. The first subgroup includes equations (a, b, c & i) and is used for the estimation (via an optimization procedure) of the appropriate values of:

i) mass fuel flow of the engine
ii) low speed and high speed shaft rotational speeds
iii) fan pressure ratio

The second subgroup, including the rest of equations, is analytically resolved in order to provide the numerical values of all the rest parameters of the engine.

The main data required for the proposed analysis are the following.

1) FAN, LPC, HPC, HPT and LPT operational maps of the specific engine under investigation
2) Aircraft drag and lift curves
3) Specific calorific value of fuel used
4) Engine geometry
5) Aircraft weight, velocity, acceleration and angle of flight
6) Ambient conditions
7) Combustion chamber efficiency
8) Engine bleedings
9) Pressure drop through engine intake, combustion chamber, duct and hot nozzle

For the solution of the problem, a number of approximations[10] have been comprised either explicitly or implicitly. More specifically, the problem to be solved is characterized as quasi-steady, i.e. every flight point has been separately examined, with regards to the acceleration terms in aircraft equations of motion. Accordingly, the perfect gas assumption is used during the analysis, meaning that specific heat coefficient -at constant pressure "C_p" and adiabatic coefficient (ratio of specific heats) "γ"- are single functions of temperature.

Moreover, during the calculations both duct and nozzle are ambient-adapted, meaning that the static pressure at the duct and nozzle outlet is equal to the corresponding ambient pressure.

Finally, during the power equilibrium equations concerning the two rotating shafts of the engine, the transient phenomena are assumed negligible (i.e. $dn_H/dt=0$ and $dn_L/dt=0$), being in accordance with the quasi–steady state assumption made in the aircraft equations of motion.

For the solution of the problem, one should consider the complicated form of the governing equations, which usually depend on a large number of parameters. Besides, the engine components operational maps are not available in analytical forms, as they are usually presented as numerical data (i.e. data pairs). For this purpose, the subsequent procedure has been followed:

[1] Calculate, using the aircraft's equation of motion, the thrust required to maintain aircraft flight condition.

[2] Select a mass fuel flow value "m_f", starting from a first initial guess, and subsequently modify the proposed value according to the sign of the difference between engine thrust and aircraft required thrust, i.e. $T=T(m_f)$.

[3] Define the numerical range from which "n_L" and "n_H" take values, on the basis of the operational maps of the engine.

[4] Check, using an iterative procedure, for all the combinations of "n_L" and "n_H" the validation of equations (a), (b) and (c), using pre-described numerical steps, "δn_L" and "δn_H".

[5] For every "n_L" value, define the variation range of "Π_{FAN}" using the fan operational map, in order to avoid unsteady operation or operation near the surge line.

[6] For every (n_L, n_H) pair check all the available numerical values of "Π_{FAN}" taking values from "$\Pi_{FAN\ min}$" to "$\Pi_{FAN\ max}$", using a specific step "$\delta\Pi_{FAN}$".

[7] At this point one has determined the values of (m_f, n_L, n_H, Π_{FAN}). Thus, using these numerical values:

1) Analyze the engine FAN, knowing that $m=m(n_L,\Pi_{FAN})$ and $\eta_{is\ FAN} = n_{isFAN}(n_L,\Pi_{FAN})$
2) Analyze the engine duct, using the duct efficiency and geometry and the static pressure at the outlet of the duct
3) Calculate the thrust component induced by the duct (T_D)
4) Calculate the engine by pass ratio as a function of the secondary mass flow rate to the total mass flow rate of the engine.
5) Estimate the core mass flow rate entering the LPC
6) Estimate the engine LPC characteristics knowing the core mass flow rate and "n_L"
7) Estimate the engine HPC characteristics knowing the LPC outlet mass flow rate, any bleedings and "n_H"
8) Calculate the combustion chamber parameters knowing the HPC outlet mass flow rate, any bleedings, the mass fuel flow rate "m_f", the total pressure drop through the combustion chamber, the combustion chamber efficiency and the fuel specific calorific value
9) Estimate the HPT characteristics, knowing the mass flow rate and the thermodynamic quantities at the combustion chamber outlet, the characteristics of the bleeding returning and "n_H"
10) Estimate the LPT parameters, knowing the mass flow rate and the thermodynamic quantities at the HPT outlet, the characteristics of any bleeding returning and "n_L".
11) Calculate the mass flow rate at the LPT exit (m_{LPT}).
12) Calculate the residual of the low speed shaft power balance (ΔN_L)
13) Calculate the residual of the high-speed shaft power balance (ΔN_H).
14) Analyze the hot nozzle, knowing the nozzle efficiency and geometry, the thermodynamic quantities at the LPT exit and the static pressure at the nozzle outlet
15) Calculate the nozzle exit velocity and Mach, checking that the flow is subsonic for civil aircrafts
16) Calculate the thrust component due to the hot nozzle (T_N)
17) Calculate the mass flow rate through the nozzle
18) Calculate the non-dimensional difference (Δm) between the mass flow rate at the LPT outlet and the mass flow rate through the nozzle
19) Calculate the sum of the square of the residuals "RES" of the above mentioned equations, i.e.:

$$Res= ½ (\Delta N_L^2 + \Delta N_H^2 + \Delta m_N^2) \quad (1)$$

[8] Execute all the above calculations for every combination of (n_L, n_H, Π_{FAN}) in order to estimate the minimum value of the residual of the governing equations

[9] After the iterations have been completed, a specific set of (n_L, n_H, Π_{FAN}) values has been allocated, minimizing the residual of the governing equations, under the assumption of a given mass fuel flow rate value

[10] For the optimal combination of (n_L, n_H, and Π_{FAN}) repeat the engine analysis in order to calculate the duct and nozzle thrust components

[11] Calculate the engine total thrust, which is compared to the value of the thrust required by the aircraft

[12] If a remarkable difference between these two values is encountered, re-estimate the mass fuel flow and repeat the complete procedure from step [3]. Otherwise, the solution is obtained and the engine's operational point is characterized by: (m_f, T, n_L, n_H, and Π_{FAN}).

[13] Lastly, a new flight point is to be analyzed, taking into account the aircraft weight diminution -due to the mass fuel flow consumed- during the operation of the aircraft engines thus far.

4. Numerical Algorithm Presentation

By using the above described solution methodology, a new, fast and reliable numerical algorithm[11] has been developed, based on the residual minimization of the problem governing equations (equation (1)). More precisely, the problem to be solved by the proposed algorithm is the following: "*Given the mass fuel flow, find the operational point of the engine, in order to minimize the residual of equation (1), hence estimate the thrust of the engine*".

In this context, the solution is obtained after analyzing all the combinations of (n_L, n_H, Π_{FAN}), where:

$$n_{L_{min}} \le n_L \le n_{L_{max}} \qquad \text{with step "}\delta n_L\text{"} \tag{2}$$

$$n_{H_{min}} \le n_H \le n_{H_{max}} \qquad \text{with step "}\delta n_H\text{"} \tag{3}$$

$$\Pi_{FAN_{min}} \le \Pi_{FAN} \le \Pi_{FAN_{max}} \qquad \text{with step "}\delta \Pi_F\text{"} \tag{4}$$

with step "δn_L", "δn_H" and "$\delta \Pi_F$" respectively.

Keep in mind that "n_{Lmin}", "n_{Lmax}", "n_{Hmin}" and "n_{Hmax}" are defined according to the operational maps of the engine components, while "Π_{Fmin}" and "Π_{Fmax}" are estimated for every specific "n_L" value in order to ensure FAN proper operation.

It is important to mention that during the calculation procedure the sum of residuals of the following equations is computed:

- Low speed shaft power balance "ΔN_L"
- High speed shaft power balance "ΔN_H" and
- Mass conservation at the hot nozzle inlet "Δm_N"

Hence the best solution is expressed as:
Find (n_L, n_H, Π_{FAN}) that minimize Res= ½ ($\Delta N_L^2 + \Delta N_H^2 + \Delta m_N^2$), under the constraints of equations (2) to (4).

Finally, the thrust of the engine is calculated and the predicted operational point is an acceptable solution provided that the following relation is valid:

$$T_{req} = z^*T(m_f) \tag{5}$$

where "z" the number of engines used by the aircraft.

The proposed algorithm is given schematically in figure (2).

After executing a large number of calculation tests, the convergence behavior of the algorithm becomes quite stable, as very low residual values linger near the solution, also see chapter 5. It is also important to mention, at this point, that the present algorithm was originated to detect -in any case- an acceptable operational point of the engine, whereas the convergence velocity is not our primary concern.

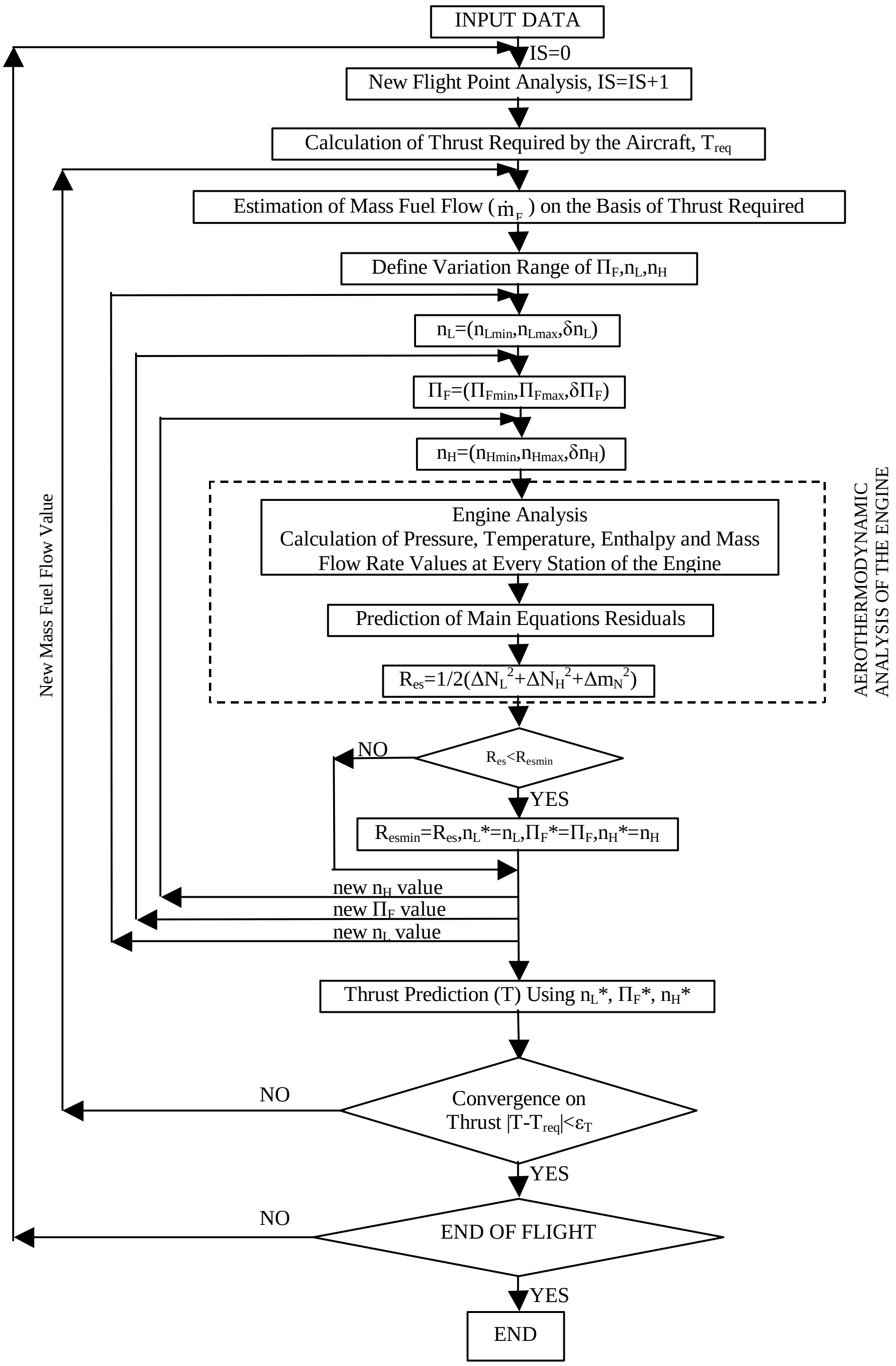

Figure 2: Logical diagram of the proposed numerical algorithm

On top of that, selecting finer searching steps may increase the accuracy of the solution. Hence, if "δn_L", "δn_H" and "$\delta \Pi_{FAN}$" get decreased the searching procedure is ameliorated at dispense of computational effort required. Finally, some additional timesaving techniques are also incorporated in the proposed algorithm, like the "sequential level searching technique". This procedure is initially based on a course searching, getting gradually transformed to finer searching process, focused near the operational region where the minimum residual -on the previous searching level- has been encountered. However, the analytical presentation of all convergence acceleration techniques[11] is beyond the scope of the present work.

5. Calculation Results

The above-presented algorithm has been applied in several cases in order to simulate the aircraft engine behavior under variable flight conditions. In the present paper, the calculation results concerning the aero-thermodynamic parameters of the CFM56-3C engine are analyzed[12].

The CFM56 is one of the most successfully operated engines in the aircraft history. The first model entered in service was CFM56-2-C1 with certification date November 1979. However, CFM delivers its first engine on March 17 of 1982 for a DC-8-71 aircraft. Since then, more than 11000 engines are operating throughout the world. One of the most successful models of CFM56 is CFM56-3C1 used by B737-300, B737-400 and B737-500.

More specifically, the CFM56-3C-1 entered in service during September 1982 and it is a high by pass turbofan engine with maximum thrust of 110000 Nt. Olympic Airways uses CFM56-3C-1 in fourteen commercial aircrafts traveling either through Europe (i.e. Paris, London etc) or throughout Greece (i.e. Rhodes, Corfu, Crete etc.).

Among the engine basic geometric characteristics, there have been its 93" length, the 60" fan diameter, its dry weight of 4301 lbs, the maximum low-speed shaft rotational speed of 5490rpm, the high-speed shaft rotational speed of 15183 rpm and its mass flow of 638/710lbs/sec. Thus far the engine operation is characterized as quite reliable, since the average time to first shop visit is after the 10000 hours of flight, while the engine applies environmental friendly technological achievements reducing noise emission and NO_X production by 40%.

The above-described calculation algorithm is going to be applied for the CFM56-3C engine analysis.

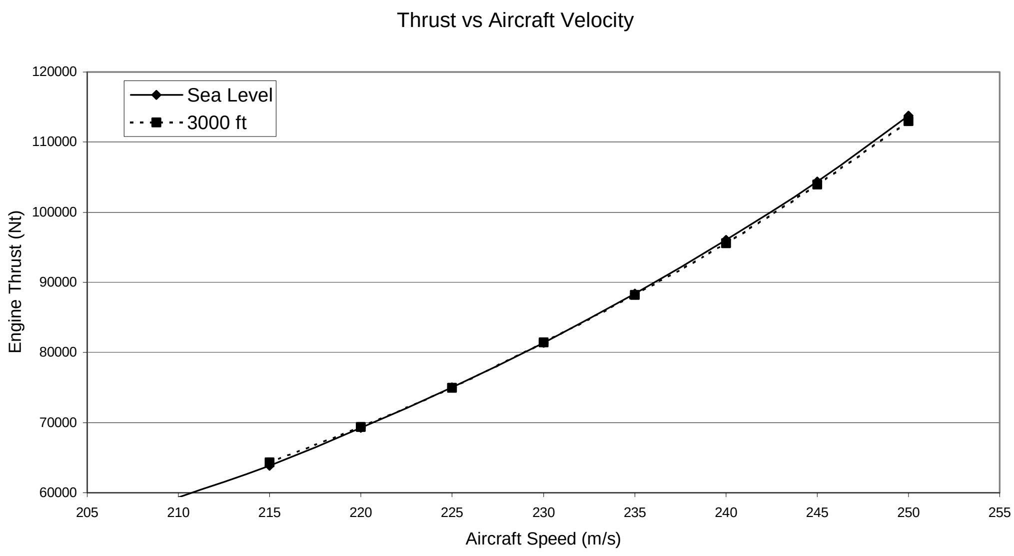

Figure 3: Calculated thrust versus aircraft speed

In order to reveal an unambiguous picture of the proposed algorithm capabilities, selected results from two different flight height cases are presented for a wide operational range of the engine.

More precisely, in figure (3) the calculated engine thrust is sited as a function of aircraft speed at sea level and at 3000 ft. As expected the engine thrust is substantially increased with the aircraft speed mainly due to the aircraft boundary layer drag increase. The results obtained are in accordance with the manufacturers data provided.

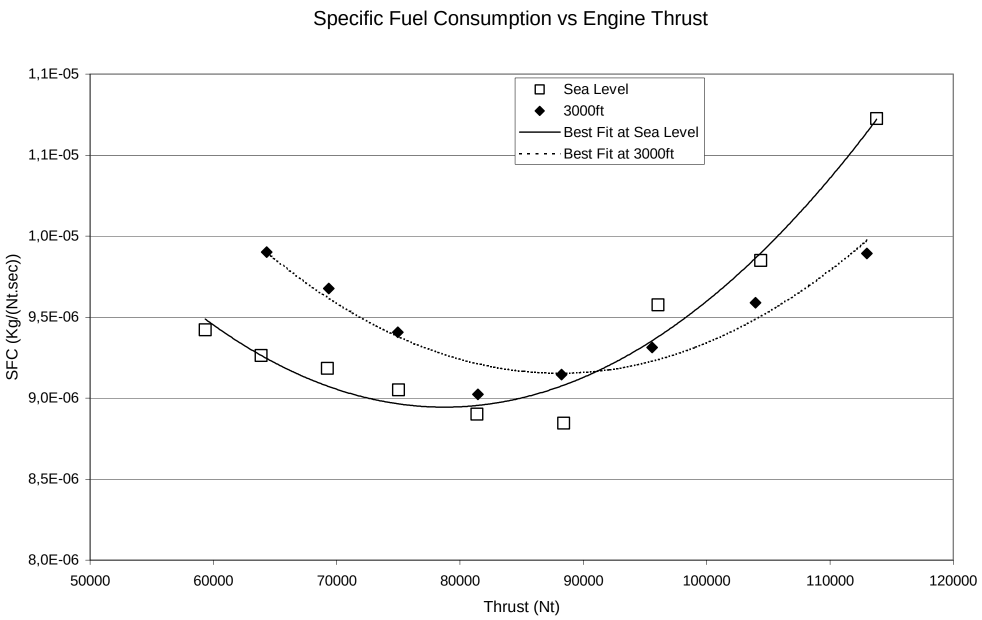

Figure 4: Calculated specific fuel consumption

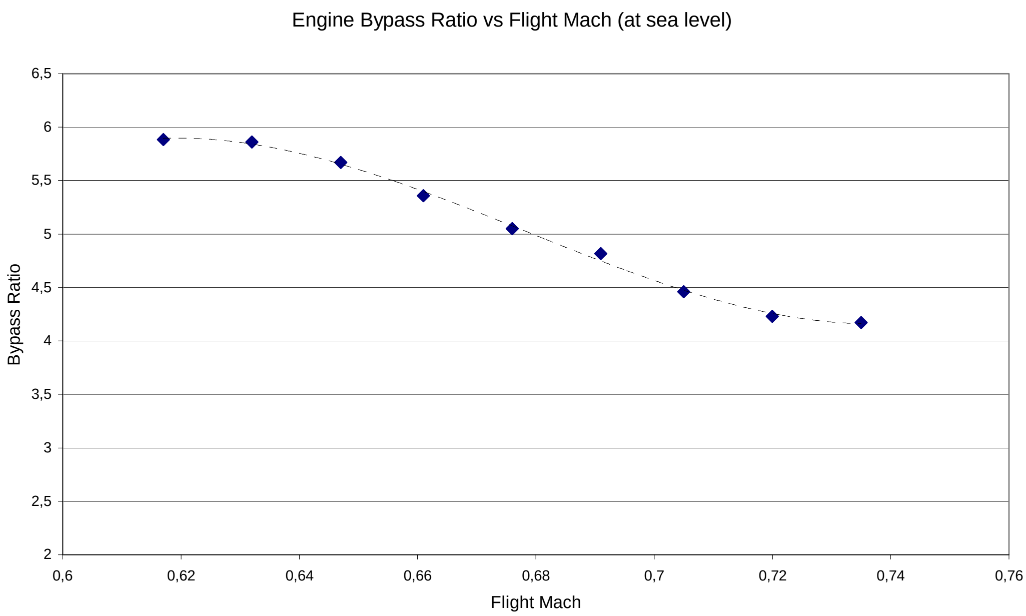

Figure 5: Calculated engine bypass ratio vs flight Mach

Accordingly, in figure (4) the specific fuel consumption (SFC) of the engine is expressed as a function of the engine thrust at two different flight altitudes. Analyzing the calculation results, one may estimate the minimum specific fuel consumption, which appears at 82000 Nt thrust value (at sea level) and at 88000Nt thrust at 3000ft. Moreover, the SFC operational value is lower at sea level than at 3000 ft

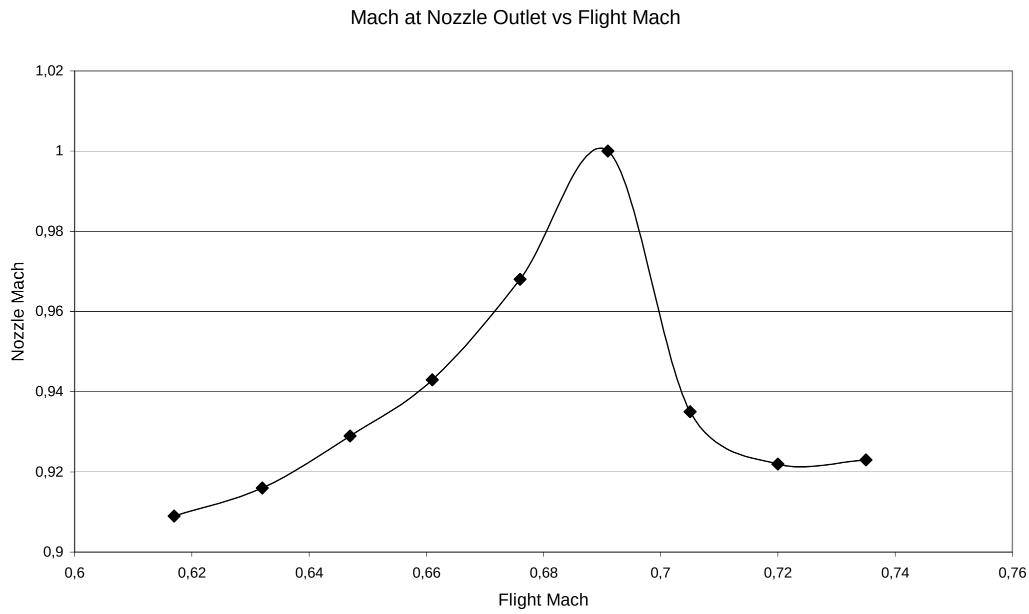

Figure 6: Calculated nozzle outlet Mach number

up to 85% engine thrust values. On the other hand, lower SFC values take place at 3000 ft, under the assumption of constant thrust values. By combining figures (3) and (4), one has the opportunity to find the optimum aircraft speed at different flight heights, under the minimum consumption target assuming standard day conditions. The proposed analysis can be applied in any flight case, by simply inserting in the program the necessary data describing the real atmospheric conditions.

Another two interesting parameters expressing the operation of a turbofan engine are the engine bypass ratio (BP) and the Mach number at nozzle outlet (M_{ex}). Using as an example the calculation results at sea level we present in figure (5) the bypass ratio evolution as a function of the flight Mach. According to the results obtained, the bypass takes values between 4.2 and 5.8, while it is continuously dropping as the flight Mach increases.

In figure (6), the calculated nozzle exit Mach is given as a flight Mach function. According to these results,

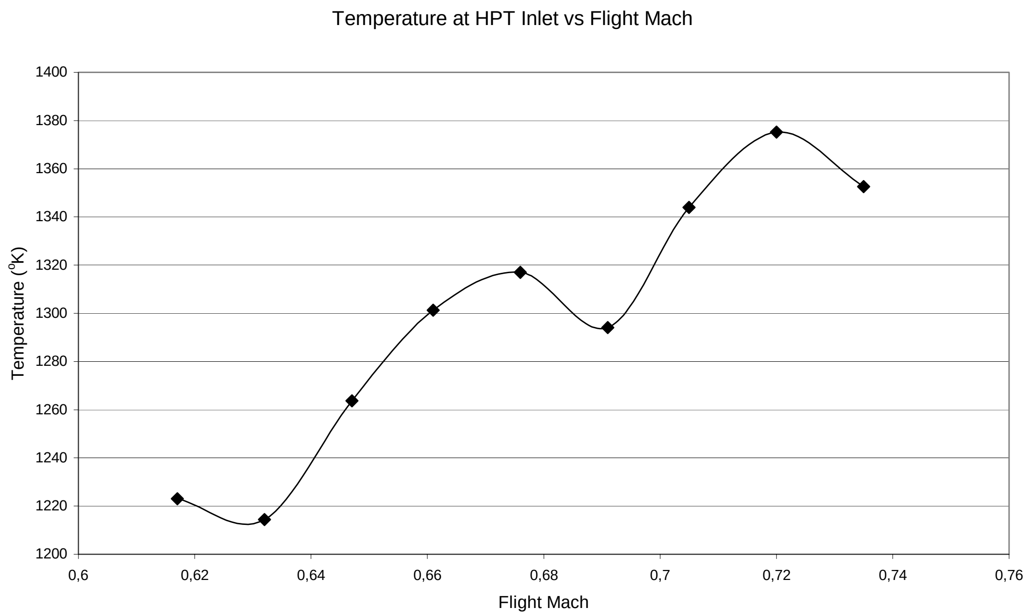

Figure 7: Calculated total temperature at HPT inlet

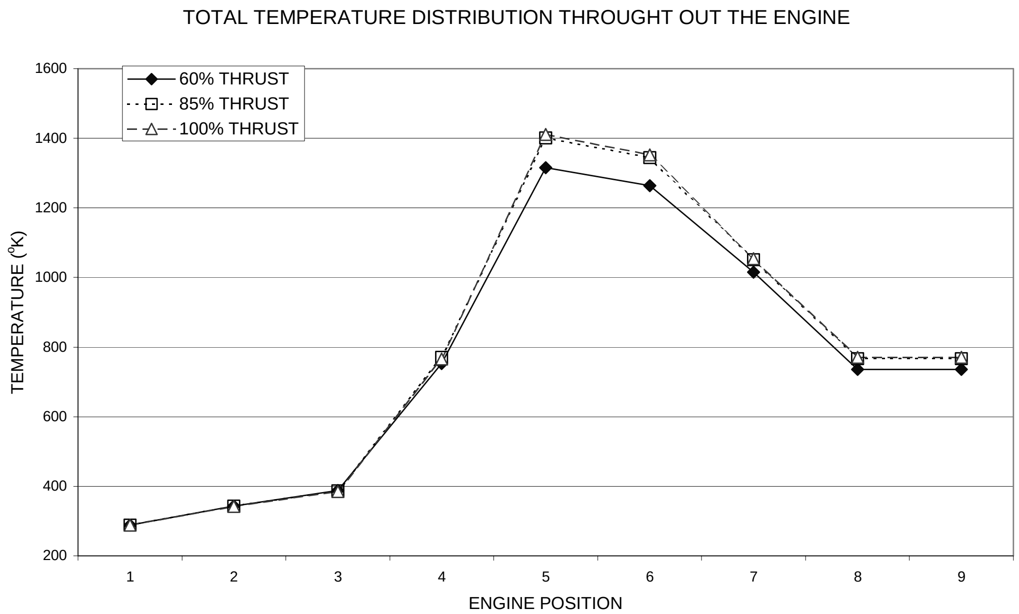

Figure 8: Total temperature distribution through the engine

the nozzle Mach increases initially up to flight Mach 0.69. In this specific case (at sea level) the nozzle is theoretically choked. Therefore, for higher flight Mach numbers, the complete operational line of the engine is altering (rotational speed changes); hence the nozzle exit Mach takes quite lower values, remaining practically constant as well.

Finally, in figure (7), the HPT inlet temperature is expressed as a function of aircraft flight Mach. This temperature value is one of the most influential parameters used to determine the service period of a gas turbine engine. By increasing the HPT inlet temperature, the HPT first blade row faces strong thermal stresses. According to the calculation results, the HPT inlet temperature varies between 940°C and 1100° C. More precisely, by using the information of figure (7), one may conclude that the HPT inlet temperature increases with the flight Mach, excluding the case of Mach 0.697, where the nozzle is chocked. Finally, the maximum temperature is calculated at flight Mach 0.72.

The second group of results presented here, contains the total temperature and total pressure distributions throughout the engine at different thrust levels. Thus, in figure (8), one may observe that the total temperature increases throughout the compressors as a consequence of the work added to the air. However, the sharpest temperature increase appears into the combustion chamber due to the fuel addition and the resulting combustion process. Subsequently, a total temperature drop is encountered either due to the mixing between combustion gases and air bleeding returns or as a result of the power extracted by HPT and LPT. This behavior is validated for a wide range of thrust values, ranging from 60% to 100% of the engine nominal thrust. As it is expected, the maximum temperature at full thrust is higher than the corresponding value at 60% thrust, by almost 100°C.

In figure (9) one may observe the total pressure distribution throughout the engine at different thrust levels. According to the computational results a remarkable total pressure increase is recorded through the FAN and the LPC of the engine. However, the main total pressure rise is observed at engine HPC. After the HPC exit a total pressure drop is predicted either due to various pressure losses (i.e. at combustion chamber or throughout nozzle) or as a result of power production by HPT and LPT. Lastly, the total pressure rise is by 10% higher at full thrust operation compared with the 60% thrust function.

Recapitulating, the proposed algorithm has been successfully applied to estimate the optimum flight points of a commercial aircraft engine at several flight speeds and at two selected representative flight

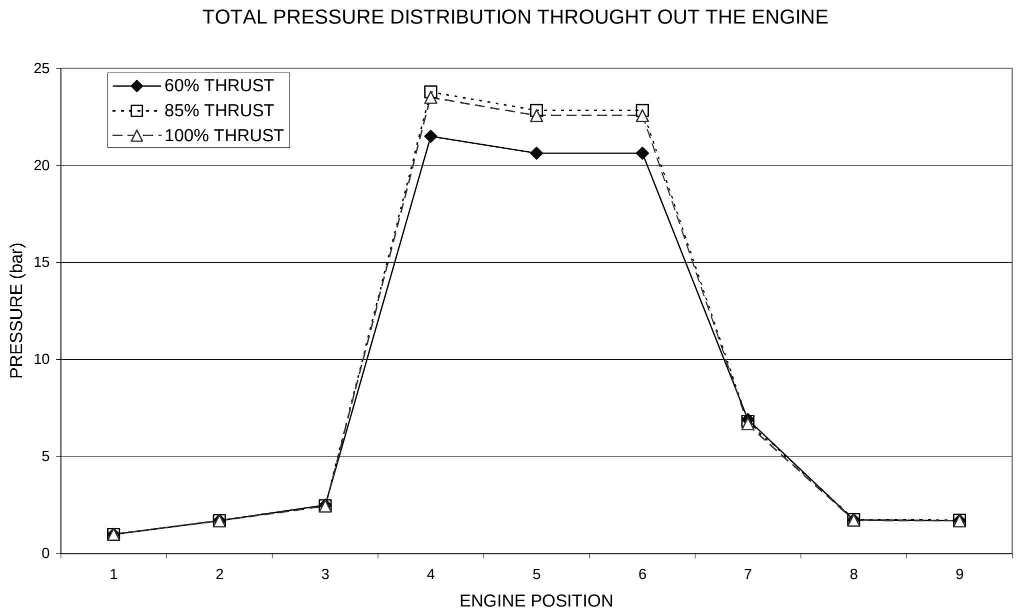

Figure 9: Total pressure distribution through the engine

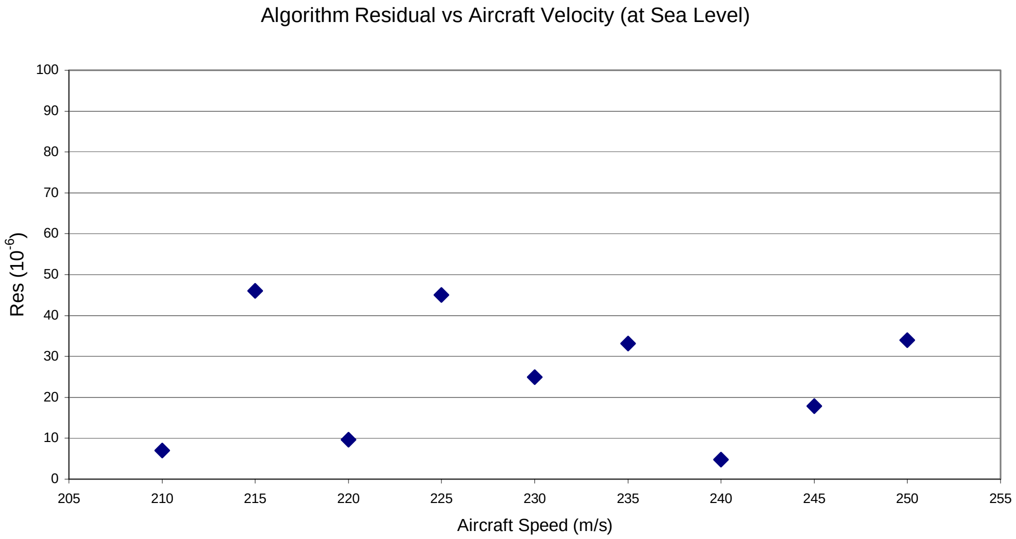

Figure 10: Algorithm residual at convergence point

altitudes. In all cases the calculation results realistically simulate the engine behavior in comparison with the available information provided by the manufacturer and the test rig measurements. As it is obvious from figure (10) the algorithm residual of the problem basic equations (equation (1)) is quite small, not exciding the $5*10^{-5}$ value, while in several cases the residual encountered is in the order of 10^{-6}. On top of that, the calculation algorithm is proved to be quite reliable, providing us **-in any case-** an acceptable operational point of the engine, while the execution time is limited even when making use of a typical contemporary personal computer.

6. Conclusions

An integrated theoretical analysis concerning the aero-thermodynamic behaviour of a modern twin-spool turbofan engine is presented. Accordingly, a new computational algorithm has been developed in order to predict the optimum operational point of a twin-spool turbofan engine, under given flight conditions. Applying the proposed algorithm, it is possible to adapt the engine operation on any runway or weather condition in an attempt to obtain a better performance operation. On top of that, special attention is paid to fulfill the flight requirements even during takeoff and landing procedures. Hence, using the proposed algorithm it is possible to estimate the optimum operational point of the aircraft engines on the basis of thrust required, under an optimization target, e.g. minimum fuel consumption or/and minimum HPT inlet temperature value.

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PART TWO

HYBRID SYSTEMS

- Stand-Alone Systems
- Wind-Hydro

OPTIMAL WIND-HYDRO SOLUTION FOR AEGEAN SEA ISLANDS ELECTRICITY DEMAND FULFILLMENT

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Abstract

Energy shortage and clean water deficit, especially during the summer, are among the main factors delaying the economic development of Aegean Sea islands. All these islands possess an outstanding wind potential. However, the stochastic behaviour of wind speed leads to significant disharmony between wind energy production and electricity demand. Hence, the prospect of creating a combined wind-hydro energy production station is found to be a vital solution for all these islands, under the preconditions of maximum energy autonomy and limited first installation cost. Accordingly, a methodology of optimum wind-hydro solution estimation is developed and subsequently applied to several typical Aegean Sea island cases, in order to define the most beneficial configuration of the proposed renewable station. All numerical calculations are based on real data, like long-term wind speed measurements, demanded electrical load and operational characteristics of the system components. In all cases analyzed, the renewable energy sources penetration exceeds 85%, while a significant part of the system wind energy surplus is forwarded to a desalination plant for clean water production.

Keywords: Wind-Hydro Power Plant; Optimum Energy Solution; Remote Islands; Energy Autonomy

1. Introduction

Wind energy is now a mature electricity production technology[1], constituting an economically attractive solution for the continuously increasing energy demand of most remote Greek islands[2]. The Aegean Archipelago is a remote Hellenic area, east of the mainland, including several hundreds of scattered islands. These islands, along with the mainland coasts, possess a very high wind potential, where the mean annual wind speed (at 10m height) varies between 8 and 11m/s. At the same time, the electricity production cost for their vast majority is extremely high[3], due to the utilization of aged autonomous (based on diesel-electric generators) power stations (APS). Additionally, energy shortage and clean water deficit, especially during the summer (high tourist season) are the main factors delaying the economic development and deteriorating the life quality of local societies[4].

According to the above-described information, wind energy is the most fiscally viable solution for the various energy-related problems of those areas[5]. One of the main obstacles of high wind energy penetration is the stochastic behaviour of wind speed, leading to significant disharmony between wind energy production and electricity demand. On the other hand, an energy storage system, when sized appropriately[6] can match a highly variable wind power production to a generally variable and hardly predictable[7] system demand, remarkably limiting the energy production cost (e.g. generating capacity savings). According to previous research[8][9], a reversible wind-hydro storage system is found to be the most suitable solution for small-medium sized islands.

Therefore, the present essay is keen on revealing an integrated methodology capable of defining the operational characteristics and predicting the optimum wind-hydro solution for the entirety of Aegean Sea islands. The developed procedure is accordingly applied to several typical Aegean Archipelago islands (small, small-medium and medium ones) with very interesting results, under the precondition of maximum energy autonomy and limited first installation cost.

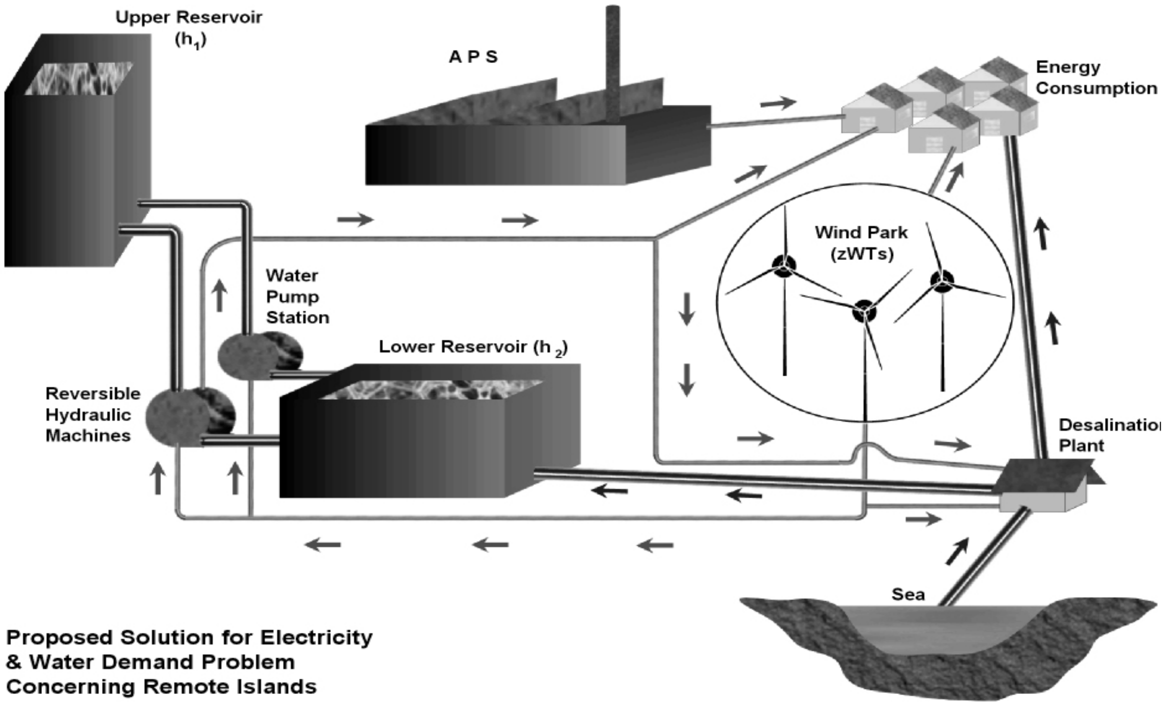

Figure 1: Schematic Presentation of Wind-Hydro Solution for Remote Aegean Sea Islands

2. Proposed Solution

Taking advantage of the up to now presented work[5][8][9], an integrated wind-hydro hybrid station (figure (1)) consists of:

a. A number "z" of wind turbines, constituting one or more wind parks of total rated power "N^*_{WP}", i.e:

$$N^*_{WP} = \sum_{j=1}^{z} N^*_j \tag{1}$$

where "N^*_j" is the nominal power of each wind turbine used. For maximum energy autonomy, the rated wind power should be high enough to fulfill the instantaneously local grid electrical-power demand "N_{peak}" (even in extreme cases of empty upper reservoir), as well as to cover the annual electricity consumption "E_{annual}", including an optional future increase (of power "δN" and energy "δE"), thus:

$$N^*_{WP} \geq \max\{(N_{peak} + \delta N), \left(\frac{E_{annual} + \delta E}{8760 \cdot CF}\right)\} \tag{2}$$

where "CF" is the installation capacity factor[10].

The most theoretically troubled energy management scenario is based on the hypothesis that there is a complete (100%) disharmony between electricity demand and wind power production, thus the total wind energy is forwarded to the consumption via the storage system, efficiency "η^*". In this case:

$$N^*_{WP} \leq \left(\frac{E_{annual} + \delta E}{8760 \cdot CF \cdot \eta^*} \right) \tag{3}$$

where the energy transformation coefficient "η^*" varies between 0.7 for large wind-hydro systems and 0.5 for small installations.

b. A small hydroelectric power plant[11][12] of at least two reversible water turbines. The rated power of the hydro-power station "$N^{*/}_H$" is determined in order to cover the local grid maximum demand "N_{peak}", including an optional future increase "δN", i.e:

$$N_{peak} \leq N^{*/}_H \leq N_{peak} + \delta N \tag{4}$$

c. A water pump station[13], which in collaboration with the reversible water turbines (operating as water pumps "N_H") should have the capability to absorb the rated wind power of the system minus the minimum electricity consumption of the grid[7], thus:

$$N^*_p = N^*_{WP} - N_{min} - N^*_H \tag{5}$$

d. Two (or more) water reservoirs[14] at bottom elevations "h_1" and "h_2" ($h_1>h_2$), working in closed circuit and the corresponding pipelines. The water level of each reservoir "y_1" (or y_2) varies between "y_{min}" and "y_{max}", while "y_{min}" is selected so as to protect the hydraulic machines from solid particles existing near the reservoir bottom and "y_{max}" is defined according to the desired energy autonomy ("d_o" days of autonomy) of the system and the corresponding cross-section area "$\bar{A}$". More precisely:

$$y_{max} = y_{min} + \frac{d_o \cdot \left(E_{annual} / 365 \right)}{\eta_H \cdot \eta_{el} \cdot \rho \cdot g \cdot H \cdot \bar{A}} \tag{6}$$

with:

ρ	the water density
g	the free fall acceleration
η_H	the water turbines efficiency
η_{el}	the electric generators efficiency and
H	the water turbines operational head

e. The existing autonomous power station (APS), based on several "n" aged internal combustion engines, so far used to produce the necessary electricity for the local community. The corresponding rated power of the local APS is given as:

$$N_{APS} = \sum_{i=1}^{n} N_i \geq N_{peak} \tag{7}$$

f. A small desalination plant (build on modular basis), properly sized[4] in order to absorb the energy surplus of the wind park, able to produce clean water from seawater, adopting the reverse osmosis (RO) technology.

The main target of the proposed hybrid system is to fulfill the electricity demand "N_D" of the local society, minimizing the oil consumption. A side benefit of this solution is the clean water production, significantly increasing the local water reserves. Finally, one of the sharpest local community problems (i.e. the power deficit during summer) is also solved, since the total (wind, hydro and thermal) power installed is more than threefold the peak demand of the local grid. This increased -at

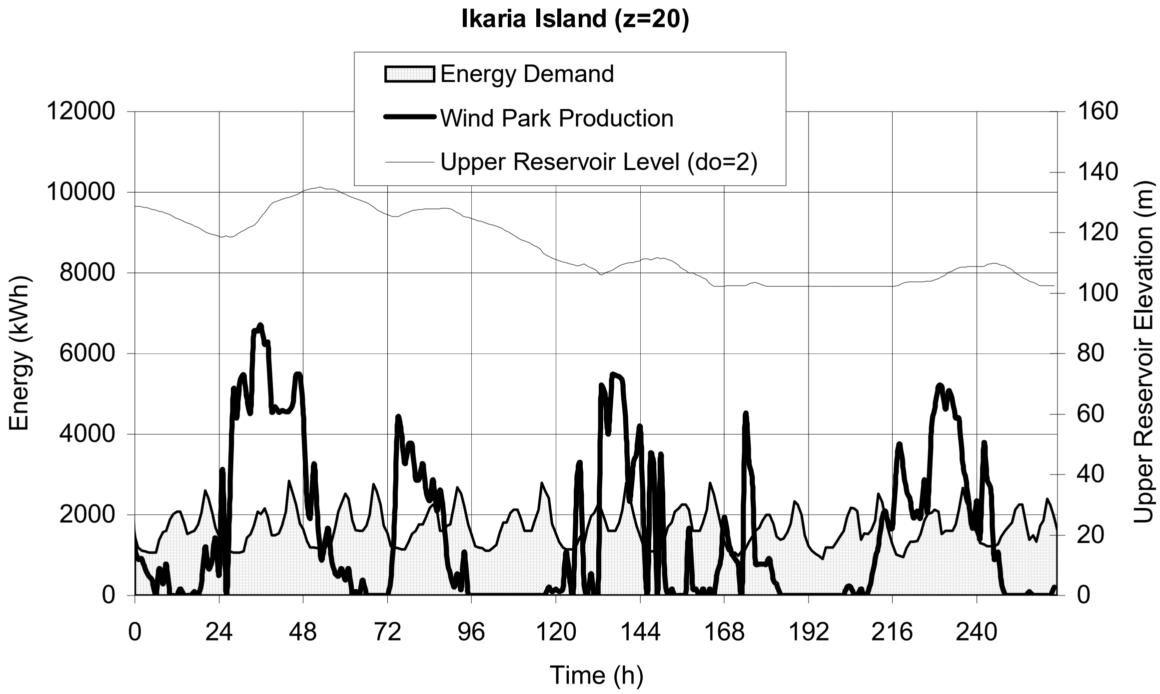

Figure 2: Energy Balance, Upper Reservoir Level for the Wind-Hydro System Proposed

first glance- first installation cost is dictated by the maximum renewable energy sources penetration target and it is finally covered by the low maintenance and operation cost of the station, in comparison with the local APS production cost.

During the operation of the proposed system, the following situations may appear:

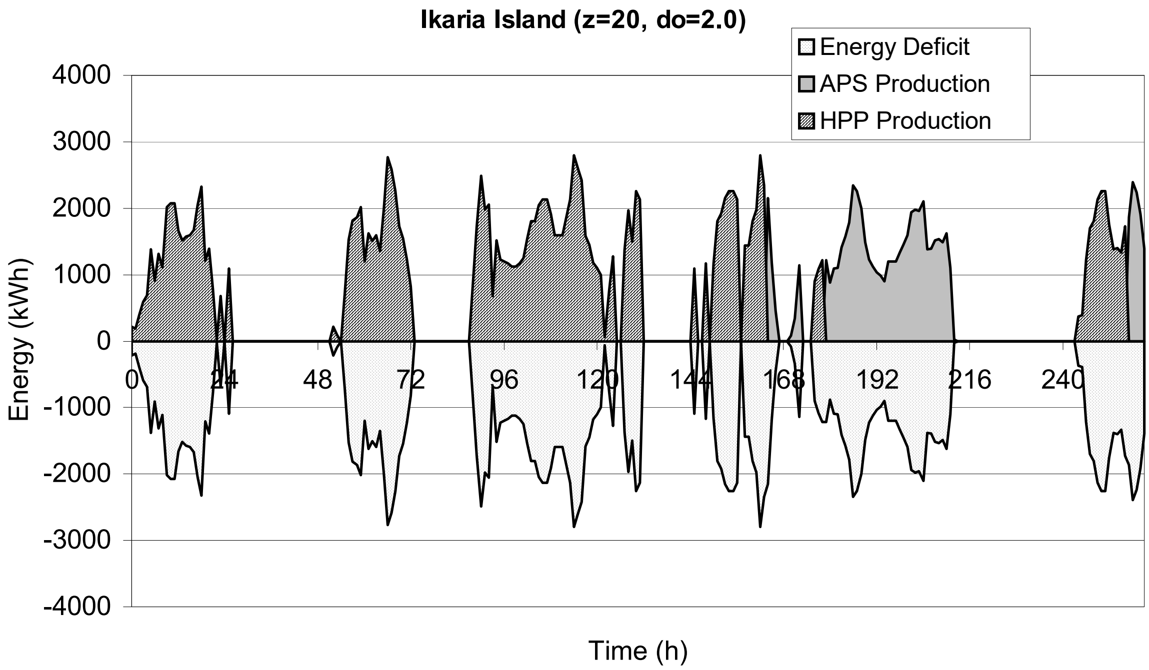

Figure 3: Energy Balance-Renewable Energy Sources Contribution for the Proposed Wind-Hydro Solution, Ikaria Island

I. The power demand is less than the power of the wind park, thus:

$$\Delta N(t) = N_{wp}(t) - N_D(t) > 0 \tag{8}$$

Ia In this case, the energy surplus is used by the water pumping system for energy storage at height "$h_1+y_1(t)$", see also (figure (2)).
Ib In case the upper reservoir is full (i.e. $y_1=y_{max}$) or the energy surplus is below the minimum value that the water pumping system can absorb -without cavitation or operational instability problems-, this energy amount is initially forwarded to the desalination plant and afterward (if necessary) to other low priority loads.

II. The power demand is bigger than the power of the wind park (figure (3)), thus:

$$\Delta N(t) = N_{wp}(t) - N_D(t) < 0 \tag{9}$$

IIa In that case, the reversible water turbines cover the power deficit (1-165 hours of figure (3)).
IIb In the extreme situation, when the upper reservoir is almost empty (i.e. $y_1 \rightarrow y_{min}$) or the power deficit is out of the expected range, the internal combustion engines of the "APS" start their operation under a minimum[15] fuel consumption plan (e.g. 183-213h, figure (3)).

3. Optimum Solution Determination

The optimum energy management solution for each case analyzed includes the estimation of:

- The size and type of wind converters
- The size and operational characteristics of reversible wind turbines
- The rated power and operational range (static head, flow rate) of water pumps
- The exact location, volume and geometry of water reservoirs
- The number and dimensions (diameter, length) of the water circuit independent pipes
- The operation plan of internal combustion engines of the existing APS
- The capacity of desalination plant

Bear in mind that the objective target of this proposed analysis is to maximize the local system energy independence (i.e. minimum oil consumption), under the preconditions of complete and continuous capability to cover the local community electricity demand and rational first installation cost of the hybrid station. In the following, the basic principles of predicting the operational characteristics of the hybrid station components are briefly presented.

3a Wind Turbines Selection

For the size and type estimation of the wind turbines to be utilized, a multi-criteria method[16] is adopted, taking into consideration the local wind potential quality, along with several other parameters, see for example Table I.

Considering the dimensions of the contemporary commercial wind turbines, the limited infrastructure of the Aegean Sea islands and the electricity networks capabilities, the selected wind turbine size "N^*" is between 200kW and 500kW. Finally, despite the low-cost purchase (ex-works) advantage of 500kW machines, a 300kW wind turbine is found[19] to be the most appropriate choice for small and medium-sized islands, in case that specific energy production (i.e. annual energy production per kW of nominal power or "8760.CF", expressed in kWh/kW.year -see also equations (12) and (13)) and complete first installation cost (turnkey) are included.

Accordingly, the wind turbine number "z" is chosen as the first optimization parameter of the problem. Keep in mind that for every island-case examined, "z" takes values between a minimum "z_{min}" and a maximum "z_{max}" value, where:

$$z_{min} = \frac{1}{N^*} \cdot \max\left\{(N_{peak} + \delta N\ ), \left(\frac{E_{annual} + \delta E}{8760 \cdot CF}\right)\right\} \qquad (10)$$

and

$$z_{max} = \frac{1}{N^*} \cdot \left(\frac{E_{annual} + \delta E}{8760 \cdot CF \cdot \eta^*}\right) \qquad (11)$$

Table I: Typical Parameters Sample for a Multi-criteria Wind Turbine Selection Analysis

Criterion Used	**Weight Factor**
Specific Annual Energy Production (kWh/kW.year)	50
Turnkey Specific Price (Euro/kW)	50
Local Service Facilities	40
Proper Performance Bond (Guarantee) Period	35
Number of Similar Engines Installed in Europe	30
Model Age	30
Company Experience in Local Market	25
Standardization Certificates	20
Environmental Impacts	20
Local Agency Activities	10

Table II: Wind Energy Production for Several Small-Medium Sized Wind Turbines, Kithnos Island

Wind Turbine Model	**Rated Power (kW)**	**Mean Power Coefficient "ω"** (see equation (13))
Bonus Mk III	300	0.3619
Enercon E-30/230	230	0.3702
Enercon E-40	500	0.3377
Micon M700-225/40	225	0.3387
MWT 250	275	0.2966
MWT 450	450	0.3506
Nordex N29/250	250	0.3380
NW 31/2	250	0.3254
NW 41/2/500	500	0.3023
TW 300	300	0.3371
V29-225	225	0.3636
Wind Master CS 28	300	0.3008
Wind World W-3000	250	0.3376
Z-40-FS	550	0.3144

As already mentioned by the authors[17], the existing wind potential strongly influences the exact number of wind turbines used, via the capacity factor value[10] or more accurately via the mean power coefficient "ω". Bear in mind that the capacity factor is the product of the technical availability "Δ" with the mean power coefficient "ω" of the installation, i.e:

$$CF = \Delta \cdot \omega \qquad (12)$$

where:

$$\omega = \int_o^T \frac{N(t)}{N^*} \cdot dt = \int_o^\infty \frac{N(V)}{N^*} \cdot f(V) \cdot dV \tag{13}$$

with T=1year(=8760x3600sec), "N(V)" the corresponding wind turbine power curve versus wind speed "V" and "f(V)" the wind speed probability density function at hub height, describing the local wind potential[18]. Using extended wind speed data (for more than one year) and official power curves taken from "Windbase II" (a database developed at the Soft Energy Application Laboratory since 1999[19]) of several representative wind turbines, the calculation results are summarized in Table II.

Generally speaking, the technical availability factor "Δ" mainly depends on the technological status of the machines used. Nowadays, the contemporary wind turbines achieve a high quality level, obtaining a technical availability of the order of 95%. It is also fundamental to mention the accessibility difficulties -due to bad weather conditions- of almost all Greek islands, especially during the winter[20].

3b Hydro Power Station Characteristics

The exit power of each water turbine constituting the hydro-power station is a function[21] of the turbine net head "H'" and the corresponding flow rate "$\dot{V}'$", thus:

$$N'_{H_i} = \rho \cdot g \cdot H'_i \cdot \dot{V}'_i \cdot \eta_H \cdot \eta'_{el} \tag{14}$$

with

$$H' \le (h_1 - h_2) + (y_1 - y_2) - k_H \cdot (\dot{V}')^2 \tag{15}$$

where "k_H" is the total hydraulic loss (lengthwise and local) coefficient, when the water circuit is used for energy production. In order to minimize the water volume consumed for a given power demand, the following remarks should be taken into consideration:

- Relation (15) should be used as equation (i.e. $H'=(h_1-h_2)+...$)
- The minimum exit power of a selected water turbine should be as low as possible, in order to minimize the flow rate surplus
- The selected operation head of a water turbine should validate equation (16) that guarantees the effectively collaboration of water reservoirs geometrical and water turbines operational characteristics, during the energy storage process, i.e:

$$(h_1 - h_2) + (y_{1_{max}} - y_{2_{min}}) < H_{max}' \text{ and } H_{min}' < (h_1 - h_2) + (y_{1_{min}} - y_{2_{max}}) \tag{16}$$

Using available data by manufacturers, the water turbine net operation head and exit power may be expressed as:

$$H' = H'(\dot{V}', \alpha) \tag{17}$$

and

$$N_H = N_H(\dot{V}', \alpha) \tag{18}$$

where "α'" is the opening parameter of the turbine selected, see for example[9].

3c Water Pump Station Characteristics

The water pump system, in conjunction with the reversible water turbines -operating as water pumps, is chosen to transfer water from the lower to the higher reservoir[13], absorbing the wind energy surplus of the hybrid station.

Selecting, for increased reliability reasons, a constant speed water pump, its input power depends[22] on the net hydraulic head "H" and the corresponding flow rate " $\dot{V}$ ", thus:

$$N_p = \frac{\rho \cdot g \cdot H \cdot \dot{V}}{\eta_p \cdot \eta_{el}} \tag{19}$$

with "η_p" the water pump efficiency and "η_{el}" the efficiency of the water pump electric motor, while:

$$H = H(\dot{V}) \tag{20}$$

and

$$\eta_p = \eta_p(\dot{V}) \tag{21}$$

Keep in mind that the static head "H" of each water pump should satisfy the following equation, i.e:

$$H \geq (h_1 - h_2) + (y_1 - y_2) + k_P \cdot (\dot{V})^2 \tag{22}$$

where "k_p" is the total hydraulic loss coefficient, when the water circuit is used for energy storage.

In order to maximize the water volume stored, for a given power surplus, the following remarks are essential:

- The reversible hydraulic machines should be preferred (for water pumping) during the operation management plan, as their efficiency appears to be higher than the water pumps one
- The minimum operation flow rate of a water pump -in order to avoid cavitation problems- should be as low as possible, so as to increase the energy storage capacity of the system
- The selected operational range of water pump head should fulfill the following restriction:

$$(h_1 - h_2) + (y_{1_{max}} - y_{2_{min}}) < H_{max} \tag{23}$$

Summarizing, it is interesting to mention that one of the problems optimization parameters is the rated power "N^*_p" of the water pumps used, taking into consideration the necessary maximum pumping power and the existing market models.

3d Water Reservoirs-Piping System

The water reservoirs creation[14] is one of the most important variables of the methodology developed, because it affects:

i The initial installation cost
ii The storage capacity-energy autonomy
iii The long-term operation energy loss
iv The environmental impacts

of the complete project. In an attempt to significantly deteriorate the first installation cost, the proposed solution should also take advantage of the various existing lake-tanks[23] (i.e. artificially waterproofed-isolated natural cavities mainly used for agricultural water storage purposes) in most Aegean Sea islands, see for example Table III. Finally, the storage capacity (days of energy autonomy of the system "d_o") is the third optimization parameter of the problem.

Subsequently, the diameter (cross section area) of the selected water pipes should be large enough for the water velocity to obtain acceptable values, in order to minimize the hydraulic loss of the system[24].

On the contrary, the water network length should be minimum, to limit the lengthwise hydraulic loss along with the corresponding first installation cost.

Table III: Main Characteristics of Island Cases Analyzed-Best Solution Choice

	Kithnos	**Karpathos**	**Ikaria**
Area (km^2)	94	301	255
Population	1700	7200	6100
Peak Load (kW)	1960	6500	5400
Annual Electricity Consumption (MWh)	5216	24369	18570
Maximum/Minimum Load	6.5/1	4.4/1	5.25/1
APS Capacity Factor (%)	28.5	43.3	38.2
Lake-Tanks Volume (m^3)	1,000,000	2,000,000	800,000
Average Wind Speed (m/s)	6.8	9.6	9.8
Specific Wind Energy Production (kWh/kW.year)	3065	4900	5010
Minimum wind turbine number "z_{min}"	5	13	13
Maximum wind turbine number "z_{max}"	20	27	27
Days of System Energy Autonomy	$1 \le d_o \le 3$	$1 \le d_o \le 3$	$1 \le d_o \le 3$
Water Reservoir Volume per Day of Energy Autonomy (m^3)	60,000	250,000	150,000
Optimum (predicted) wind turbine number "z_{opt}"	13	20	20
Optimum Reservoir Size (m^3)	90,000	500,000	300,000

Table IV: Local Autonomous Power Station (APS) Internal Combustion Engines Characteristics, Greek Public Power Corporation Official Data[27]

Kithnos		**Karpathos**		**Ikaria**	
Diesel Engine Type	Exit Power (kW)	Diesel Engine Type	Exit Power (kW)	Diesel Engine Type	Exit Power (kW)
Hencscel-6RA516A	60	OTTENSENER 10PC2V	1800	FIAT B308ESS	750
Hencscel-6RA516A	60	CKD 12V27	2250	FIAT B308ESS	750
Hencscel-6RA516A	60	CKD 12V27	2250	FIAT B308ESS	750
MWM TBD603V12	400	USSR Γ-72	650	FIAT B308ESS	750
MWM TBD603V12	400	USSR Γ-66	450	FIAT B308ESS	750
MWM TBD603V12	400	USSR Γ-66	450	CKD 6-27.5 B8S	1280
Deutz A8M-428	150	FINCANTIERI BL230	2000	CKD 6-27.5 B8S	1280
Deutz A8M-428	150	FINCANTIERI BL230	2000		
SACM (2722)	600				

3e Autonomous Power Station Operation Mode

The vast majority of Aegean Sea APS consist of relatively old internal combustion engines (e.g. Table IV), thus their real fuel consumption is quite high. In an attempt to reduce the hybrid station fuel consumption, an analytical decision plan should be prepared, based on the idea[15] of using the most cost efficiency engines (figure (4)), according to the power demand of the grid. It is also interesting to mention, that according to the results obtained in most cases analyzed, a remarkable number of internal combustion engines of the existing APS are no longer considered necessary (zero hours of operation for a whole year), hence some of them could be removed in other locations.

4. Application Results

4.1 Brief Presentation of Selected Island Cases

The above-described solution is now applied to selected representative Aegean Sea islands, i.e. to a small island (Kithnos), to a small-medium sized island (Ikaria) and to a medium-sized island (Karpathos), which are spread around Aegean Archipelago, figure (5).

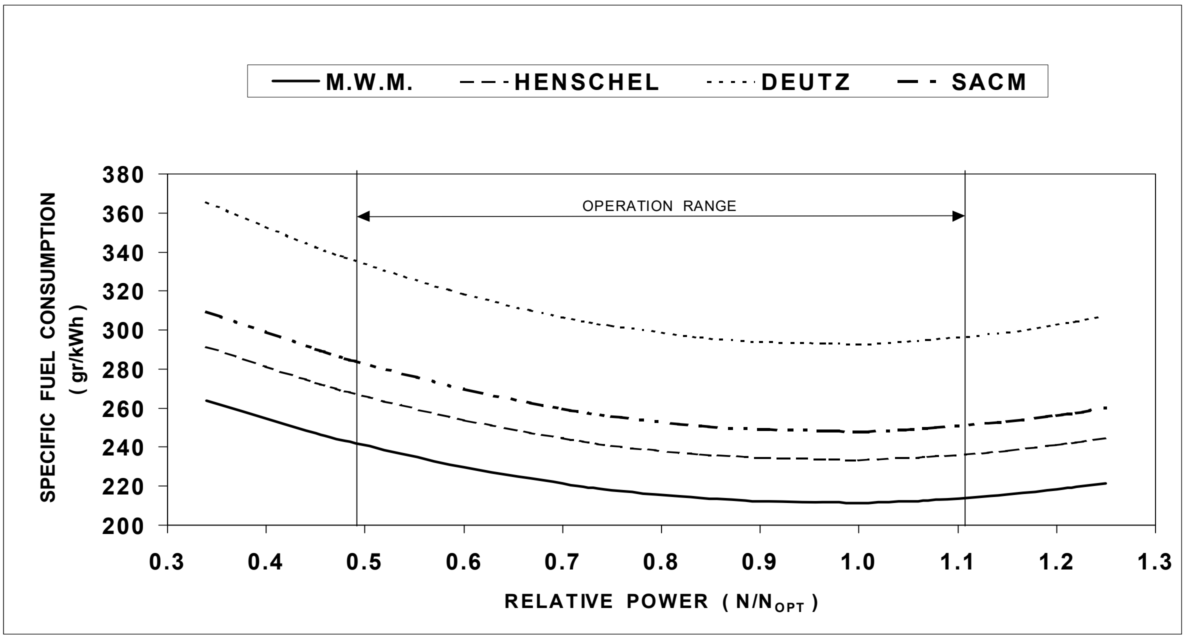

Figure 4: Specific Fuel Consumption of Internal Combustion Engines of Kithnos Autonomous Power Station[15]

More precisely, Kithnos is a small island (1,700 habitants, area of 94km²) of Aegean Sea, located approximately 60km southeast of Athens. The topography of the island is typically Aegean, i.e. gentle slopes, absence of flat fields, low mountains and sparse vegetation. Its major village is Hora Kithnou with 800 habitants, and the main economic activities of the local society are agriculture, merchant marine and tourism. The annual energy production of the local autonomous power station was only 5,200MWh for 1999. The peak load demand - approximately 1960kW- appears during summer, while the corresponding minimum value is 300kW. The island has an outstanding wind potential, since in several locations the annual mean wind speed approaches 7m/s, at 10m height, Table III.

According to the existing data, the evolution of the local APS production cost presents an annual increase of 6%, see figure (6), while an important part of it (≈36%) is due to the fuel cost. The autonomous power station of Kithnos consists (1999) of nine internal combustion engines along with their electrical generators. Unfortunately, since all the existing diesel machines are aged -the most recent is almost twenty years old- their real fuel consumption (the manufacturer curves are no more valid) is quite high. In the island there exists a hybrid renewable station based on five Aeroman 12.5/33 wind turbines and a Vestas V-39 (500kW) wind converter recently installed. On top of that, a photovoltaic plant was commissioned during summer of 1983, consisting of 860 PV modules, with 100 kW_p total power.

Ikaria is a small medium-sized island (population 6,100 habitants, area of 255km²) of East Aegean Sea, located approximately 240km from Athens. Its major town is Agios Kirikos with 2400 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 18,570MWh for 1999. The peak load demand -approximately 5400kW- appears also during summer, while the corresponding minimum value is 900kW. The island has an excellent wind potential, since in several locations the annual mean wind speed approaches 10m/s, at 10m height. Besides, there is a remarkable natural water reservoir at almost 700 meters elevation, which can be used as a basis for the application of the proposed wind-hydro solution, Table III.

On the other side, the evolution of the local APS production cost presents an annual increase of 4%, 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 (Table IV) along with their electrical generators, and their specific fuel consumption is 270.2gr/kWh (+0.53gr/kWh lubricants). The rated capacity of the APS is 6900kW, while in the island there exists a small wind park of seven (7x55kW) outdated WM-15S wind turbines, rated power 385kW.

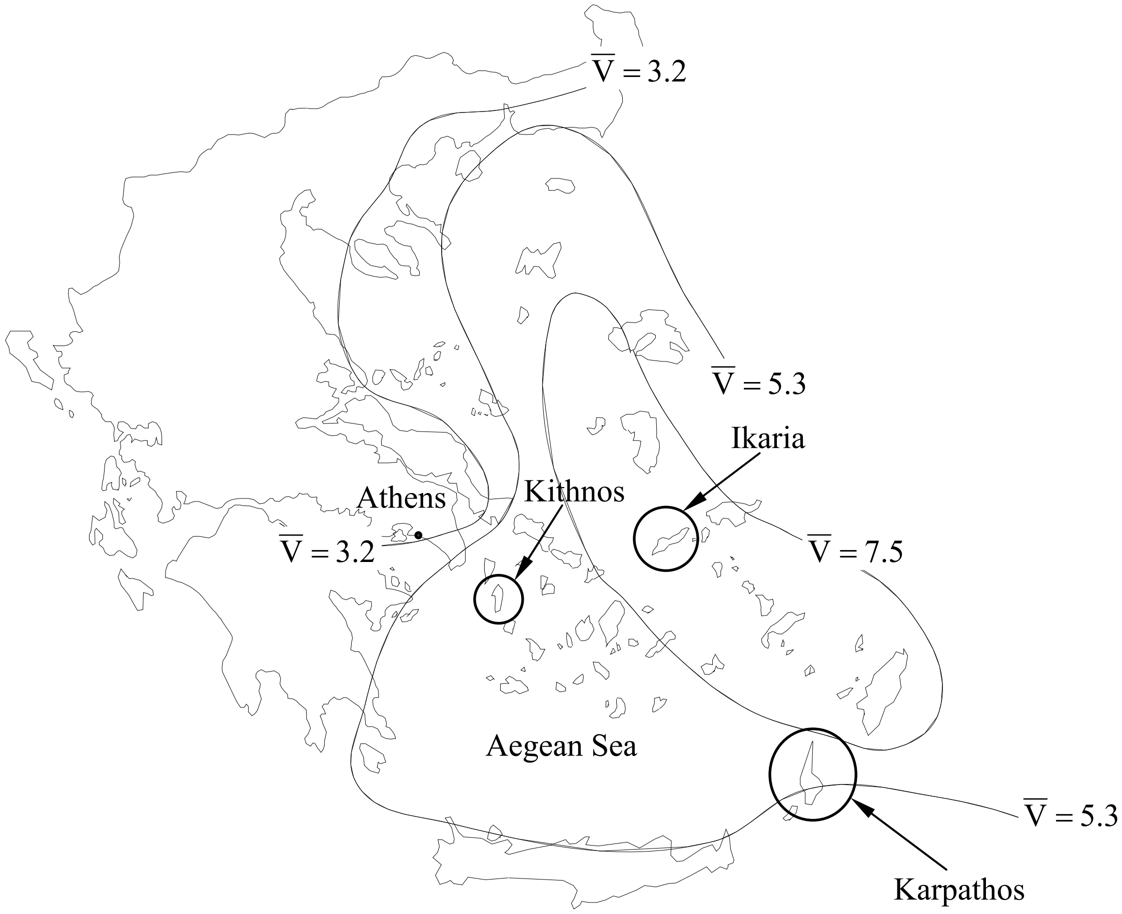

Figure 5: Wind Potential Estimates for Selected Aegean Sea Islands[9][26]

Finally, Karpathos is a medium-sized island (population 6100 habitants, area of 301km²) of South-East Aegean Sea, belonging to the Dodekanesa complex (the second biggest after Rhodes). Its major town is Pigadia with 1700 habitants. The local terrain is characterized by rocky mountains with sharp slopes and absence of flat fields. The annual energy production of the local APS (which covers also the electricity requirement of nearby Cassos island -1100 habitants) was 24,400MWh for 1999. The peak load demand -approximately 6500kW- appears during summer, while the corresponding minimum value is 1400kW. The island has very high wind potential, since the long-term annual mean wind speed approaches 9.6m/s, at 10m height. Besides, there is a quite large natural water reservoir (approximately 2,000,000m^3), which can be used during the application of the proposed wind-hydro solution, Table III.

Similarly to other island cases, the evolution of the local APS production cost presents a mean annual increase of 5.2%, see figure (6), while the contribution of fuel cost is almost 50%. The APS of Karpathos consists of eight internal combustion engines (Table IV) of total rated power 9000kW. In the island exists (since 1991) a very small wind park of Greek Public Power Corporation (PPC) based on five (5x55kW) outdated WM-15S wind turbines, rated power 275kW.

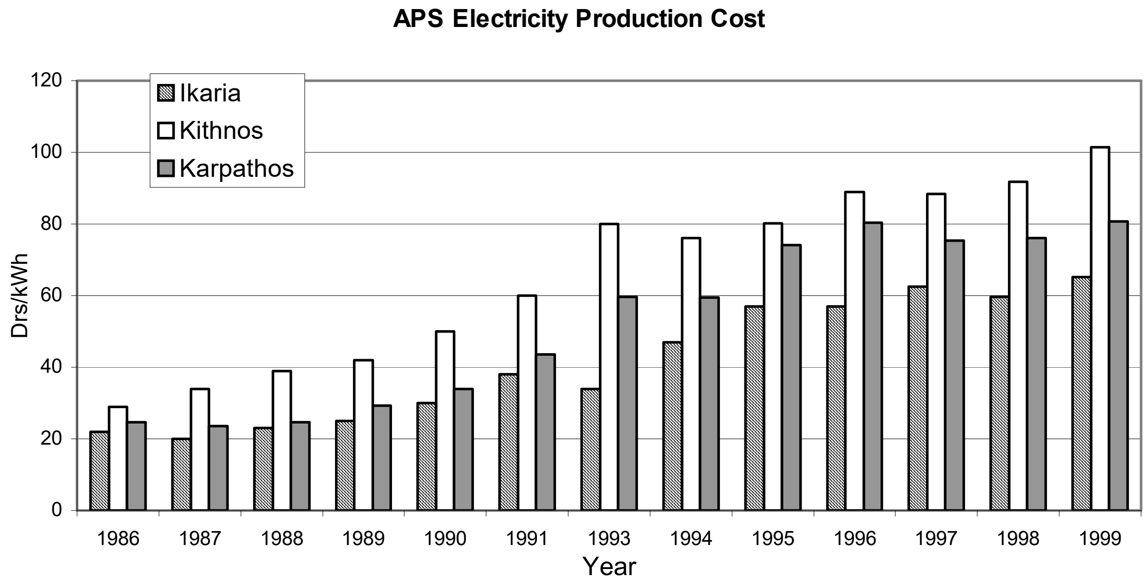

Figure 6: Local Autonomous Power Station Electricity Production Cost Time Evolution[27]

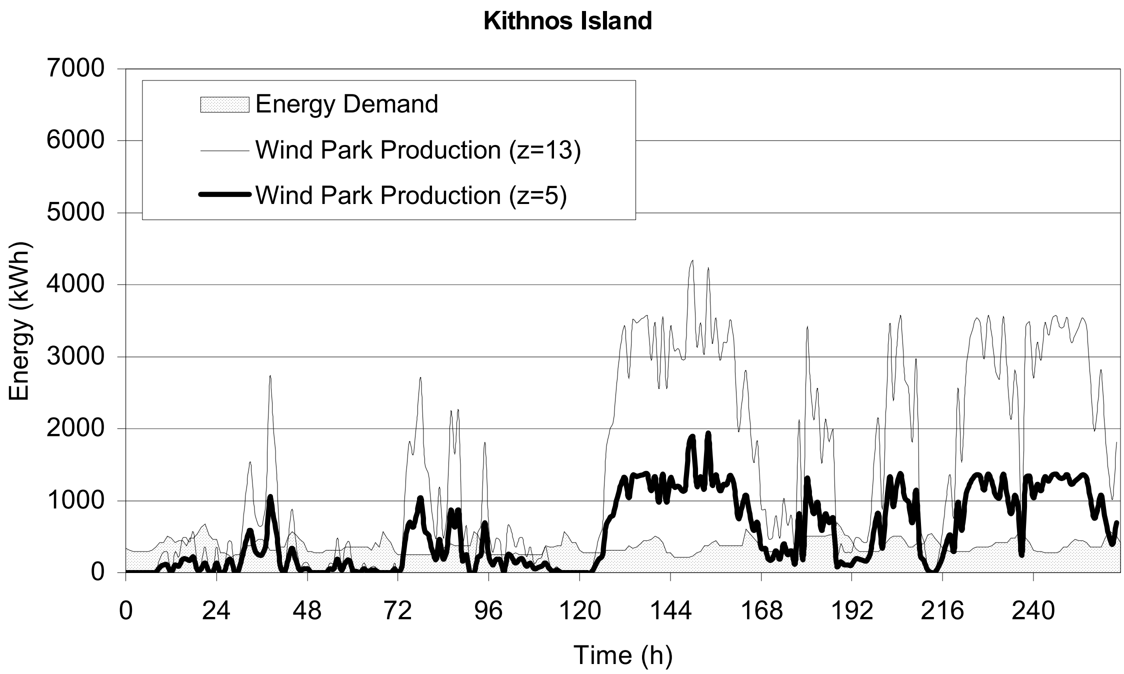

Figure 7: Energy Balance for the Proposed Wind-Hydro System, Small Island Case

4.2 Overall Energy Management Results

Applying the proposed algorithm for a complete year and selecting a representative typical ten-days period (during May), the most interesting analytical results concerning the system energy balance are the following:

a. There is a remarkable difference between the wind energy production and the maximum local grid power demand, i.e:

- Kithnos (z=5-13, peak load N_p=600kW, max N_{wp}=1500-3900kW), figure (7)
- Ikaria (z=13-23, peak load N_p=2800kW, max N_{wp}=3900-6900kW), figure (2)
- Karpathos (z=13-23, peak load N_p=4000kW, max N_{wp}=3900-6900kW), figure (8)

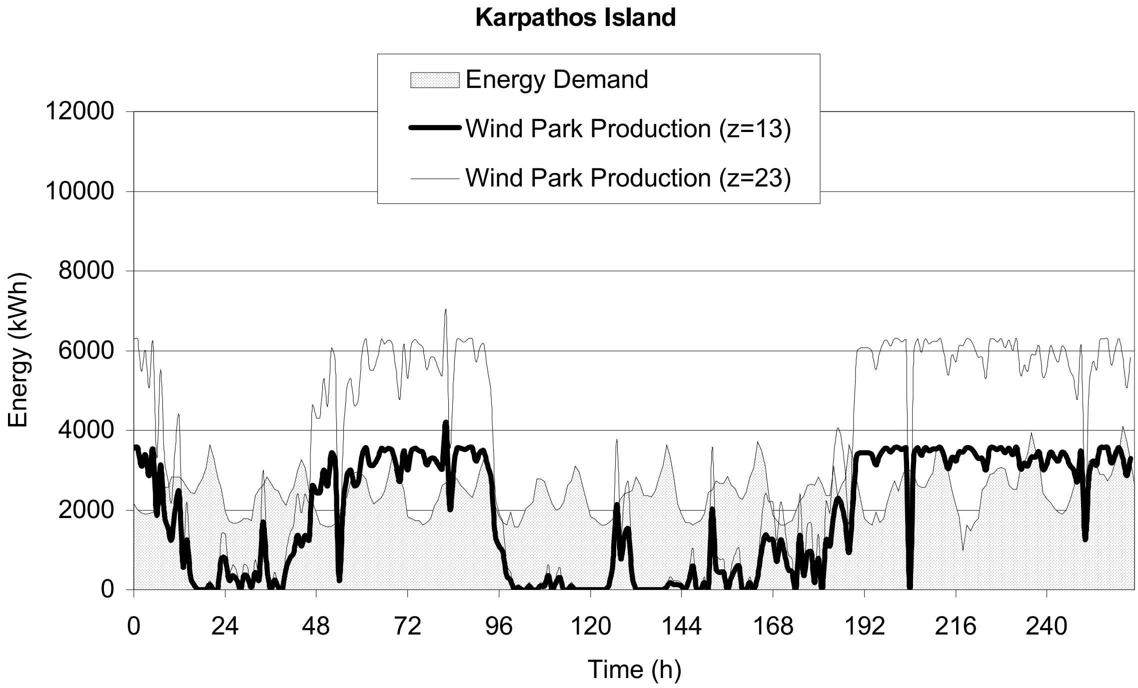

Figure 8: Energy Balance for the Proposed Wind-Hydro System, Medium-Sized Island Case

b. The calm spells are more often in Ikaria than in Kithnos, although the mean annual velocity of Kithnos is much lower. This fact underlines the necessity of a properly sized energy storage system, not depending on the high wind potential of an area.

c. The upper reservoir level is drastically depended on the number of wind turbines used, for all cases examined. However, the hours of minimum upper reservoir level is not strongly influenced by the wind turbines number.

Subsequently, in order to study the energy autonomy of the cases analyzed, under the precondition of limited (per capita) initial investment cost, the evaluation of the autonomous operation percentage of

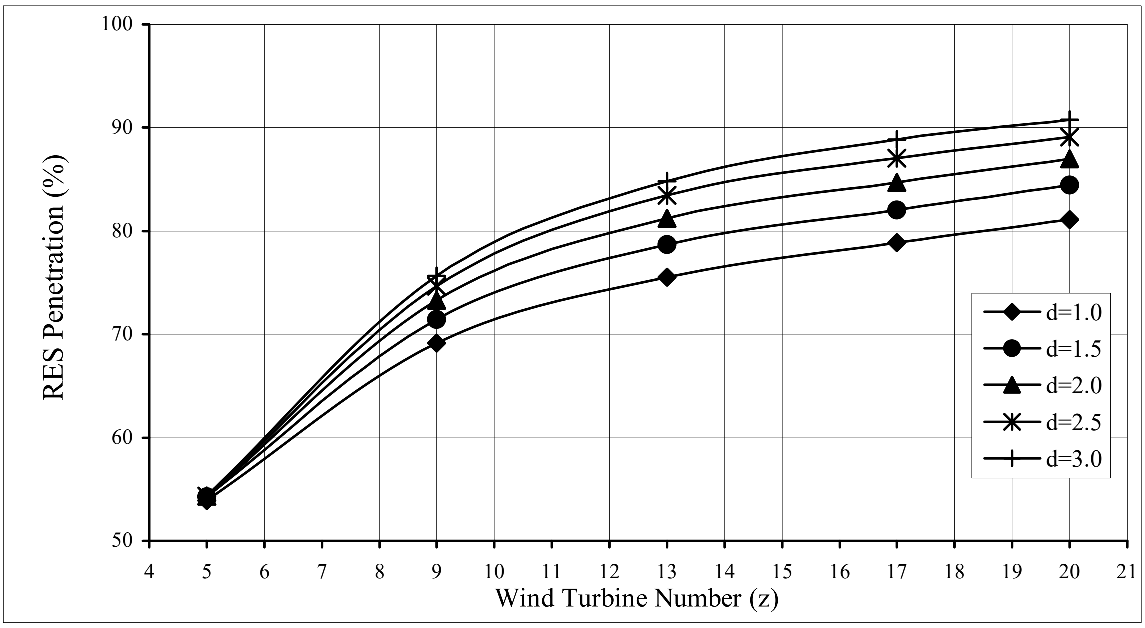

Figure 9: Renewable Energy Sources Penetration in the Local Electrical System of Kithnos

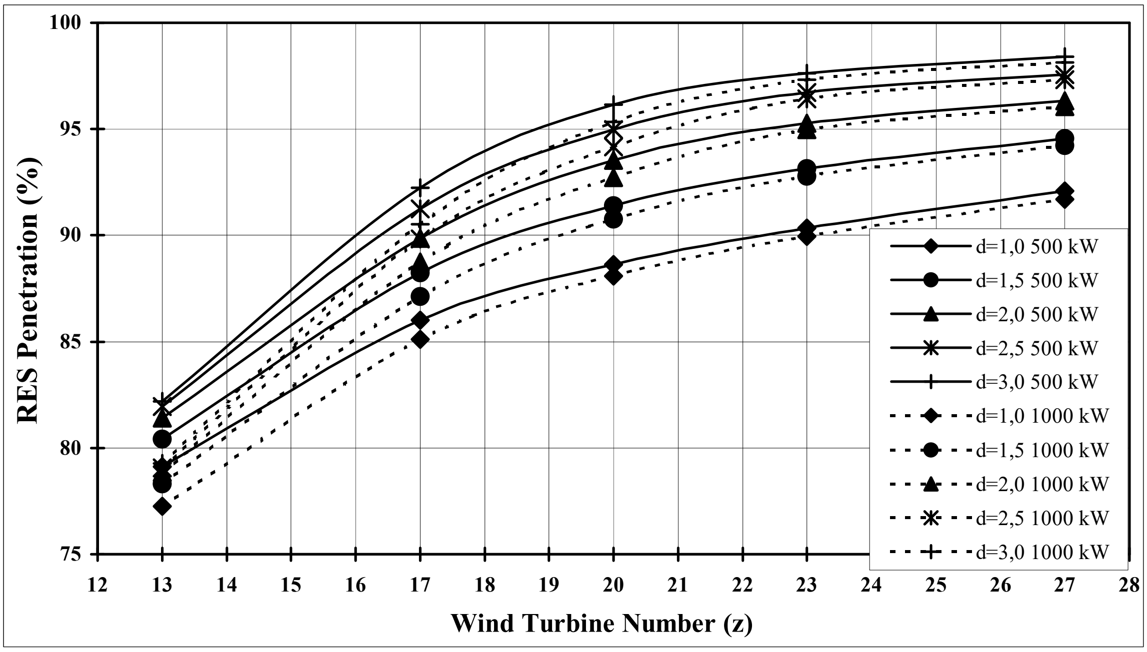

Figure 10: Renewable Energy Sources Penetration in the Local Electrical System of Ikaria

the hybrid station (diesel off mode) is presented in figures (9) to (11), for a wide range of wind turbines number ($z_{min}<z<z_{max}$) and for a significant variation of autonomy days (water reservoir size), i.e. $1<d_o<3$. As it results from these figures, the autonomy operation of the system remarkably increases with the number of wind turbines used and the size of the water reservoirs selected. However, the hours of autonomy does not linearly depend on the variation of these two parameters. More precisely, more than the ¾ of the autonomy operation increase is realized when the number of wind turbines is altered from z_{min} to $z_{min}+0.5(z_{max}-z_{min})$. At the same time a 2/3 increase of energy autonomy hours is obtained by increasing the upper reservoir size from $d_o=1$ to $d_o=2$.

Another interesting conclusion is drawn by analyzing the impact of water pumps size adopted on the energy autonomy of the system. Especially for configurations based on small wind turbines number

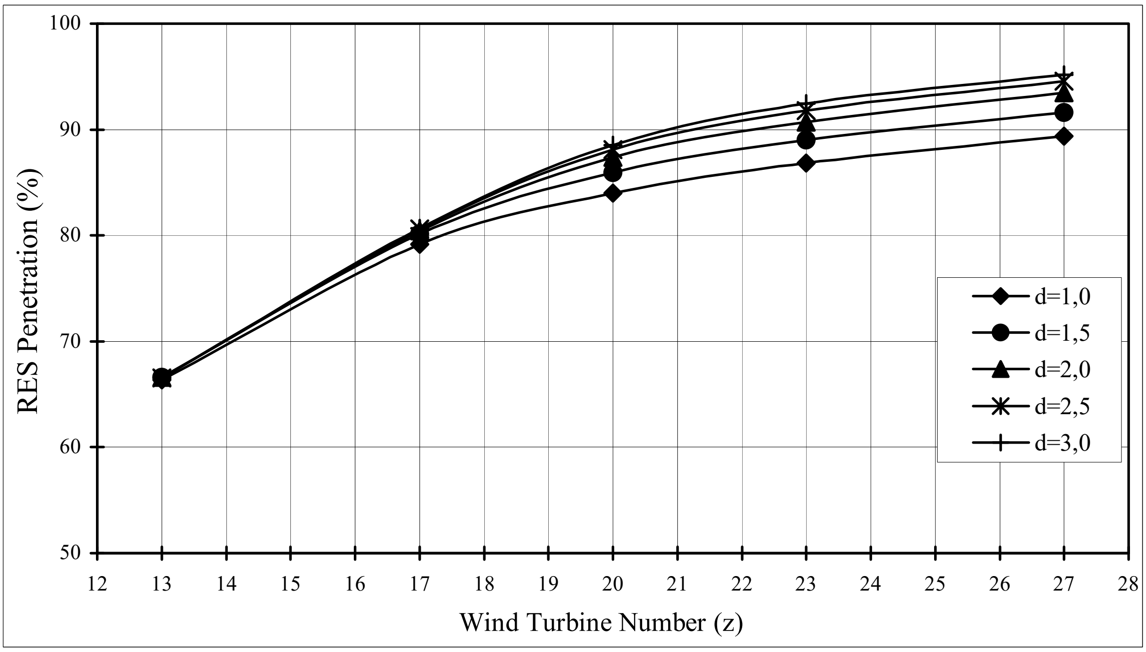

Figure 11: Renewable Energy Sources Penetration in the Local Electrical System of Karpathos

and low reservoir capacity, the hybrid station operation is pretty improved (in terms of minimum oil consumption) when the 500kW water pumps are used instead of the 1000kW ones, figure (10). This can be attributed to a better energy surplus absorbance[13] by small water pumps compared to bigger ones.

4.3 Best Configuration Choice

In order to determine the best solution for each case investigated, the calculation results of figures (9) to (11) are used, along with a mathematical optimization procedure, briefly described below. More precisely, the mathematical simulation of the problem (maximum energy autonomy-minimum first installation cost increase) can be expressed as:

$$\frac{d(IC)}{dA} \rightarrow \min \tag{24}$$

where "IC" is the initial cost of the installation and "A" is the autonomy operation percentage (hours of autonomy) of the system. During the minimization process of equation (24) the initial cost barrier (capital invested per habitant) should also be taken into account, i.e:

$$IC \leq IC_{max} \tag{25}$$

According to numerous feasibility studies carried out by the authors[25], the first installation cost of a wind-hydro station can be expressed as:

$$IC = k_1 + k_2 \cdot z + k_3 \cdot d_o \tag{26}$$

where the constant term "k_1" (independent of wind turbines number and days of autonomy) takes into account the general and management cost, the hydro power station and water piping cost etc. Keep also in mind that "IC" is not exactly[26] a linear function of "z" and "d_o" (e.g. IC~$z^{0.9}$), due to scale economies, which however are not very strong here for the values of the main parameters used, Table III.

Substituting equation (26) in equation (24) and taking into account (figures (9) to (11)) that $A=A(z,d_o)$, we get finally:

$$\frac{1}{\frac{\partial A}{\partial z}} + \frac{k_{3,2}}{\frac{\partial A}{\partial d_o}} \leq \varepsilon \tag{27}$$

with:

$$k_{3,2} = \frac{k_3}{k_2} \tag{28}$$

and "ε" an appropriate small number, selected to terminate the optimization procedure. Also, equation (26) reads in view of equation (25) as:

$$z + k_{3,2} \cdot d_o \leq \xi \tag{29}$$

where:

$$\xi = \frac{IC_{max} - k_1}{k_2} = \frac{c_{max} \cdot P - k_1}{k_2} \tag{30}$$

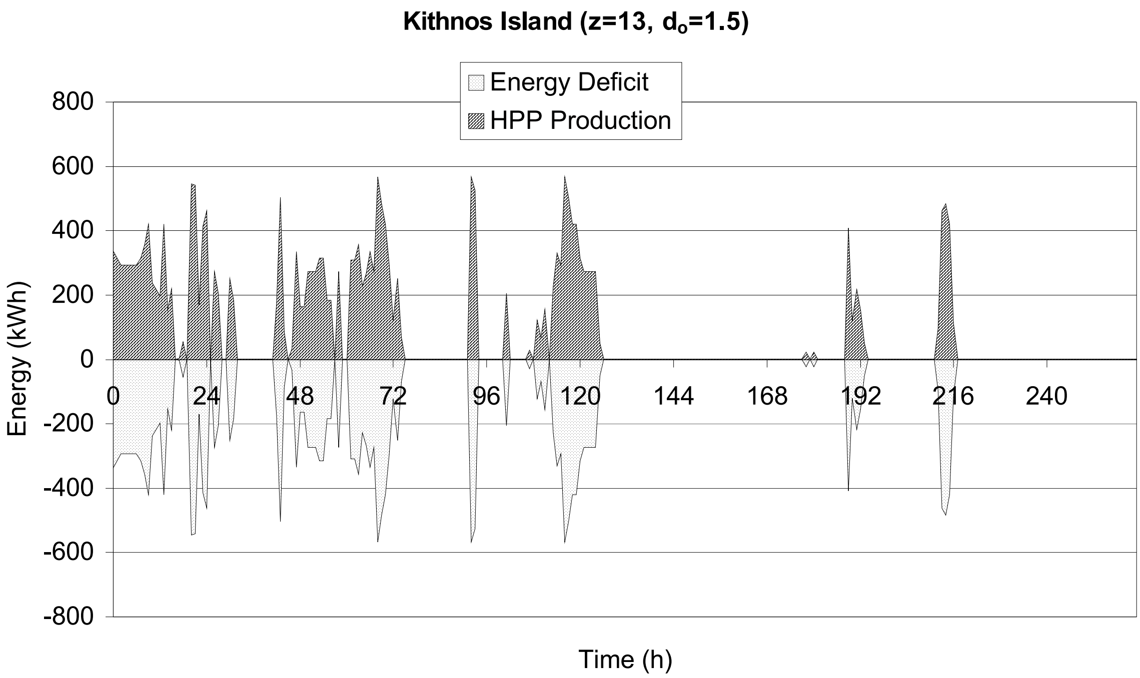

Figure 12: Energy Balance-Renewable Energy Sources Contribution for the Proposed Wind-Hydro Solution, Kithnos Island

Take notice of the fact that the maximum permissible first installation cost of the system "IC_{max}" is the product of the population "P" of the local community (Table III) with the specific maximum first installation cost "c_{max}" (e.g. $c_{max}\approx$5000-6000Euro per habitant), while the -per autonomy day- water reservoir construction cost "k_3" should take into account the different population of each island investigated or the corresponding water reservoir size, Table III.

Concluding, the optimum dimensions (Table III) of the proposed renewable energy production station are predicted using equations (27) and (29) along with the analytical results of figures (9) to (11). It is important to repeat that the proposed solution is based on maximum energy autonomy (from fossil fuels usage) of the system under the precondition of a given maximum per capita first installation cost.

4.4 Energy Balance Analytical Results

The final part of the application results presented here includes the analytical behaviour of the energy production system for a selected ten-days period, for all island cases analyzed. The results given are based on the best solution configuration, according to the above-described analytical model. Hence, in figure (12) the energy deficit of the Kithnos hybrid system is presented (z=13, d_o=1.5) for a typical electricity consumption period. As it is obvious from the results achieved the wind turbines cover a remarkable portion of the local consumption, while the energy deficit appeared is completely fulfilled by the existing hydro turbines, leading -for the specific period examined- to zero hours of operation of the local APS (zero oil consumption).

Subsequently, for the Ikaria island case (z=20, d_o=2) during the same time period, the energy autonomy of the system is accomplished for the first seven days, figure (3). During the last three days, the APS is used for almost 25 hours due to the significant calm spell existence. However, even in this difficult situation the wind and hydro turbines produce the vast majority of the system energy consumption.

Finally, for the Karpathos island case (z=20, d_o=2) the local wind park covers the local community power demand for almost 50% of the period examined, figure (13). On the contrary, the contribution

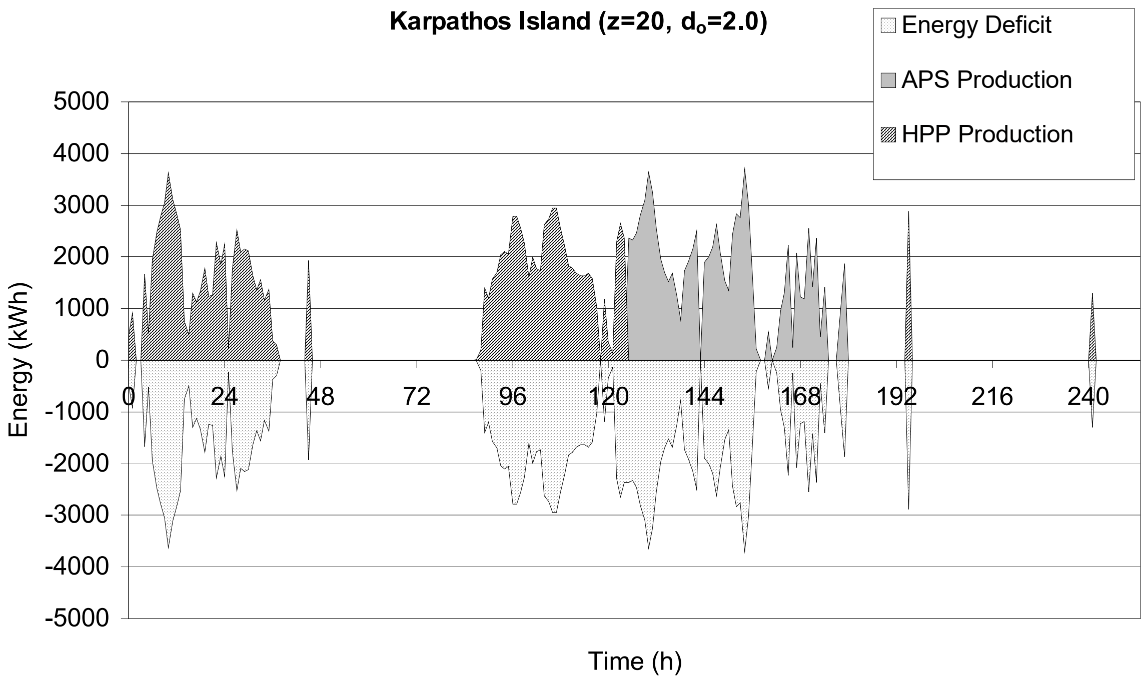

Figure 13: Energy Balance-Renewable Energy Sources Contribution for the Proposed Wind-Hydro Solution, Karpathos Island

of the proposed hydro power station is limited (≈25% of operation hours during the period investigated), while the role of the local APS cannot be disregarded (≈25% contribution).

In order to obtain a more integrated picture of the available energy sources contribution on the annual energy balance, for each case analyzed, the corresponding results are summarized in figure (14).

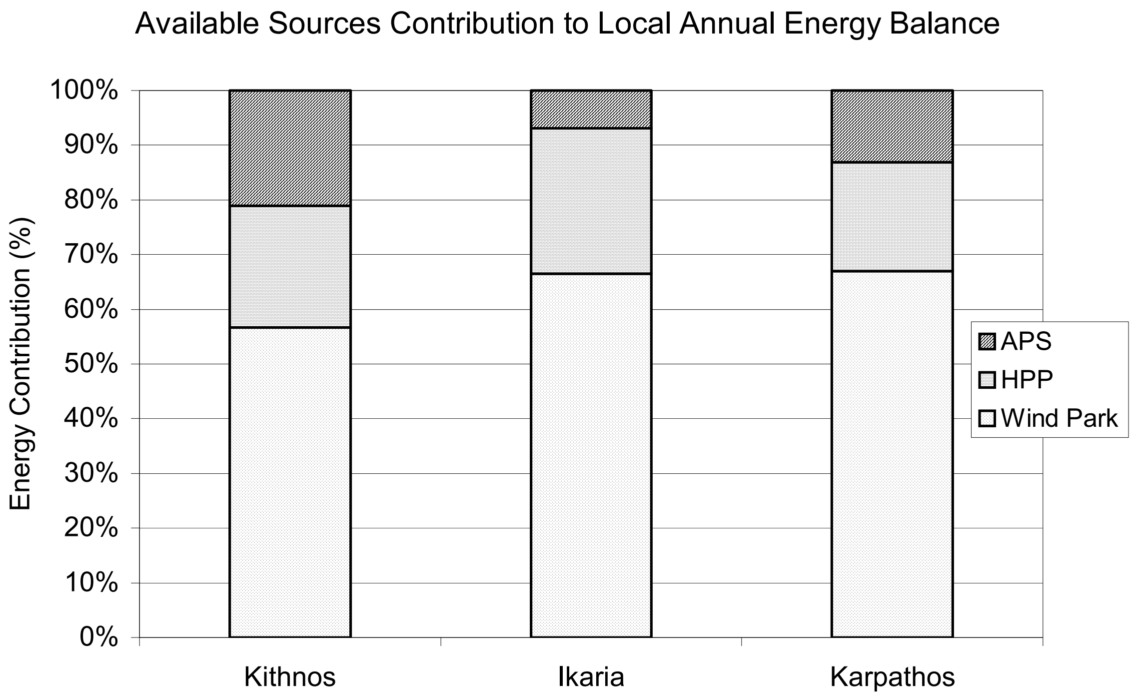

Figure 14: Available Sources Contribution to the Annual Energy Balance; for the Optimum Proposed Configuration of All Islands Analyzed

According to the results obtained for the optimum power supply scenario over an entire year (see also figures (9) to (11)), wind turbines supply directly the 55%-65% of the local communities annual energy consumption. Additionally, the proposed hydro turbines cover an extra 20%-25%, while the local autonomous power stations (based exclusively on diesel-electric generators) contribution is less than 20%, for every island examined. Keep in mind that although the hydro turbines contribution is clearly less than the wind turbines one, the small hydropower station safeguards the local electrical network stability, producing also electrical energy of very high quality.

5. Conclusions

The prospect of creating a combined wind-hydro energy production station is hereby analyzed, under the preconditions of maximum energy system autonomy from imported oil and limited first installation cost. Accordingly, a methodology of optimum wind-hydro solution estimation is developed and subsequently applied to several typical Aegean Sea island cases, in order to define the most beneficial configuration of the proposed renewable station. All the numerical calculations are based on real data, like long-term wind speed measurements, demanded electrical load, operational characteristics of the system components etc.

In order to improve the understanding of the operational behaviour of the proposed solution, the detailed electricity balance is also presented for a typical ten-days period for all islands investigated. According to these analytical results, a remarkable part of energy consumption is covered by the wind parks, while any energy deficit appearing is mainly covered by the hydropower turbines, minimizing in this way the local APS necessity.

In all cases analyzed, the renewable energy sources penetration may exceed 85%, minimizing not only the corresponding exchange loss -due to fuel imports decrease- but also most of the negative environmental effects related to the operation of the internal combustion engines. Finally, a significant part of the wind energy surplus of the system can be forwarded to a desalination plant for clean water production. Consequently, we believe that similar electricity production solutions remarkably improve the economic development of the Aegean Archipelago remote islands communities, with rational installation cost, contributing to the life quality amelioration of their habitants.

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WIND ENERGY SURPLUS MANAGEMENT FOR REMOTE CONSUMERS USING A WATER PUMPING STORAGE SYSTEM

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Abstract

A great number of small islands represent an important part of Greek territory. Their location, however, causes serious problems to their electricity and water supply. On the other hand, Greek islands along with the mainland coasts, have a very high wind potential all over the year. This situation has led quite a few remote consumers to install micro wind power system combined with a battery storage device, in order to fulfill their needs. However the stochastic availability of wind energy and the fluctuation of electricity demand, result to significant energy surplus, which in many cases cannot be stored. In the present analysis, the appropriate size of a water pumping system is predicted, so as to absorb the energy surplus of a stand-alone electricity production system, in case the batteries are full. The water pump is used to transfer water from a well to a storage reservoir for irrigation needs. Finally, emphasis is laid on the first installation cost, which is increasing with the size of the installation and the dimensions of the reservoir.

Keywords: Wind Pumps; Stand-Alone System; Energy Storage

1. Introduction

A great number of small islands -most of them scattered in the Aegean Archipelago- represent an important part of Greek territory. Their location, however, causes serious problems to their electricity supply, since it is impossible to connect them to the mainland grid. Thus, in many cases, isolated consumers cannot obtain access to the local electrical grids due to the long distance, which increases the corresponding cost.

On the other hand, Greek islands, as well as the coasts of the mainland, have very high wind potential almost all over the year. In these regions, more than 50,000 isolated consumers can solve their electricity demand problem by using an integrated autonomous wind power system. However, the stochastic availability of wind energy and the fluctuation of electricity demand, along with the installation cost constraints, result to significant energy surplus, which in many cases cannot be stored to the existing battery storage systems.

In the present analysis, there is defined the appropriate size of a water pumping system, able to absorb the energy surplus of a remote micro wind power turbine, combined with a battery storage device, in case the batteries are full. The water pump is used to transfer water from an existing well to a storage reservoir for irrigation needs. The water pump size is determined by the energy surplus of the system and the economic behavior of the proposed extension. On top of that, emphasis is laid on the first installation cost, which increases with the size of the water pump selected and the dimensions of the reservoir.

2. Position of the Problem

According to previous work[1], a micro wind power station combined with a battery storage system could cover the electricity demand of a remote consumer. Taking into consideration the computational frame of the numerical algorithm "WINDREMOTE-II" the optimum size of a stand-alone system

***Kavadias K.A., Komnimoglou A., Kaldellis J.K., 2001**, "Wind Energy Surplus Management for Remote Consumers Using a Water Pumping Storage System", European Wind Energy Conference, Conference Proceedings, pp.972-975, Bella Centre, Copenhagen.*

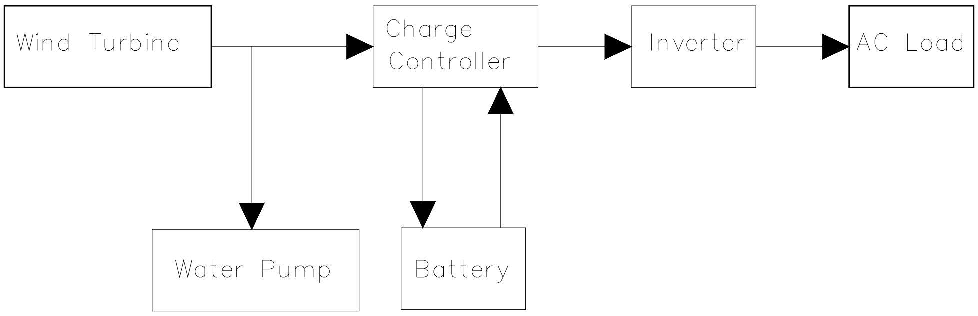

Figure 1: Stand-alone wind power installation along with a water pumping system

(battery capacity, wind turbine nominal power) is estimated, under the condition of full energy autonomy with minimum installation cost. Using the results of this analysis as input an integrated autonomous stand-alone wind-pumping system is selected[2] as an extension of the initial installation, see also figure (1).

Due to the stochastic behavior of the wind, the existence of a properly sized energy storage system (e.g. battery system), able to match the electricity demand of the consumer and the energy output of the wind turbine, is absolutely necessary. Keep in mind that the battery size strongly influences the operational cost of the system.

Thus, taking into consideration the remarkable energy excess and the battery cost barriers, a water-pumping system is installed in order to cover irrigation needs. The extended installation consists of (figure (1)):

a. A micro wind turbine of "N_o" kW
b. A lead acid battery storage system (24 Volt), with cell capacity of "Q_{max}" Ah
c. An AC/DC rectifier of "N_o" kW,
d. A DC/DC converter of "N_o" kW/24Volt,
e. A UPS of "N_o" kW,
f. A DC/AC inverter of "N_o" kW.
g. A water pump of "N_o" kW nominal power
h. A water reservoir of "V_o" m^3 volume capacity

3. Proposed System

The proposed system consists of a wind turbine. Its rated power depends on the system electricity demand, the available wind potential and the operational characteristics of the machine[3].

The wind turbine is supported by a battery storage system. The battery size is defined[4] by the autonomy hours "h_o" of the system, the total energy demand "E_{tot}", the efficiency "η_s" of the storage system and the maximum permitted depth of the batteries discharge "DOD_L".

Finally, since most commercial applications use alternative current, a DC/AC inverter should be used at the outlet of the system, which is also framed by an AC/DC rectifier, a DC/DC converter and -optionally- a UPS.

According to the results of "WINDREMOTE-II" algorithm[1], the optimum dimensions of a stand-alone wind power system in Andros island for an individual consumer (~5000kWh/year) consists of a wind turbine of N_o=3kW, and a storage system of Q_{max}=7000Ah capacity.

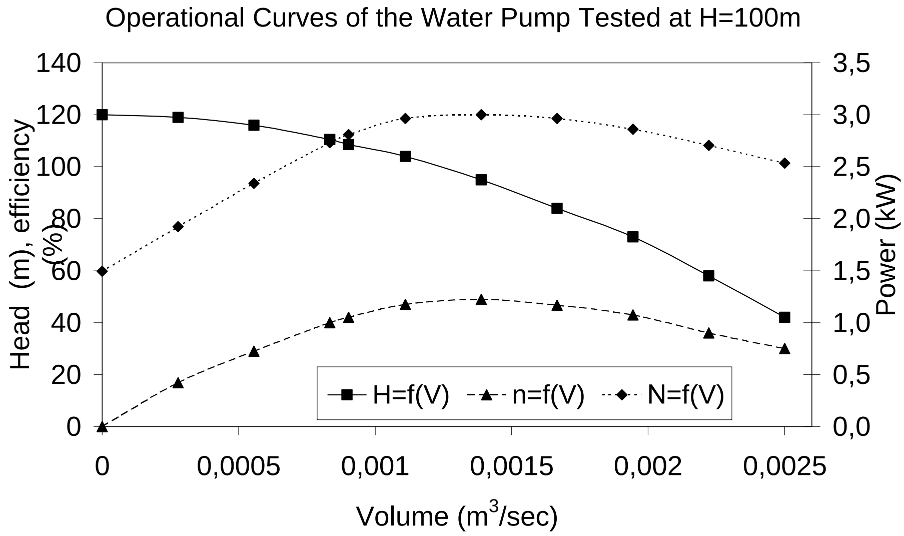

Figure 2: Operational curves of a water pump

However, the strict "no-load rejection" condition usually imposes overestimation of the stand-alone system dimensions, leading to remarkable energy surplus; thus a water pump device is included, so as to absorb the significant energy excess and cover irrigation needs of the remote consumers. The water pumping system comprises of a pump, a water reservoir and the required pipelines.

3.1 Water Pump

The nominal power of the water pump[5] is determined by the maximum power of the wind turbine, since the water pump must have the ability to absorb the maximum energy excess[6] in case of full batteries and no electricity consumption. Four different water pumps-having the same rated power (3kW)- were tested in order to face different static pressure head values "H", examined in this study. The water pumps selected are (for simplicity and increased-reliability reasons) constant speed ones, having operational characteristics according to figure (2). Therefore:

$$N_p = \frac{\rho \cdot g \cdot H \cdot \dot{V}}{\eta_p \cdot \eta_{el}} \tag{1}$$

where:

$$H = H(\dot{V}) \tag{2}$$

and:

$$\eta_p = \eta_p(\dot{V}) \tag{3}$$

Note also that the pump's head must validate[7] the following expression:

$$H \geq h + \delta H_{fl} \tag{4}$$

where "h" is the hydrostatic head and "δH_{fl}" are the total hydraulic losses, both lengthwise $\left(\lambda \cdot \frac{L}{d}\right)$ and local (ζ).

More precisely:

$$h = h_1(t) - h_2(t) \tag{5}$$

and:

$$\delta H_{fl} = \left(\lambda \cdot \frac{L}{d} + \zeta\right) \cdot \frac{8 \cdot \dot{V}}{g \cdot \pi^2 \cdot d^4} \quad (6)$$

Note that "h_1" and "h_2" are the elevations of the upper reservoir and the existing well, respectively.

3.2 Water Reservoir

As previously explained, when the energy surplus cannot be stored in the batteries, the energy excess is accordingly used to transfer water from height "h_2" to "h_1". Thus, the total water volume stored "V_{st}" is given as:

$$V_{st}(t) = V_{st}(t_0) + \int_{t=t_0}^{t} \dot{V}_t(t')dt' \leq V_{max} \quad (7)$$

On the contrary, when a water need exists, the water volume of the upper reservoir is decreasing with time "t", according to equation (8), i.e.:

$$V_{st}(t) = V_{st}(t_0) - \int_{t=t_0}^{t} \dot{V}_t{}'(t')dt' \geq V_{min} \quad (8)$$

where "V_{max}" and "V_{min}" are the maximum and minimum storage capacities of the upper reservoir, respectively.

The dimensions of the upper reservoir are defined by water daily needs and the reservoir autonomy hours "h_o". In fact, during the present study, the upper reservoir size "V^*" is one of the optimization parameters of the problem, thus "V^*" takes values between 10 and 100 m^3.

3.3 Pipelines

Considering the maximum flow speed through pipelines and the preferable flow rate "$\dot{V}$", the diameter "d" of the ducts used is estimated. More precisely, during system optimization process, the diameter of the pipes influences both hydraulic loss[8] (equation (6)) and the corresponding initial cost. Additionally, the pipeline network length "L" depends on the elevation difference "h" of the system along with the peculiarities of the specific installation (i.e. L>h).

4. Input Data

The main input data of the present analysis include:

a. The power excess "ΔN_{res}" of the electrical system. More specifically, the following input situations may exist:

- $\Delta N_{res}=0$ (i.e. the wind power "N_w" is less than the electrical demand "N_D"
- There is excessive energy surplus that cannot be completely absorbed "N_{st}" by the batteries, i.e.:

$$\Delta N_{res} = N_w - N_D - N_{st} > 0 \quad \text{and} \quad Q < Q_{max} \quad (9)$$

- The entire energy surplus is forwarded to water pumping, since the batteries are full, i.e.:

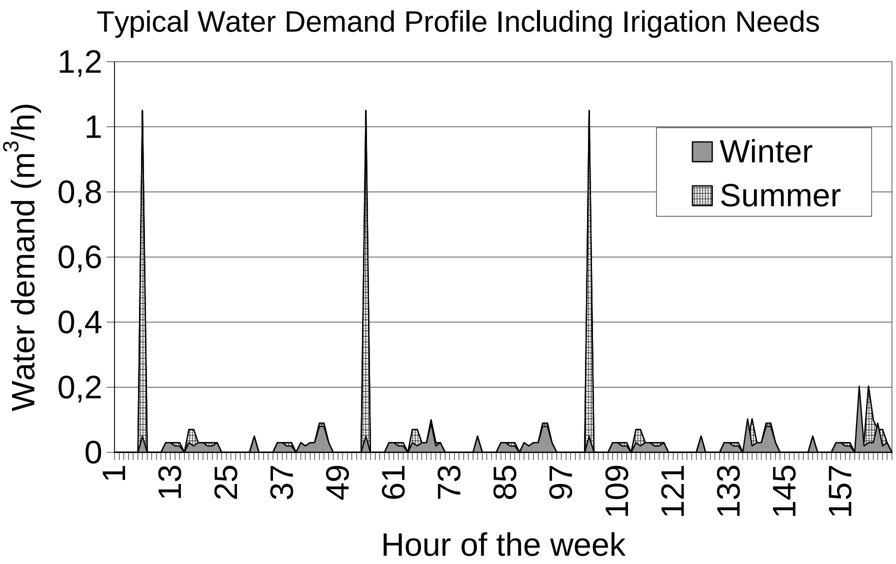

Figure 3: Typical water demand profile

$$\Delta N_{res} = N_w - N_D > 0 \quad \text{and} \quad Q = Q_{max} \tag{10}$$

b. The water consumption profile, figure (3), designed to meet the irrigation needs of a remote consumer. As it is expected, the water demand is low during winter, while remarkably increased during summer. Using the distribution of figure (3) as a basis, calculations may also be repeated for double or triple consumption demand.
c. The characteristics of the water pump used, see for example figure (2).
d. The water pipelines dimensions.
e. The hydrostatic head "h" of the system, depending mainly on the well depth. In order to analyze different well configurations, "h" is selected as one of the basic variables for a detailed parametrical analysis (i.e. $20 \leq h \leq 150$m).
f. The water reservoir storage capacity chosen also as a parametrical analysis variable, taking values between $10m^3$ and $100m^3$.

5. Operational Modes

During the operation of the system, the follow situation may appear:
i. Significant energy excess "ΔN_{res}" appears and the upper reservoir is not full, thus the energy is used by the pumping system to transfer water to the upper reservoir.

$$\Delta N_{res} > 0 \wedge V_{st} < V_{max} \Rightarrow N_p = \Delta N_{res} \tag{11}$$

ii. There is remarkable energy excess, however the upper reservoir is full. In this case the energy excess is not used.

$$\Delta N_{res} > 0 \wedge V_{st} = V_{max} \Rightarrow N_p = 0 \tag{12}$$

iii. No energy excess appears, while the upper reservoir is not empty. Accordingly, water is forwarded from the upper reservoir to consumption.

$$\Delta N_{res} = 0 \wedge V_{st} > V_{min} \Rightarrow N_p = 0 \tag{13}$$

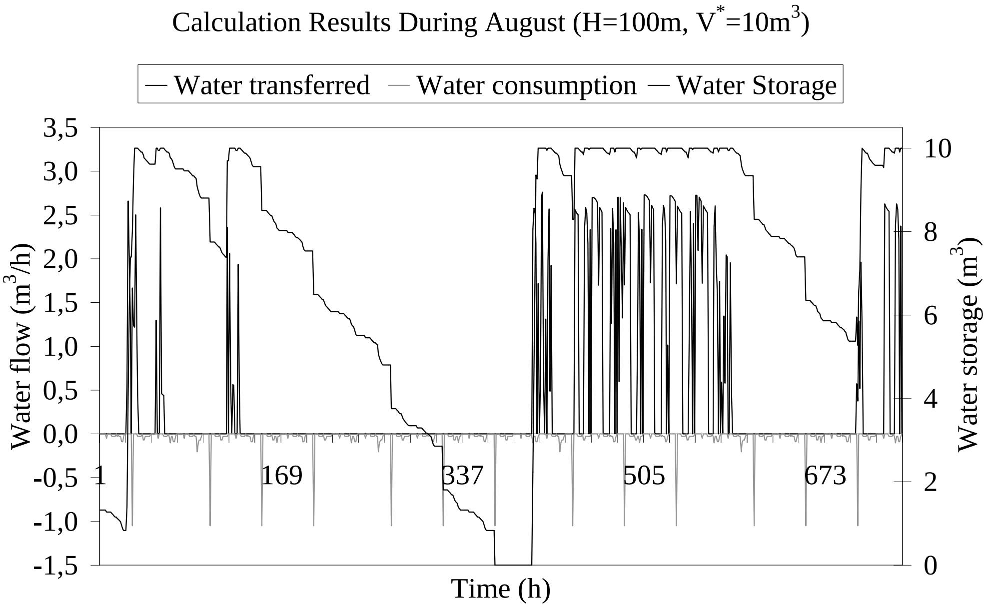

Figure 4: Application results during summer (H=100m, V^*=10m^3)

iv. No energy excess is available, while the upper reservoir is almost empty; hence energy is absorbed from the batteries "δN_{st}" in order the pump to cover the water demand.

$$\Delta N_{res} = 0 \wedge V_{st} \approx V_{min} \Rightarrow N_p = \delta N_{st} \qquad (14)$$

6. Application Results

The proposed methodology is subsequently applied to several remote consumer installations in an effort to meet both electricity and water demand needs. The cases analyzed include consumers with different water demand and well configurations.

For a typical remote consumer case with basic irrigation needs and hydrostatic head of (h=)100m, the calculated water pumped profile is given in figures (4) and (5), corresponding to water reservoir capacity of 10m^3 and 50m^3, for August. In the same figures the water reservoir elevation is also mentioned.

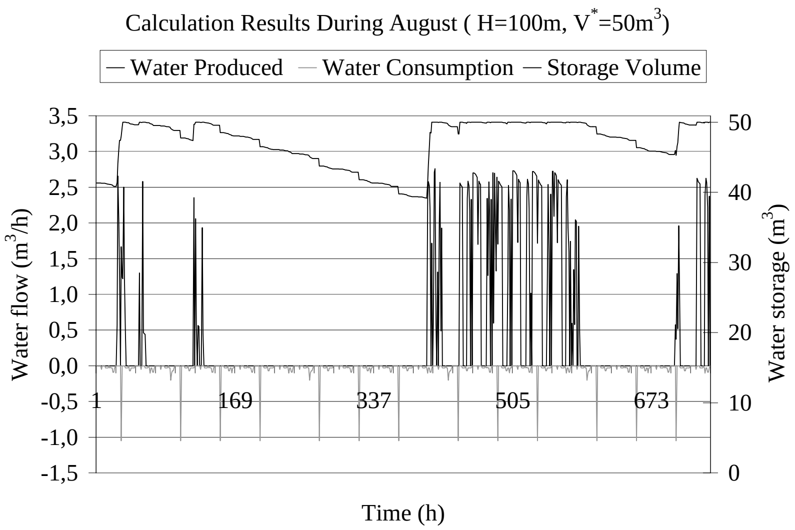

Figure 5: Application results during summer (H=100m, V^*=50m^3)

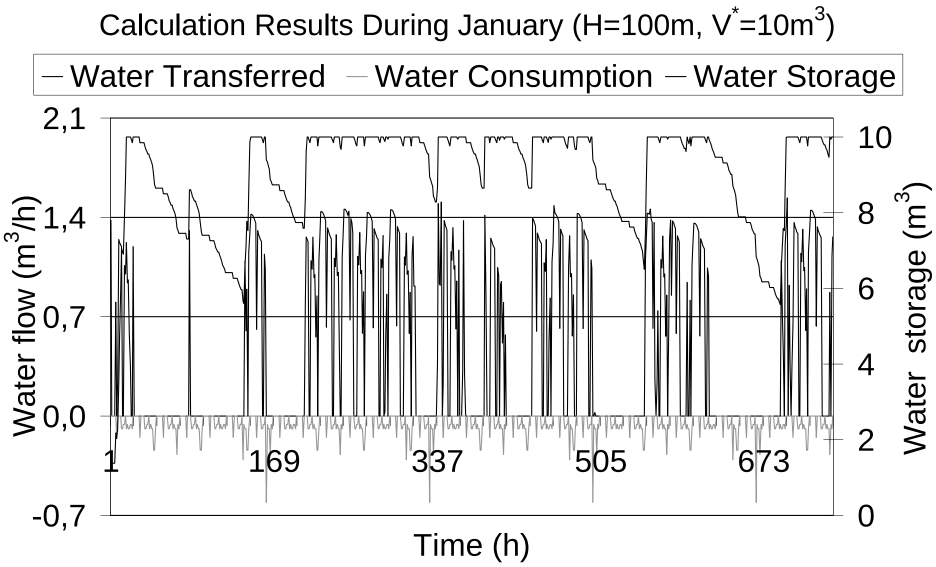

Figure 6: Application results during winter (H=100m, V^*=10m^3)

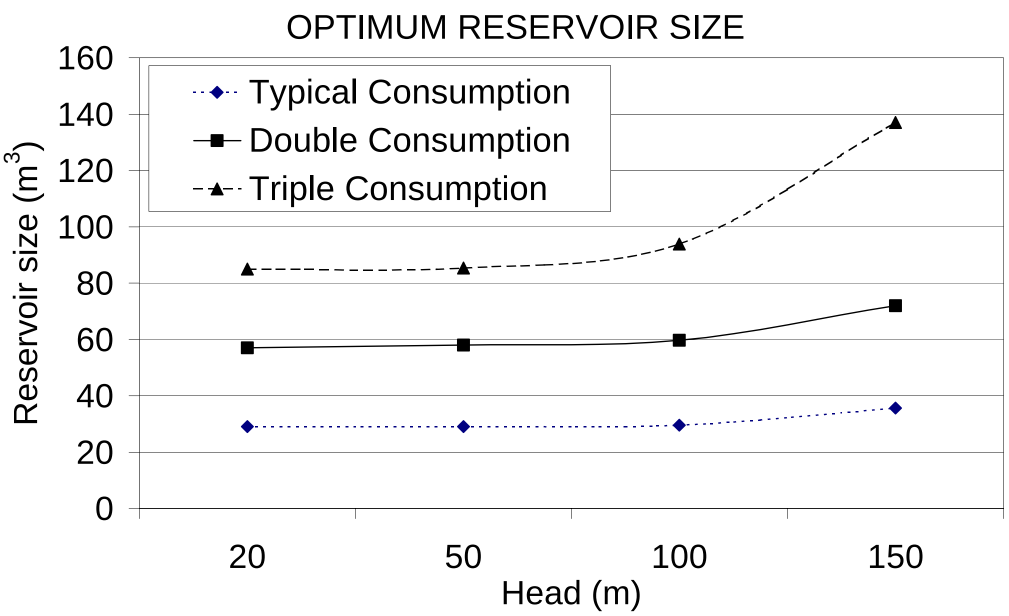

Figure 7: Optimum reservoir size values for different hydrostatic heads

According to the results obtained, there is no significant energy excess (i.e. $\Delta N_{res} \approx 0$) especially during the first two weeks of the month. Therefore, the small water storage system cannot fulfill the increased water consumption for almost 190 hours, during August. On the contrary, the 50m^3 water reservoir meets the water demand, despite the long-term energy input deficit.

Subsequently, in figure (6) we display the corresponding (to figure (4)) profiles for a winter period (i.e. January). As it is obvious from figure (6), the stand-alone system presents remarkable energy surplus, while the water reservoir storage volume is higher than 50% for the entire month.

Finally, in figure (7), the minimum water reservoir size is given as a function of the system hydrostatic head, so as no water deficit of the system to appear. For the three typical water demand profiles selected and for hydrostatic head values up to 100m, the water reservoir best choice seems to be

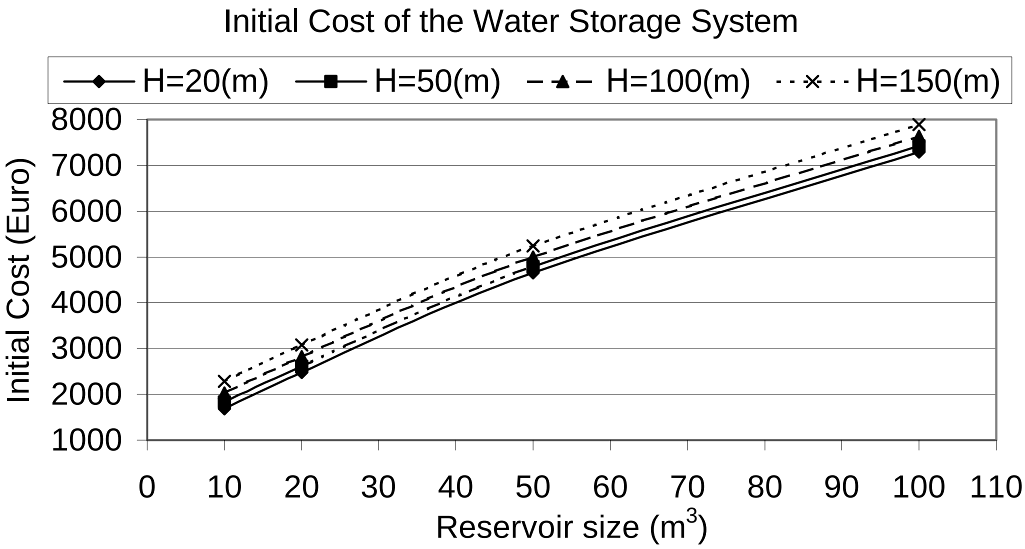

Figure 8: Initial cost of the water pumping system

almost independent from "h". For higher "h" values, the water reservoir volume increases almost parabolically, especially for high water consumption cases.

In order to obtain a more integrated picture of the problem, one has to take into account that - according to local market cost values- the water reservoir size is the most important factor determining the initial cost of a similar investment, figure (8).

7. Conclusions

Wind energy based autonomous stand-alone systems, frequently present remarkable energy surplus, which cannot be stored in the system batteries. Hence, in the work briefly described here, an alternative wind energy surplus management solution is developed, using an appropriate water pumping system.

In the proposed investigation, consequently, the optimum dimensions of the system water pump and water reservoir are predicted for a great range of desired water consumption autonomy, hydrostatic head and water demand profiles. Special attention is paid to guarantee no water deficit during a whole year, taking also into consideration the initial cost of the selected system.

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INTEGRATED ENERGY BALANCE ANALYSIS OF A STAND-ALONE WIND POWER SYSTEM, FOR VARIOUS TYPICAL AEGEAN SEA REGIONS

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Abstract

The wind power industry is nowadays a mature energy production sector, disposing to market commercial wind converters from 50W up to 5MW. In the present work, the possibility of using stand-alone electricity production systems based on a small wind turbine, in order to meet the electricity requirements of remote consumers, is analyzed for selected Aegean Sea regions, possessing representative wind potential types. The proposed configuration results after an extensive long-term meteorological data analysis, on a no-load rejection condition basis during the entire time period examined. Accordingly, an integrated energy balance analysis is carried out for the whole time-period investigated, including also the system batteries depth of discharge distribution versus time. Finally, the predicted optimum system configuration is compared to other existing techno-economical alternatives on a simplified total production cost basis. The results support the viability of similar solutions, especially for high or medium wind potential areas.

Keywords: Stand-Alone Wind Power System; Optimum System Configuration; Energy Balance; Small Wind Turbine; Economic Viability

1. Introduction

After twenty-years of creative development and substantial innovations, commercial wind turbines -of any size- constitute an economically attractive technological solution for the worldwide increasing electricity consumption[1]. In this context, small or micro wind converters are characterized as one of the best alternatives[2][3][4] to meet the electricity demand of isolated consumers, especially in regions with medium-high wind potential. Besides, even in cases that the financial comparisons are marginally positive, environmental and macroeconomic reasons encourage the selection of the proposed solution at dispense of grid extension or the usage of oil-fired engines. In several other cases, hybrid systems, like wind-diesel[5][6] or wind-hydro[7][8] ones, are also considered as an economically viable strategy to meet the electrification requirements of small or medium-sized remote communities.

In Greece, as in many other world regions, there are[9] numerous (≈100,000) remote consumers (e.g. private farms, very small villages, shelters, telecommunication stations, etc) which cannot easily obtain access to an electrical grid. The vast majority resides in the Aegean Sea area. More precisely, Aegean Archipelago is a remote Hellenic area, at the east side of the mainland, including several hundreds of scattered islands. These islands, along with the mainland coasts, possess a very high wind potential, where the mean annual wind speed (at 10m height) varies between 7 and 11m/s.

Up to now, those remote consumers can hardly cover their electricity demand using small oil-fired diesel-electric generators, usually operating at a very high cost level. On the other side, the idea of a regional electrical-grid-extension is often prohibited[10] either for environmental protection reasons or simply due to the absence of any electrical network in the major area under investigation. Moreover, even for beneath one-kilometer distances between the existing grid and the remote consumer, the corresponding grid extension choice[11] is quite expensive (e.g.≈10,000Euro/km).

Therefore, the initial point of this current study is determining the optimum dimensions of an appropriate stand alone wind power system, able to guarantee the energy autonomy of remote consumers located in various typical Aegean Sea regions. Accordingly, emphasis is laid on a detailed energy balance analysis of the selected configurations, on an hourly basis at least. Thus, the energy autonomy (no-load rejection) of the system is ensured for several representative wind potential types and for a remarkable time period (3-years minimum). The necessary energy balance analysis is based on a simple, fast and reliable numerical code -WINDREMOTE- in order to obtain the detailed numerical values of the problem's governing parameters.

At this point, it is important to mention that the zero-load rejection constraint is a very strict one, leading to storage devises[12] over sizing. Hence, it is actually replaced by a 95% or 99% system reliability condition (i.e. the system is annually out of power for 100h to 500h). However, in the last part of the present analysis, the optimum energy autonomous wind power configuration (according to the zero-load rejection condition) is favorably compared -on a simplified operational cost basis- to the grid extension and the diesel-electric generator solutions, see also[3][13].

Recapitulating, the present work examines the energy balance of a stand-alone wind power system, for three typical Aegean Sea regions and for a remarkably long time-period. The main target of this analytical study is the challenge of using wind power as the sole electricity production source, given that the usage of imported diesel-oil is extremely expensive, provoking environmental pollution and also being rather unavailable on a regular basis, mainly due to bad weather conditions or further access problems. On the other hand, the grid extension solution, if not impossible, is usually quite difficult to get accomplished due to insufficient infrastructure problems. Hence, the present work is definitely focused on estimating the optimum configuration of a stand-alone wind power system that ensures the system energy autonomy without using fossil fuel-fired engines.

Consequently, the energy balance behaviour of a stand-alone wind power system applied at several remote consumer cases, along with its cost competitive advantage -in comparison with other available alternatives- outline the proposed solution as a motivating prospect for the energy demand problems of numerous existing isolated consumers.

2. The Energy Fulfillment Problem and the Proposed Solution

In the present investigation, a serious effort is made to settle the electricity demand difficulty of a typical isolated consumer (e.g. a four to six member family), using a properly sized stand-alone wind power system. After an extensive local market survey a representative weekly electricity consumption profile is adopted, being also depended on the year period analyzed (i.e. winter, summer, other). The load profile used is basically a rural household profile (not an average load taken from typical users) selected among several profiles provided by Greek Statistical Agency[14]. More precisely, the numerical load values vary between 30W (refrigerator load) and 3300W.

Thus, the annual electricity consumption -on an hourly basis- is the first input of the present analysis. Additionally, the corresponding wind speed, ambient temperature and pressure values are also necessary to integrate the energy balance calculations. Finally, the operational characteristics of all the components (e.g. wind turbine power curve at standard day conditions, inverter efficiency etc.) composing the stand-alone system under investigation are also required.

More precisely, the proposed (figure (1)) stand-alone wind power system is based on:

i. A small wind converter of "N_o" kW
ii. A lead acid battery storage system for "h_o" hours of autonomy, or equivalently with cell capacity of "Q_{max}" and maximum discharge capacity "Q_{min}"
iii. An AC/DC rectifier of "N_o" kW
iv. A charge controller of "N_o" kW
v. A UPS of "N_p" kW
vi. A DC/AC inverter of "N_p" kW

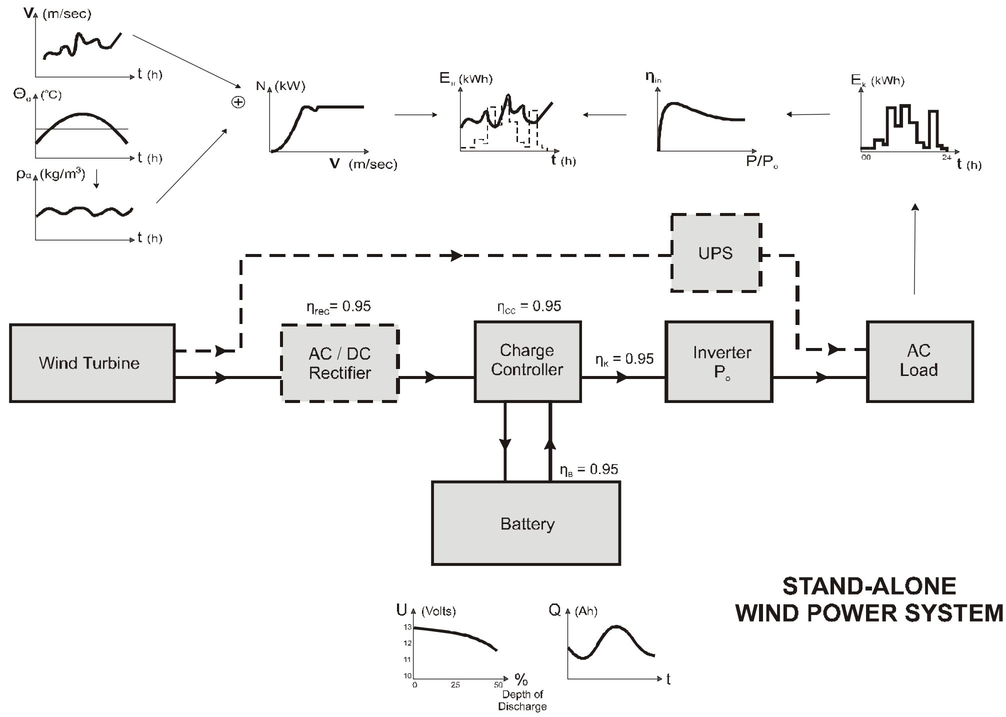

Figure 1: Proposed Stand-Alone Wind Power System

where "N_p" is the maximum load demand of the consumption, including a future increase margin (e.g. 30%). The proposed safety margin is based on a long term analysis of local electrical parameters[15], indicating that the Greek electricity consumption increase has approximated 4% per annum, while the maximum (peak) load increase of the mainland electrical grid is much more abrupt (6%). Hence, since the proposed system has an operational life of at least ten years, it is assumed reasonable to take into consideration a five-year forecast of the expected electricity consumption.

As mentioned above, the main scope of the present work is primarily to estimate the appropriate dimensions of a stand-alone wind power system for every remote consumer examined and to analyze the complete system energy behaviour. The two governing parameters used during the optimization procedure are the rated power "N_o" of the wind turbine used and the battery maximum necessary capacity "Q_{max}". To confront similar problems, a computational algorithm "WINDREMOTE-II" is developed[3]. This specific numerical code (see Chapter 4 for more details) is used to carry out the necessary parametrical analysis on an hourly energy production-demand basis.

The initial (minimum) value of "N_o", i.e. "N_{init}" is predicted as:

$$N_{init} = E_{tot} / (8760 \cdot CF) \tag{1}$$

where "E_{tot}" is the system annual electricity consumption, increased by 20% to take into account future changes[15].

Accordingly, the initial value of "Q_{max}", i.e. "Q_{init}" is given as:

$$Q_{init} = \frac{h_{min} \cdot E_{tot}}{8760 \cdot \eta_s \cdot DOD_L \cdot U} \tag{2}$$

depending on the minimum acceptable hours "h_{min}" of the system energy autonomy. Keep in mind that "η_s" is the storage branch efficiency, used to feed the consumption (including inverter efficiency and power line loss) and "DOD_L" is the maximum permitted depth of batteries discharge. In the present case the battery operation voltage "U" is taken equal to 24Volt.

Subsequently, for each "N_o" and "Q_{max}" pair the "WINDREMOTE-II" algorithm is executed for all the time-period selected (e.g. one month, six-months, one year or even for three years) and emphasis is laid on obtaining zero-load rejection operation. More precisely, for every time point analyzed, the system energy demand is compared to the wind turbine energy production. The wind turbine output is defined by the wind speed, the ambient density and the manufacturer power curve. Thus, during the long-lasting operation of the proposed stand-alone system, the following situations may appear:

a. The power demand "N_D" is less than the power output "N_w" of the wind turbine, ($N_w>N_D$). In this case the energy surplus ($\Delta N=N_w-N_D$) is stored via the rectifier and the battery charge controller. If the battery is full ($Q=Q_{max}$), the residual energy is forwarded to low priority loads.
b. The power demand is greater than the wind turbine power output ($N_w<N_D$), which is not zero, i.e. $N_w \neq 0$. In similar situations, the energy deficit ($\Delta N=N_D-N_w$) is covered by the batteries via the battery charge controller and the DC/AC inverter. During this operational condition, special emphasis is laid on the two-electricity production subsystems management plan.
c. There is no wind energy production (e.g. low wind speed, machine non available (a 80% mean annual technical availability is assumed-a realistic value for small remote wind converters operating usually without permanent service stuff and spare parts stock)), i.e. $N_w=0$. In this case the entire energy demand is fulfilled by the battery charge controller -DC/AC inverter subsystem, under the condition that $Q>Q_{min}$.

In cases (b) and (c), when the battery maximum depth of discharge is exceeded a load rejection takes place, hence the battery size is increased and the calculation is re-evaluated up to the case that the no-load rejection condition is fulfilled for the complete time period examined, i.e. $Q^*=\min\{Q_{max}\}$ that verifies the following equation:

$$N_{exit}(t) \geq N_D(t) \qquad \forall t \tag{3}$$

Next, another wind turbine size is selected and the calculations are repeated. Thus, after the integration of the analysis a (N_o-Q^*) curve is predicted under the no-load rejection restriction.

Finally, for every (N_o-Q^*) pair ensuring the energy autonomy of the remote system, a detailed energy production and demand balance is available along with the corresponding time-depending battery depth of discharge, "DOD", with:

$$DOD(t) = \frac{Q(t)}{Q_{max}} \geq DOD_L \qquad \forall t \tag{4}$$

For practical reasons, in an attempt to preserve the stand-alone system energy autonomy, an emergency energy consumption management plan is also necessary, in order to face unexpected energy production problems related to "Force Majeure" events.

3. Wind Potential Analysis for Selected Aegean Archipelago Islands

In the following, the above described calculation methodology is applied to three representatives, for the Aegean region, test cases, figure (2). The first region to be analyzed has an excellent-wind-potential (island of Andros); while the second one experiences a medium-high wind potential (island of Kithnos). The last region investigated sustains the lowest wind potential (island of Kea) but even in this case the local wind potential is characterized as a medium quality one.

Figure 2: Wind Potential Estimates for Representative Aegean Sea Islands at 30m height[10][17]

Andros is a small medium-sized island (the second biggest one) of the Cyclades complex (population 12000 habitants, area of 384km^2), located in the middle of the Aegean Sea. The local terrain is very intense, including several rocky mountains with relative sharp slopes. The island has one of the best wind potential in Greece ($\overline{V} \approx 10$m/s), while in the island exists a PPC (Greek Public Power Corporation) owned wind park of 7x225kW V-27 wind turbines, operating with outstanding results since 1993, despite the modest average technical availability of PPC wind parks during the same period[16].

Kithnos is also a small island (1700 habitants, area of 94km^2) of Aegean Sea, located approximately 60km southeast of Athens. The topography of the island is typically Aegean, i.e. gentle slopes, absence of flat fields, low mountains and sparse vegetation. Due to the insufficient infrastructure (e.g. road network) there are many isolated consumers, who have no access to the local electrical grid. The island has an outstanding wind potential, since in several locations the annual mean wind speed approaches 7m/s, at 10m height.

Finally, Kea is a small island (2300 habitants, area 103km^2) close to Athens. The local topography is similar to Kithnos one, while the main economic activities of the local society are agriculture, cattle breeding, beekeeping and tourism. The corresponding wind potential is good enough (annual mean wind speed ≈6.5m/s) to feed contemporary wind turbines, for electricity production.

Using the available wind speed data[17] for a three-year period, the experimental 3-year mean wind speed probability density function distribution "f(V)" is created, for all three regions investigated, see

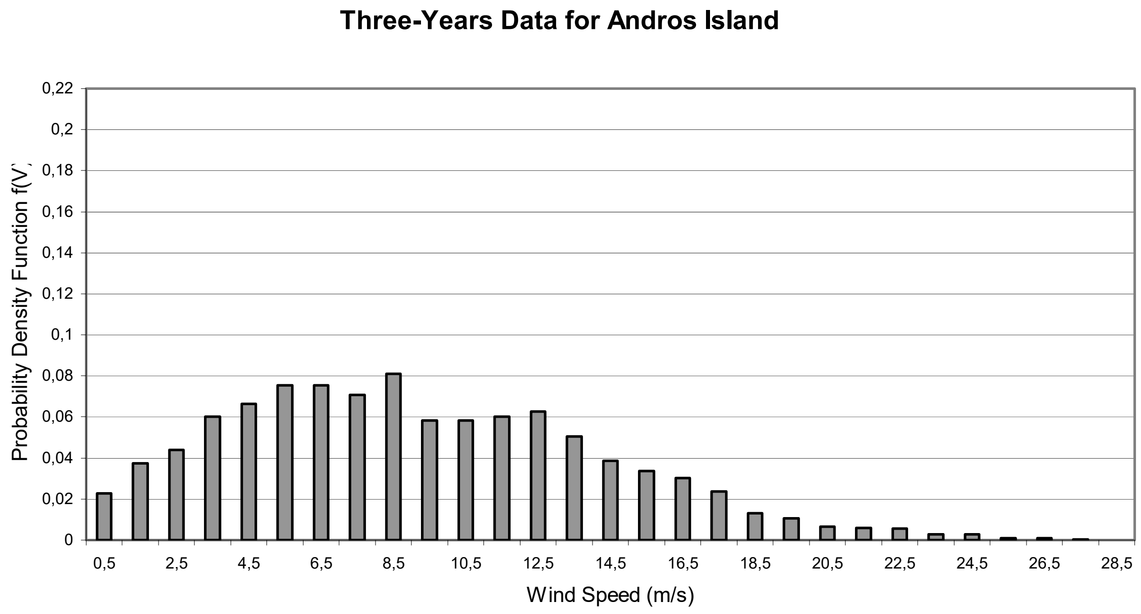

Figure 3: Wind Potential Data for Andros Island

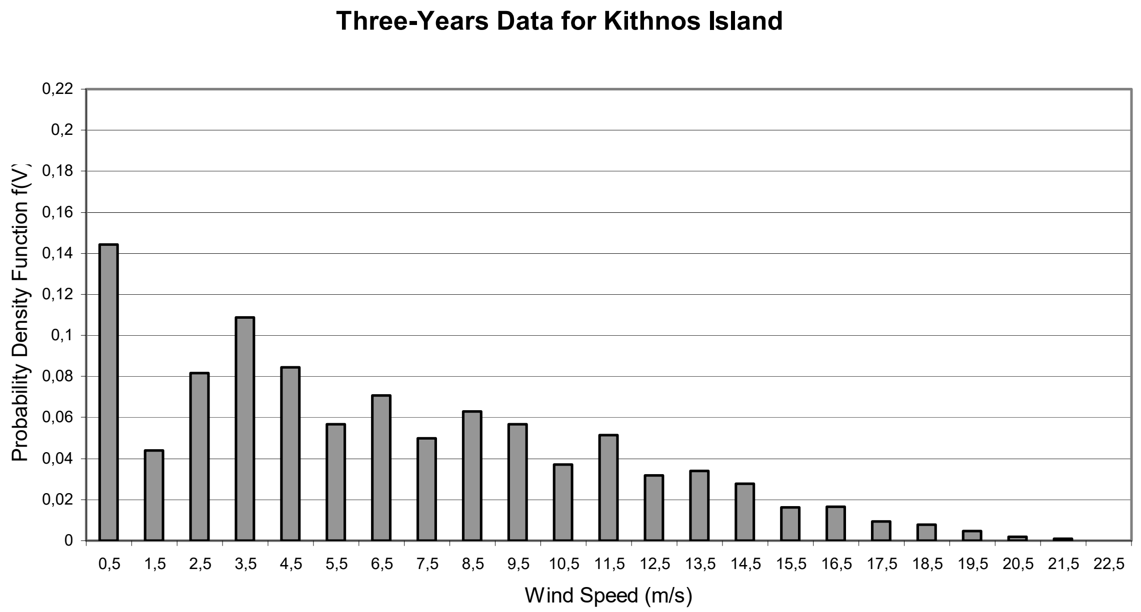

Figure 4: Wind Potential Data for Kithnos Island

also figures (3) to (5). It is important to mention that the 3-years period selected includes the maximum calm spells during a fifteen-year period, where extensive wind speed measurements exist. Generally speaking, using the wind speed data for a three-year period one may obtain an almost accurate picture of the wind potential of an area in order to create a new wind farm. On top of that, a three-year period is assumed enough by Milligan and Artig[18] to choose wind power plant locations and sizes, although they also possess multi-year wind speed measurements. Finally, as stated by the authors[10] (pp.298) by increasing the wind speed measurements period from 36 to 60 months the reliability level increases not more than 5% (i.e. from 83% to 88%).

As it is expected, the Andros wind potential is quite higher than the Kithnos and Kea ones, while the last two regions maintain similar quality wind potential. Of course the zero-wind speed possibility is

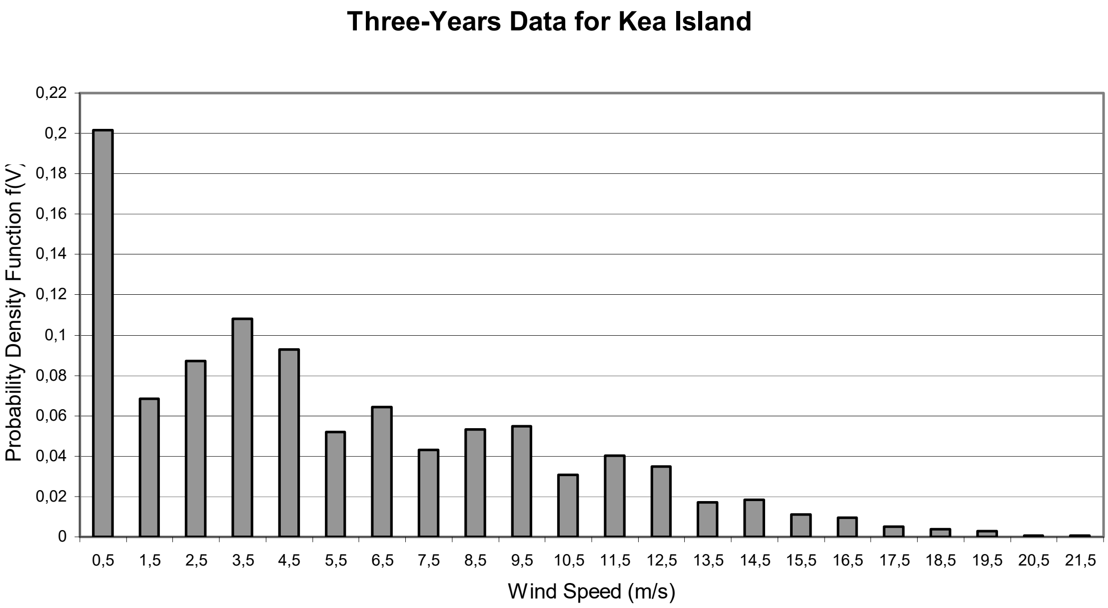

Figure 5: Wind Potential Data for Kea Island

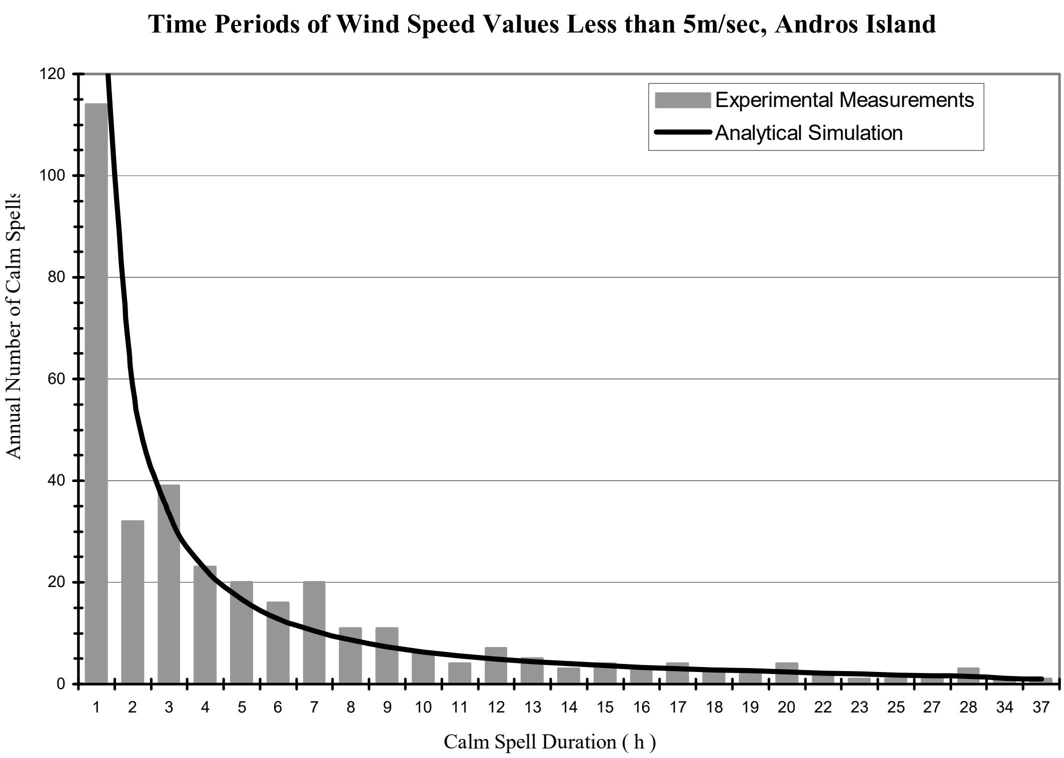

Figure 6: Long-Term Calm Spell Periods for Andros Island

much bigger in Kea (≈20% of the year) than in Kithnos. On the contrary, the zero-wind speed possibility is almost zero (≈2%) for Andros.

This fact is also supported by figures (6) to (8) where the corresponding calm spells for the three islands analyzed are presented (i.e. wind speed values less than 5m/s), after a thorough analysis of the available detailed wind speed values[19].

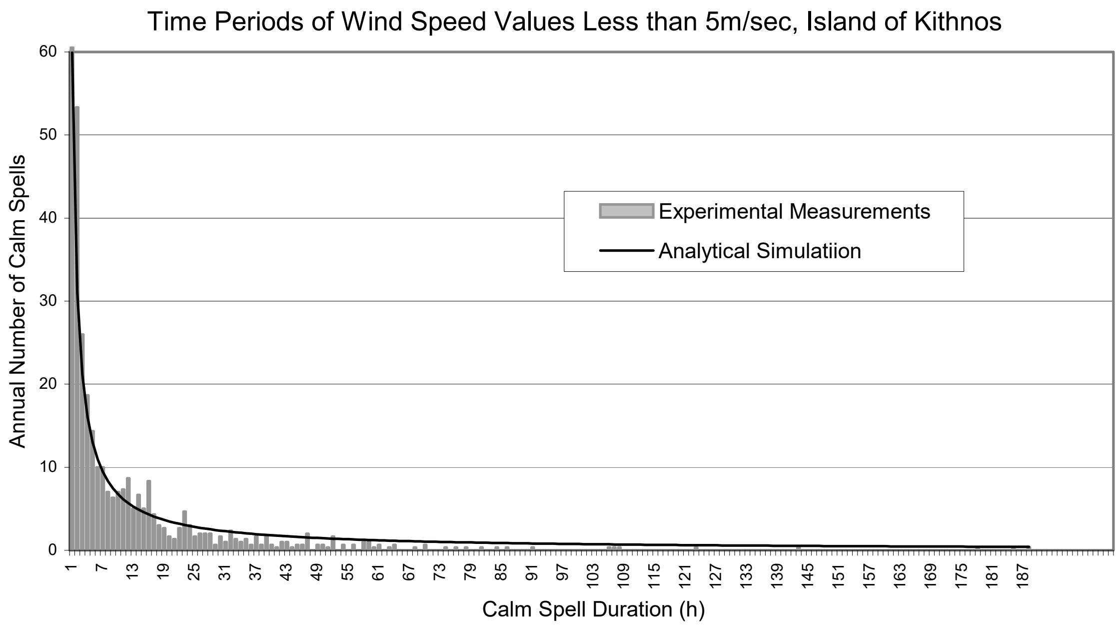

Figure 7: Long-Term Calm Spell Periods for Kithnos Island

Finally, in Table I the annual average wind speed values for all three years and regions examined are presented, along with the corresponding Weibull[10][20] parameters (i.e. "C" is the wind speed normalizing factor and "k" is the corresponding shape factor) and the maximum calm-spell-periods

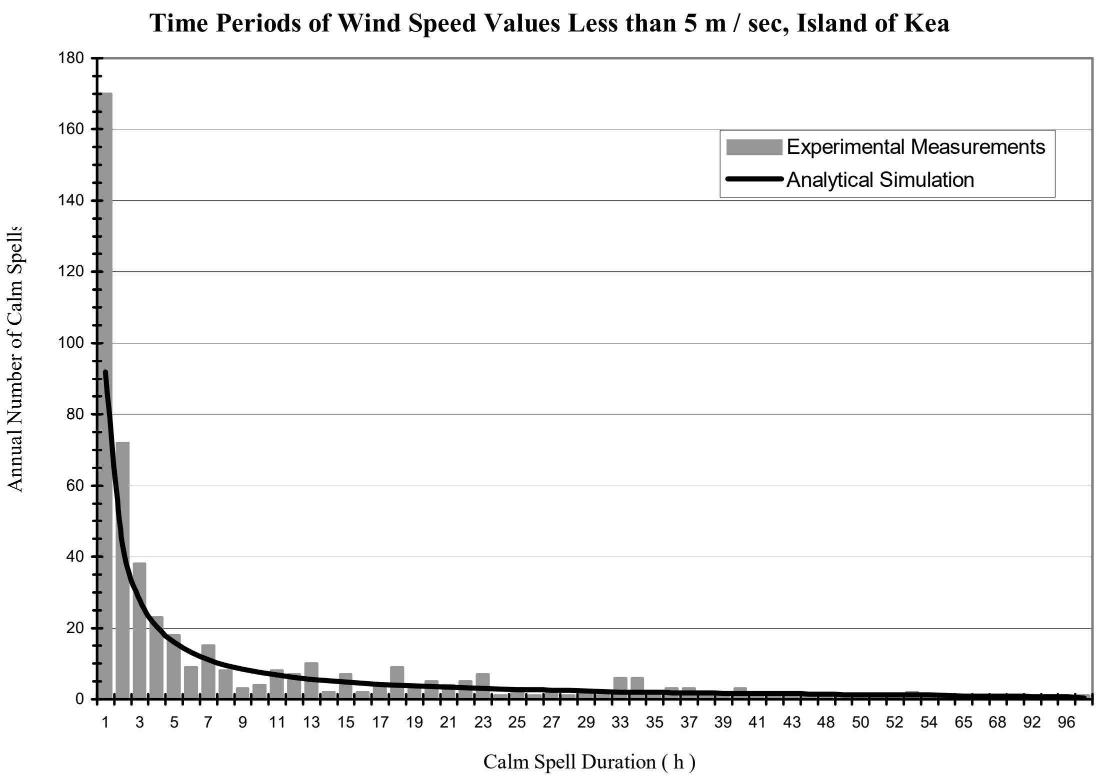

Figure 8: Long-Term Calm Spell Periods for Kea Island

duration. According to the available information, based on three years detailed measurements, one may conclude that Andros possess an excellent wind potential with very high wind speeds and limited calm spell periods. Subsequently, Kithnos wind potential is slightly better than Kea one, without big differences. Bear in mind that both islands present high wind speeds all year round, although the existence of remarkable calm spell periods cannot be disregarded.

Table I: Main Annual Wind Potential Characteristics of the Areas Analyzed

	Andros			Kithnos			Kea		
	1st Year	2nd Year	3rd Year	1st Year	2nd Year	3rd Year	1st Year	2nd Year	3rd Year
$\overline{V}$ (m/s)	8,892	9,565	9,011	6,4535	6,7855	6,392	5,482	5,403	5,596
C (m/s)	9,478	10,234	9,777	6,563	6,717	6,445	5,273	5,165	5,438
k	1,842	1,834	1,830	1,364	1,337	1,264	1,302	1,299	1,313
max calm spell duration (h)	36	34	37	178	185	188	165	158	161

4. Best Configuration Choice

As mentioned above, during the last year a new numerical algorithm "WINDREMOTE-II" has been created[3][21], able to analyze in details the energy behaviour of stand-alone systems for a selected time period. The main steps of this algorithm are:

i. For every region analyzed, select a "N_o" and "Q_{max}" pair.
ii. For every time point of a given time period (with a specific time step) estimate the wind energy produced "N_w" by the wind turbine, taking into account the existing wind speed, the ambient density and the selected wind turbine power curve.
iii. Compare the energy production with the isolated consumer energy demand "N_D". If any energy surplus occurs (N_w>N_D), the energy is stored to the battery system and a new time point is analyzed (i.e. proceed to step ii). Otherwise, proceed to step (iv).
iv. The energy deficit (N_D-N_w) is covered by the energy storage system, if the battery is not near the

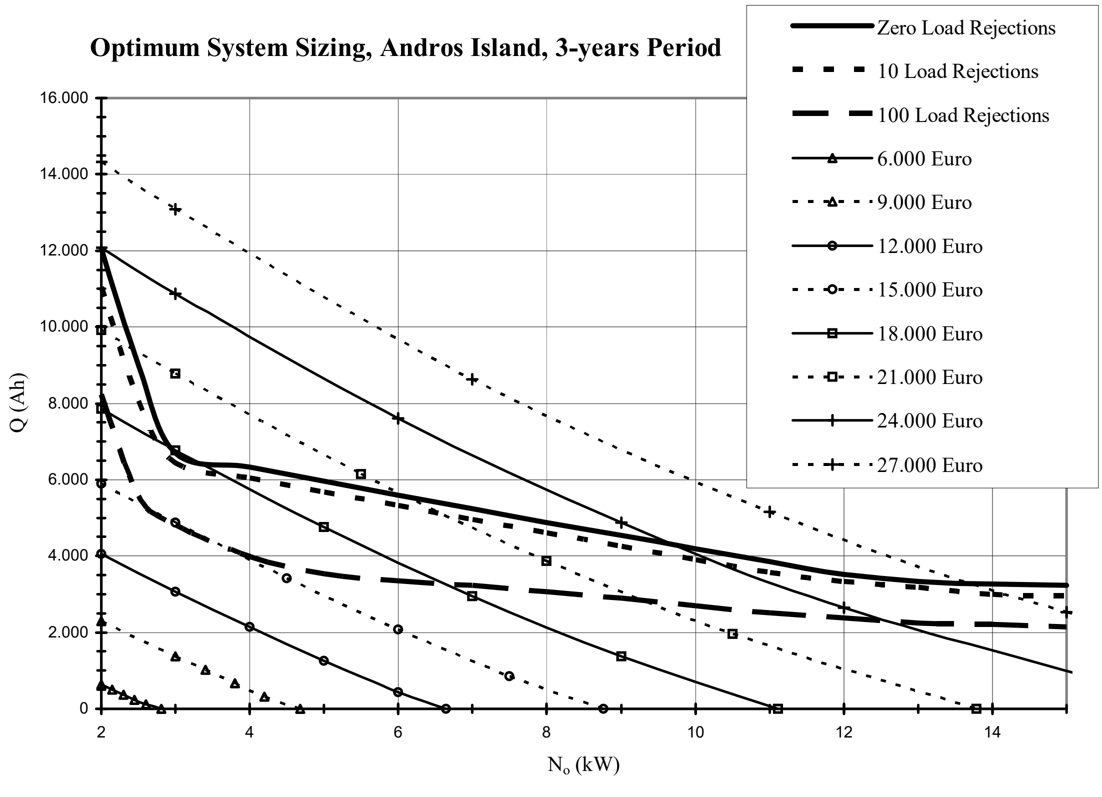

Figure 9: Calculation Results for Andros Island, 3-years Period Analyzed

lower limit ($Q>Q_{min}$). Accordingly proceed to step (ii). In cases that the battery is practically empty ($Q \leq Q_{min}$), the battery size is increased (by a given quantity) and the complete analysis is repeated from the beginning, starting from step (i).

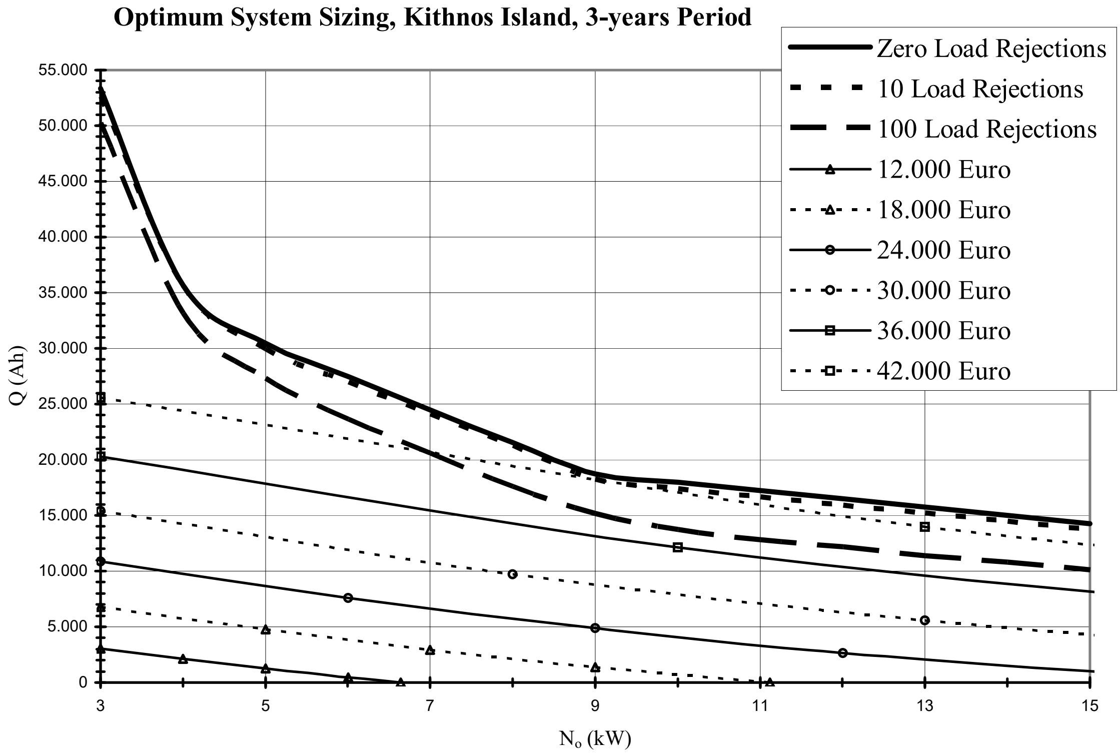

Figure 10: Calculation Results for Kithnos Island, 3-years Period Analyzed

Applying the "WINDREMOTE-II" algorithm to the Andros island case, the calculation results are summarized in figure (9), for the complete 3-years period examined. In the same figure one may observe the corresponding 10 and 100-load rejection (or hours without electricity) curves, for the same period. According to our results, there is a significant battery capacity reduction with the increase of the wind turbine rated power, up to 4kW. For bigger wind turbines the battery storage capacity continuous to decrease, though in a dropping rate. For over 12kW wind turbines, the battery size distribution presents an almost asymptotic behaviour.

Keep in mind that in order to get a clue for the expected initial cost of the proposed installation, the preliminary economical data by the authors[3][12][21] -concerning the local market- are included here as constant initial cost curves. Thus, the minimum initial cost solution (≈18000Euro) for Andros case is based on a 3kW wind converter and on a 7,200Ah/24V battery row. The proposed configuration guarantees 3-year energy autonomy (excluding "Force Majeure" events) of the remote consumer, located in a windy area of Andros. Finally, by accepting 100 load rejections per 3-years a similar configuration may be used, based on the same wind turbine but using a 5000Ah/24V battery storage device.

Next, the Kithnos island stand-alone system is investigated, figure (10). In this case, the battery capacity-reduction related to the wind turbine size-increase is remarkably up to 9kW. For bigger wind turbines, the necessary battery storage capacity-decrease is decelerated, approaching a 13,000Ah value as "N_o" tends to 15kW. Using the same economical data as for Andros case, the minimum initial cost solution (≈41800Euro) is based on a 9.5kW wind converter and on an 18,000Ah/24V battery row. The proposed configuration guarantees 3-year energy autonomy of the remote consumer, located in the

Kithnos Island. Similarly, the 100-load rejection curve gives quite decreased battery dimensions for the same wind turbine size.

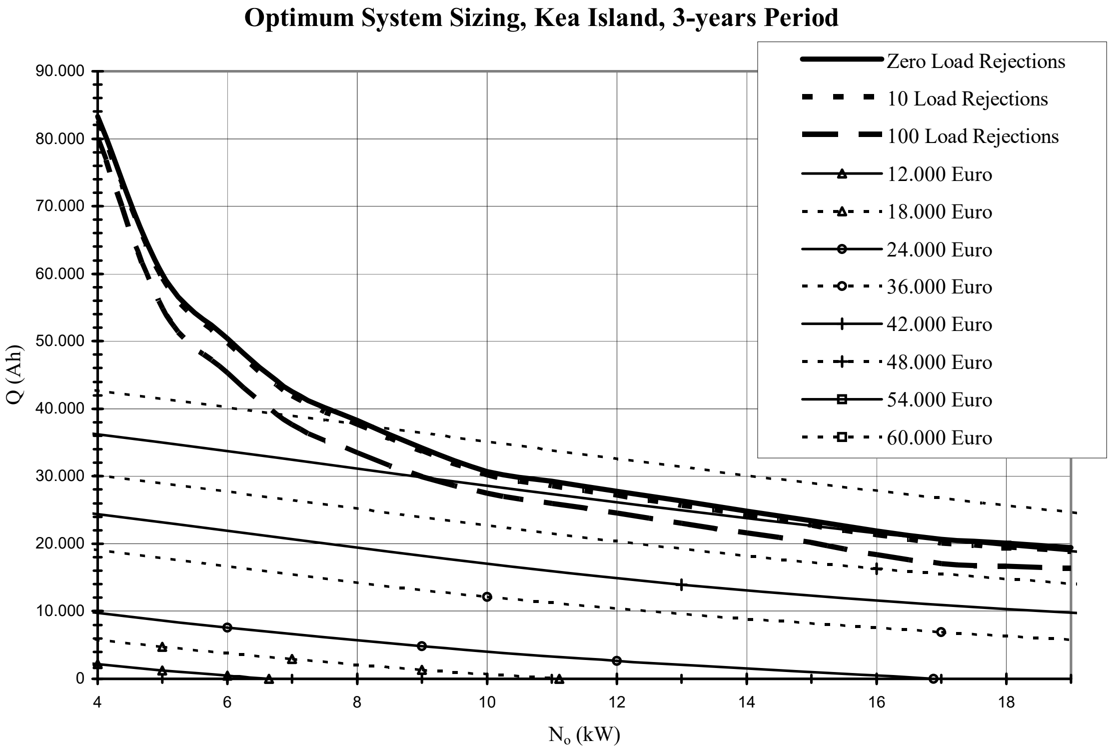

Figure 11: Calculation Results for Kea Island, 3-years Period Analyzed

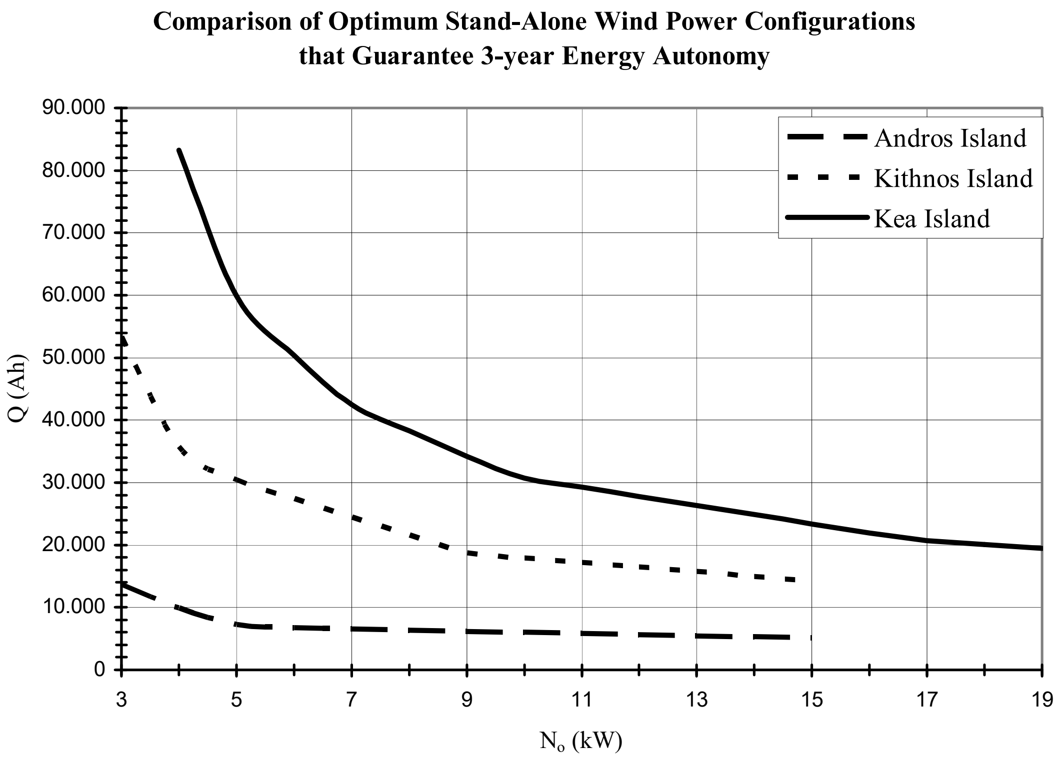

Figure 12: Comparison of Optimum Configurations that Guarantee 3-year Energy Autonomy for three Representative Remote Consumers of Aegean Sea Area

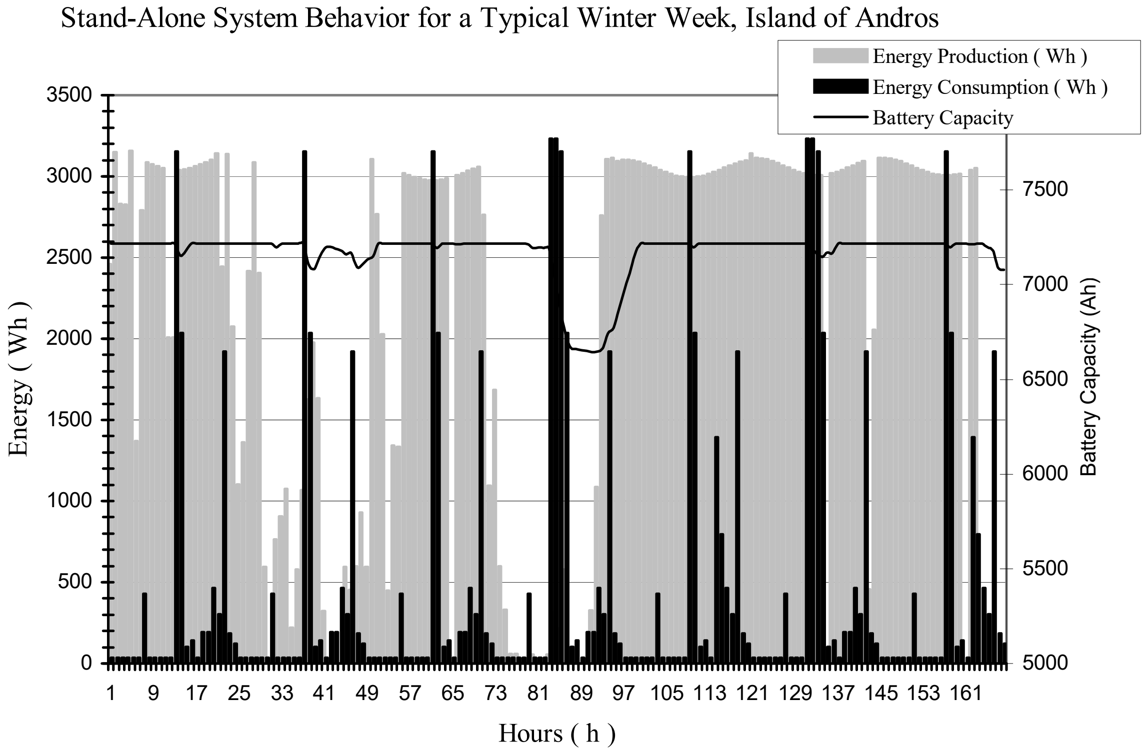

Figure 13: Stand-Alone System Main Parameters Evolution, Best Wind Potential Area, Winter

The last region analyzed in this current paper concerns a stand-alone system located in Kea Island. As it results from figure (11), the system -in order to obtain complete energy autonomy for a 3-year period- is quite sizeable. Bear in mind that a substantial battery-size decrease is realized as the wind turbine size increases from 4kW to 10kW. Accordingly, the battery-size decrease is decelerated, achieving an asymptotic value of 17,000Ah. Taking into account the preliminary economic information[10][21] already used in the other two cases, the minimum initial cost 3-year energy autonomous solution (≈51900Euro) should be based on a 17kW wind converter and on a 20,000Ah/24V battery row.

Recapitulating, the zero-load rejection curves for the 3-year time period investigated and for all three regions analyzed are concentrated -for comparison purposes- in figure (12). As it is obvious from the results obtained, the necessary dimensions of a stand-alone wind power system for the Andros case are by far less than the Kithnos and Kea islands corresponding ones. On the other side, a stand-alone system in Kea should be based on enormous battery capacity values, even for wind turbines of rated power higher than 15kW. This remarkable system extension in comparison to the other two cases may be attributed to the lower wind speed mean values, as far as the wind turbine nominal power is concerned. Similarly, the excessive battery capacity needed is strongly related to the remarkable calm spells duration in the area under investigation.

5. Energy Balance Analysis

As already stated, one of the main targets of the present study is to extensively analyze the energy balance of the proposed stand-alone system for the complete time-period investigated. To get a representative picture of the proposed system behaviour, we present in figures (13) and (14) a typical 7-days energy balance profile of the optimum configuration (3kW-7,200Ah) for the best wind potential area, i.e. Andros island. The periods selected are a typical winter one (mid-January) and a corresponding summer one (mid-July). In the same figure the battery capacity variation is also given as a function of time.

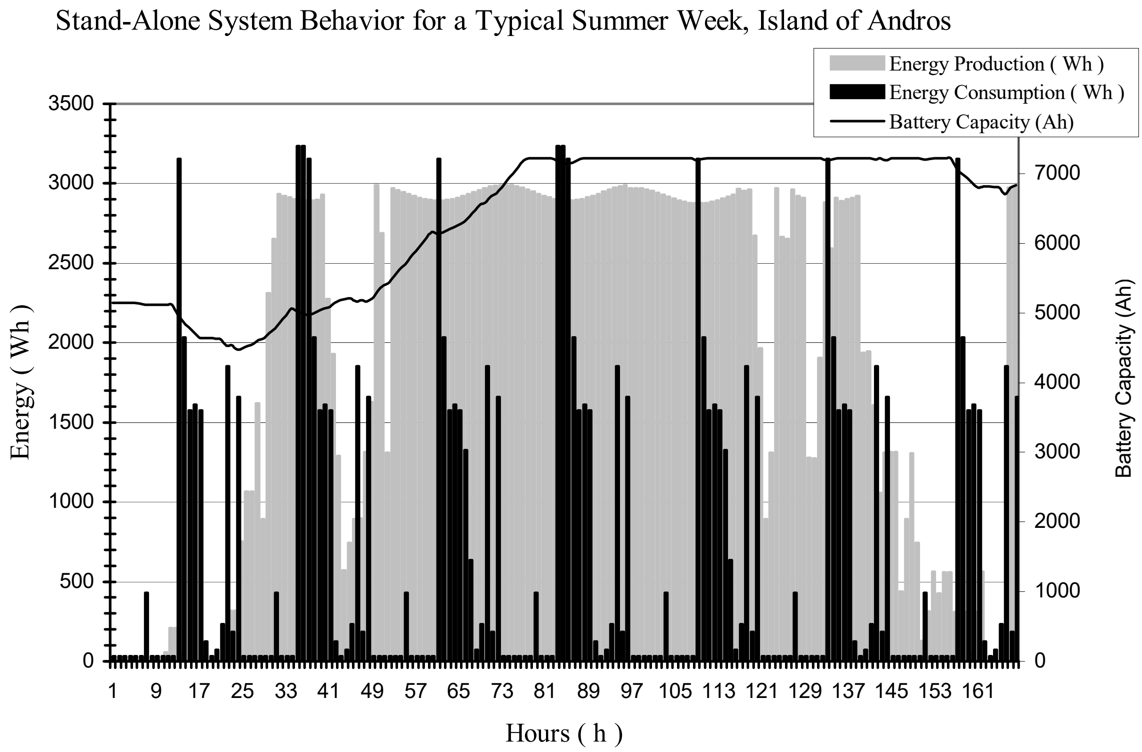

Figure 14: Stand-Alone System Main Parameters Evolution, Best Wind Potential Area, Summer

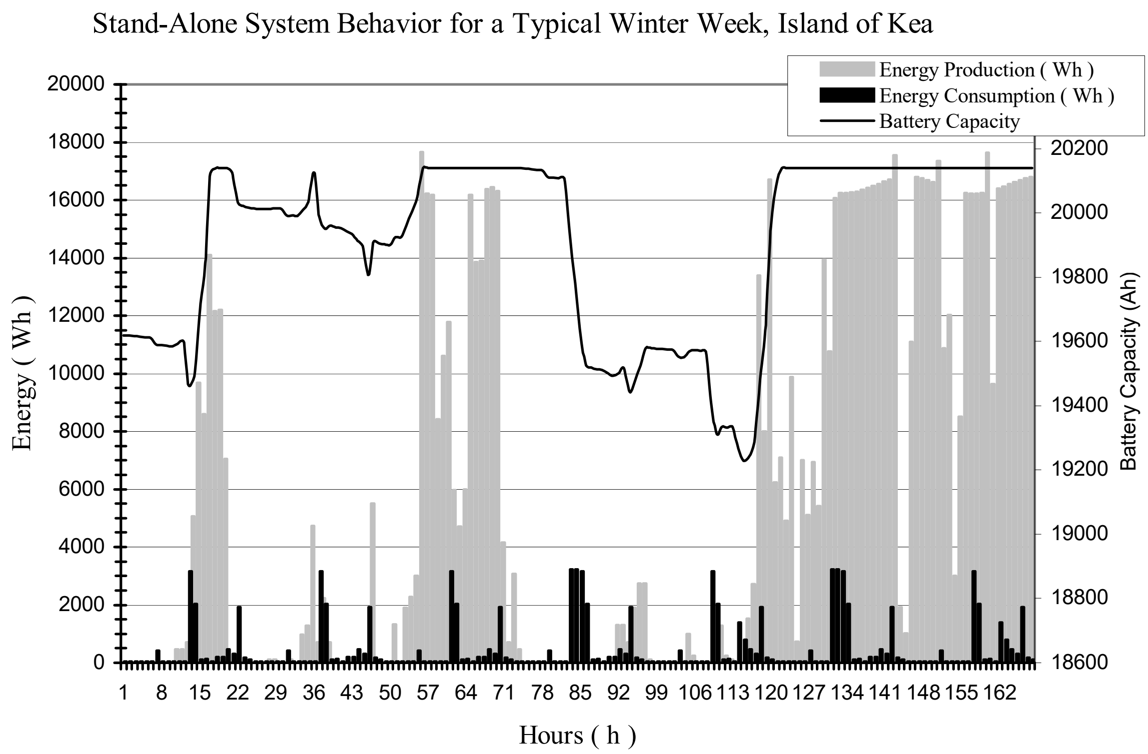

Figure 15: Stand-Alone System Main Parameters Evolution, Low Wind Potential Area, Winter

Considering that the winter electricity consumption is lower than the summer one, it is reasonable that the battery is full almost the ¾ of the week examined. Only during the middle of the winter week there is a remarkable DOD increase, due to an almost 20 hours calm spell. Subsequently, during the summer week analyzed, there is an important energy deficit during Monday (1st day) but accordingly the

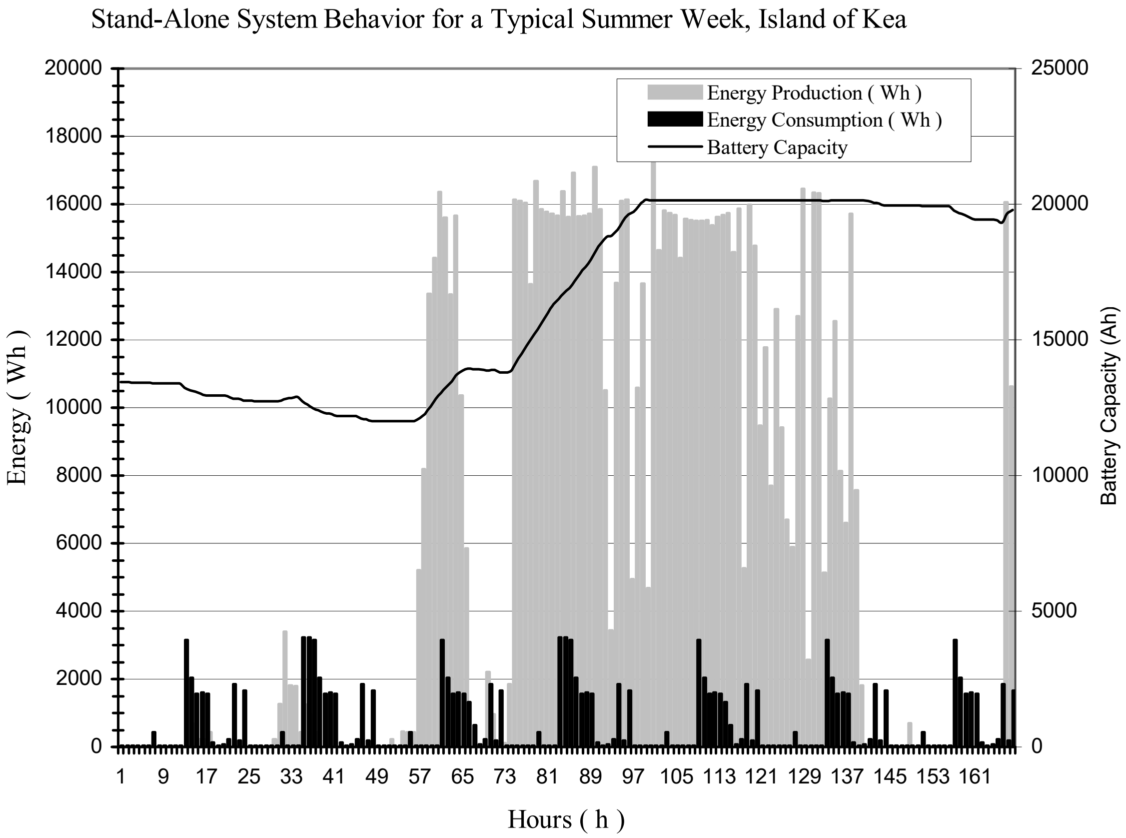

Figure 16: Stand-Alone System Main Parameters Evolution, Low Wind Potential Area, Summer

battery is gradually fully charged, despite the significant energy consumption at the same period. Another interesting remark concerns the maximum wind turbine power outlet[10][22], dropping for the summer period due to the low air density, becoming therefore clearly lower than the consumption peak load demand.

In the following figures (15) and (16) the corresponding typical 7-days energy balance of the optimum configuration (17kW-20,000Ah) for the Kea island, possessing the lowest wind potential, is also sited. For comparison purposes, the winter period selected is the same with the Andros case, while the corresponding summer week is the "worst" one (in terms of low wind potential) of the 3-year period examined. In the same figure the battery capacity variation is also given as a function of time. According to the results presented, the rated power of the wind turbine used is almost quadruple the isolated consumer peak load demand. Similarly, the battery capacity diminution during the long-lasting calm spells, although remarkable in absolute terms, does not lead to significant depth of discharge increase of the storage system, excluding the "worst" week case presented in figure (16).

Another important conclusion drawn from the Kea island analysis is the significant energy surplus appearing on windy days, when the system batteries are full. This severe -for Kea stand-alone system- problem is not so important for Andros case because the wind turbine rated power in Andros is quite smaller than the Kea one. On top of that, this remarkable energy excess may be used either for water pumping[23] or for seawater desalination[24] especially in sizeable wind power system cases.

6. Comparison of Available Solutions for a Stand-Alone System

As predicted above the first installation cost of a stand-alone system based on a small wind converter is quite high, approaching the 18000Euro even for sites with excellent wind potential. In order to check the viability of the proposed wind power based solution, to meet the electricity demand of a remote consumer with rational cost, a preliminary comparative study is undertaken including also the possibility to realize an electrical grid connection or to use a small autonomous diesel-electrical generator system. It is the authors' opinion that in the present study there is no space for detailed economic data presentation, while some information is given in the published references[3][10][12][21][25][26]. The detailed comparative evaluation of all available electrification solutions for remote small-size consumers may be the subject of a future work.

i. Grid Extension Solution

According to the existing market data[10][25], the typical grid extension cost for a remote consumer to be connected to the PPC (Greek Public Power Corporation) local grid using overhead-medium over-voltage lines is approximately 10000Euro/km. At the same time the current electricity market price for all Greek consumers (increased by 10% to incorporate the maintenance cost of the new remote grid) is 0.12Euro/kWh. Neglecting for simplicity reasons the time-variations of the above parameters, the total electricity cost "C_{GC}" of the consumer after "n" years of utilizing the extended electrical grid, being at a distance "z" from the existing electrical network, can be described by the following relation:

$$C_{GC} = 10000 \cdot z + 0.12 \cdot E_{tot} \cdot n \qquad (5)$$

ii. Usage of a Diesel Engine

The most widely applied solution for the remote consumers to fulfill their electrification needs is to install a small internal combustion engine in combination with a small electrical generator. Although the efficiency of such a system is quite small ($\eta_d \approx 20\%$) the corresponding buy cost is very low (≈140Euro/kW), increasing the short-term economic attractiveness of this solution. On the other hand, the service period life of a whole-year operating system is taken equal to six (6) years and the corresponding M&O cost (mainly due to fuel cost) is between 3100 and 5000 Euro per year. Consequently, selecting a 5kW autonomous system and accepting a 0.8 to 1.7Euro/lit cost of the diesel oil used (the maximum value takes into account the increased transportation cost), the total electricity cost "C_d" of the installation after "n" years of operation is given as:

$$C_{d\,min} = 700 + 3100 \cdot n + V_n \qquad (6)$$

or

$$C_{d\,max} = 700 + 5000 \cdot n + V_n \qquad (7)$$

where "V_n" term describes the replacement cost of the diesel engine every six years

iii. Wind Energy Based Stand-Alone Solution

Using the optimum configuration dimensions (under the no-load rejection restriction) of the stand-alone system for every island analyzed (e.g. Andros. IC_o=18000Euro) and a 3% (m=0.03) annual maintenance and operation cost coefficient[26], the total electricity production cost by applying the wind energy solution can be approximated as:

$$C_{WE} = IC_o + m \cdot IC_o \cdot n + V'_n \qquad (8)$$

while the "V'_n" term is used to describe the battery replacement cost (e.g. for Andros 11700Euro) every seven years.

For comparison purposes, the calculation results are summarized in figure (17), for various distances from the existing grid ($1 \le z \le 10$km) and for the three regions investigated. As it is clearly stated by

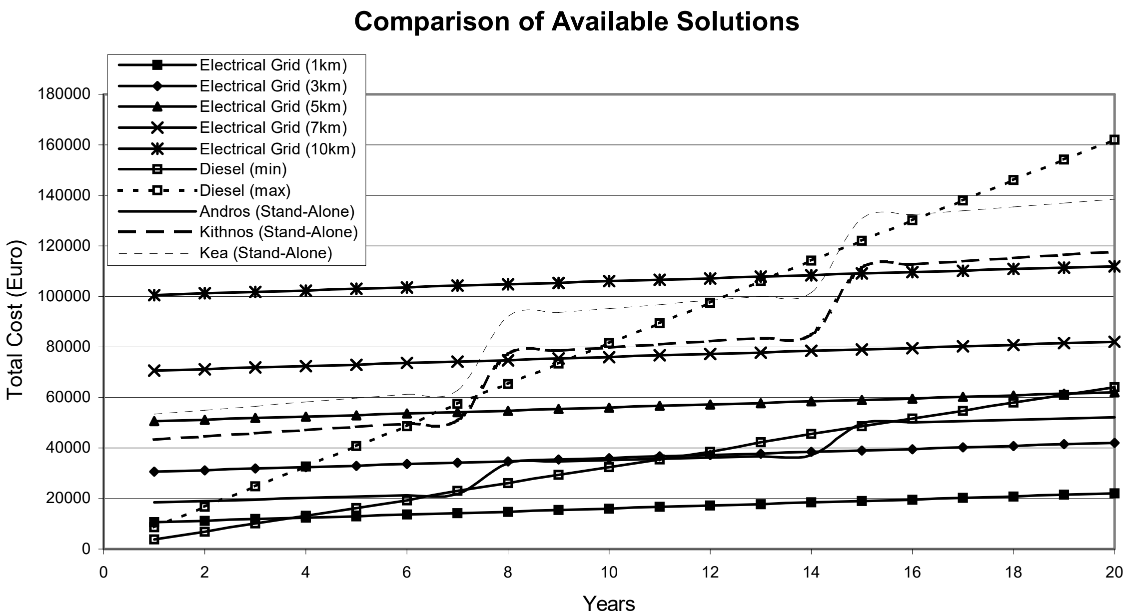

Figure 17: Total Cost Comparison Between Available Electrification Solutions

figure (17) for z<1km the grid connection is the best choice, for medium to long-term operation of the system (n>4years). Accordingly, for Andros Island, the proposed stand-alone system is an economically interesting solution for (2≤z≤4km), especially when the maximum diesel cost values are taken into consideration.

For z≥4km the proposed stand-alone wind power solution is by far the best alternative, excluding the minimum diesel cost production scenario and short-term operation cases (i.e. n≤6years).

Subsequently, the proposed stand-alone configuration for Kithnos island presents an financially competitive advantage for installation regions being more that seven kilometers (z≥7km) away from the local grid and for medium to long term operation cases (n≥9years). Finally, for the Kea island case, the financial advantage of the proposed stand-alone wind power system, in comparison with the other alternatives, is validated for relative long distances from the local electrical network (z≥12km) and for long-term operation of the system (n≥12years). In all other cases, the diesel or the grid extension solutions should be preferred on a pure energy production cost basis.

7. Conclusions

The central target of the present study is to estimate the optimum dimensions of a stand-alone wind power system, under the precondition of the minimum first installation cost, without the utilization of fossil fuel-fired engines. In order to underline the pros and the cons of similar solutions, several different cases are analyzed. According to the preliminary financial results based on the simplified analysis of Chapter 6, there are many cases that the proposed configuration has the competitive advantage against any other available solution, but this is not generally the rule.

Hence, the optimum dimensions of a stand-alone wind power system are defined for three representative Aegean Sea islands, using long-term meteorological data. It is important to mention that the first case analyzed concerns a high wind potential area (mean annual wind speed ≈10m/s), while the other two cases represent medium-high quality wind potential regions (annual average wind speed ≈7m/s and ≈6.5m/s, respectively).

Accordingly, a detailed energy balance analysis is carried out for the entire time period examined, in order to verify that -for every time point- the electricity requirement of the remote consumer is fulfilled by the proposed solution. Similarly, the battery depth of discharge (battery capacity) time evolution is also investigated, to ensure that the corresponding "DOD" values do not exceed the existing lower limit value.

Finally, the proposed configuration is favorably compared to other existing technically viable alternatives, using a simplified total energy production cost analysis versus time. According to the preliminary results obtained the stand-alone wind power system is an economically attractive medium-long term solution for remote consumers, especially for windy regions and for distances greater than 2km from the local electrical grid. Bear also in mind that the proposed configuration presents indeed a competitive advantage over the diesel-electric generator choice, in cases that there is no available electrical network in the nearby region.

In an attempt to decrease the remarkable first installation cost -mainly due to the excessive batteries used- of the stand-alone system analyzed, the substitution of the strict no-load rejection condition by a more realistic system reliability value (e.g. 99% or even 95%) should be further analyzed in a future work.

Summarizing and considering the representative long-term results of the present study, one may support that a wind power stand-alone system is a motivating techno-economical solution to meet the electricity demand of several remote consumers in our area, especially in regions with high or medium wind potential quality.

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MINIMUM STAND-ALONE WIND POWER SYSTEM COST SOLUTION FOR TYPICAL AEGEAN SEA ISLANDS

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Abstract

Stand-alone wind power systems provide a solution for the electrification of isolated families. However, optimal sizing is usually based on simplified cost analysis of the initial installation. In this paper, a complete long-term energy production cost investigation is developed. This considers the fixed and variable costs of maintenance, operation and financing, in addition to initial costs. The new model includes local economic parameters, technological improvements concerning the system components and the local wind characteristics. By using the proposed model, the requirements and costs of the appropriate stand-alone system are recalculated and then compared with those based only on the initial installation. According to the results obtained, the proposed configuration uses larger wind turbines and smaller batteries than that the installation-only scenario. Finally, the energy production values are compared to available operational data from autonomous thermal power plant on various small Greek islands.

Keywords: Stand-Alone System; Wind Power; Minimum Cost; Electrification

1. Introduction

Energy supply, especially electricity, is considered a significant aspect of contemporary societies, as are clean water and air. However, official statistics estimate that almost two billion people have no direct access to electrical networks[1], with 500,000 of these living in the European Union, of which more than one tenth are in Greece[2].

All such remote consumers can be divided into two separate groups. The first group live at isolated rural locations, with a total absence of any electrical grid in their nearby area. The second group live nearer to existing electrical grids, but the connection cost[3] is comparatively high due to the well above average distance from the grid or the difficult topography of the area.

Until recently, the great majority of such rural consumers had no other choice in practice than using small diesel-electric generators in order to meet their electrification needs, or, for the second group, making a long and expensive grid-connection.

A long way from centres of influence and usually having limited political influence, most isolated consumers feel abandoned with insufficient resource infrastructure[4][5]. The importance of having an electricity supply however, is not based on simply techno-economic criteria but mainly on social, and even national, reasons for survival. Thus, as a contribution to the quality of life of these isolated habitants, an integrated solution based on an energy-autonomous stand-alone wind power system has been developed by the authors[6][7] during the last five years.

However, during the energy supply validation of the proposed system[7][8], a preliminary cost analysis was only incorporated as part of the process to determine optimum system size. Although that analysis provided an order of magnitude estimate of initial installation cost, the long-term cost should include maintenance and operational costs also. Such an overall cost for autonomous supply may then be compared with long-term operational data, concerning very small, yet permanent, habitations of 20 to

100 families served by mini-grids from isolated power stations belonging to Greek Public Power Corporation (PPC), see figure (1)[9].

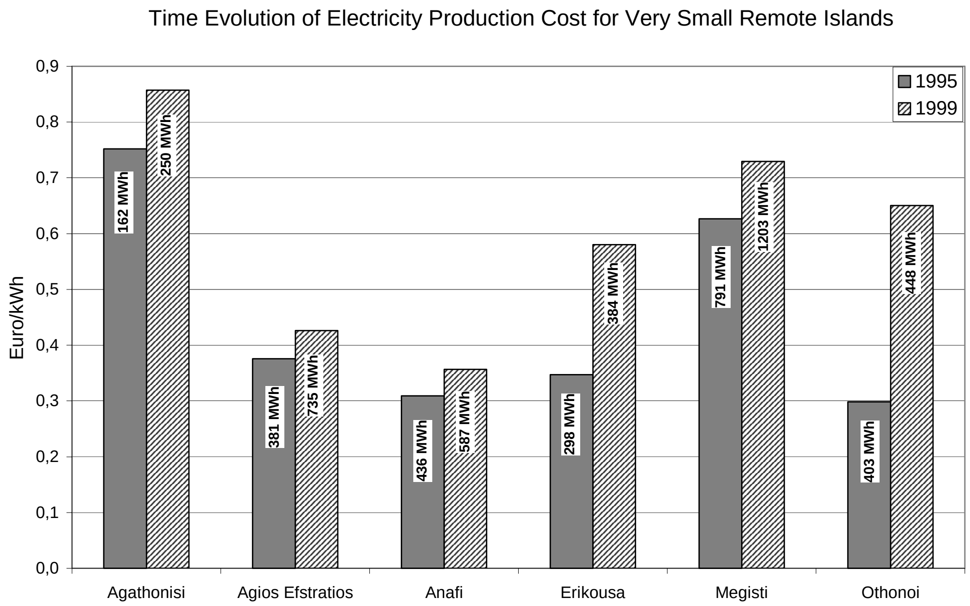

Figure 1: Electricity Production Cost Time-Evolution for Remote Consumers

2. Brief Presentation of the Proposed Solution Optimum Sizing

Based on previous work[6][7] of the authors, figure (2) shows the proposed stand-alone energy production configuration, consisting of:

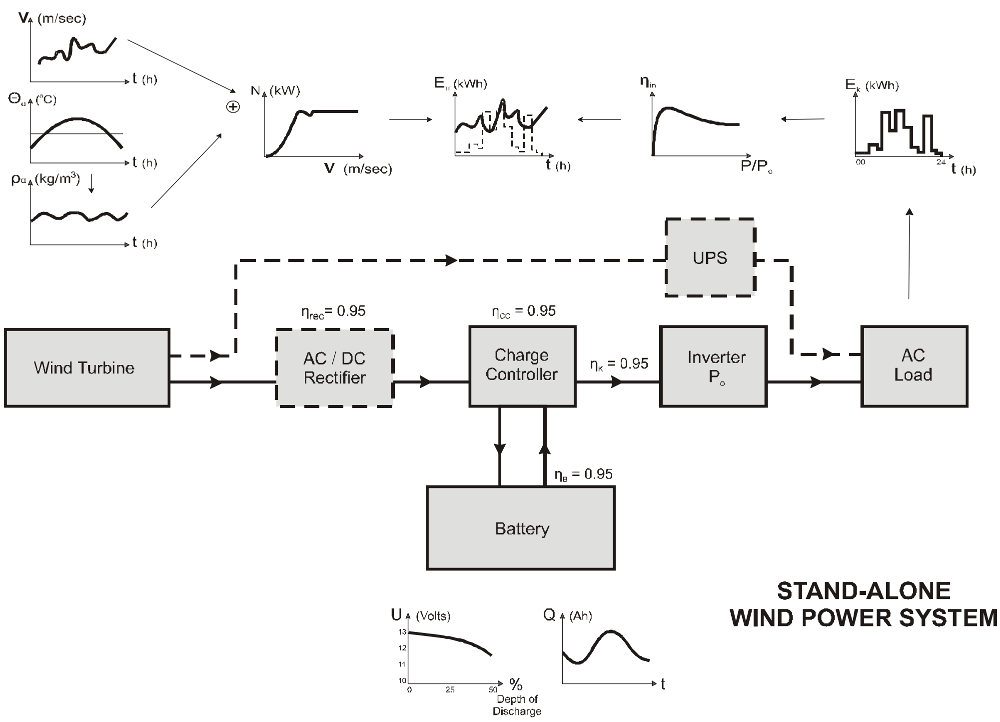

Figure 2: Proposed Stand-Alone Wind Power System

i. a small wind converter of capacity "N_o" (kW)
ii. a lead-acid battery with cell capacity of "Q_{max}", maximum depth of discharge "DOD_L" and output voltage "U"
iii. an AC/DC rectifier of "N_o"
iv. a charge controller of "N_o"
v. a UPS (Uninterruptible Power Supply) of "N_p" (kW)
vi. a DC/AC inverter of "N_p"

Accordingly, during the long-lasting service period of the installation (20 years is assumed to be realistic), the following operational modes may appear:

a. The power demand "N_D" is less than the power output "N_w" of the wind turbine, ($N_w > N_D$). In this case the surplus power ($\Delta N = N_w - N_D$) is stored via the rectifier and the battery charge controller. If the battery is full ($Q = Q_{max}$), the residual energy is forwarded to low priority loads.
b. The power demand is greater than the power output of the wind turbine, ($N_w < N_D$), and $N_w \neq 0$. In similar situations, the power deficit ($\Delta N = N_D - N_w$) is covered by the batteries via the charge controller and the DC/AC inverter. During this operational condition, special emphasis is put on the two-electricity production subsystems management plan.
c. There is no wind energy production (e.g. low wind speed, machine not available), i.e. $N_w = 0$. In this case all the energy demand is met by the battery-charge controller-DC/AC inverter subsystem, under the condition that $Q > Q_{min.}$ In cases (b) and (c), when the battery capacity is near the lowest limit, an electricity demand management plan should be applied; otherwise the load would be rejected. In this context, a system-monitoring device may remarkably improve the efficient operation of the autonomous wind power station.

The main parameters defining the size, and subsequently the first installation cost, of a suitable system include (i) the necessary wind turbine rated power "N_o", (ii) the battery maximum capacity "Q_{max}", sufficient to guarantee energy autonomy for the defined time-period, and (iii) the electronic equipment (UPS, inverter) peak load capacity "N_p". Thus, for the initial cost estimation of a suitable system, a local market survey should be carried out and the results obtained should be introduced to the feasibility analysis presented below.

3. Economical Analysis of the Proposed Solution

The future value (after –n years of operation) of the investment cost of a stand-alone wind power system is a combination of the initial installation cost and the corresponding maintenance and operation cost, both quantities used are given in current values[10].

3.1 First Installation Cost

The initial investment cost "IC_o" includes the market (ex-works) price of the installation components (wind turbine, $IC_{WT;}$ battery, $IC_{bat;}$ inverter, UPS, rectifier, charge controller, etc IC_{elec}) and the corresponding balance of the plant cost, f.IC_{WT}. Thus

$$IC_o = IC_{WT} + IC_{bat} + IC_{elec} + f \cdot IC_{WT} \tag{1}$$

Where the wind turbine (ex-works) cost for small wind converters ($N_o \leq 100$kW) can be approximated[11] by the following expression:

$$IC_{WT} = \left(\frac{a}{b + \{N_0/kW\}^x} + c \right) \cdot N_o \qquad \text{(in Euro)} \tag{2}$$

with a=8.7x10^5 Euro/kW; b=621; x=2.05 and c=700 Euro/kW.

The battery purchase cost can be expressed as:

$$IC_{bat} = c_b \cdot Q_{max} \quad (3)$$

where "c_b" is slightly depended on the battery capacity. Taking into account data from a local market survey[6] concerning lead-acid batteries, the value of "c_b" can be approximated by the following semi-empirical relation:

$$c_b = \xi / Q_{max}^{\omega} \quad (4)$$

(ξ=5.04 and ω=0.078; Q_{max} in Ah)

The cost of the electronic equipment is a function of both the peak load demand of the system (for the UPS and inverter), and the wind turbine size (for the rectifier and charge controller). Thus, the following simplified relation may be applicable for the Greek market:

$$IC_{elec} = \lambda \cdot N_p^{1-\tau} + B \cdot N_o \quad (5)$$

where λ=483.6, τ=0.083 , B=380Euro/kW and N_p in kW.

Finally, the balance of the plant cost[11] is given as a function "f" of the wind turbine ex-works price, where "f" is called the first installation cost coefficient. Excluding the cost of electronic equipment, the corresponding numerical value of "f" for small-sized applications ranges from 0.15 to 0.30. Thus (1), with (2) to (5), becomes:

$$IC_o = \left(\frac{a}{b + N_o^x} + c \right) \cdot N_o \cdot (1 + f) + \xi \cdot Q_{max}^{1-\omega} + \lambda \cdot N_p^{1-\tau} + B \cdot N_o \quad (6)$$

3.2 Maintenance and Operation Cost

During long-term operation, the maintenance and operation (M&O) cost can be split[10] into the fixed "FC_n" and the variable "VC_n" maintenance cost. Usually, the annual fixed M&O cost is expressed as a function "m" of the initial capital invested. Here the other factors is an annual increase of the cost, "g^{Σ}", being also equal to the M&O cost inflation rate, incorporating the annual changes of labor cost and the corresponding spare parts. Thus,:

$$FC_n = m \cdot IC_o \left[\prod_{l=2}^{l=n} (1 + i_l) \cdot (1 + g_1^{\Sigma}) + \prod_{l=3}^{l=n} (1 + i_l) \cdot \prod_{j=1}^{j=2} (1 + g_1^{\Sigma}) + \ldots + (1 + i_n) \cdot \prod_{j=1}^{j=n-1} (1 + g_j^{\Sigma}) + \prod_{j=1}^{j=n} (1 + g_j^{\Sigma}) \right] \quad (7)$$

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

The variable maintenance and operation cost "VC_n" mainly depends on the replacement of "k_o" major parts of the installation, which have a shorter lifetime "n_k" than the complete installation. Using the symbol "r_k" for the replacement cost coefficient of each one of the "k_o" major parts (battery, rotor blades, etc.) the "VC_n" term can be expressed as:

$$VC_n = IC_o \cdot \sum_{k=1}^{k=k_o} r_k \{ \sum_{l=1}^{l=l_k} \left[(1 + g_k) \cdot (1 - \rho_k) \right]^{l \cdot n_k} \cdot (1 + i)^{(n - l \cdot n_k)} \} \quad (8)$$

where "l_k" is the integer part of the following equation, i.e.:

$$l_k = \left[\frac{n-1}{n_k}\right] \tag{9}$$

while "g_k" and "ρ_k" describe the mean annual change of the price and the corresponding level of technological improvements for the k-th major component of the system.

Finally, the future value of the total investment cost "C_n" of the stand-alone installation is :

$$C_n = IC_n + FC_n + VC_n \tag{10}$$

where:

$$IC_n = (1-\gamma) \cdot IC_o \cdot (1+i)^n \tag{11}$$

and expresses the future value of the initial capital invested after n years of operation. Here "γ" is the subsidy percentage by the Greek State[10][11], according to the existing development law (e.g. γ=40% according to the 2601/98 law).

In order to achieve a closed formulation of the stand-alone system total operational cost over the n year period, the long-term average values of the parameters "i", "g^{Σ}" and "g_k" are used (for the impact of time evolution of all these quantities[12]), thus equation (10) yields:

$$C_n = IC_o \cdot (1+i)^n \cdot \{(1-\gamma) + m \cdot \frac{1+g}{g-i} \cdot \left[\left(\frac{1+g}{1+i}\right)^n - 1\right] + \Psi\} \tag{12}$$

where:

$$\begin{aligned} &\Psi = 0 \quad \text{for } n \le n_b = 7 \\ &\Psi = r_{bat} \cdot \left[\frac{1+g_b}{1+i} \cdot (1-\rho_b)\right]^{n_b} \quad \text{for } n_b + 1 \le n \le 2n_b \\ &\Psi = r_{bat} \cdot \left[\frac{1+g_b}{1+i} \cdot (1-\rho_b)\right]^{n_b} + r_{bat} \cdot \left[\frac{1+g_b}{1+i} \cdot (1-\rho_b)\right]^{2n_b} \quad \text{for } 2n_b + 1 \le n \end{aligned} \tag{13}$$

Note, that equation (12) results from equations (7) and (8) by assuming that the M&O annual inflation rate may be approximated by the local market inflation rate (i.e. $g^{\Sigma} \approx g$). Similarly, the battery purchase cost inflation rate can also be estimated by accepting that $g_b \approx g$.

3.3 Main Parameters Influencing the Economic Behaviour of the System

According to equations (6), (12) and (13), the initial cost "IC_o" is a function of the wind turbine rated power "N_o", the battery capacity "Q_{max}" and the corresponding peak load demand "N_p", while the total operational cost "C_n" is additionally a function of the local market inflation rate, the capital cost index and the local market subsidization percentage.

Subsequently, taking also into consideration the replacement cost[13] of the system batteries every "n_b" (6 to 8) years, a significant modification of the optimum solution values (N^*_o, Q^*_{max}) is expected in comparison with the one based only on the initial cost minimization[14]. The new solutions should be based on larger wind turbine size (N^*_o increase) and lower battery capacity values (Q^*_{max} decrease). In the following, the ten-year and the twenty-year total operational cost of the system under investigation is to be used as the best choice criterion, expressed as follows:

$$C_{10} = IC_o \cdot (1+i)^{10} \cdot \left[(1-\gamma) + m \cdot \frac{x}{x-1} \cdot (x^{10} - 1) + r_{bat} \cdot (1-\rho_b)^7 \cdot x^7 \right] \quad (14)$$

and

$$C_{20} = IC_o \cdot (1+i)^{20} \cdot \left[(1-\gamma) + m \cdot \frac{x}{x-1} \cdot (x^{20} - 1) + r_{bat} \cdot [(1-\rho_b)^7 \cdot x^7 + (1-\rho_b)^{14} \cdot x^{14}] \right] \quad (15)$$

where:

$$r_{bat} = \frac{c_b \cdot Q_{max}}{IC_o} \quad (16)$$

and

$$x = \frac{1+g}{1+i} \quad (17)$$

If a constant value (in terms of 2002) is desired for a parameter "C", one may write:

$$\tilde{C}_n = \frac{C_n}{\prod_{j=1}^{j=n} (1+g_j)} = \frac{C_n}{(1+g)^n} \quad (18)$$

which is equivalent to the current value of a quantity normally divided by the total inflation (during a – n year period) of the economy.

4. Application Results

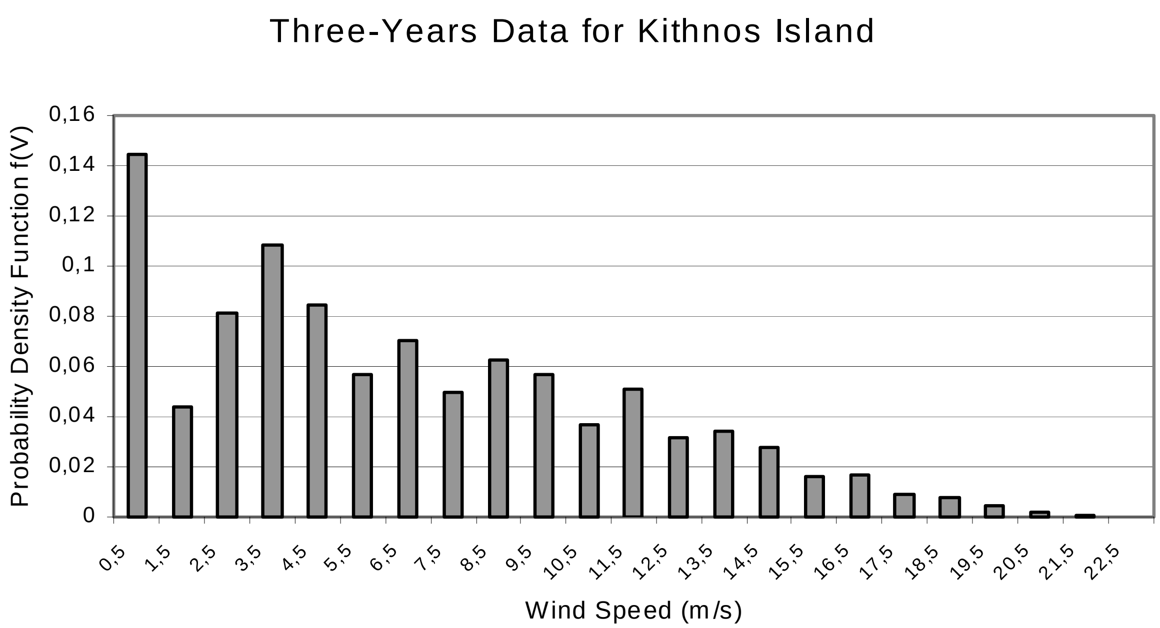

Figure 3: Wind Potential Data for Kithnos Island

The first case analyzed concerns a remote consumer located at Kithnos island. This case has already been analyzed[15] as far as the system dimensions are concerned, by using two different analytical methods. The monthly electricity consumption of the isolated consumer under investigation varies between 300kWh and 425kWh, while the existing wind potential is characterized as medium-high, see also figure (3).

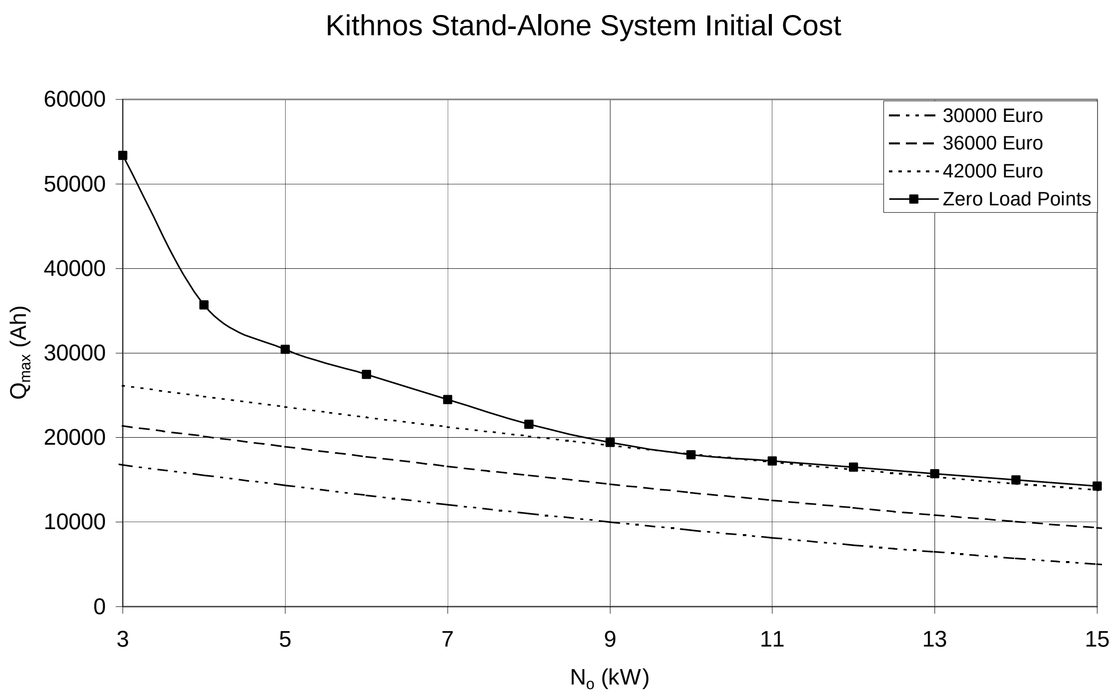

Figure 4: No-load Rejection Configuration on the Basis of Minimum Initial Cost for Kithnos Island

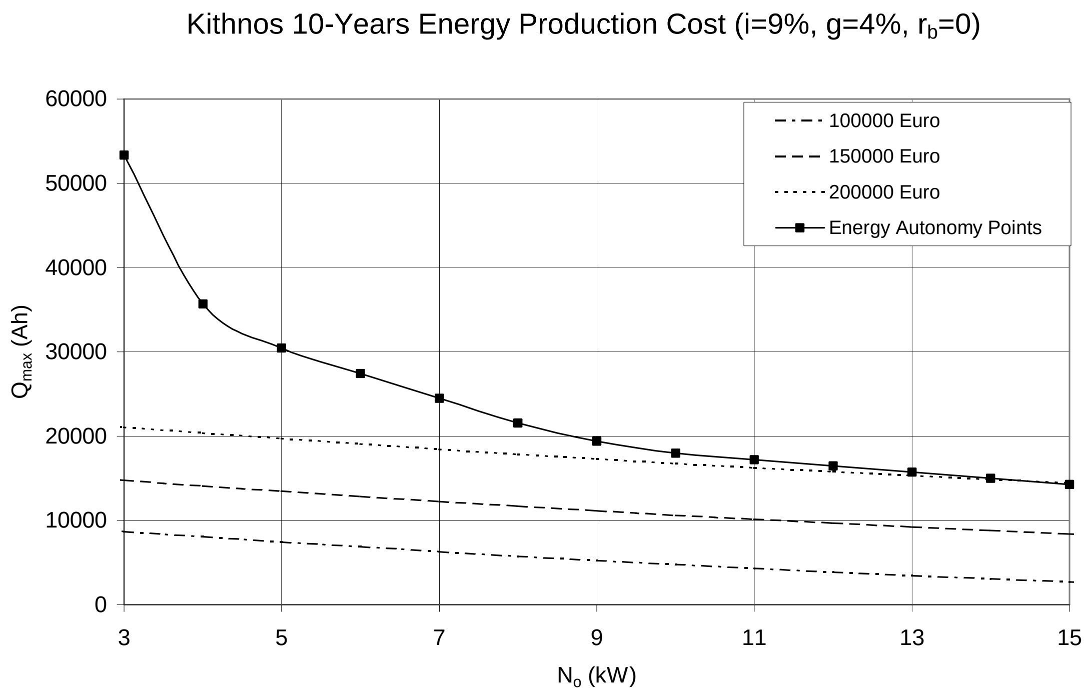

Figure 5: No-load Rejection Configuration on the Basis of Minimum 10-Years Cost, Kithnos Island

Using the available three-year wind speed data and the corresponding electricity consumption profile presented in[14][15], the no-load rejection curve is given in figure (4). Bear in mind that every (N_o-Q_{max}) pair belonging to this curve guarantees the energy autonomy of the system for the entire period examined.

Accordingly, in the same figure the constant initial cost curves (i.e. IC_o=ct) are drawn, using equation (6), with N_p=5kW. The minimum first installation cost solution is based on a 9.5-10kW wind turbine and on 18000Ah (24V, 75% DOD_L) new battery, while the corresponding initial investment cost (without taking into account the 40% State subsidization) is 70,000€.

Subsequently, considering that a similar stand-alone wind power system is being developed to operate during the next ten to twenty years, it seems appropriate to investigate primarily the ten-years total energy production cost distribution, if a medium-term evaluation of the available energy autonomy (N_o-Q_{max}) combinations is expected. Thus, in figure (5), the constant "C_{10}" curves are also given, pushing the minimum energy production cost configuration to lower "Q_{max}" value (=15000Ah) and to higher wind turbine size (N_o=14 to 15kW). During the calculations presented, it is assumed that the local economy inflation rate is 4%, the market capital cost is 9%, and no remarkable technological improvements concerning batteries occurs for the replacement every seven years of operation. The minimum ten-years energy cost solution future value is almost 200,000€ or 135,100€ in constant 2002 values. On the other hand, the minimum first installation cost solution leads to 215,000€, i.e. 8% higher value than the minimum total cost one.

Table I: Optimum Stand-Alone Wind Power System Dimensions, Using Various Approximations, for Kithnos Island

	Initial Cost	**10-Years Cost**	**20-Years Cost**	**10-Years (γ=0)**	**10-Years (r_b=0.1)**	**10-Years (i=18%)**
Wind Turbine Size	9.5kW	14.5kW	16kW	15kW	12.5kW	17kW
Battery Capacity	18000Ah	15000Ah	13500Ah	14000Ah	16000Ah	13000Ah
10-Years Cost in Constant Values	145000€	135000€	-	180000€	115000€	154000€

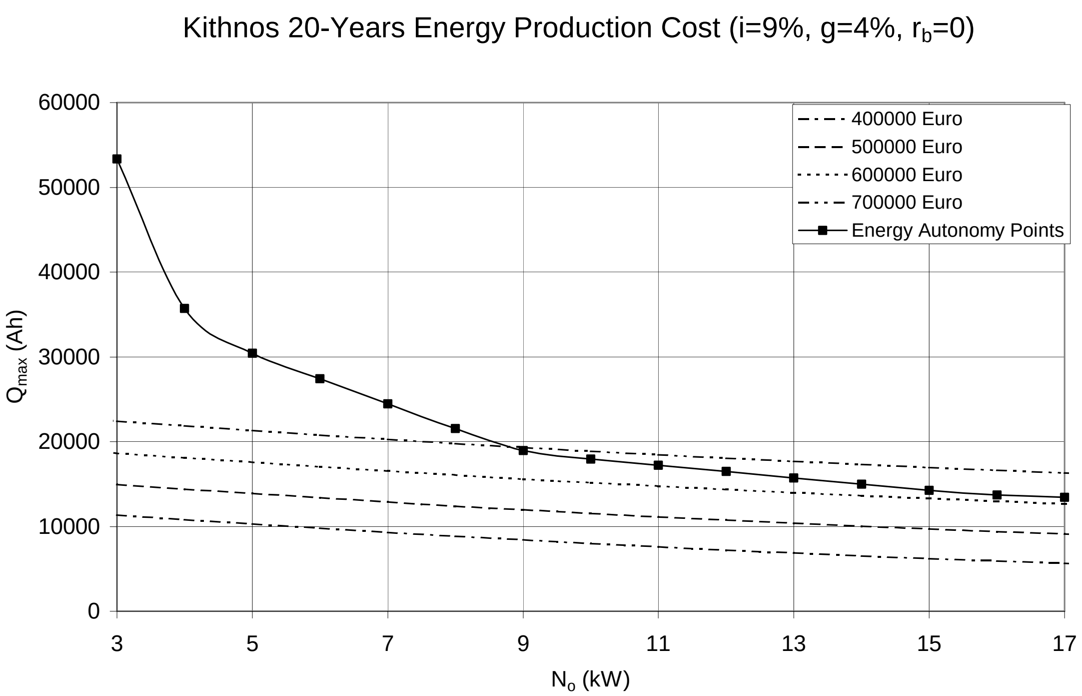

Figure 6: No-load Rejection Configuration on the Basis of Minimum 20-Years Cost, Kithnos Island

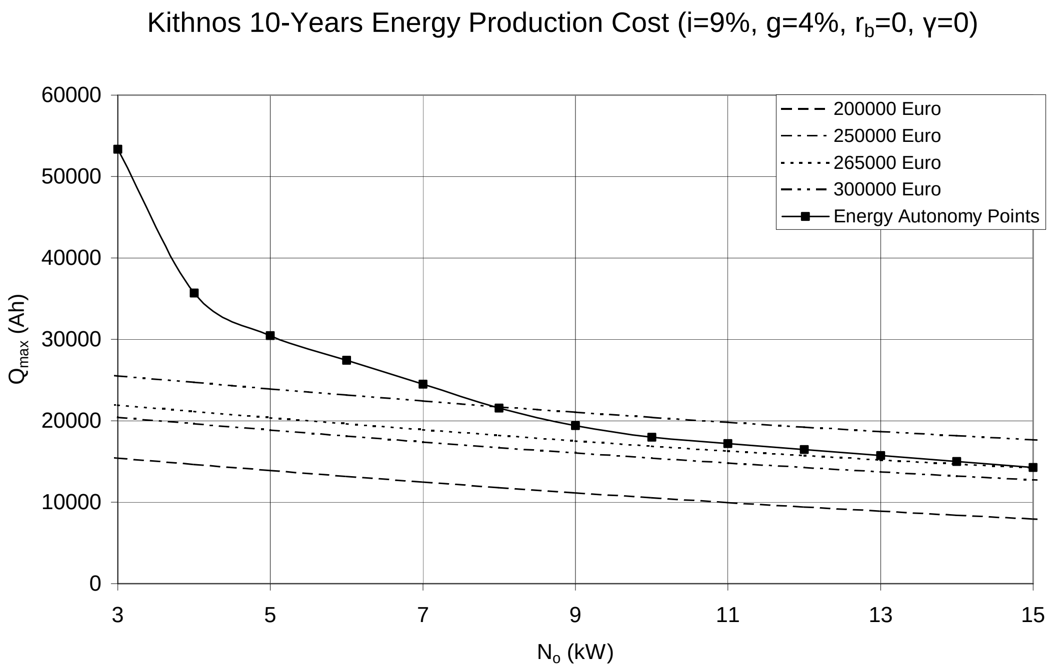

Figure 7: No-load Rejection Configuration on the Basis of Minimum 10-Years Cost, Zero Initial Cost Subsidization

Finally, extending our calculation to 20-years (i.e. long-term operation), being the usually acceptable wind turbine replacement period, the corresponding minimum energy production cost "C_{20}" value is obtained, figure (6), for 16kW wind turbine rated power and 13500Ah battery capacity. The corresponding minimum 20-year energy cost future value is 615,000€, or 280,700€ in constant 2002 values.

Recapitulating, the minimum energy production cost scenario is quite different if the evaluation is based on the system initial cost value only, instead of using the system 10-year or 20-year total cost configuration, see Table I. More precisely, for medium or long-term operation, a remarkable increase of the wind turbine used rated power occurs, along with a significant decrease of the necessary battery capacity. On top of that, the minimum initial cost choice presents an almost 8% higher total operational cost than the minimum 10-year total cost solution.

5. Parametrical Investigation of the Minimum Energy Production Cost Solution

5.1 Impact of subsidies

The Greek State and/or the European Commission significantly supports energy production applications, with 20% to 60% grants, based on the exploitation of available renewable energy resources. This subsidy is given as a percentage of the first installation cost, since all the renewable energy applications are characterized as capital intense ones. Bear in mind that any financial measures taken in favour of renewables is only a minor quantification[16][17] of the remarkable social-environmental benefits resulting from the substitution of fossil fuels by renewable energy sources. In an attempt to estimate the impact of the State subsidization on the minimum ten-years cost solution obtained, the no-subsidization calculation results concerning the ten-years operation of the proposed stand-alone wind power configuration are sited in figure (7). From this, it is apparent that the cancellation of the subsidization schemes leads to slightly larger wind turbines (~15kW) and smaller batteries (14000Ah), while the corresponding minimum "C_{10}" solution approaches 265,000€, or 179,000€ in 2002 values.

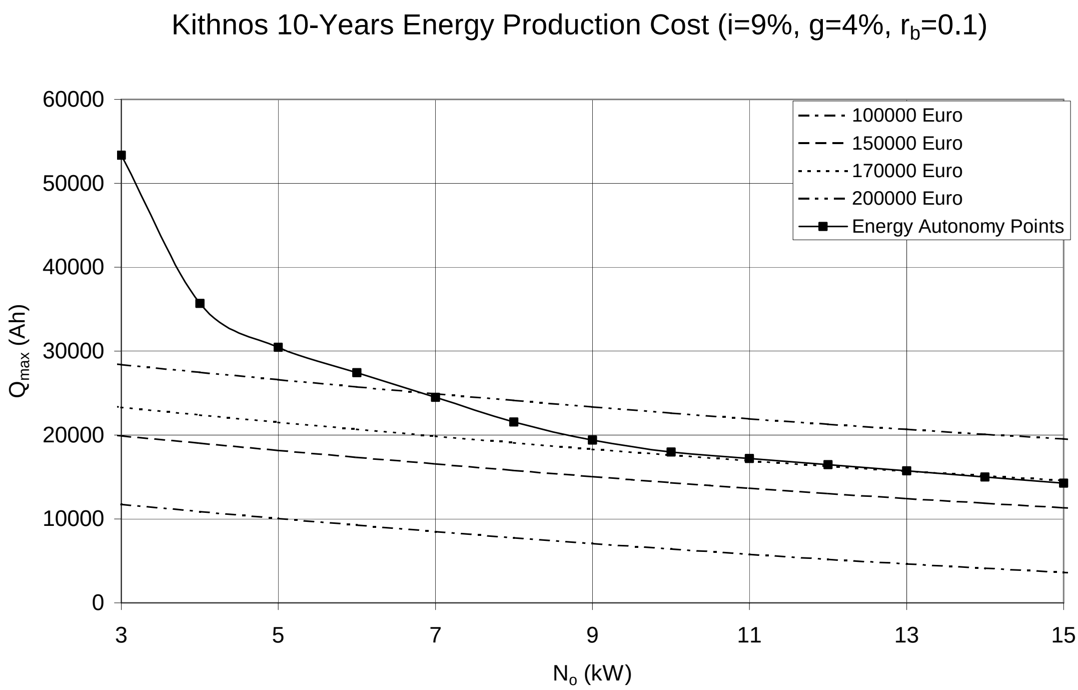

Figure 8: No-load Rejection Configuration on the Basis of Minimum 10-Years Cost, Battery Technology Improvement Incorporated

5.2 Battery Technology Improvements

The battery is one of the most important parts[13][18] of an energy autonomous wind power system, (a) storing the energy surplus during windy days for use during high consumption and low wind speed periods, and (b) maintaining the voltage in the system. Besides, the batteries used represent a

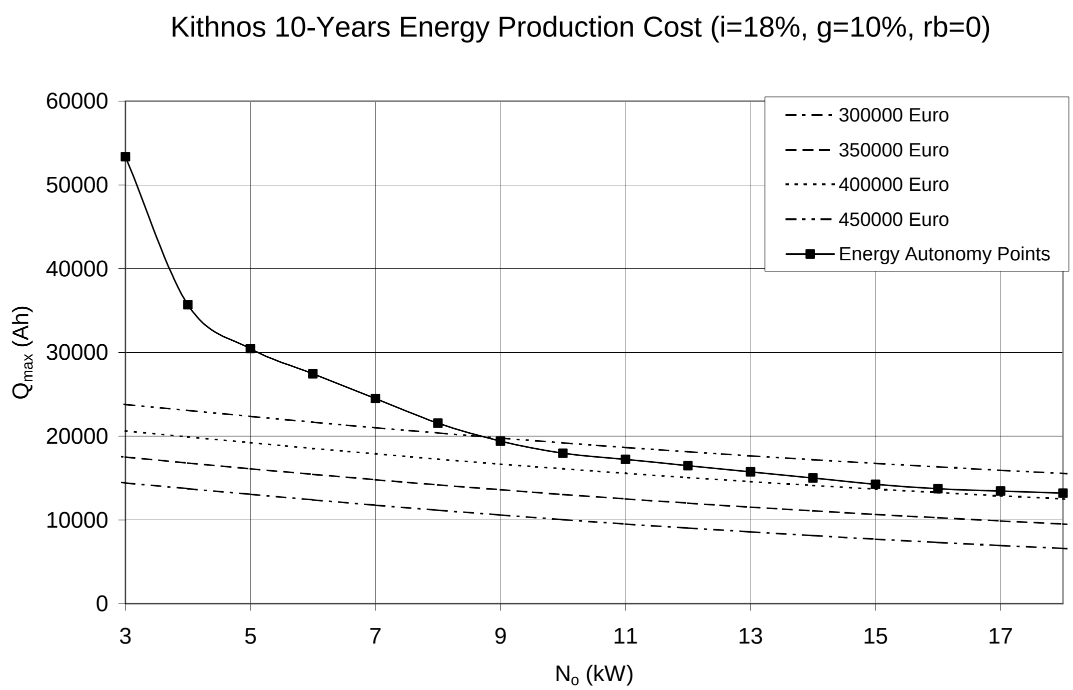

Figure 9: Zero-load Configuration on the Basis of Minimum 10-Years Cost, Local Market Capital Cost Impact

remarkable percentage "r_b" (up to 80%) of the complete system initial cost, hence any technological improvement concerning this sector will significantly ameliorate the economical behaviour of the entire system.

In this context, by introducing a 10% annual improvement of the commercial lead-acid batteries operational characteristics, the medium-term optimum solution is realized, figure (8), using 12 to 13kW wind turbines and approximately 16,000Ah batteries capacity. The corresponding 10-years operational cost is 170,000€, or 114,850€ in 2002 values.

5.3 Local Economy Situation

One of the most important parameters describing the local market situation is the corresponding annual inflation rate. More precisely, the inflation rate expresses the tendency of every-day life cost to increase and it is quantitatively approximated by the average rise in price levels. Also, the value of the inflation rate greatly influences the corresponding capital cost index, since usually the capital cost is the sum of the inflation premium, the pure time-preference and the risk premium[19][20].

Thus, by using the values experienced within the local economy during the previous decade (1990-99), i.e. i=18%, g=10%, the calculation results are summarized in figure (9). Here it is obvious that the optimum (10-years minimum cost) solution tends to higher wind turbine rated power ($N_o^* \to 17$kW) and lower battery capacity ($Q^*_{max} \to 13,000$Ah) values in comparison with the results of figure (5). On the other hand, although the 10-year total cost of the system seems much higher (400,000€) than the present economy situation (200,000€), there is no substantial differentiation in constant 2002 values (154,000€ vs 135,000€).

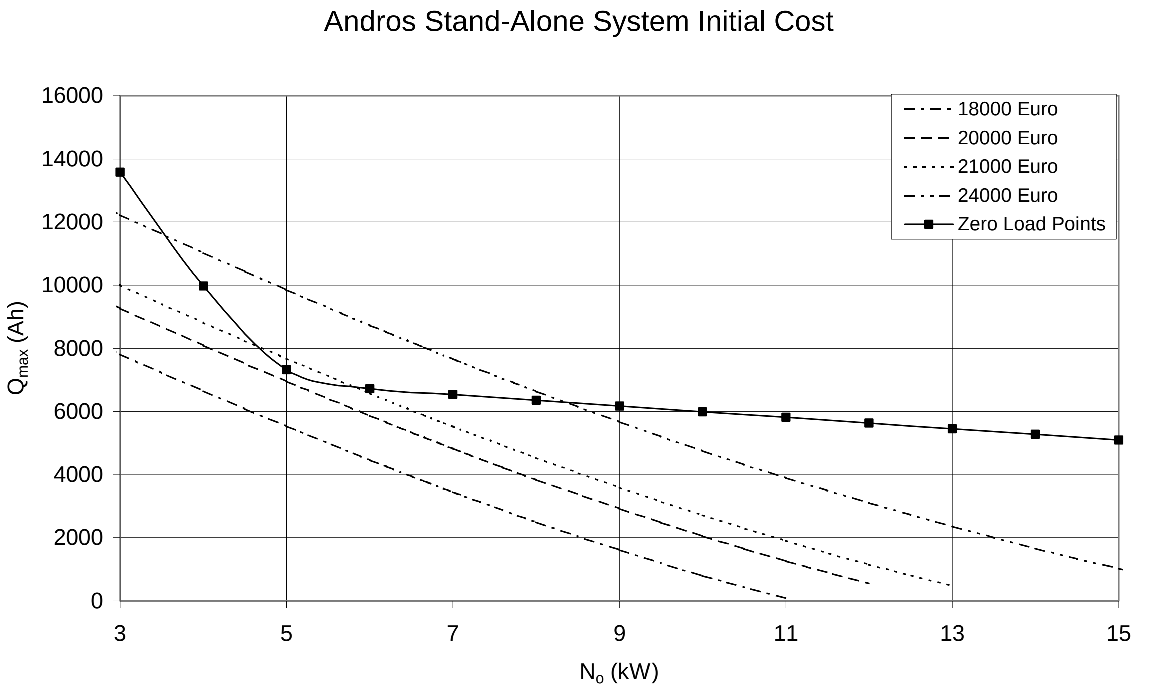

Figure 10: No-load Rejection Configuration on the Basis of Minimum Initial Cost for Andros Island

6. Wind Potential Impact on the Optimum Solution Configuration

In an attempt to investigate the impact of the wind potential on the optimum solutions obtained, two additional cases are analyzed, using three years detailed wind speed and meteorological data[14][15]. More specifically, the first case analyzed concerns a high wind potential island (annual average wind speed approximately 9.5m/s), i.e. Andros island. In figure (10), the no-load rejection curve is given

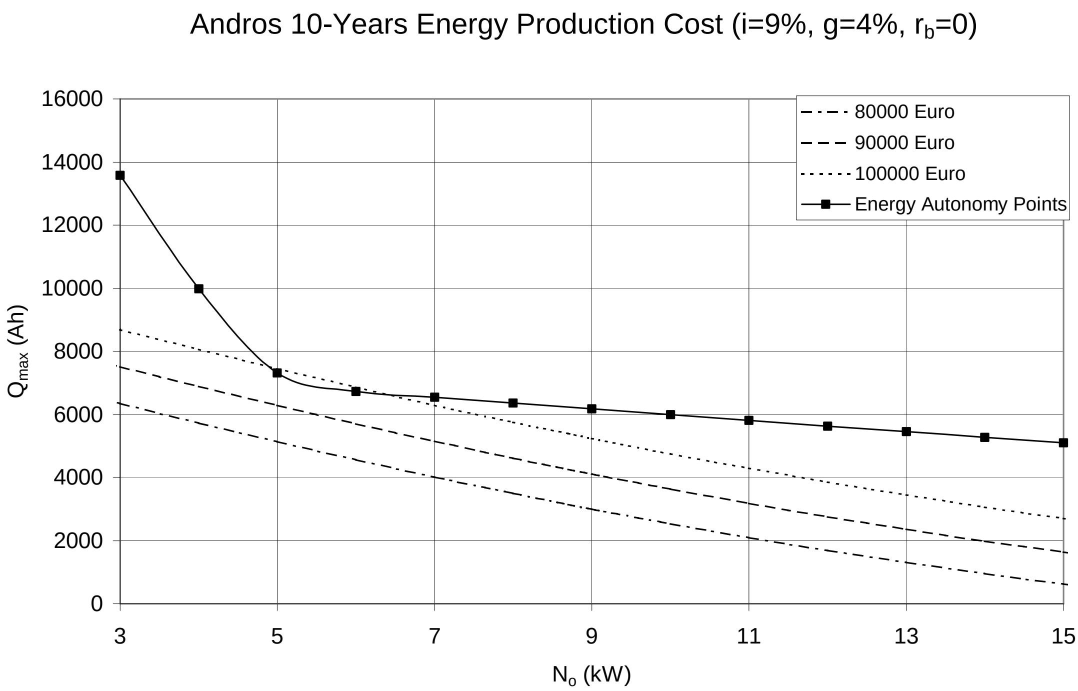

Figure 11: No-load Rejection Configuration on the Basis of Minimum 10-Years Cost, Andros Island

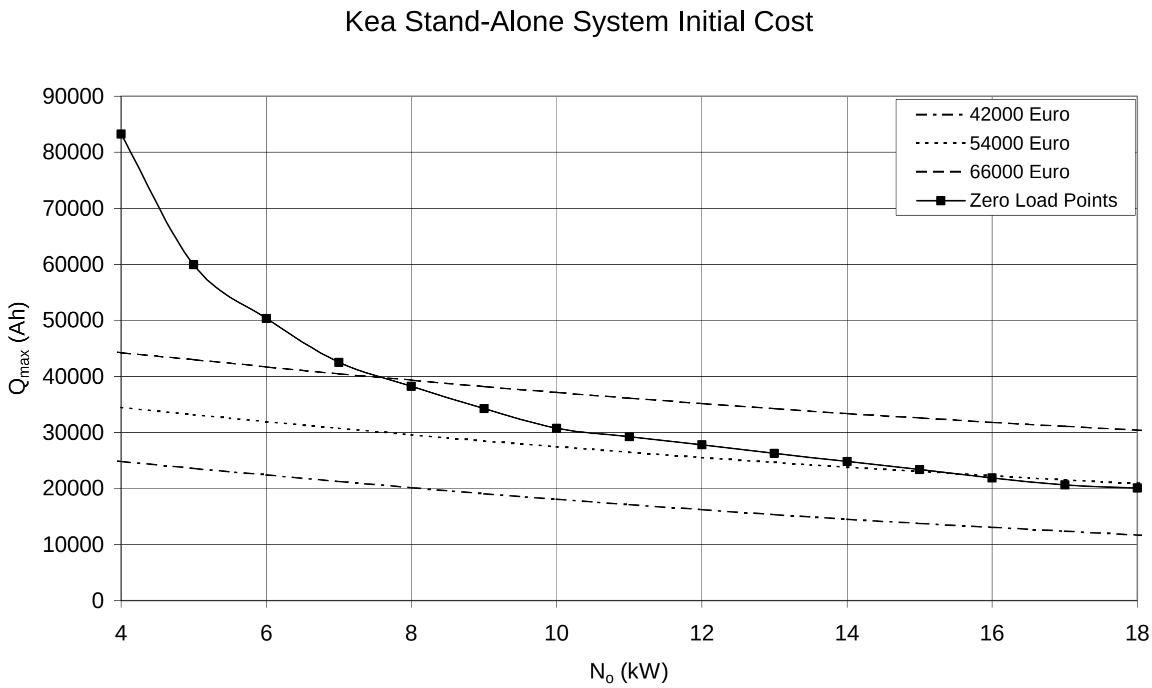

Figure 12: No-load Rejection Configuration on the Basis of Minimum Initial Cost for Kea Island

along with the corresponding constant-initial cost curves. The minimum energy autonomy wind power based solution consists of a 5kW wind turbine and a battery of 7,200Ah storage capacity.

On the other hand, the minimum 10-year total cost solution, figure (11), is based on a 5.5kW wind converter and a 6,700Ah battery size. Both solutions guarantee 3-year energy autonomy[15][21] of the system, while the second ensures a slightly lower long-term operational cost.

The second case analyzed is the island of Kea, a medium quality wind potential area (annual mean wind speed equal to 5.5m/s). In figure (12) the minimum initial cost no-load rejection combination is based on a 17kW wind turbine and a 21,000Ah battery , while the minimum 10-year operational cost solution demands, figure (13), greater wind turbine rated power (19kW) and 2000Ah (9.5%) less battery capacity.

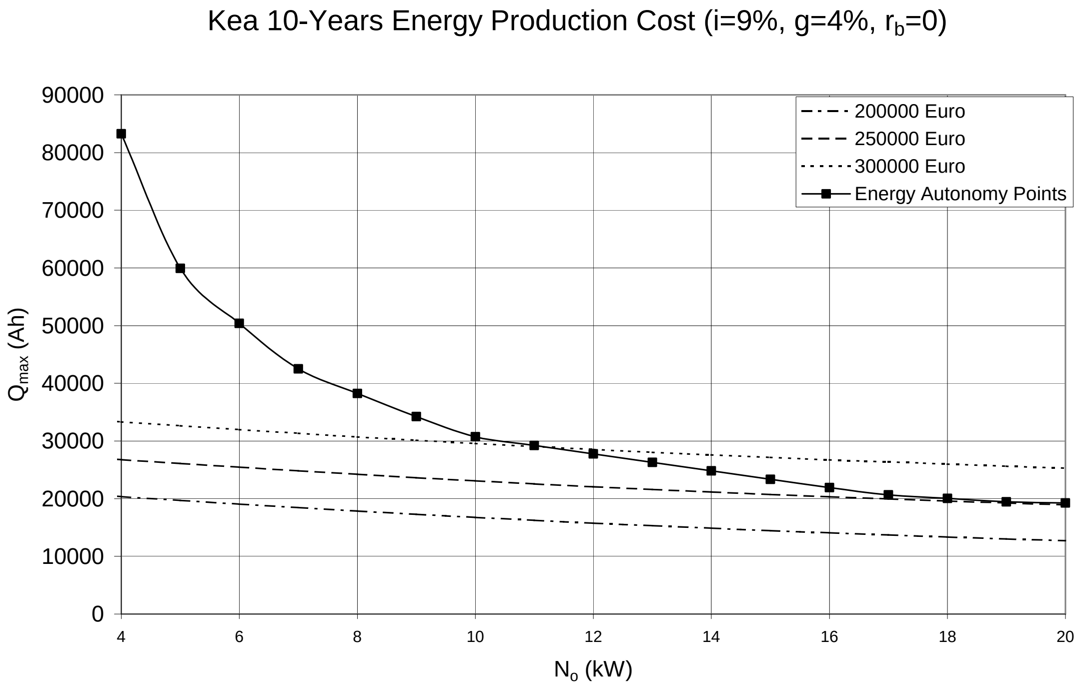

Figure 13: No-load Rejection Configuration on the Basis of Minimum 10-Years Cost, Kea Island

Recapitulating, the difference between the minimum initial cost and the minimum 10-year operational cost solutions are substantial, because the available wind power potential is lower. Finally, in order to get an integrated picture of the stand-alone wind power system components cost evolution with the available annual mean wind speed, the results of figure (14) have to be taken into consideration. According to the results obtained, the battery and wind turbine purchase cost constitute the largest part of the system first installation cost. However, for long-term operation, both fixed and variable M&O cost represent a considerable part of the energy production cost, while neither the financial surcharges can be neglected. In this context, bear in mind that the required battery and the wind turbine costs both decrease as the average wind speed increases. Similarly, the battery replacement cost becomes much greater as the mean average wind speed value decreases.

7. Conclusions

An integrated cost-benefit analysis was presented concerning the economic evaluation of stand-alone wind power systems, used to fulfill the electricity requirements of remote consumers on small Greek islands. During this study, the optimum solution is predicted not only on a first installation cost basis, but also taking into consideration the complete long-term energy production cost of the system. According to the results obtained, there is a remarkable difference between solutions based only on the first installation cost minimization, and on those resulting from the complete 10-year or 20-year financial analysis. In fact, the latter solutions require smaller batteries and larger wind turbines.

Accordingly, using the developed theoretical frame, the impact of several important parameters on the solutions obtained is examined. In this context, the influence of State and EU subsidies, local market capital cost-inflation rate, technological battery improvements and wind potential quality on the

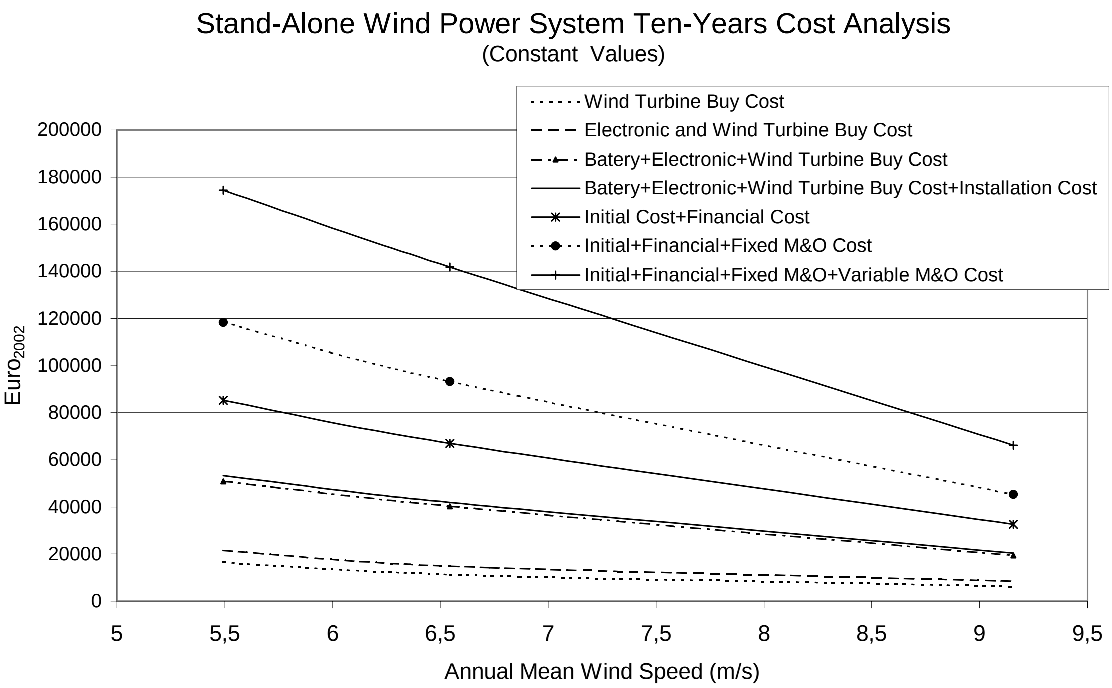

Figure 14: Stand-Alone Wind Power System Ten-Years Cost Analysis versus Annual Wind Speed, Subsidization Included

proposed configuration dimensions is investigated. Using the experience gained from the present analysis, one may conclude that the technological improvements and the wind potential amelioration significantly influence the economic attractiveness of similar applications. Similarly, the State subsidization and the local market situation fairly influence the economic behaviour of the stand-alone system.

Finally, as it is expected, by increasing the available mean wind speed values both the recommended battery and wind turbine capacities decrease, pushing the long-term energy production cost from 3.0€/kWh to 1.0€/kWh in constant value terms. These values are in fact comparable with the corresponding values of the various local thermal power stations spread through Aegean Archipelago and used to cover the electrification needs of small remote communities, i.e. 20-100 families. In addition, substitution of the thermal power stations by wind turbines also abates several environmental and air pollutants, and helps the national economy by reducing the expense of imported oil.

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PART THREE

RENEWABLES

- Renewable Energy Market
- Stand-Alone Systems
- Environmental Impacts

CRITICAL EVALUATION OF SOLAR COLLECTOR MARKET IN GREECE USING LONG-TERM SOLAR INTENSITY MEASUREMENTS

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Abstract

Solar thermal applications have been one of the best alternative solutions to the chain environmental consequences caused by the excessive usage of fossil fuels. According to long-term solar intensity measurements, Greece possesses excellent solar energy potential. In this context a critical evaluation of local solar collector market is presented, based not only on an integrated cost-benefit analysis but also on the harmful air-pollutants emissions avoidance, thus remarkably contributing towards a sustainable future for European citizens.

Keywords: Solar Collector; Feasibility Analysis; Heat Production Cost; Environmental Benefits

1. Introduction

It is widely known that the excessive usage of fossil fuel has world-widely caused chain environmental consequences[1][2]. The solution to this problem has been assigned to the renewable energy sources, including solar energy[3]. More precisely, as public concern regarding polluting and non-sustainable nature of our present energy sources increases, people are gradually turning to clean, renewable energy sources to meet their heating needs. The contemporary solar thermal systems may be a response to this demand. These systems are characterized as reliable and efficient, thus they are widely used especially in the domestic sector. Solar collectors are also environmentally sound; therefore they include a wide range of advantages constituting them a crucial part of European energy strategy[4].

Recent policy papers issued by European Commission underline the need to tackle Europe's increasing greenhouse gas emissions and dependence on imported fuels[3][5]. Solar thermal applications have a major role to play in addressing these problems. Although the CO_2 emissions problem in Greece is mainly a "supply side" issue, energy conservation nevertheless constitutes an immediate priority, which can substantially improve the energy and economic efficiency of every relative system reducing also the emissions of CO_2 and other greenhouse gases as well[6].

More specifically, according to the Greek National Program for Climate Change[7], solar energy applications are expected to be considerably expanded for the heating of usage water with the installation of approximate 1.3 million m^2 of solar collectors from 1990 to 2000, in order to meet the national targets related to the greenhouse gases emissions restriction.

It is interesting at this point to mention that Greek solar thermal industry has reached maturity[8] after 25 years of technical development and quality improvement. High quality products are obtainable by several medium sized companies, hence solar systems are nowadays reliable and their productivity may be certified by existing quality control centers[9].

Kaldellis J.K., Vlachou D.S., Koronakis P.S., Garofalakis J.E., 2001, *"Critical Evaluation of Solar Collector Market in Greece Using Long-Term Solar Intensity Measurements", "Balkan Physics Letters" Journal, SI/2001, pp.181-193.*

2. Solar Collectors Market Situation in Greece

It is widely accepted that Greece possesses excellent solar energy potential according to existing long-term measurements, see for example figure (1), leading to significant opportunities for Solar Collector applications[10][11]. Their market, however, illustrates a deep debacle during the last few years[8]. This fact, as a first approach, characterizes a controversy. On one side, similarly to other renewable energy sources, a continuously declining initial investment cost evolution is reported in constant terms. On the other side, a sales and interest decrease is testified to the Solar Collectors market[12].

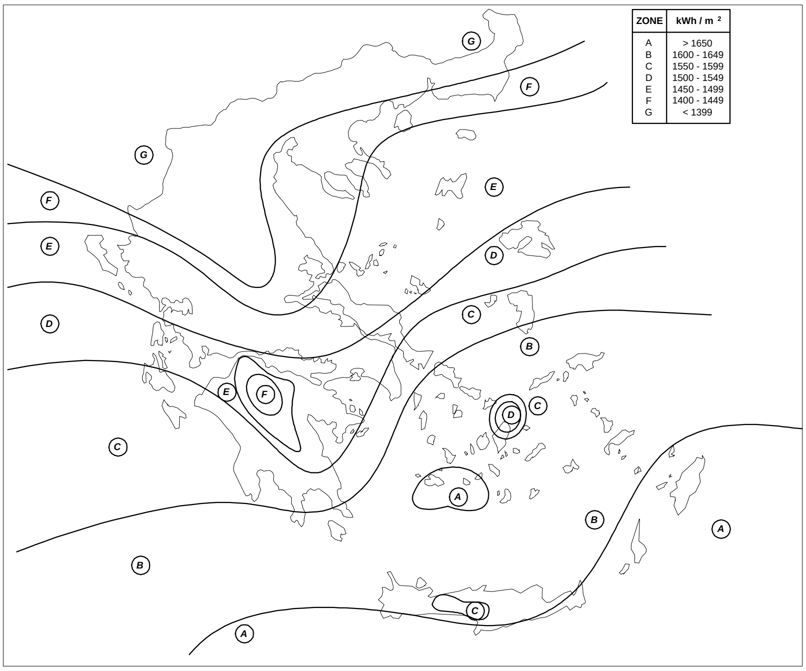

Figure 1: Solar Potential of Greece

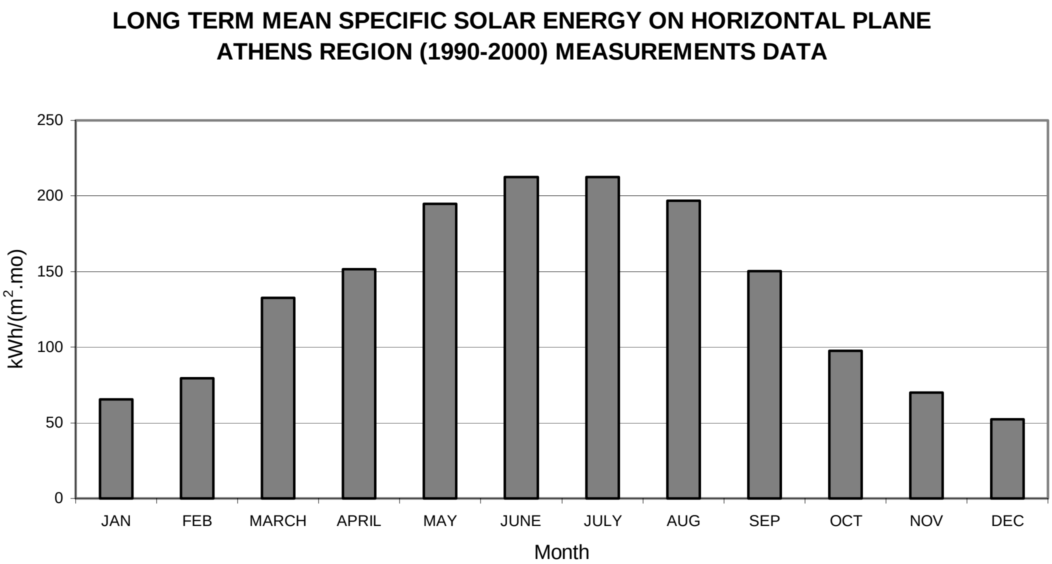

Figure 2: Solar Radiation Experimental Measurements (1990-2000) for Athens Region

To analyze this situation one should take into consideration that Greece is located in a major geographical region (SE Mediterranean area) with an abundant and reliable supply of solar energy (figure (1)), even during winter. Hence, the available annual solar energy exceeds the 1400kWh/m^2, while there exist several locations that the corresponding value overpasses the 1700kWh/m^2 in horizontal plane, see for example figure (2). More specifically, according to long-term measurements (1990-200) concerning Athens region[10], the mean monthly solar energy varies between 52 and 213kWh/(m^2.mo), while the corresponding annual average value is 135kWh/(m^2.mo). This fact is directly related to the impressive increase of solar collectors applications in our country during the previous decade, figure (3).

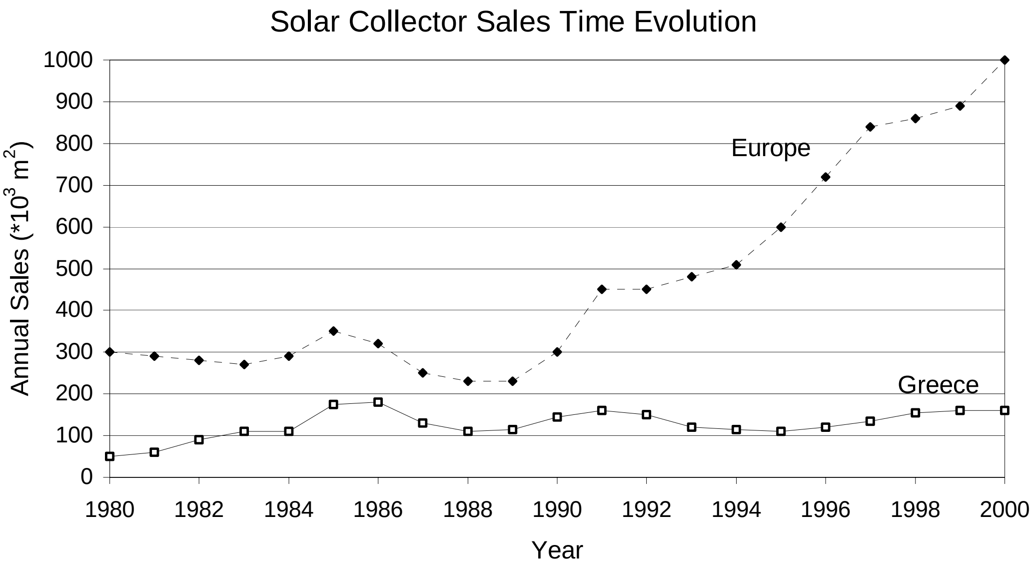

Figure 3: Solar Collector Sales Time Evolution in Greece and Europe

More precisely, the Greek solar collector industry has its origins in the mid-70s, along with the presented oil-price crisis. However, the real evolution of the local market took place during 1980-90, when most companies were founded. During this period, a typical Greek household used electric boilers, thus every price rising supported the usage of alternative technologies substituting electricity. At the same period, a State supported advertising campaign -along with serious research efforts-pushed the local market to an annual installation of new systems of the range of 200,000m^2. On top of that, the Greek market dominates the whole European sector, since the annual sales in Greece represented the majority of sales of the entire Europe[13]. Unfortunately, after 1987, the local market started to decline while during the last decade the annual sales are almost stable, slightly varying between 120,000m^2 and 160,000m^2. At this point it is important to mention that a remarkable part of these annual sales is related to the replacement of old-fashioned systems installed in the early 80s. According to estimations by the authors only 30,000 to 35,000 new systems are annually installed in Greece during the last ten years, fairly contributing to the realization of the E.U. target of 500m^2 solar collectors for every 1000 persons. Consequently, the entire E.U. has hardly achieved the 1/3 of the "ALTENER" target for 2005[8].

Finally, after an extensive local market survey taken place between 1995 and 2000[14][15][16] there is a small price increase of solar collectors (less than 12%) in current values (drachmas), which is equivalent to a system price decrease by 7% in constant terms. Similarly, the buy-cost of a typical system for a single-family house (collector area 2 to 3.5m^2 and storage capacity of 120 to 200lt) has significantly reduced (25%) in Euro terms. In figure (4) the specific solar collector cost in Euro/m^2 is given for the local market as a function of the total collector surface of the system installed. The average specific price of a solar collector system is approximately 230 to 310 Euro/m^2 of installed collector surface. An additional side effect of the sector continuous technological progress is the significant quality improvement realized during the last ten years, leading to an increased system technical reliability and hence to a better system economic efficiency[11].

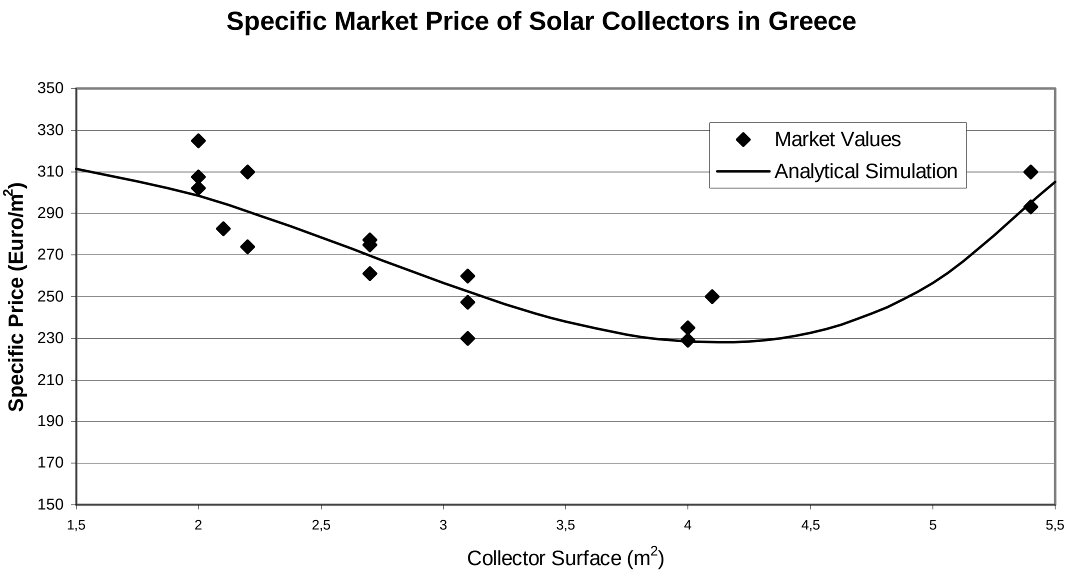

Figure 4: Solar Collectors Specific Market Price in Greece (2000)

3. Solar Collectors in the Local Market - "Solar-Boiler" Data Base

In an attempt to contribute to a substantial penetration of solar-heat systems in the local and the European market, it is important to gather, analyze, organize and classify the main characteristics of the solar collectors available; enabling thus any interested person to obtain a first comparative market study[11].

For this reason, an almost complete database "BOILER" was built[14][15][16] during the last six years by our research team of the Soft Energy Applications & Environmental Protection Lab of TEI Piraeus, including the majority of the existing commercial systems in the local market. Using the "BOILER-00" information, it is possible to compare directly solar collectors belonging in the same range of collective surface or boiler capacity and make a first evaluation of the domestic solar systems under consideration.

The "BOILER-00" is the second version[16] of an integrated database resulting from teamwork started in 1995. The first version "BOILER-97" was prepared[14][15] since 1997, while the new version is written in "Access 7.0" for Windows-98. The current version of "BOILER" includes more than 200 solar collectors systems belonging to almost 40 companies of the sector.

Among the main data existing in "BOILER-00" are:

- the storage capacity (in lt)
- the collector surface (in m^2)
- the usage of open or closed water circuit
- the way that the boiler is placed (horizontal or normal)
- the collector surface type (e.g. selective or not)
- the material used for collector surface
- the material used for boiler construction
- the insulation type of boiler
- the insulation type of collector surface
- an indicative ex-works price of the system
- the manufacturer brief company profile

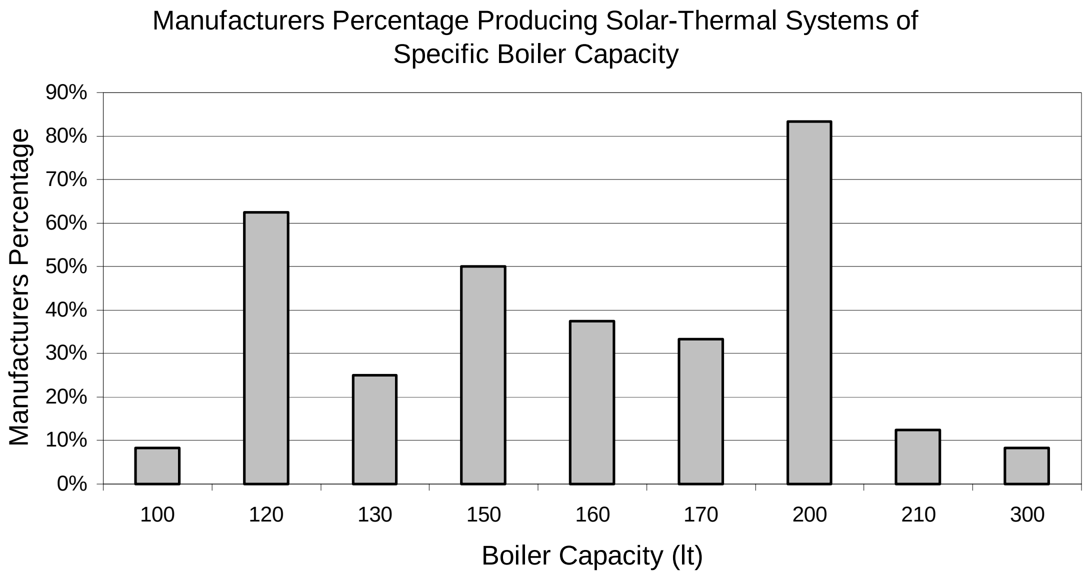

Figure 5: Manufactures Offering to the Market Solar-Boilers of Specific Capacity

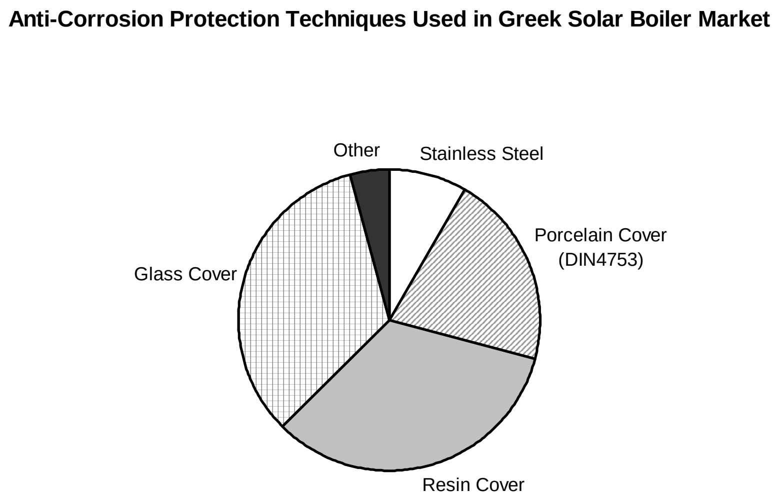

Figure 6: Anti-corrosion Protection Techniques used by Manufactures of Solar-Boilers in Greece

On top of that, the available software gives one the opportunity to select the available solar systems of the local market on the basis either of the desired investment amount or the collective surface and boiler capacity.

Finally, after analyzing the information of "BOILER-00" one may extract some interesting conclusions concerning the main characteristics of available market products. Thus, in figure (5) the percentage of the manufacturers offering the market boilers of specific capacity are sited. Accordingly, in figure (6) the anti-corrosion protection techniques used for the system boiler by the local manufacturers are also given.

4. Solar Collectors Efficiency Analysis

According to the existing theoretical analysis[11], the thermal output "$\dot{Q}$" of a solar collector is a function of the collector characteristics given by the manufacturer and the available solar intensity, along with the temperature difference between the collector surface and the ambient. Thus one may write:

$$\dot{Q} = F_R \cdot A_c \cdot [G_T \cdot (\tau \cdot \alpha) - U_L \cdot (\overline{\theta} - \theta_a)] \quad (1)$$

where:
A_c the collector surface
G_T the solar intensity
F_R the solar-thermal coefficient of the collector surface
τ the collector cover transparency factor
α the collector surface absorbency coefficient
U_L the collector total thermal loss coefficient
$\overline{\theta}$ the collector surface mean temperature
θ_a the ambient temperature

Similarly, the thermal output of the collector may also be estimated on the basis of the temperature difference "θ_{ex}-θ_{in}" of the liquid (water) circulating through the system, hence:

$$\dot{Q} = \rho \cdot \dot{V} \cdot C_w \cdot (\theta_{ex} - \theta_{in}) \quad (2)$$

with
$\dot{V}$ the system flow rate at the collector inlet
ρ the water density at the collector inlet
C_w the water specific heat at constant pressure

Subsequently, the collector efficiency "η" is defined as:

$$\eta = \frac{\dot{Q}}{A_c \cdot G_T} \quad (3)$$

which can be equivalently written:

$$\eta = A + B \cdot \zeta \quad (4)$$

where "A" and "B" coefficients resulting[11] from equations (1) to (3) or given by experimental measurements[17] and

$$\zeta = \frac{\overline{\theta} - \theta_a}{G_T} \quad (5)$$

In figure (7) typical (η-ζ) distributions for several solar collector types are presented, while one should take into consideration that a second order polynomial function (η-ζ) may also be used instead of the linear one of equation (4).

Summarizing, the total thermal output of a domestic solar heating system is given as:

$$\dot{Q}_{exit} = \dot{Q} - \delta\dot{Q} - \dot{Q}_{b.loss} \quad (6)$$

where "$\delta\dot{Q}$" is any heat loss in the system pipes and "$\dot{Q}_{b.loss}$" is the heat loss of the installation boiler.

Thus, the efficient operation of a domestic solar collector-boiler system depends on the manufacturer efficiency (η-ζ) curve, on the temperature difference between collector surface and ambient as well as on the available solar radiation intensity. Remarkable impacts on the system efficiency constitute the heat pipe loss (depending on pipe length, on material used and on insulation status) and the boiler loss (depending on the time shift between maximum solar intensity and hot water usage, the location of the boiler as well as the material used and the insulation type). Generally speaking, boiler and pipe loss may represent up to 50% of the complete system loss.

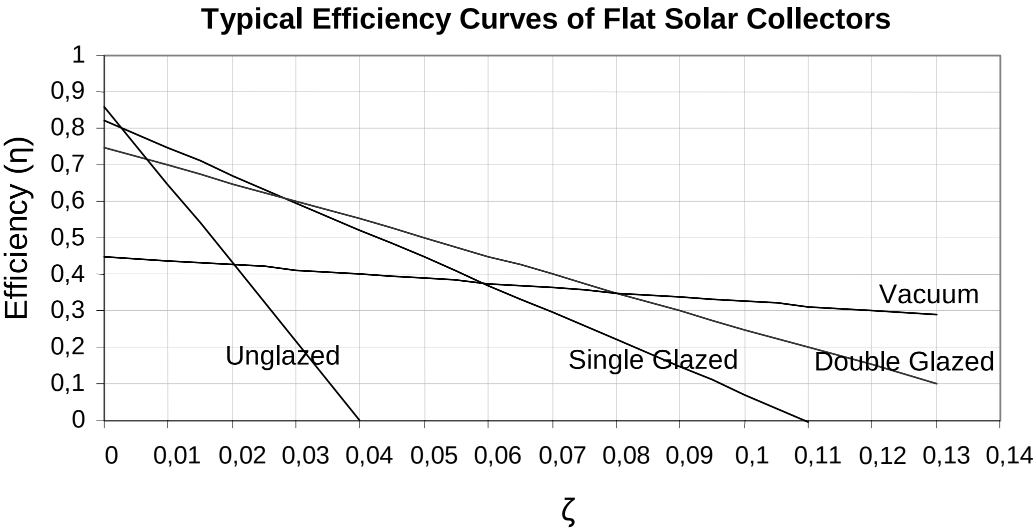

Figure 7: Typical Efficiency Curves of Domestic Flat Solar Collectors

5. Feasibility Analysis of a Domestic Solar System

Solar thermal energy systems are devices using energy from the sun to provide hot water in households, hotels, factories and other applications. Such systems typically incorporate a roof-mounted solar collector, an insulated hot water storage tank and a heat transport system with control and security devices. The solar collector receives sunlight and converts it into heat. It contains an absorber plate, which is often painted matt black or coated with a special "selective" coating. To minimize heat loss the collector is insulated and has a transparent cover of special glass or plastic. The heat is pumped to the storage by means of a circulation pump or through natural flow in "thermosyphon" systems commonly used in our country[11]. Such a system may provide more than 2/3 of the annual hot water demand, while a conventional heat source (such a gas-oil boiler or electric heater) provides the remainder.

The economic viability and attractiveness of a domestic solar thermal system results by comparing the thermal energy production cost values with the corresponding energy market prices of the available alternative solution (i.e. electric heater, gas-oil boiler). In case that the heat production cost by the proposed system is lower than the existing alternative solutions corresponding one on a specific time-period basis (e.g. 10 years), then the solar system is assumed economically viable and attractive under specific preconditions.

The future value of the investment cost of an energy production system[18] after n years of operation "C_n" is a combination of the first installation cost "IC_o" (subtracting any State subsidy percentage "γ")

along with the corresponding maintenance and operation cost "FC_n", both quantities expressed in current values. More precisely, one may write:

$$C_n = IC_n + FC_n \tag{7}$$

where

$$IC_n = (IC_o - \delta I) \cdot (1+i)^n \tag{8}$$

and

$$FC_n = m \cdot IC_o \cdot \frac{(1+g_\Sigma)}{(1+i)} \cdot [1 + \left(\frac{1+g_\Sigma}{1+i}\right) + ... + \left(\frac{1+g_\Sigma}{1+i}\right)^{n-1}] \cdot (1+i)^n \tag{9}$$

The maintenance and operation (M&O) cost is expressed as a function "m" of the initial cost, while an annual increase of the cost is also taken into account via the M&O mean annual inflation rate "g_Σ". Finally, "i" is the mean capital cost of the economy. Keep in mind that the turn-on key cost of a solar heating system is given as:

$$IC_o = Pr \cdot A_c \cdot (1+f) \tag{10}$$

where "f" expresses the installation cost as a fraction of the ex-work price of the system, and "Pr" is the specific ex-works price (Euro/m^2) of the system, see also figure 4. Accordingly, "δI" is given as:

$$\delta I = \gamma \cdot IC_o \tag{11}$$

Similarly, the total savings (in current values) over an n years period "R_n" due to the thermal energy produced by the solar system, replacing conventional energy sources, are given as:

$$R_n = R_o \cdot \frac{(1+e)}{(1+i)} \cdot [1 + \left(\frac{1+e}{1+i}\right) + ... + \left(\frac{1+e}{1+i}\right)^{n-1}] \cdot (1+i)^n \tag{12}$$

where:

$$R_o = E_o \cdot c_o \tag{13}$$

and

c_o is the present value of the effective cost coefficient of the replaced conventional energy (Euro/kWh)

E_o is the net annual heat output of the system, assumed constant over the entire operational period of the device

e is the mean annual rate of change of the market price of the replaced energy sources (i.e. thermal energy price escalation rate)

The effective cost coefficient value "$c_o^{(n)}$" after –n years of operation of the solar system can be predicted by equating the future value of the investment cost with the corresponding total savings, i.e.:

$$R_n = C_n \tag{14}$$

After several numerical manipulations equation (14) reads:

$$c_o^{(n)} = [(1-\gamma)\cdot g_1 + m\cdot g_2]\cdot x \quad (15)$$

with

$$x = \frac{IC_o}{E_o} = \frac{Pr\cdot(1+f)}{\varepsilon_o} \quad (16)$$

and "ε_o" the reduced annual heat production per square meter of collector surface (kWh/year.m^2), i.e.:

$$\varepsilon_o = \frac{E_o}{A_c} \quad (17)$$

Accordingly, the following relations are valid for "g_1" and "g_2" parameters:

$$g_1 = \frac{1}{\frac{1+e}{e-i}\cdot[\left(\frac{1+e}{1+i}\right)^n - 1]} \quad (18)$$

$$g_2 = \frac{\frac{1+g_\Sigma}{g_\Sigma - i}\cdot[\left(\frac{1+g_\Sigma}{1+i}\right)^n - 1]}{\frac{1+e}{e-i}\cdot[\left(\frac{1+e}{1+i}\right)^n - 1]} \quad (19)$$

Applying the above analysis to a typical system for a single-family house (collector area A_c=2.5m^2 and storage capacity 150lt) the present value of produced heat effective cost is given in figures (8) and (9) for ten (n=10) and fifteen (n=15) years of operation respectively.

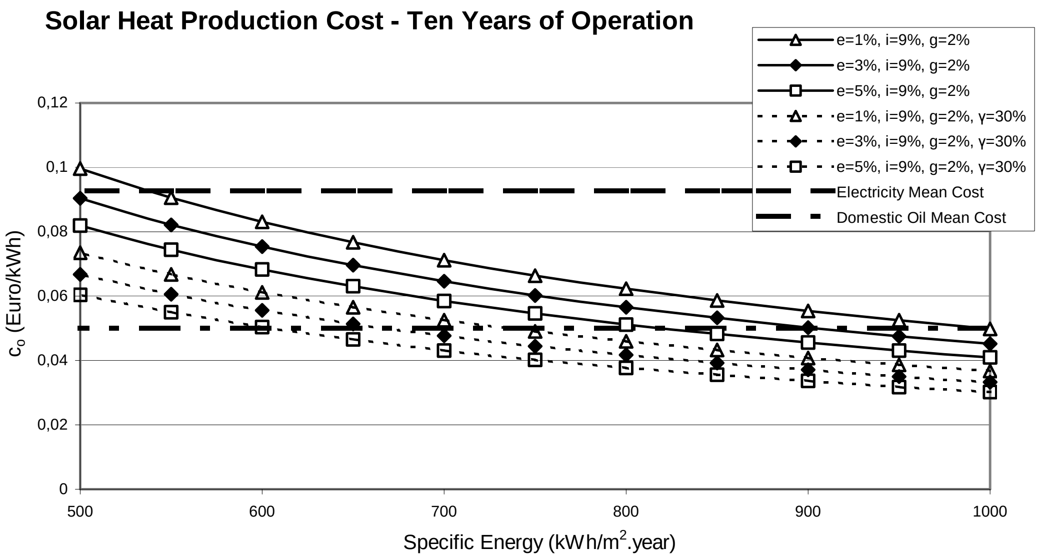

Figure 8: Feasibility Analysis Results of Domestic Solar Collectors in Greece (n=10)

As it is obvious from the results obtained, the solar-heat production cost (present value) is quite lower than the current electricity market price, even without (γ=0) State subsidization, for ten years service period of the installation. On the contrary, the solar-heat systems present a competitive production cost advantage in comparison with the domestic oil/gas solution only after a 30% subsidization and annual heat production greater than 750kWh/m^2, figure (8).

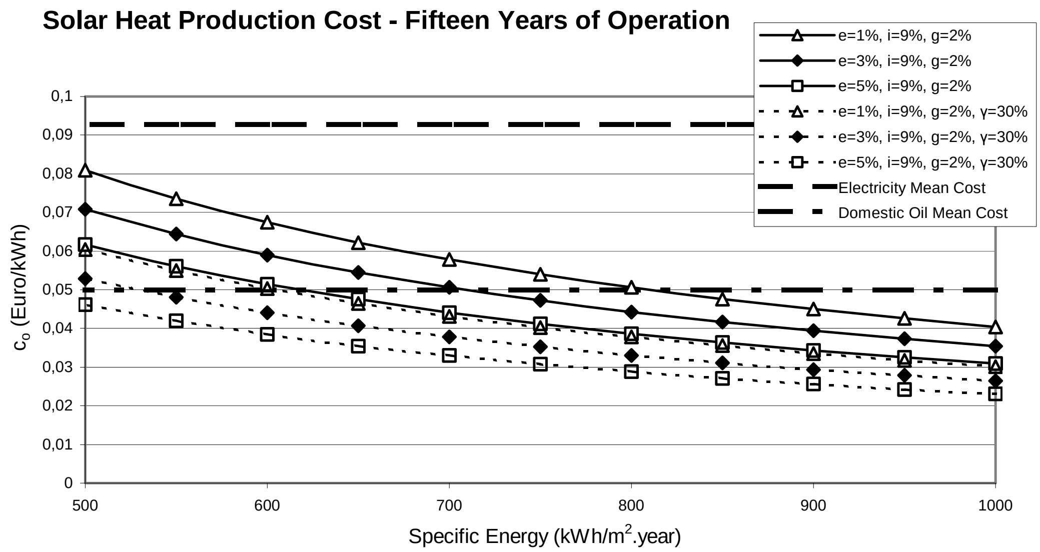

Figure 9: Feasibility Analysis Results of Domestic Solar Collectors in Greece (n=15)

Accordingly, for fifteen years service period of the installation assumed, the proposed solar-thermal solution is not only viable (figure (9)) but also economically attractive compared to the electrical heater one. The same conclusions are also valid in comparison with the oil/gas choice, only under a 30% State subsidization precondition.

Having validated the economical viability of the proposed solar-thermal systems it is also important to estimate the annual air-pollutants emissions diminution per square meter of collector surface installed. For this purpose, official data[19] and recent research results[20] concerning the main air pollutants emissions are used and the principal results are summarized in Table I. According to the results obtained, every square meter of solar thermal system installed contributes annually to the environmental protection by saving 165kg to 932kg of CO_2, 0.3kg to 24kg of SO_2, 0.03kg to 0.166kg of CO, 0.125kg to 1.57kg of NO_x and 0.01kg to 0.055kg of HC.

Table I: Avoided Annual Air-Pollutants Emissions per Square Meter of Collector Surface due to Solar Collector Usage in Greece

kg/m^2/year	Mazut-Electricity min	Mazut-Electricity max	Diesel-Thermal min	Diesel-Thermal max
CO_2	466.2	932.4	164.7	329.5
SO_2	12.1	24.1	0.315	0.629
CO	0.083	0.166	0.030	0.060
NO_x	0.79	1.57	0.125	0.250
HC	0.028	0.055	0.010	0.020

Bear in mind that carbon dioxide (CO_2) is mostly responsible for the greenhouse effect and mainly blamed for the temperature increase of the Earth. Taking into consideration that CO_2 emissions in Greece has increased by 16.7% during the previous decade, the accelerated penetration of solar-thermal systems in the local market should greatly contribute to the European effort for 8% decrease of CO_2 emissions by 2012. Additionally "NO_x" and "SO_2" are among the most common air pollutants of the urban areas, being also ingredients of the smog appearing in many cities. Both gases have a very annoying and characteristic smell and in combination with humidity are finally transformed to strong acids, being primary responsible for the acid rain. Finally carbon monoxide "CO" is a very toxic and poisonous gas, while hydrocarbons "HC" are strongly related with several cancer types.

Summarizing, the economic viability of the domestic solar-thermal systems analyzed in the present study is proven, while their remarkable contribution on the environmental quality amelioration is also confirmed. Thus, both -economic and environmental- criteria strongly support the further diffusion of similar systems in the Greek market.

6. Conclusions

A critical evaluation of solar collector market study in Greece was presented, in view of the excellent solar energy potential of the country. The study includes experimental values of meteorological and environmental parameters, while an integrated feasibility analysis of the available in the market domestic solar-thermal systems was described. Accordingly, the environmental benefits related to the installation of solar-thermal systems are predicted, on the basis of the several air-pollutants emissions decrease.

Recapitulating, the utilization of domestic solar-thermal systems for hot water production is not only an economically viable solution, but also the acceleration of solar collectors penetration in the energy balance of Greece is in accordance with the Kyoto protocol, effectively contributing towards a sustainable future for European citizens.

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COMBINED PHOTOVOLTAIC AND WIND ENERGY OPPORTUNITIES FOR REMOTE ISLANDS

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Abstract

Energy shortage and poor infrastructure are the principle factors delaying the economic development of remote island societies. The prospect of creating a combined wind-solar power station is investigated, in order to minimize their dependence on the local thermal power stations, with an acceptable investment cost. For this purpose, a complete analysis is carried out, taking into consideration the local energy demand, the number and characteristics of the existing diesel machines, the local wind and solar potential, along with the individual peculiarities of the islands under investigation. By introducing a new wind park and a photovoltaic power station, using also a conventional battery storage system, the renewable energy penetration is significantly increased, minimizing the dependency on imported oil and remarkably reducing all negative environmental effects. Finally, only the most cost efficient engines are hereafter necessary, giving the opportunity of removing the excess thermal power.

Keywords: Wind Energy; Photovoltaic; Remote Islands; Hybrid Station

1. Introduction

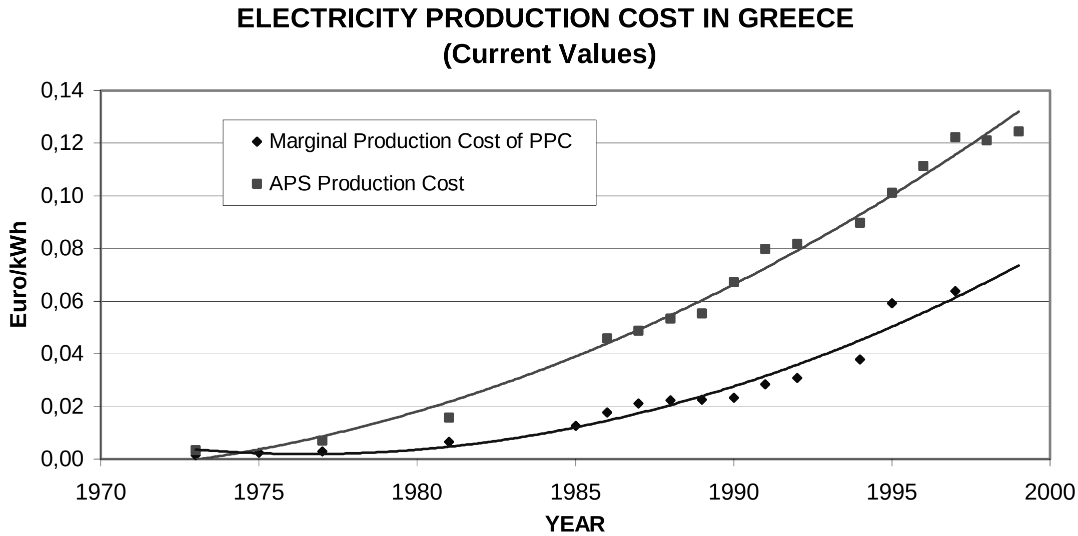

Figure 1: Electricity Production Cost for Remote Islands

Energy shortage and poor infrastructure are the principle factors delaying the economic development of remote island societies and complicating their habitants' everyday life. More precisely, the energy production cost for the remote Greek islands majority is extremely high, due to the autonomous thermal power stations (APS) used, figure (1). Moreover, in all these cases fuel transportation is very difficult, especially during the winter period, while during summer the maximum local grids power is often less than the demanded load, thus leading to electrical black outs.

Thiakoulis Tr., Kaldellis J.K., 2001, "Combined Photovoltaic and Wind Energy Opportunities for Remote Islands", "Renewable Energies for Islands" International Conference, Paper No 54, Chania, Crete, Greece.

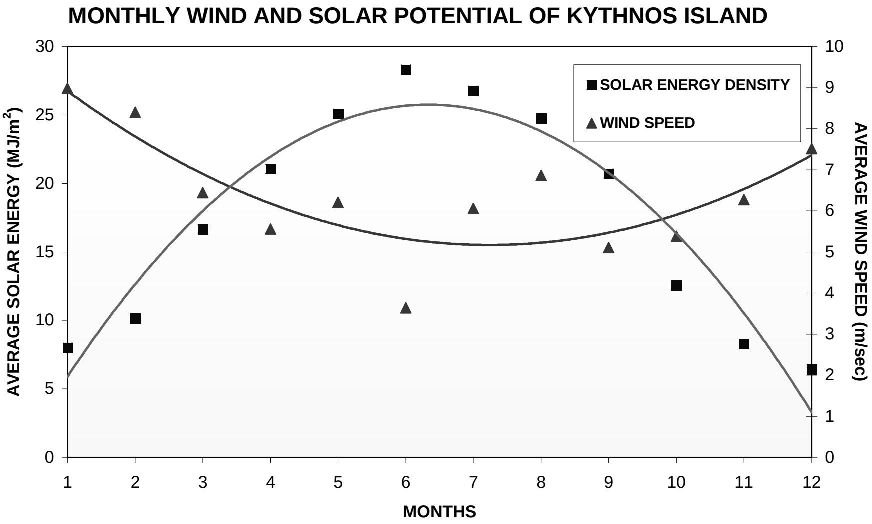

Figure 2: Wind-Solar Potential of a Typical Remote Island

On the other hand, all Greek islands are located in regions with an abundant and reliable solar energy supply, even during winter, while their majority also possesses excellent wind potential, figure (2). For all these reasons, in the present work, the prospect of creating a combined wind-solar power station[1] is investigated, in order to minimize their dependence on the local thermal power stations, with an acceptable investment cost[2]. For this purpose, a complete analysis is carried out, taking into consideration the local energy demand, the number and characteristics of the existing diesel machines, the local wind and solar potential[3], along with the individual peculiarities of the islands under investigation. The majority of Aegean Sea islands, for example, present a considerable daily and

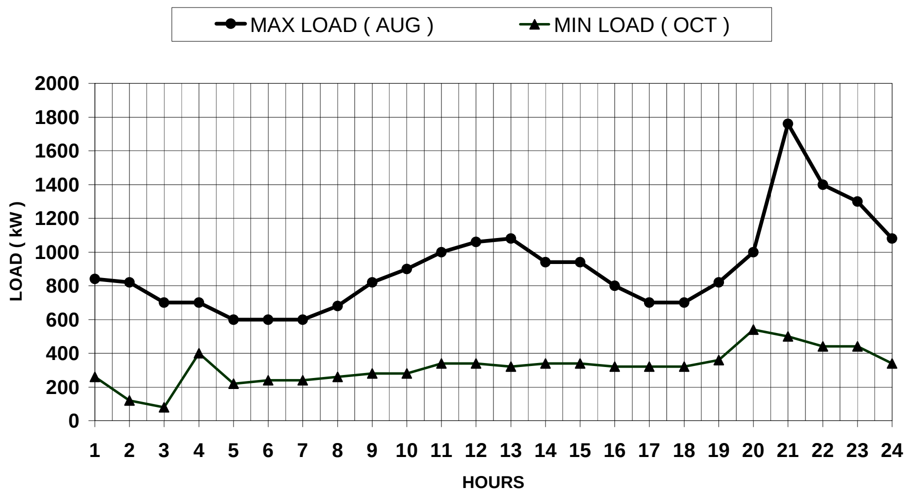

Figure 3: Daily Load Curves of a Remote Island

seasonal fluctuation of electricity demand (figure (3)), posing serious limitation on the wind energy installations size, provided that local grid stability should be maintained[4].

2. Proposed Solution

In order to face all the above described problems, taking advantage of the local RES potential, a new hybrid system is developed (figure (4)) based on the existing APS, the local outdated photovoltaic (100kW) station[1] and the small obsolete (5x33kW) wind park[5]. The present study examines the impact of a new 500kW wind turbine, as well as the influence of a modular (100kW up to 400kW) PV extension on the operational-energy behaviour of the hybrid plant under investigation. In an attempt to strengthen the local system stability a new battery storage system is considered along with several

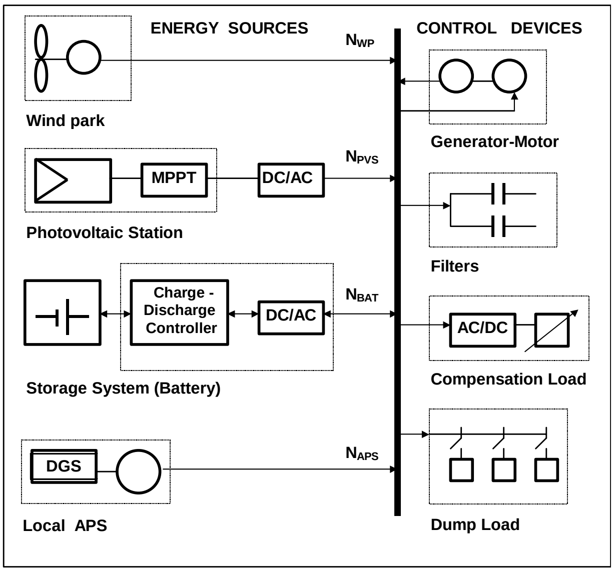

Figure 4: Proposed Hybrid Station for Remote Islands

control devices, like grid frequency filters, a phase shifter machine, static compensation devices and a DC/AC battery inverter[6].

More precisely, during the proposed system analysis process, the following design steps are taken into account:

a. Record the hourly and peak load values of the consumption
b. Determine the future demand in electrical power and energy
c. Design a new load management plan for the existing APS diesel generator sets
d. Remove the old and inefficient internal combustion engines of the local APS
e. Estimate the necessary battery size, so that the peak load demand is firmly covered, despite the removal of the outdated diesel engines
f. Evaluate the local wind and solar potential of the examined area
g. Estimate the appropriate size of the wind park and/or photovoltaic station, to be installed
h. Analyze the economic viability of the proposed hybrid system

Applying the above steps on the assembly of figure (4), the following situations may appear during operation of the proposed energy production station:

i. The power demand is less than the sum total of the wind park and the photovoltaic station power (diesel generators out of operation). The prospective energy surplus loads the battery and feeds any dump-loads, if necessary.
ii. The power demand is marginally higher than the power of the wind park and the photovoltaic station. The power deficit is covered by the battery, so that no diesel generator is ignited.
iii. The power demand is significantly higher than the power of the RES station. The power deficit is covered by the local APS.
iv. The power demand-peak load is larger than the power sum of total RES and local APS. The battery covers the deficit, so that any black out danger is avoided.

One of the most common problems accompanying similar hybrid type installations is the relatively high first installation cost. This is particularly elevated in cases of high PV penetration[7]. On the other side, the marginal cost of the local APS is continuously increasing[8], approaching the 0.3Euro/kWh value for 2000. On the other side, the maintenance and operational cost of a similar hybrid station is limited[3], therefore a complete cost-benefit analysis[2] is necessary for each case analyzed, in order to obtain the optimum system configuration.

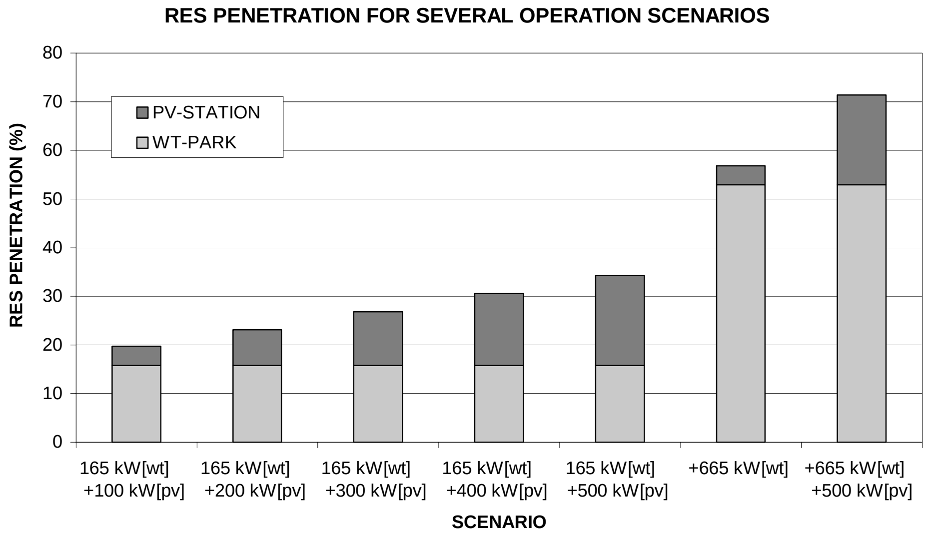

Figure 5: RES Penetration Values for a Remote Island Case

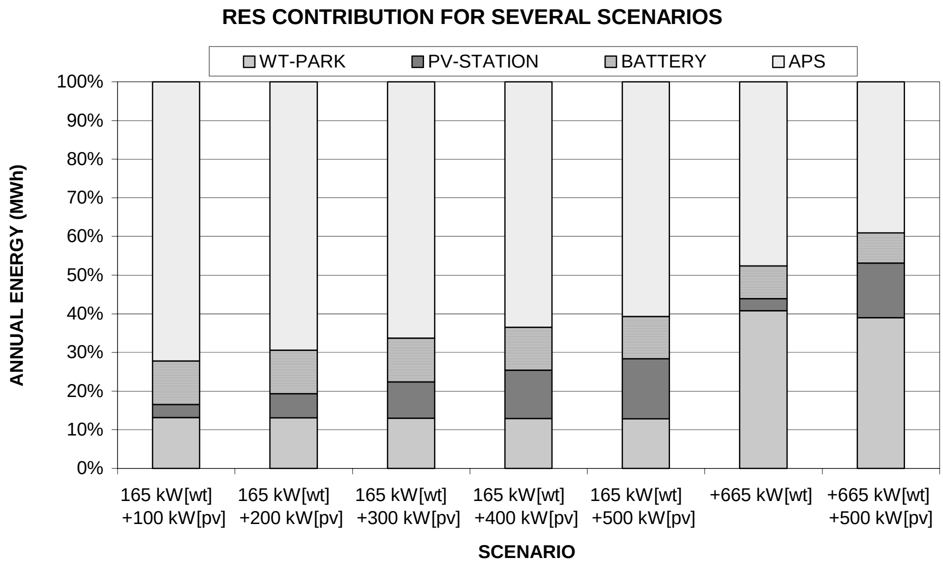

Figure 6: RES Contribution on Local Electricity Balance

3. Simulation Results

In the present analysis, a remarkable number of possible configurations are tested, mainly based on the gradual increase of the PV station size. More precisely, the combinations used here are based on the existence of 165kW of wind power and 100kW of photovoltaic. Accordingly, the nominal power of PV station is increased by 100kW steps, up to 500kW rated power. Finally, the incorporation of an additional 500kW wind converter is also taken into account.

Thus, using the results of figure (5), one may conclude that a remarkable RES penetration may be realized, achieving values of 72%, compared to the modest 16% of today. It is also interesting to mention that the gradual installation of further PV panels leads to an almost linear increase of the RES station contribution on the local system energy balance. However, the maximum PV contribution is only 19% in comparison to the 53% value of the 655kW wind park. On the other side, one should also take into consideration the high quality of the PV system electrical current output and its practically zero maintenance requirements.

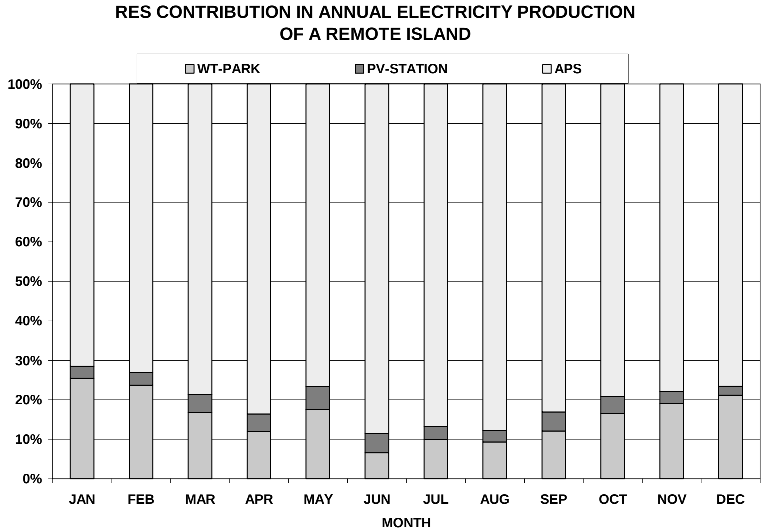

Figure 7: RES Electricity Contribution, Low Penetration Case

Subsequently, in figure (6) we present the expected RES contribution on annual energy balance of the local network, for all configurations analyzed. According to the results obtained, the maximum wind turbines contribution is slightly under 40%, while the corresponding PV maximum participation is of the order of 15%. Another interesting remark related to these data is the significant contribution of the battery system (≈10%) on the local energy balance, especially for low RES penetration scenarios. Finally, the APS share is remarkably decreased, as the RES penetration is augmented, reduced to less than 40% values.

Very interesting conclusions are also drawn by examining on a monthly basis the RES contribution to the local system energy balance for a low and a high RES penetration case, figures (7) and (8). More specifically, for the low RES penetration scenario (existing case 100kW+165kW) the RES contribution should be in the order of 20%, achieving higher values during the winter, either due to low energy consumption or to high wind potential, figure (7). Unfortunately, the values realized by the

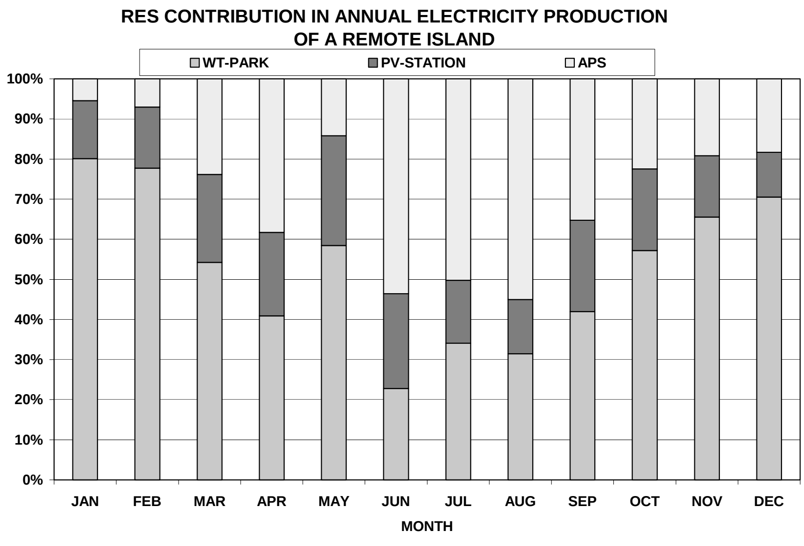

Figure 8: RES Electricity Contribution, High Penetration Case

PPC installations during the last two years are less than 5%. For this low penetration case, the contribution of the PV station is very limited (≈3%).

On the other hand, for the maximum RES penetration case (figure (8)) the RES contribution on a monthly base is greater than 45% for every month. On top of that, during winter (low electricity demand period) the RES contribution exceeds 90%.

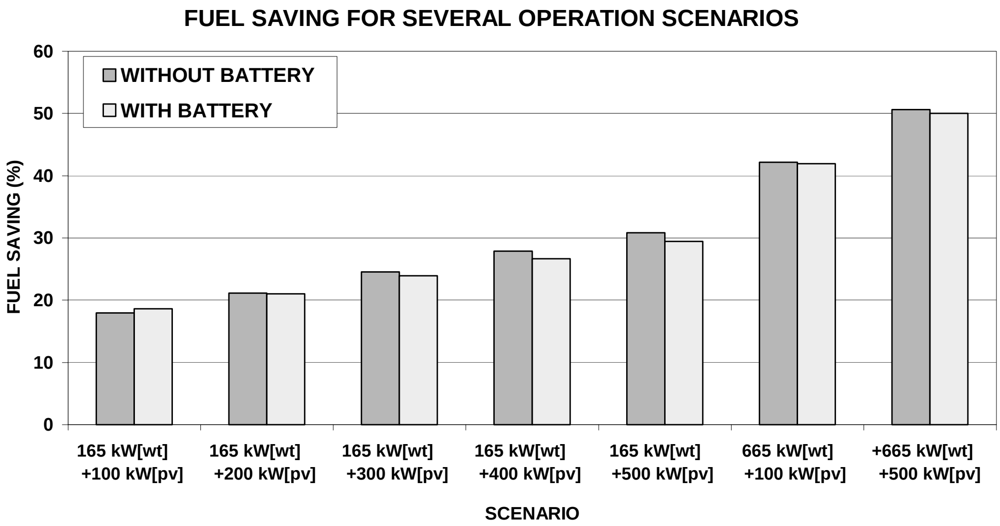

Figure 9: Fuel Saving due to the Proposed Hybrid System

All the above described RES contribution on the local market energy balance leads to a significant fuel saving, approaching values higher than 50% of the typical APS oil consumption. More precisely, two separate simulation categories are examined, with and without the usage of the new battery storage[9] system, figure (9). According to the existing results, the presence of a battery does not really affect the fuel saving. On the contrary, the battery system dominates the hours of APS operation, figure (10). Consequently, a more than 50% decrease is obtained if the battery storage system is utilized along with the RES station. The impact of battery is much more evident in low RES penetration cases.

Using the simulation results of figure (9), one may conclude that the fuel saving realized due to the PV station enlargement is rather modest achieving values of the order of 4% per 100kW of additional PV

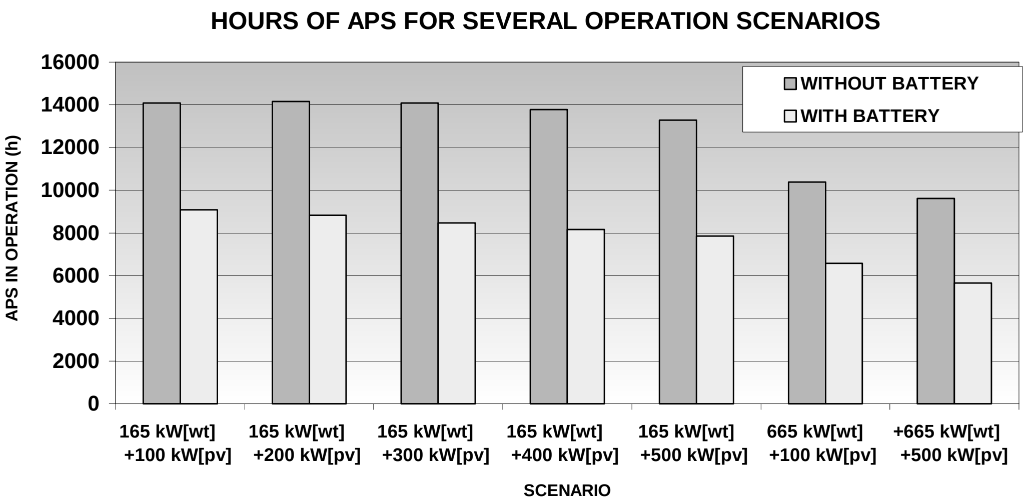

Figure 10: APS Operation Hours Decrease due to the Proposed Hybrid System

power. This is not the case for the 500kW wind power introduction, since an almost 25% oil consumption decrease is encountered.

Finally, the influence of the RES station enlargement on the operational hours is not as important as the existence of a battery storage system, figure (10). In any case, a small reduction of the APS operation hours takes place as the RES penetration is amplified. Thus, the total operation hours of the nine internal combustion engines of the local APS are minimized, achieving values of the order of 9500h per year without battery and 6000h per year with the existence of battery. One of the most interesting finding of the present study is the opportunity to remove all the inefficient outdated engines, without any power deficit danger.

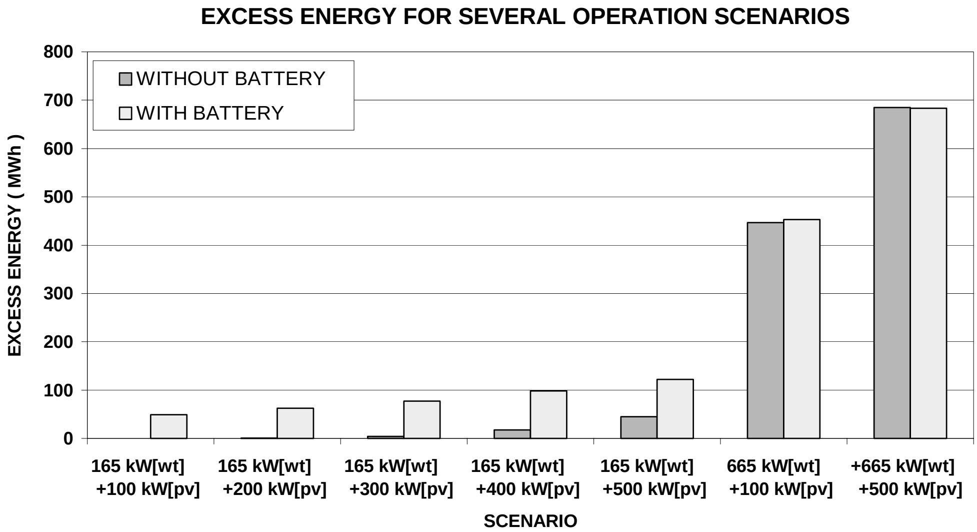

Figure 11: Energy Surplus of the Proposed Hybrid System

Lastly, a remarkable energy surplus appears in cases of high RES penetration, figure (11). This energy excess is limited before the introduction of the 500kW wind converter. However, the presence of the 500kW wind converter and the by 400kW enlargement of the existing photovoltaic plant leads to cumulative energy surplus. In this last case, an almost 700MWh electrical energy excess is encountered representing the 14% of the local annual consumption. This energy amount can be forwarder to either a desalination plant[10] (for clean water production) or to other low priority loads (e.g. pumping storage), increasing the development opportunities of the local society[11].

Recapitulating, the proposed hybrid system is the best alternative for almost all Aegean Archipelago remote islands, providing a remarkable RES penetration in the local electrical systems and taking advantage of the significant local wind and solar potential.

According to the results presented this energy solution leads to:

- ✓ Remarkable fuel savings (up to 50%)
- ✓ Significant environmental benefits[12], due to the diesel oil consumption reduction
- ✓ APS operational hours diminution (from 14000h to 6000h per year).
- ✓ APS nominal power reduction, since there is the opportunity of transferring the inefficient and no necessary engines
- ✓ No power deficit during the summer (high demand) season, due to the maximum power increase of the complete system
- ✓ Better quality of provided electricity, due to the improved electricity production control devices
- ✓ Remarkable energy surplus, to be used for development needs
- ✓ Positive financial results, taking into account the high RES potential and the extremely high (up to now) electricity production cost

4. Conclusions

The prospect of creating a combined wind-solar hybrid power station, based on available renewable resources (mainly wind and solar), is investigated. The proposed solution is the best alternative in order to minimize the dependence of the remote Aegean islands on the existing old-fashioned thermal power stations, with an acceptable investment cost. More precisely, by introducing a small wind park and a photovoltaic (PV) power station, a significant amount of fuel (20%) may be saved. The corresponding fuel saving is 220 tons of oil, finally translated to 50000 Euro per year. Increasing (by 500kW) the wind power of the local grid and using a conventional battery storage system, the renewable energy penetration is significantly improved up to 55%, minimizing accordingly the dependency of the regional electricity production system on imported oil, and remarkably reducing the corresponding negative environmental effects. On top of that, only three of the nine diesel engines -the most cost efficient ones- are hereafter necessary (1300kW instead of 2700kW), giving the opportunity of transferring at least 1000kW power to another remote system.

Finally, in view of the rapid development of the PV systems and their continuous price diminution, an increased contribution of PV generators on the local electricity system is examined, since the PV systems can provide electrification to remote consumers more reliably than wind parks, considering the pure stochastic time behaviour of wind energy.

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AN INTEGRATED RENEWABLE ENERGY SOLUTION FOR VERY SMALL AEGEAN SEA ISLANDS

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Abstract

The numerous very small Aegean Sea islands present serious problems related to limited water resources, high electricity production cost, insufficient infrastructure and continuous decrease of population. In order to face all these island communities' urgent necessities, an integrated renewable energy based solution is developed. More precisely, their electricity requirement may be covered by a combination of small wind converters and photovoltaic systems, along with the appropriate energy storage devices. Additionally, their thermal needs can be fulfilled using solar collectors and low enthalpy geothermy. Finally, fresh water supply should be supported by the renewable energy stations production. In an attempt to improve our simulation results an experimental system is under construction in the Soft Energy Application Lab facilities, including a small wind converter, several solar collectors, an anaerobic bioreactor and a new photovoltaic station.

Keywords: Very Small Islands; Water Resources; Electricity Production Cost; Renewable Energy Sources

1. Introduction

The numerous small Greek islands spread throughout Aegean Sea are located either in N. Aegean Department or in Cyclades and Dodekanessa complexes. In all these tiny islands (less than 500 habitants) a continuous decrease of population has been encountered during the last forty years. This is not the case for the summer season, where a more than 300% increase of population is observed, due to the visiting tourists.

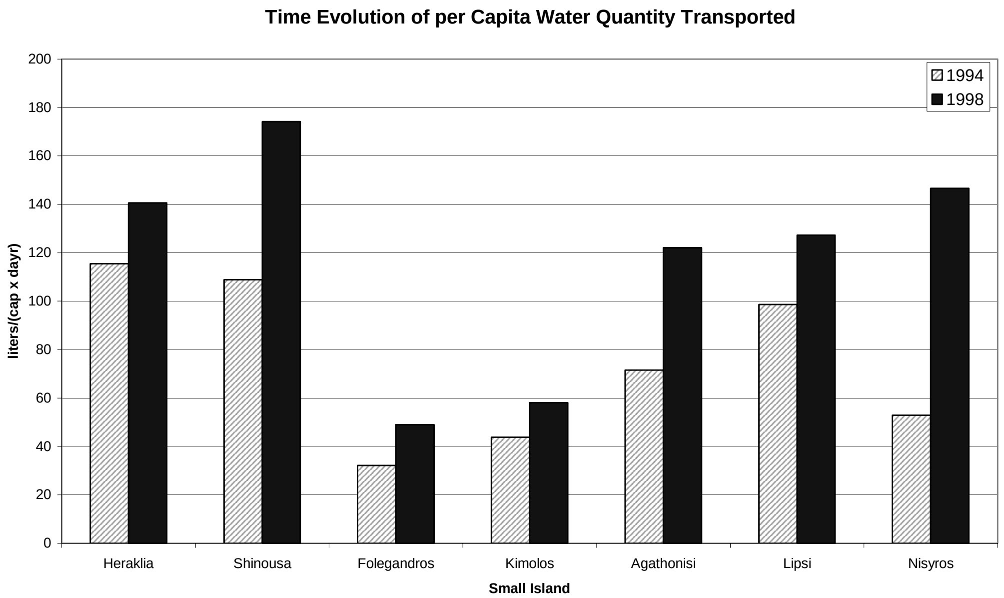


Figure 1: Time-Evolution of Water Transported

__Kaldellis J.K., Vlachou D., Kavadias K., 2001__, "An Integrated Renewable Energy Solution for Very Small Aegean Sea Islands", "Renewable Energies for Islands" International Conference, Paper No 68, Chania, Crete, Greece.

For the vast majority of these islands, the water resources are quite restricted, therefore in most of them almost 80% of the fresh-water needed is imported[1][2], figure (1). On top of that, the electricity production cost[3], due to the autonomous small thermal powers utilized, is extremely high, figure (2), while extended grid failures (electrical black outs) arise all over the year.

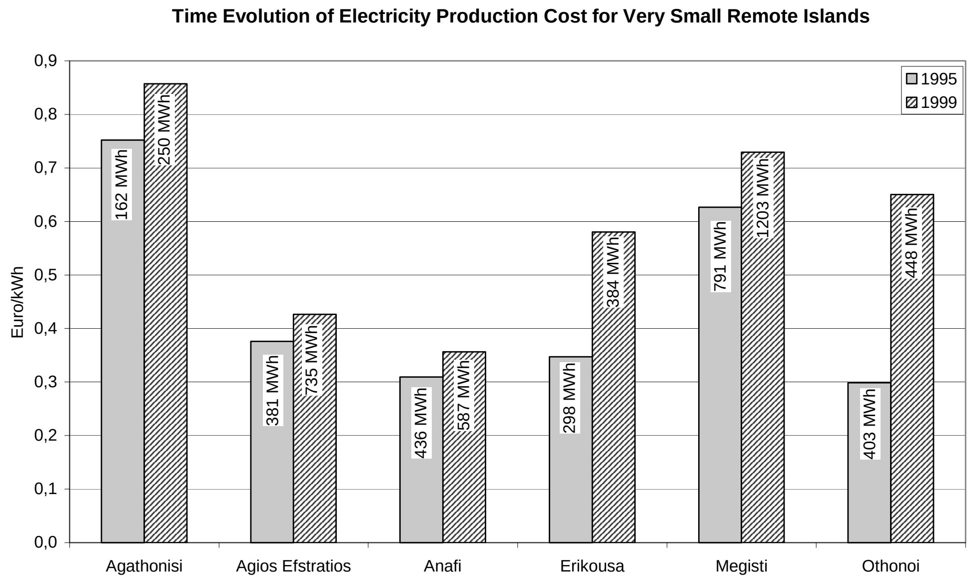


Figure 2: Time-Evolution of Electricity Production Cost

Afar from decision centres and having limited political influence, these islands are usually abandoned, presenting a dramatically insufficient infrastructure situation. Their importance, however, is not only based on socio-economic criteria but mainly on national survival reasons.

As a contribution to life quality amelioration of these isolated Greek territories remaining habitants, an integrated solution is under consideration, based on 100% usage of renewable energy sources (RES) in order to cover the local growth needs.

Finally, in an attempt to improve our experience and realistically simulate such an integrated hybrid plant, an experimental system is under development[4] in the Soft Energy Application Lab facilities, including a small wind converter, several solar collectors, an anaerobic bioreactor and a new photovoltaic station.

2. Position of the Problem

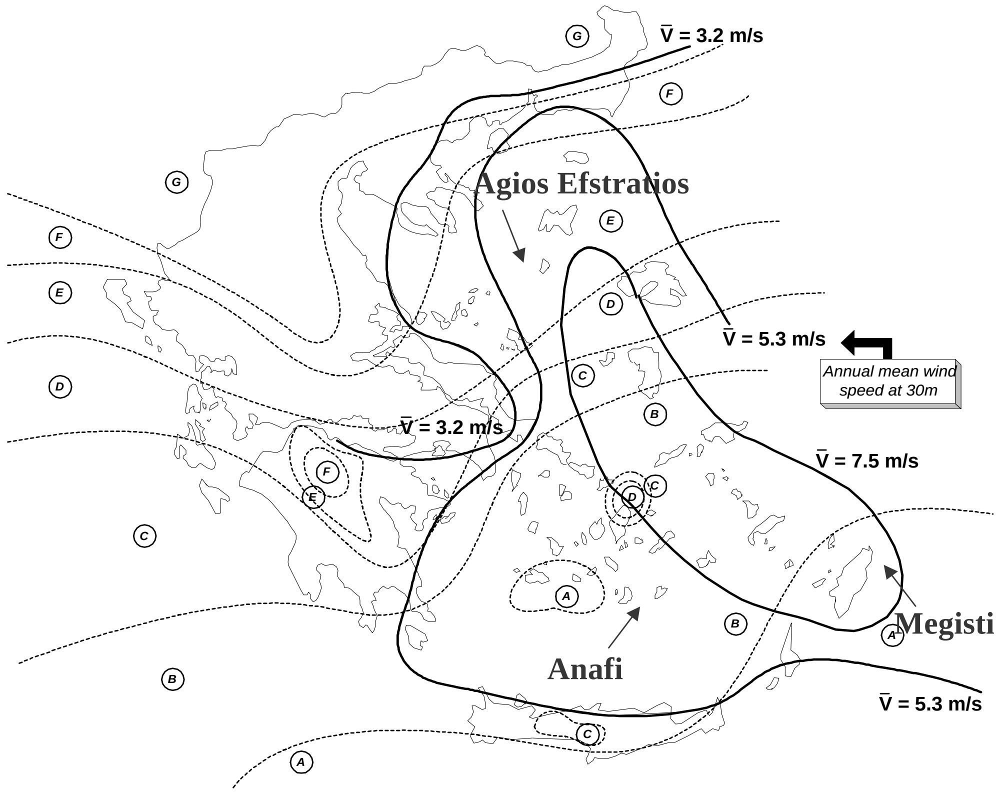
In order to face the urgent necessities of all these tiny Aegean islands, an integrated renewable energy based solution has been devised. Thus, it is necessary to collect[5] any available information concerning each small island's local topography, climate and existing water resources -including precipitation values-, solar intensity and wind speed, their corresponding demographic profile and economic activities, along with all existing natural resources. On top of that, it is important to respect their electricity and clean water annual demand profile and the corresponding thermal needs, together with any wastewater treatment requirements.

Accordingly, an integrated autonomous energy solution is proposed, exclusively based on RES application, in a case-by-case analysis.

Subsequently, a simulation algorithm is developed to thoroughly study the main local parameters behaviour for a typical one (or more) year time period. The calculation results are going to provide all necessary information to optimize the proposed solution.

Finally, a techno-economic evaluation process[6] is applied for all achievable solutions, in an attempt to select the most appropriate alternative for every island analyzed.

WIND & SOLAR ENERGY IN GREECE



Solar potential

ZONE	kWh / m ^{2}
A	> 1650
B	1600 - 1649
C	1550 - 1599
D	1500 - 1549
E	1450 - 1499
F	1400 - 1449
G	< 1399

Figure 3: Wind-Solar Potential for Very Small Aegean Islands

Our research team selects three representative tiny island cases, in order to test the applicability of the proposed method on real world problems solution.

3. Presentation of Available Information

As already mentioned three typical very small islands have been selected representing (figure (3)) the three major divisions of Aegean Archipelago area, i.e.:

- Agios Efstratios Island (N. Aegean Department)
- Anafi Island (Cyclades Complex)
- Megisti Island (Dodekanessa Complex)

More precisely, Agios Efstratios is a small triangular volcanic island (286 habitants, area of $49km^2$) of N. Aegean Sea, located between Lesvos, Limnos and Skiros islands. The topography of the island is typically Aegean, i.e. gentle slopes, absence of flat fields, low hills and sparse vegetation. The main economic activities of the local society are agriculture, merchant marine and tourism. The annual energy production of the local APS was only 811MWh for 2000. The peak load demand,

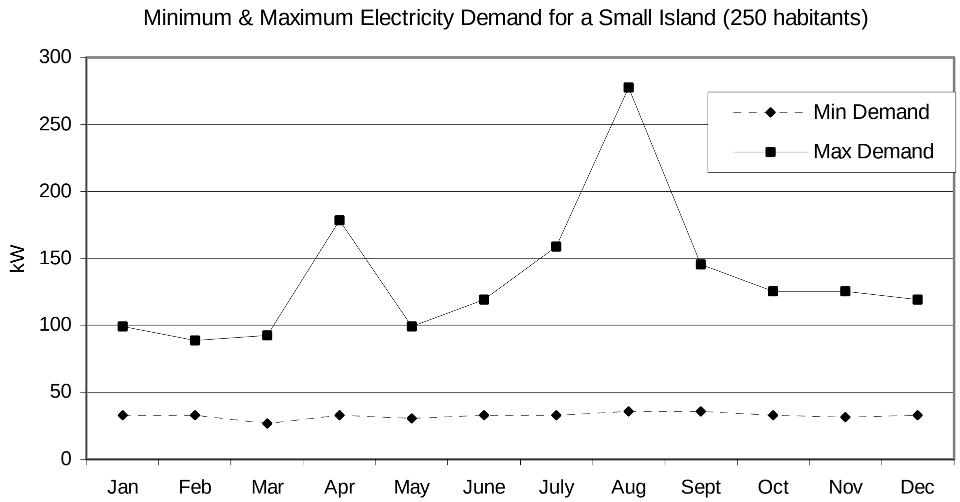


Figure 4: Typical Electricity Demand Profile

approximately 250kW, appears during August 15, while the corresponding minimum value is 40kW (3 January), see also figure (4). The island has an outstanding wind potential, since the annual mean wind speed approaches 9m/s, at 10m height. For this reason, in the island exists an experimental autonomous (not-grid connected) wind converter of 110kW.

Anafi is a very small island (population 261 habitants -approximately 70 families- area of $39km^2$) 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. At the west side of the island, there exist certain geothermal springs, not used up to now. The main economic activities of the local society are fishing, and tourism. The annual energy production of the local APS was 685MWh for 2000. The peak load demand -approximately 350kW- appears on August 15, while the corresponding minimum value is 40kW (2 December). The island has very good solar potential, since the annual mean solar energy approaches $1700kWh/m^2$, at horizontal plane. Besides, the traffic network of the island is only 2km, connecting the only village of the island to the small port.

Finally, Megisti is the easterly European Union territory, located almost 72 miles from Rhodes. The island area is only $9km^2$ and the population includes 275 permanent habitants (approximately 70 families). The local terrain is arid and rocky with several caves. The annual energy production of the local APS was 1465MWh for 2000. The peak load demand -approximately 355kW- appears on July 25, while the corresponding minimum value is 100kW (22 October). The main economic activities of the local society are fishing and tourism, although in the past the habitants were excellent merchants. The island has also excellent solar potential, since the annual mean solar radiation exceeds $1700kWh/m^2$, at horizontal plane. There is no traffic network in the island despite the existence of a small airport.

In Table I we present the available data concerning the mean monthly values of several meteorological parameters (like temperature, precipitation, solar radiation, mean wind speed, sunlight hours). According to the existing data, Anafi Island has the minimum precipitation value ($400mmH_2O$), Megisti presents the higher annual mean temperature (19°C) and Agios Efstratios the maximum mean wind speed (8.3m/s).

Table I: Available Information Concerning the Islands under Investigation

Island ↓	Month→	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Mean Annual
Agios Efstratios	Mean Wind Speed (m/s)	9,1	9,3	8,7	8,2	7,3	7,0	7,1	8,2	8,2	8,5	8,8	8,7	**8,3**
	Mean Temper. (°C)	9,5	10,3	11,4	15,7	19,7	24,1	26,8	26,1	22,0	18,2	13,9	11,2	**17,4**
	Sunlight Hours	103	116	161	213	305	344	383	357	285	207	147	111	**228**
	Solar Energy (kWh/m^2) (0°)	48,0	63,5	106	139	187	204	214	196	146	98,5	61,0	46,5	**125**
Anafi	Mean Wind Speed (m/s)	7,8	7,8	7,7	6,5	5,7	5,0	5,3	6,7	6,2	6,5	7,5	7,7	**6,7**
	Mean Temper. (°C)	11,5	11,5	12,7	15,9	22,3	25,0	26,6	26,6	23,5	19,9	16,5	13,5	**18,8**
	Sunlight Hours	93,7	87,6	166	260	327	389	424	399	32q	195	162	95,8	**243**
	Solar Energy (kWh/m^2) (0°)	53,0	60,0	107	159	200	227	241	220	168	102	72,0	49,0	**138**
Megisti	Mean Wind Speed (m/s)	7,9	8,0	7,8	7,4	6,7	5,9	6,1	7,0	7,1	7,1	7,2	7,5	**7,1**
	Mean Temper. (°C)	11,5	12,0	13,5	17,0	20,7	25,0	27,2	27,6	24,8	20,4	16,2	13,0	**19,1**
	Sunlight Hours	138	142	206	247	315	356	387	373	314	240	184	142	**253**
	Solar Energy (kWh/m^2) (0°)	64,0	77,0	122	155	196	214	227	211	166	117	79,0	61,0	**141**

Recapitulating, these islands' main characteristic is their dry Mediterranean climate. As a result, their water resources are quite restricted, limiting their local societies' economic development and

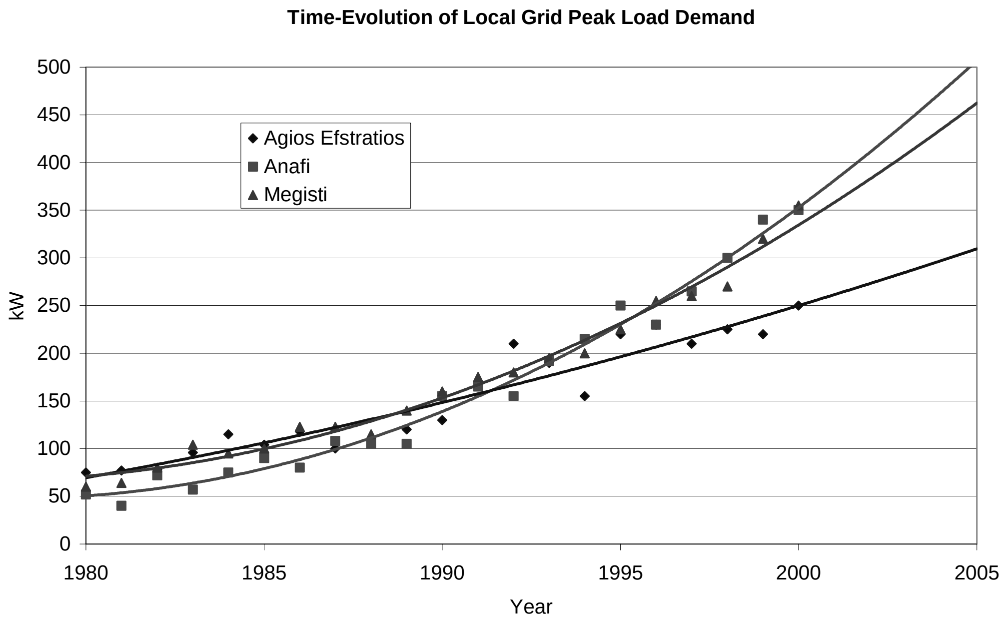


Figure 5: Time-Evolution of Local Grid Peak Load

deteriorating their habitants' life quality level. More precisely, the climate of the region is typical coastal Mediterranean; winters are relatively mild with only few rainfalls and summers are hot and dry. The rainy periods are mainly between December-January and March-April, whereas precipitation varies on an average basis in the range of 350 to 550mm in Cyclades and Dodekanessa[1] reaching the 750mm in the NE Aegean region. There are no rivers in the islands, while the existing very small streams have merely seasonal character.

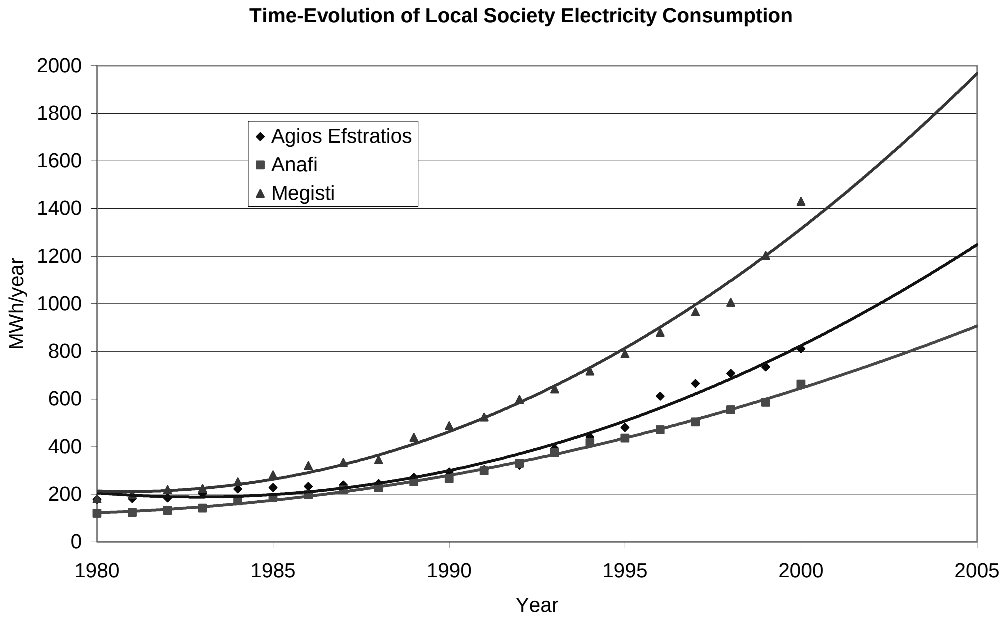


Figure 6: Time-Evolution of Local Grid Energy Consumption

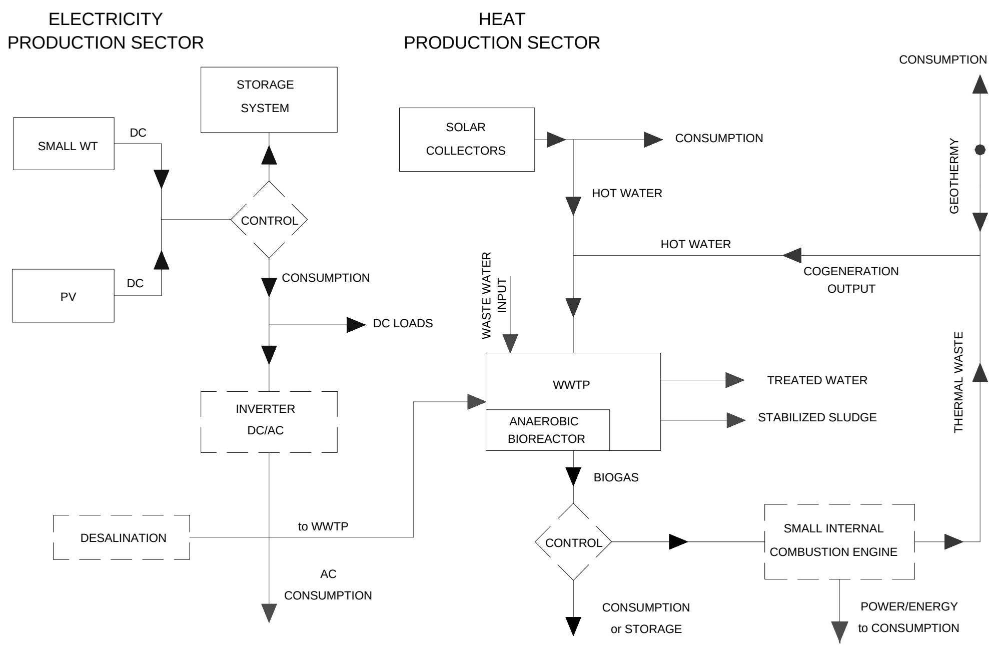


Figure 7: Integrated RESolution for Very Small Islands

Additionally, due to their relative distance from the mainland, an economic development deficit with the rest E.U. regions is also encountered. Their basic infrastructure networks are small in scale and high-priced in construction and operation. In figures (5) and (6) the time evolution of the electricity annual consumption and the corresponding peak load demand are given, for the three islands under consideration.

4. Proposed Solution

As an outcome from the previous analysis, the main problems of all isolated tiny islands are the insufficient water resources and the extremely high electricity production cost, achieving values in the range of 0.5 to 2 Euro/kWh.

In order to face these serious problems, for each very small island examined, an integrated autonomous energy solution is proposed (figure (7)), exclusively based on RES application. More precisely, their electricity requirements may be covered by a combination of small wind converters and photovoltaic systems (central or stand-alone), along with the appropriate energy storage devices[7].

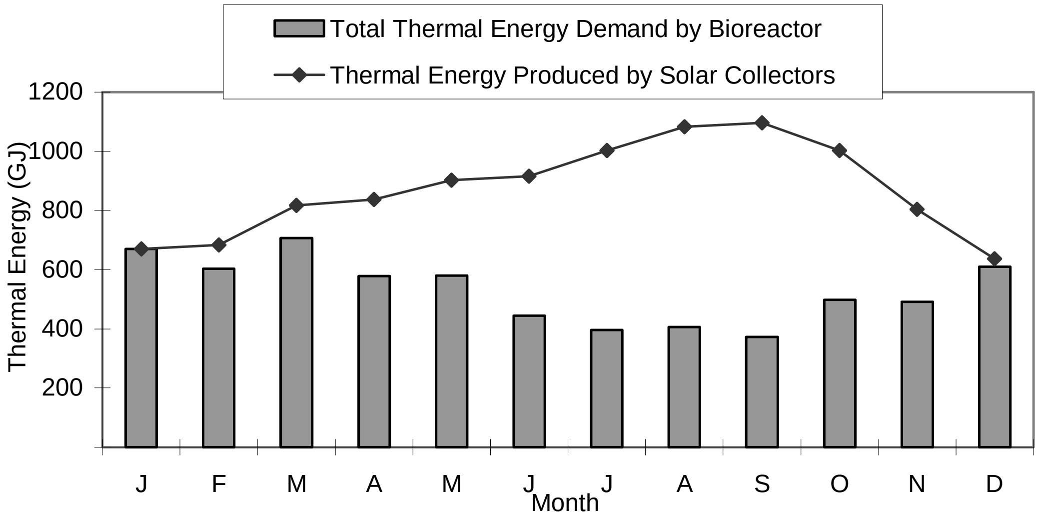


Figure 8: Thermal Energy Balance of a Proposed Wastewater Treatment System for Very Small Islands

Additionally, the thermal needs can be fulfilled using solar collectors and low enthalpy geothermy (e.g. Anafi island). An alternative customary renewable energy sources application is biomass burning for cooking and hot water production, especially for Agios Efstratios island case.

Another interesting possibility is an energy-autonomous integrated wastewater treatment plant[8], able to cover the requirements of a very small Aegean island, especially during the summer months, where an excessive population increase takes place. Because of the polluted seawater, fish stocks will eventually shrink and swimming will become dangerous; therefore tourists will simply not visit these islands. The system under consideration should be energy autonomous, since electrical needs would mainly be covered by wind or even solar power surplus, while thermal load is primarily fulfilled by solar collectors, figure (8). In this case the whole amount of biogas produced may be used for other applications, like electricity production by the internal combustion engines of the local APS.

Finally, fresh water supply should be supported by the energy production of the renewable energy devices. According to previous research[9], the RO seawater desalination solution (in modular basis) is found to be the best alternative, essentially for applications in remote, off-grid areas with small and medium local water demand.

Keep in mind that energy requirement for desalination plants depend on the salinity and temperature of the feedwater, the quality of the water produced, and the desalting technology used[1]. On top of that, the energy consumption is much higher for small-scale RO plants. Performance test results -made for similar size cases- conclude that the RO unit efficiency reaches at best almost $20kWh/m^3$ of fresh-water. The energy consumption is even higher (e.g. $35kWh/m^3$) if energy storage and power transformations are necessary.

5. Proposed Solution Experimental Simulation

The necessary information needed to accurately simulate the proposed integrated renewable energy solution can be significantly enhanced by using an experimental facility. Thus, in an attempt to improve our experience and to realistically simulate such an integrated hybrid plant, an experimental system is under preparation[4] in the Soft Energy Application Lab facilities, including a small wind converter, several solar collectors, an anaerobic bioreactor and a new photovoltaic station[10]. This small pilot installation (scale 1:50 to 1:100) can be employed in order to select the necessary information concerning the mass and energy balance of the full-scale plant. More precisely, in the Soft Energy Application & Environmental Protection Lab of TEI of Piraeus, the following devices exist:

a. An experimental wind turbine of 2.5 kW along with a remote indicating wind speed system.
b. A number of flat plate solar collectors, of 6 m^2 total area.
c. A small anaerobic bioreactor-thickener device able to simulate an integrated Wastewater Treatment Plant operation. The Plant capacity is 100 liters.
d. A small photovoltaic system of 4x55W to be installed before the end of summer.
e. A small lead acid battery storage system (24V), scheduled to replace the existing aged batteries.

In the near future an existing small diesel engine may be modified to consume biogas, while a 2 to 5kW (DC/AC) inverter has also been scheduled to purchase.

Using the above presenting experimental facility, it is possible to investigate first experimentally and afterward analytically the energy behaviour of such an integrated autonomous system, based on 100% RES utilization.

Finally, if the computational results agree with the experimental measurements to a great degree, the developed algorithm is going to be applied for real world cases, concerning the simulation of the three selected islands.

6. Conclusions

An integrated energy solution is developed, based on available renewable resources (mainly wind and solar), for the numerous remote very small Aegean Archipelago islands. The proposed solution takes into account any available information concerning their local topography, climate and existing water resources -including precipitation values-, solar intensity and wind speed, their corresponding demographic profile and economic activities, along with all existing natural resources. The main target of the present study is to fulfill the electricity and clean water annual demand profile, the corresponding thermal needs and any wastewater treatment energy requirements. Finally, in order to improve our simulation results an experimental system is under construction in the Soft Energy Application Lab facilities, including a small wind converter, several solar collectors, an anaerobic bioreactor and a new photovoltaic station.

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ENVIRONMENTAL BEHAVIOR OF A CHARCOAL GASIFICATION SYSTEM. EXPERIMENTAL AND THEORETICAL INVESTIGATION

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Abstract

The energy production in Greece -due to the fossil fuels used- is found responsible for a significant quantity of harmful gasses emitted to the atmosphere. At the same time, every Greek farmer destroys -by free combustion- more than 5 tones of small and medium sized woods per year, which are a kind of biomass. One attractive option of using this biomass is the gasification process. The present work investigates, both experimentally and theoretically, the operational behavior of an existing charcoal "dual fuel" gasification device, while special emphasis is put on the environmental benefits of the system. The charcoal utilization, actually, substitutes at least 70% of the total fuel consumption of the installation, leading to remarkable diminution of the corresponding air pollutants.

Keywords: Biomass; Gasification; Fuel Saving; Air Pollution; Charcoal

1. Introduction

The significant increase of energy consumption in Greece during the last thirty years[1] is mainly covered either by imported oil or locally extracted lignite, therefore, significant amounts of hazardous gasses, e.g., CO_2, SO_x and NO_x are produced[2]. At the same time, the international community realizes that Global Warming, along with the corresponding climate change, is one of our planet's worst enemies for the next century[3]. On top of that, acid rain deteriorates, among others, the most cherished monuments of Western civilization, like the Acropolis of Athens[4].

Furthermore, every Greek farmer destroys -by free combustion- approximately more than 5 tones of small and medium sized woods per year[5], which are a kind of biomass. The specific calorific value of almost 1,000,000 tn of this kind of biomass is approximately 4000÷7000 kJ/kg, giving the opportunity to save almost 100,000 toe of imported oil. Here we also note that this kind of biomass (small goods, brands, straws) cannot be used elsewhere due to their size[6][7].

One attractive option of using the above mentioned remarkable quantity of biomass is the gasification process[8], a method of converting raw biomass into mixture of gases, which have a potential to be burnt in combustion engines for the production of electricity, substituting imported oil or low quality lignite.

This work investigates, both experimentally and theoretically, the operational behavior of an existing charcoal "Dual Fuel" Gasification device, while special emphasis is laid on the environmental benefits of the system.

2. What is Gasification?

Gasification is a thermal process[9], that has been discovered since 1798, converting any dry biomass feedstock into a mixture of gases, primarily carbon monoxide and hydrogen, that can be burnt in internal combustion engines and gas turbines to generate electricity or steam.

***Sakkas Th., Kaldellis J. K., 2001**, "Environmental Behavior of a Charcoal Gasification System. Experimental and Theoretical Investigation", International Conference on "Ecological Protection of the Planet Earth I", Vol. II, pp.625-632, Xanthi, Greece.*

The gasification process can be divided[10] into three sub-procedures. The first step is a process of pyrolysis, during which the biomass is converted by heat into charcoal, steam, methanol, acetic acid and tars. The second procedure is based on an exothermic reaction where part of the carbon is oxidized to carbon dioxide. In the last phase, part of the carbon dioxide, the volatile compounds and the steam are reduced to carbon monoxide, hydrogen and methane.

3. Experimental Facility

The present study is based[11] on the experimental facility at Caythorpe-England, (figure (1)). The experimental gasifier consists primarily of a vertical cylindrical reactor with an extension hopper, mounted above it. The unit is loaded through a removable hatch at the top. Primarily air enters through a water-cooled nozzle (figure (2)). Gas leaves the gasifier through an outlet pipe located on the reactor wall opposite the nozzle. There is also a hatch for emptying and cleaning the reactor located at the reactor wall near the base.

Figure 1: Gasification experimental device

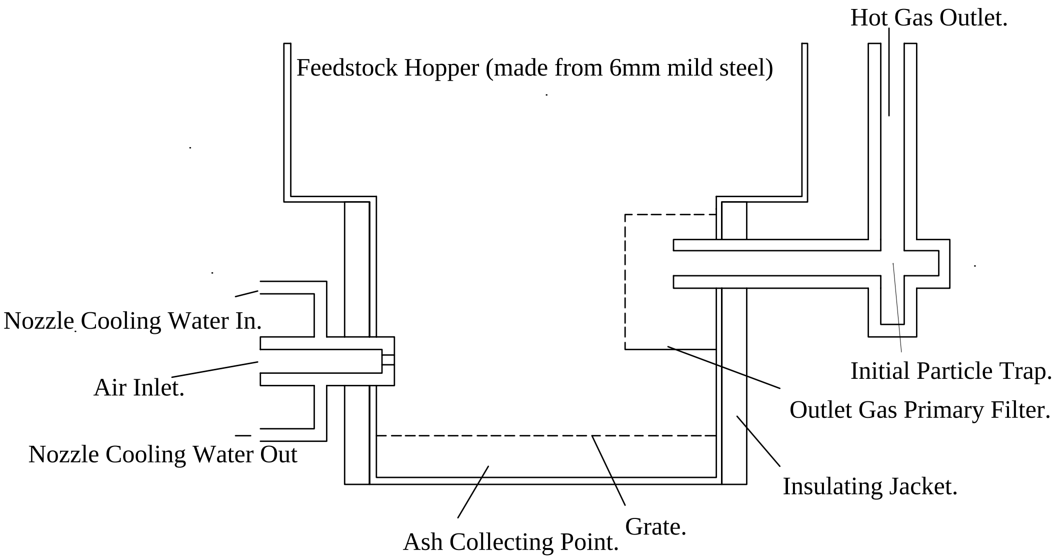

Figure 2: Schematic presentation of gasifier reactor

After leaving the reactor the gas passes through a large particle trap. From the particle trap the gas enters a cyclone with a port at its base for the removal of the collected dust. Then the gas flows through an assembly of three cooling pipes with external vanes. Two cylindrical-vessel filters follow these cooling pipes. In the first one, the gas must bubble through water situated at the bottom. The second one accumulates water-ash from the previous vessel plus condensed water. The last one is a small cyclone that collects mostly condensed water and tar.

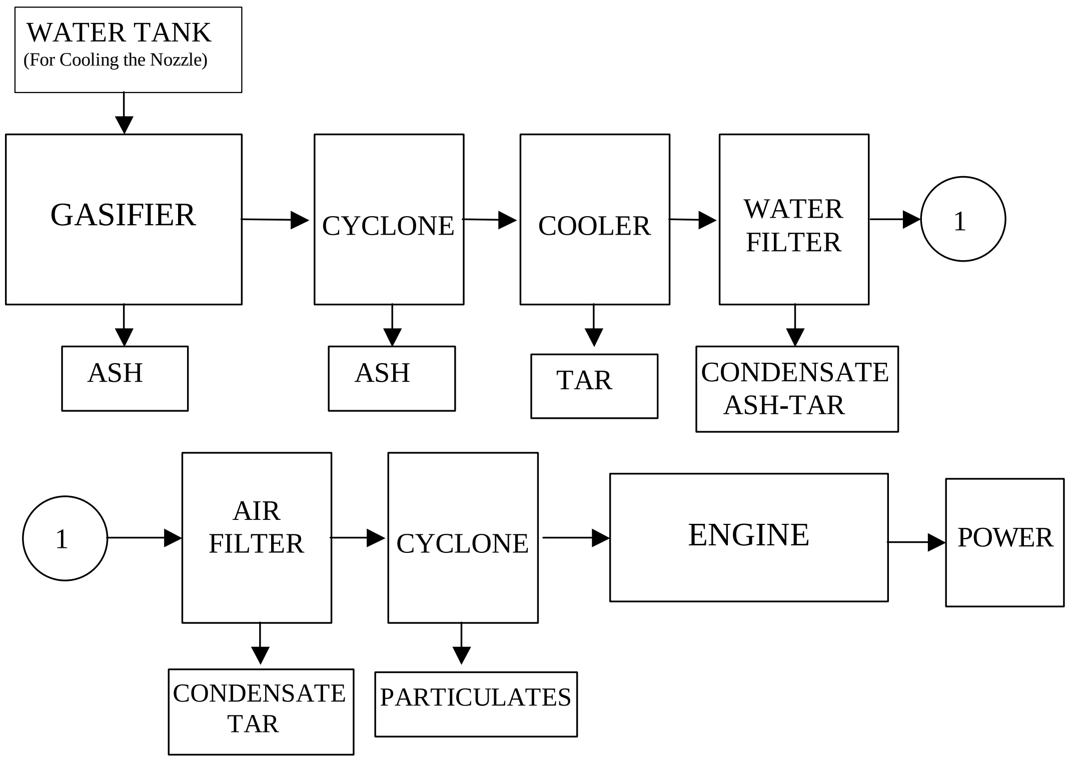

Figure 3: Actual block diagram of the installation

The resulting cleaned and cooled gas is then piped to the engine (figure (3)). The conducting pipe has a hand-adjustable butterfly valve, which allows control of the gas flow. One meter before the engine manifolds the gas is joined in a "T" junction to the air inlet. The gas to air ratio is varied by throttling with another hand-adjustable butterfly valve located in the air line.

For load control and measurement, the engine was shaft coupled to a hydraulic dynamometer. The dynamometer has an accurate torque measuring apparatus, consisting of a balance arm, to which weights and a spring balance are coupled. The engine speed is measured using a photo contact tachometer.

4. Experimental-Calculation Results

During the experimental measurements[11] the internal combustion engine used was started following the normal procedure running on 100% diesel fuel and with no load. Once the engine is operating smoothly, air is drawn through the gasifier. With the engine drawing air through the gasifier the charcoal is ignited using small-lighted charcoal particles, which are deposited into the reactor through the air inlet. After a period of less than five minutes the engine is running in dual mode.

An initial set of trials was conducted to establish the performance of the engine when running only on diesel fuel. The fuel consumption is measured by recording the time spent for the engine to use a known volume of fuel. This operation was carried out at 900, 1200 and 1400 rpm. These experimental data provide a baseline for the comparison of engine performance when running on dual-fuel (gas-diesel) mode.

The second set of experiments repeat the previous procedure using the gasifier, with the engine running on dual-fuel mode. During this set of measurements, remarkable reduction in diesel used by the system was encountered. In order to estimate the charcoal consumption for every operating point of the engine the following procedure was utilized. After loading the gasifier with a known weight of

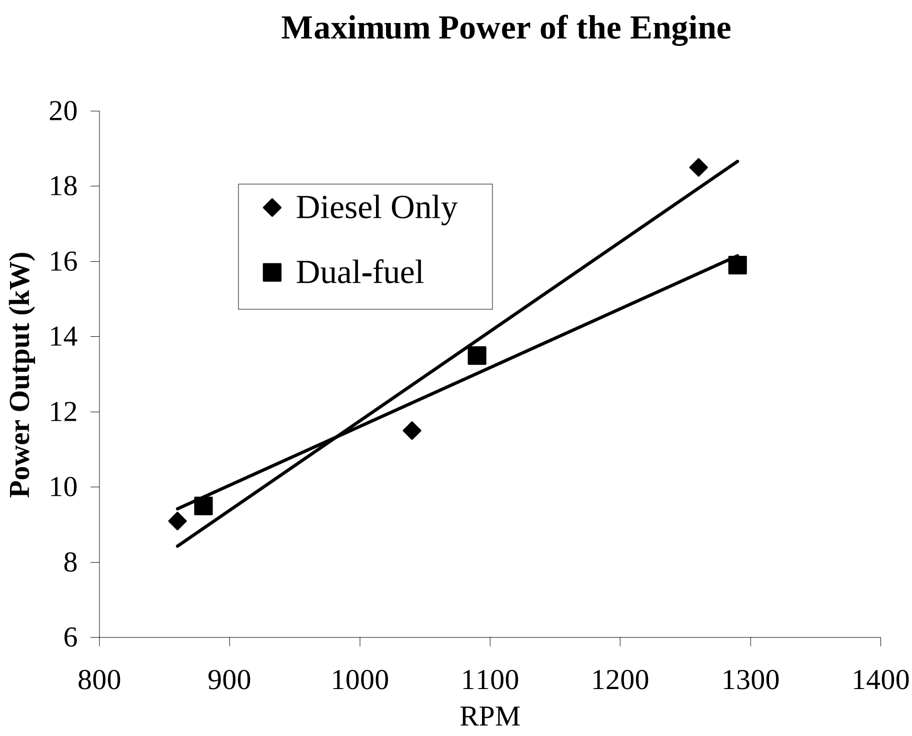

Figure 4: Maximum Power Output of the System

charcoal (between 30 and 40 kg), the engine was started with diesel only at the set up speed (i.e., 900 or 1400 rpm) and without load. The gasifier was ignited ten minutes later and the load was gradually increased until the set up load was reached. The engine was always halted before the charcoal charge was totally burnt. This residual charcoal was removed and weighed the next day.

Analyzing the experimental measurements, one may conclude that for all engine speeds tested no significant power loss occurred between the diesel only and the dual-fuel mode of operation (figure (4)). The overall efficiency of the engine is approximately 30%, while the lowest recorded efficiency is 28% and the highest 35%.

During the dual-fuel operation the total efficiency "η_{tot}" of the system, defined as:

$$\eta_{tot} = \frac{N_{ex}}{m_d \cdot Hu_d + m_g \cdot Hu_g} \qquad (1)$$

decreased remarkably in comparison to the diesel only operation mode. However, the diesel quantity needed to run the system is only 15% of the initial consumption. All the other energy used results by the charcoal gasification. In equation (1) N_{ex} is the output power, m_d and m_g are the diesel and the gas mass flow rate, respectively, and Hu_d and Hu_g are the corresponding specific calorific values of the fuels used. Taking into account the gasification efficiency "η_{gas}" expressed as:

$$\eta_{gas} = \frac{m_g \cdot Hu_g}{m_{biom} \cdot Hu_{biom}} \qquad (2)$$

with m_{biom} and Hu_{biom} the mass flow rate and the specific calorific value of biomass feedstock, it is possible to estimate the diesel consumption by the following relation:

$$m_d = \frac{N_{ex}}{\eta_{tot} \cdot Hu_d} - \eta_{gas} \cdot m_{biom} \cdot \frac{Hu_{biom}}{Hu_d} \quad (3)$$

Finally, the specific fuel mass consumption "sfc" is given as:

$$sfc \equiv \frac{m_d}{N_{ex}} = \frac{1}{\eta_{tot} \cdot Hu_d} - \eta_{gas} \cdot \left(\frac{m_{biom}}{N_{ex}}\right) \cdot \frac{Hu_{biom}}{Hu_d} \quad (4)$$

Using a similar analysis for the diesel only operation mode, the corresponding specific fuel consumption sfc^* can be estimated as:

$$sfc^* \equiv \frac{m_d^*}{N_{ex}} = \frac{1}{\eta_d \cdot Hu_d} \quad (5)$$

with η_d the diesel engine efficiency. Subtracting equation (4) from (5) one may calculate the diesel saving "δsfc" for a given exit power of the system N_{ex} as:

$$\delta sfc = \frac{1}{Hu_d}\left(\frac{\eta_{tot} - \eta_d}{\eta_{tot} \cdot \eta_d}\right) + \eta_{gas} \cdot \left(\frac{m_{biom}}{N_{ex}}\right) \cdot \frac{Hu_{biom}}{Hu_d} \quad (6)$$

According to equation (6) diesel consumption decreases as the efficiency of the gasifier and the feedstock biomass specific calorific value is increased and also depends on the difference between the total efficiency of the system and the efficiency of the diesel engine. Here we also note that during this experimental analysis the gasifier efficiency takes values in the range of 60%.

Applying the above-described analysis on the experimental data, it is interesting to schematically present the specific fuel consumption for the two operation modes of the system (figures (5) and (6)). As it is obvious from the experimental and calculation results an almost 60% diesel saving is encountered for all the operating points of the system. More precisely, near the minimum consumption region of the operation map, the diesel saving is more than 85% (figure (6)).

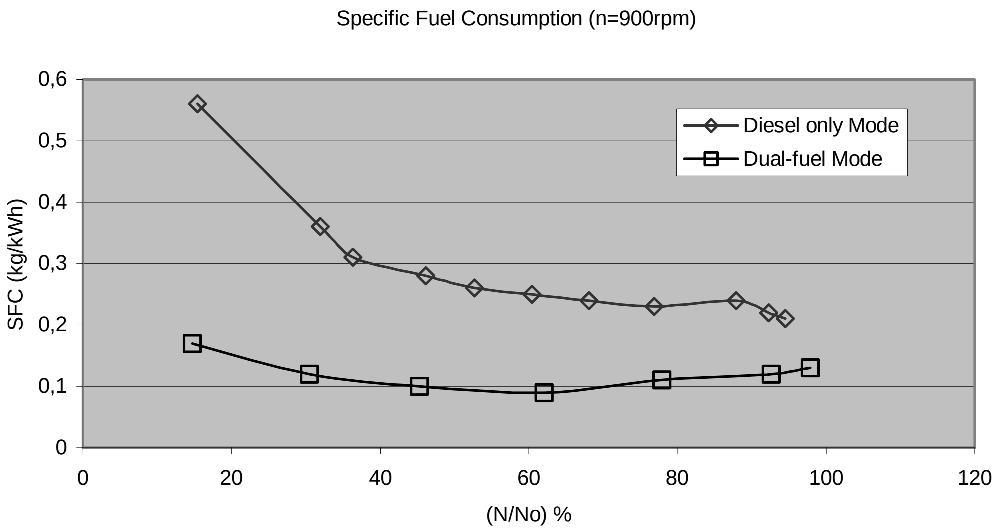

Figure 5: Experimental Values of sfc at 900 rpm

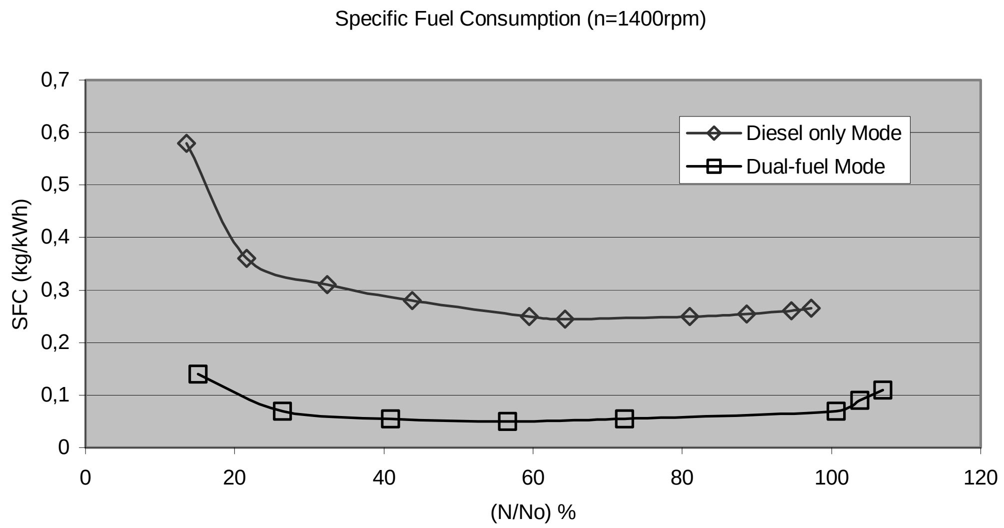

Figure 6: Experimental Values of sfc at 1400rpm

Summarizing, the carried out analysis indicates that during the gasification process the charcoal supplied a minimum of 70% and a maximum of 90% of the total energy used by the system, while the overall efficiency of the system reaches values up to 21%. The gasification process has better efficiency at high load of engine, since in these cases the combustion chamber temperature is higher, improving the conversion of solid feedstock to fuel gas. This is anticipated to be of greater significance in small (autonomous) gasification systems, having higher heat losses, while this will weaken in larger (central) systems, mainly due to their gasifier geometry.

5. Environmental Benefits

The destruction of the environment by the flue gases from fossil fuels is an immediate and imminent threat to the life conditions of the contemporary societies. The harm already done cannot be easily restored, although continued destruction can be prevented by the use of suitable energy production technologies.

In the existing Greek energy production frame, diesel oil is assumed "guilty"[12][13] for the 20% of the

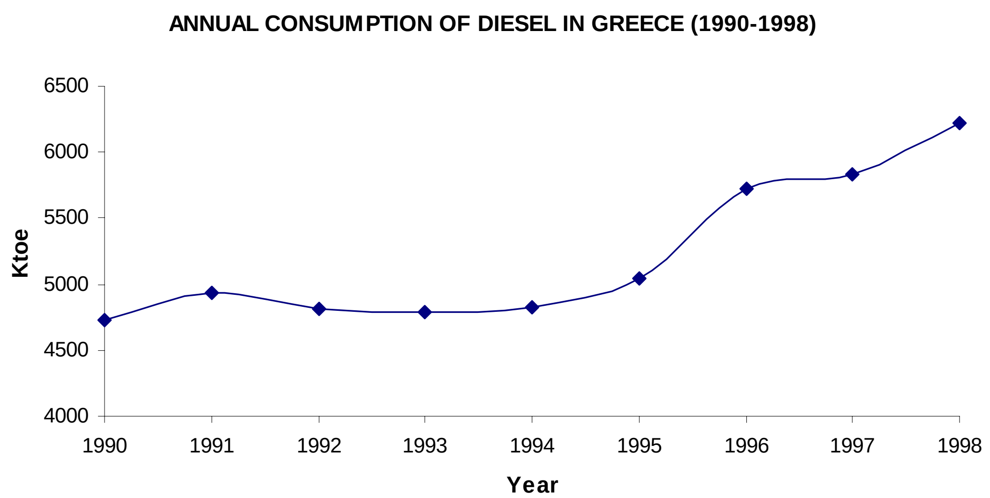

Figure 7: Time Evolution of Diesel Consumption in Greek Energy Market

local annual NO_x production, while every year more than 40,000 tn of SO_x and 35,000 tn of CO are attributed to the diesel oil consumption. On top of that, every toe of diesel is responsible for almost 32,000 kg of CO_2 and a remarkable quantity of C_xH_y (not accurately quantified up to now) emitted in the air. Additionally, the diesel consumption has been significantly increasing (almost by 40%) during the last ten years (figure (7)), since the Greek society is not seriously taking into account the corresponding air pollution increase encountered at the same period.

More precisely, the nitrogen oxides NO_x are the results of the reaction between nitrogen and oxygen in very high temperatures, existing inside the combustion chambers of cars, industries and central heating systems. Although NO is not a real pollutant on its own, it is easily transformed to NO_2, which is very toxic and has a very annoying and characteristic smell.

Accordingly, the SO_2 is produced when the sulphur -existing in diesel- is burned. The SO_2 is one of the most common air pollutants of the urban areas and one of the main ingredients of the smog appearing in many cities. The SO_2 has no colour but it has a very characteristic smell. In combination to humidity it is finally transformed to sulphuric acid, which is one of the strongest acids and primary responsible for the acid rain.

The CO is mainly produced by the internal combustion engines and it is the result of the incomplete reaction between carbon and oxygen. This gas cannot be easily detected, due to the lack of colour and smell, however, it is a very toxic and poisonous one. Finally, the CO_2 is produced whenever carbon burns completely. The CO_2 is not toxic, however, the presence of large quantities of CO_2 in a closed area may cause asphyxia. On the other hand, the carbon dioxide is the main suspect of the greenhouse effect.

Using the experimental and calculation results summarized in (figures (5) and (6)), one may conclude that for every kWh of energy produced, by adopting the dual-fuel mode instead of the diesel only operation, 0.15 to 0.2 kg of diesel oil are saved. This amount of diesel is replaced by raw biomass, which is up to now destroyed by free combustion. Taking also into account[12][13] that for every kg of diesel used by the local energy production market there are emitted 3200 gr CO_2, 65 gr CO, 15 gr NO_x and 9 grSO_2, one can easily assert that the replacement of diesel by the product of the gasification process proposed here may decrease the air pollutants by 700 gr CO_2, 13 gr CO, 3 gr NO_x and 2 gr SO_2 per kWh produced by the internal combustion engine of the system.

6. Conclusions and Proposals

The proposed work investigates both experimentally and theoretically, the operational behavior of a prototype charcoal "dual fuel" gasification device, presenting also the environmental benefits of the system, in cases of energy production by replacing the diesel fuel with the gaseous output of the gasification process. Keep in mind that the gasification procedure examined here converts raw biomass -charcoal with a particle size between 10mm and 25mm- into combustible gas, with energy content within the region of 60-70 % of the original biomass feedstock.

According to the preliminary results obtained, the utilization of charcoal substitutes a minimum of 70% and a maximum of 90% of the total diesel consumption of the installation, leading to remarkable diminution of the corresponding air pollutants as well as zero emission of sulphur oxides and heavy metals. By applying the proposed device in the local agriculture sector, more than 300,000 tn of CO_2 and 1000 tn of SO_2 are annually prevented, supporting Greece to meet the E.U. targets and to ameliorate the living quality level of the Greek citizens. In the near future, further work will be carried out to improve the gasification efficiency and ameliorate the economic behavior of the complete system.

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PART FOUR

ENVIRONMENTAL IMPACTS

- Visual Impact
- Social Impact
- Risk Analysis

RENEWABLE ENERGY SOURCES VERSUS NUCLEAR POWER PLANTS FACE THE URGENT ELECTRICITY DEMAND OF AEGEAN SEA REGION

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Abstract

East Mediterranean European countries present remarkable energy consumption amplification, related to the significant annual GNP increase, during the last years. In the present work the capability of available renewable energy sources versus nuclear power stations to fulfil the forthcoming electricity demand of local societies is examined, on an integrated techno-economic basis, social-environmental cost included. It is important to mention that the development choices of each country will strongly affect the future of the whole area.

Keywords: Renewable Energy Sources; Nuclear Power; Techno-Economic Analysis; Social-Environmental Cost

1. Introduction

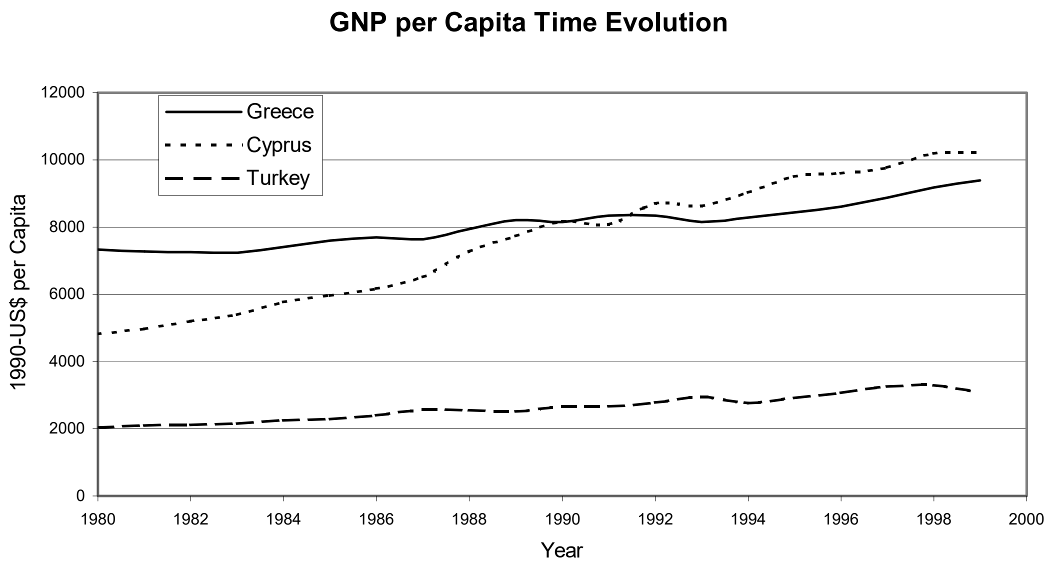

Figure 1: GNP Time Evolution for European East Mediterranean Countries

East Mediterranean countries like Cyprus, Greece and Turkey -being full or connected members to European Union- have presented a remarkable annual Gross Natural Product (GNP) increase through the last years, figure (1). This development effort is strongly depended on the existence of low-cost and sufficient energy, being among the major parameters determining the success of such a process. In order to face this increased energy consumption, the above-mentioned countries are almost exclusively based on the usage of fossil fuels, mainly imported oil and natural gas[1].

More precisely, energy consumption in Greece has significantly been increased, figure (2), during the last two decades, approaching the 32000ktoe in 2000. Similar evolution is valid for Cyprus and Turkey as well. At the same time, an electricity consumption increase in the range of 4% per annum (figure (3)) has also been encountered for Greece, while the corresponding values are 8.2% for

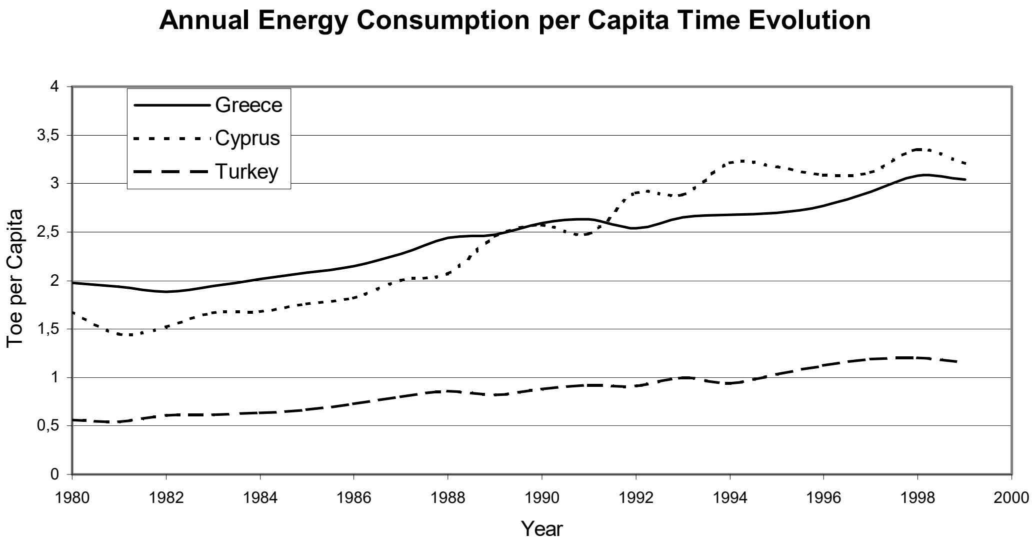

Figure 2: Specific Energy Consumption Time Evolution for European East Mediterranean Countries

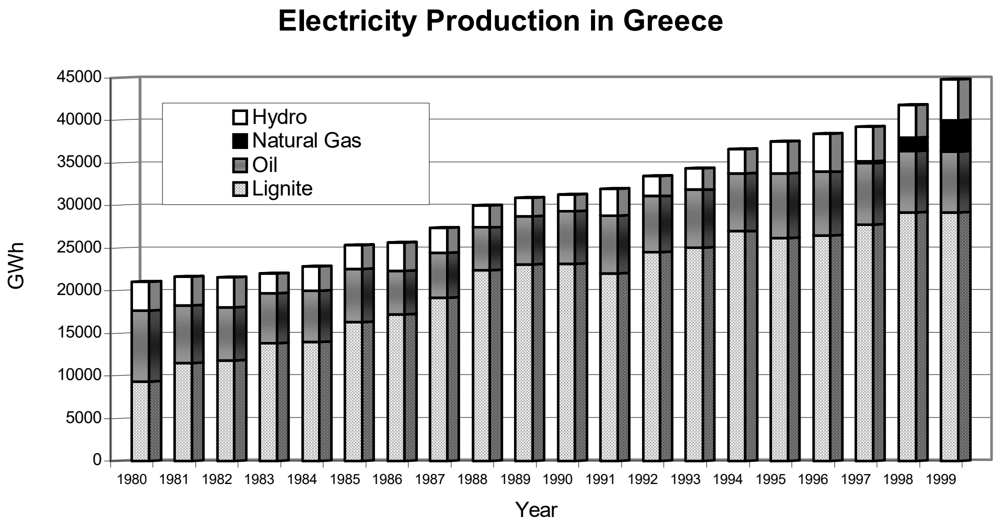

Figure 3: Time-Evolution of Electricity Production Profile in Greece

Cyprus and 10% for Turkey. For this purpose, the establishment of new electricity production plants is characterized as an extremely urgent problem[2], so as to protect the local economy of undesired electricity shortage and guard the corresponding electrical networks from several impediments, like voltage and frequency instability.

It is interesting at this point to mention that -in several cases- the attempt to erect new energy production facilities have caused serious local opposition[3], finally canceling the complete project. However, in view of this unquestionable need for additional electricity production, local societies are now obliged to decide on the power stations type with the purpose of fulfilling the urgent electricity requirements. In view of this decision, one should also consider the international effort to limit the Greenhouse gases emissions and the expected fossil fuel reserves depletion in the years to come. In this context the following question should be properly answered: "Should the new erected electricity production stations be based on renewable energy applications or on nuclear power plants?" Hence,

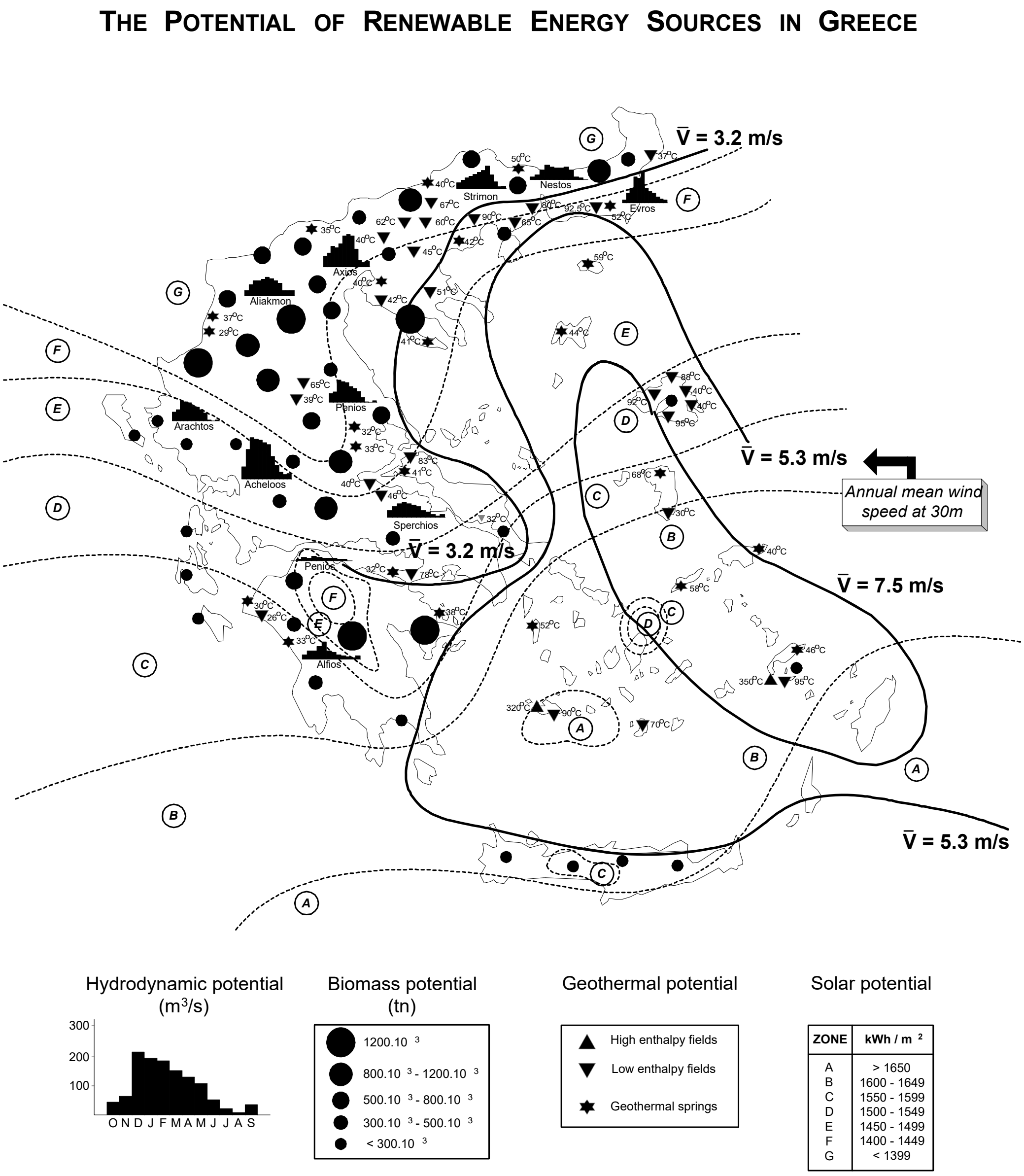

Figure 4: Estimation of RES potential in Greece

the residual paper is devoted to obtain a reasonable reply to the above question, taking also into account the peculiarities of Aegean Sea Region.

2. Renewable Energy Sources Possibilities in Aegean Sea Region

Wind energy, solar energy, hydropower, even biomass and geothermal energy, are no longer alternative sources of energy. Production of wind or hydro-generated electricity significantly contributes to the worldwide electricity demand. At the same time, solar collectors, bioreactors and low enthalpy geothermic fields supply a large number of consumers with hot water. In addition, the application of RES (**R**enewable **E**nergy **S**ources) is a viable solution to the environmental deterioration and energy resource preservation[4]. Especially in our country, the exploitation of the excellent wind and solar potential (figure (4)) is expected to considerably contribute to reducing energy imports dependence and minimising the implicit costs of conventional energy systems.

To be more precise, Aegean Sea region is a geographical area with abundant and reliable solar energy supply, even during winter, while it also possesses excellent wind potential, since in several locations the annual mean wind speed approaches 10m/s, at 30m height. Besides, in some islands there exist

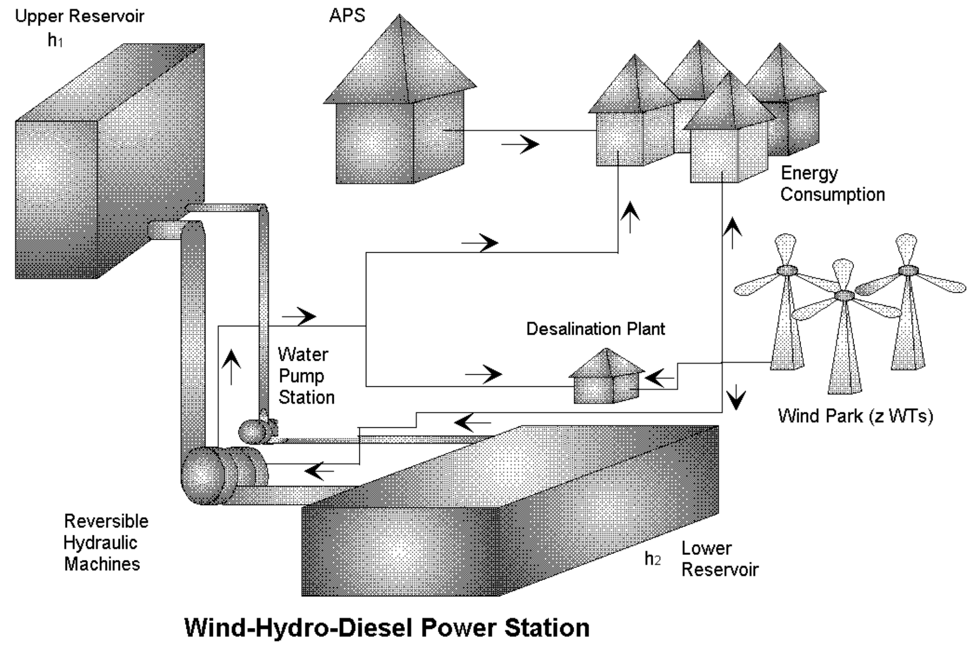

Figure 5: Combined Wind-Hydro Solution for Aegean Sea Islands

remarkable high or medium-high enthalpy geothermal reserves, figure (4), able to provide several hundred of electrical MWs.

The main problem connected to the extensive utilization of wind energy for electricity production is due to the fluctuations of daily and seasonal electricity demand in almost all island grids[5]. This aspect results in a substantial wind-parks-size restriction, as the local grid stability should be maintained. Additional barriers against the wind energy penetration in these autonomous grids also derive from the stochastic availability of the wind speed, leading to important disharmony between the wind energy production and the electricity demand. To face the above-described problem, the possibility of creating a combined Wind-Hydro energy station is extensively investigated[6][7] on a techno-economic basis, figure (5). According to the conclusions obtained[7][8], the proposed solution is the most fundamental method to cover the local electricity demand for the majority of the Aegean Archipelago islands, with rational installation, maintenance and operation cost, minimizing thus the dependence of the Greek economy on imported fuel.

Similarly, in small-sized islands cases, the prospect of creating a combined wind-solar electrical power station is investigated with encouraging results[9], so as to minimize these areas' dependence on the local thermal power stations, keeping an acceptable investment cost. The proposed system might use either a battery row -as an energy storage device[10]- or the existing outdated internal combustion engines as back up systems.

Finally, the existing high-enthalpy geothermal fields can be exploited, once the significant electricity production amount is absorbed by the local market and the native negative reaction is mitigated.

Thus far, unfortunately, the contribution of RES applications in the annual electricity demand coverage is rather poor, as less than 150MW of wind power have been installed all over Aegean Archipelago; their vast majority mainly located in two regions: East Crete and S. Euboea. Similarly, the corresponding photovoltaic electrical power is less than 1MW, while the sole geothermic-electrical station of 2MW in Milos Island has been out of order since 1989.

Despite this pessimistic situation, it is widely accepted that -by applying RES based hybrid stations- the electricity production opportunities will grow to be boundless, giving the capability of not only covering the local energy requirements but also transferring electrical energy to the mainland, in case the required grid connection be integrated.

To be objective, apart from the remarkable prospects of RES utilization, some remarkable drawbacks also subsist[11], being responsible for their yet modest penetration to the local energy balance, i.e.:

- Low energy density available (W/m^2) leading to large dimensions (land use) in order to obtain the energy amount required
- Irregularity (stochastic behaviour) of wind and periodical availability of solar radiation impose significantly sized energy storage devices
- Power quality instability, mainly due to the random variation of wind speed
- Limited capability of available potential exploitation (e.g. 45% maximum value for wind, 15% for solar and 12% for geothermic fluid of 300°C).
- The relatively high initial investment cost, especially for photovoltaic panels

On the other side, the available RES utilization presents significant benefits, like:

- Independence of fossil fuel imports (exchange savings) and their market price continuous fluctuation (better production cost programming)
- Absorption of significant E.U. subsidization (up to 50%), remarkably deteriorating the first installation cost
- Zero air-pollutants emissions
- Limited environmental impacts
- Unaffected by high earthquake frequency
- Practically zero technology dependency
- Embedded (decentralization) generation, contributing to distribution system reinforcement

3. Nuclear Power Opportunities in Aegean Sea Region

Nuclear power plants are almost exclusively based on nuclear fission of uranium-235 and plutonium-239, an artificial splitting of an atom into two or more parts. When such an occurrence takes place a very large amount of heat is released, which is gradually converted into electricity (35-40%) and heat waste to the environment (60-65%)[12]. Although there are many different types of fission reactor designs, their basic mechanism is similar. The majority of reactors in operation today are either "boiling water" or "pressurized water" reactors, using either normal or heavy water to both cool and moderate the fission reaction. Gas-cooled reactors and "breeder" reactors are newer reactor designs, which are not yet as widespread as the earlier generation of reactors.

Past in the time, nuclear reactors were envisioned (early 60s) as a clean and cheap source of electricity, capable of meeting vastly increased demand in the future. At the present time, about 420 nuclear reactors are connected[13] to the world electricity networks (343GW(e) of nuclear capacity are actually in use), supplying 15% of the corresponding electricity demand. Additionally, only 20 nuclear reactors remain under active construction, while each year, a growing number of aging reactors are retired.

The vast majority (90%) of these reactors is located in the industrialized countries of the world (e.g. USA, France, Germany), mainly due to the relatively high initial investments and the technological infrastructure needed. However, during the last years the nuclear construction in Western Europe (excluding France) was completely ceased. Sweden completed its last plant in 1985, Spain in 1988, Germany in 1989 and Great Britain in 1995. Besides, the last U.S.A. plant in Tennessee was completed in February 1999 and the last Canadian plant was finished a year earlier. On top of that, European countries -like Sweden and Germany- have passed laws calling for the phasing out of nuclear power before 2020. The general conclusion drawn is that in most industrialized countries the nuclear plans are either decelerated or completely abandoned, although several manufacturers desperately try to sell their technology in the developing world.

The increasing cost of nuclear power plant construction is a common explanation why nuclear energy has not lived up to its potential[14]; however the main reason is safety concerns. Nuclear power plant major accidents -such as those at Three Mile Island in Pennsylvania and Chernobyl in the former U.S.S.R.- have drastically increased public opposition to nuclear power applications. More specifically, despite normal expectations, nuclear costs have grown rather than shrunk, as the technology used "matured", mainly as a consequence of higher levels of safety and reliability achievements. On top of that, no nuclear power plants have been ordered in U.S.A. since Three Mile Island episode, while in Europe no new plants have been scheduled since Chernobyl.

Additionally, there has not yet been any approved method of permanently disposing[15] radioactive waste; thus they are usually piled up in temporary holding tanks. Keep in mind that some of the radioactive waste produced by fission reactors -being a potential source of the material required for the production of nuclear weapons- will remain highly radioactive for thousand of years. For example, nearly 40 years after the first U.S.A. nuclear plant went into operation in Pennsylvania, the USA government reveals that it will take at least another decade before permanent waste disposal may begin. As a consequence, some utilities are already making plans of turning today's nuclear reactors into aboveground waste sites.

Finally, the dark underside of nuclear power has always been its potential for nuclear weapons proliferation, either through the production of plutonium or through the transfer of sensitive nuclear information, technology and materials. Hence, in several developing countries the existing political-military regimes treat nuclear power applications as an easy way to obtain nuclear weapons technology via the uncontrolled proliferation of fissile materials.

Recapitulating, the main advantages of nuclear power utilization include:

- Cost-effective energy production, especially for modern plants
- Zero air-pollutants emissions
- Relatively low operational cost
- Limited land use for the single power station installation (uranium mining and processing not included)
- Reliable electricity supply for the entire year

On the other hand, the main points of nuclear power applications disapproval are:

- Only huge reactors are really cheap
- High first installation cost (financing constraints), since nuclear power constructions are capital intensive
- No safe method of permanent disposing radioactive byproducts
- Wide-range (transboundary) negative consequences in case of major accidents
- Enormous heat waste to the nearby environment (almost twice the electrical output)
- Technology dependence of developing countries

4. Comparison of Two Alternatives on Economic Basis

For the techno-economic evaluation of the above described energy production alternatives, an integrated cost-benefit analysis model by authors[16][17] is going to be applied, excluding for simplicity reasons the time dependency of the main problem parameters[18]. More specifically, the present value of the energy production cost "c_o" of any electrical power station after –n years of operation is a combination of the first installation cost "IC_o" (subtracting any State subsidy "δI") along with the corresponding maintenance and operation cost "FC_n", both quantities expressed in current values, thus:

$$c_o = \frac{(IC_o - \delta I) + FC_n}{E_o \cdot \frac{1+e}{1+i} \cdot \left[\frac{\left(\frac{1+e}{1+i}\right)^n - 1}{\left(\frac{1+e}{1+i}\right) - 1} \right]} \tag{1}$$

where:

$$FC_n = m \cdot IC_o \cdot \left(\frac{1+g_\Sigma}{1+i}\right) \cdot \left[\frac{\left(\frac{1+g_\Sigma}{1+i}\right)^n - 1}{\left(\frac{1+g_\Sigma}{1+i}\right) - 1} \right] \tag{2}$$

and "E_o" is the net annual energy production of the system under examination. Bear in mind that the annual energy yield is given as:

$$E_o = CF \cdot N_o \cdot 8760 \quad (kWh / year) \tag{3}$$

where "CF" is the capacity factor of the installation and "N_o" the nominal power of the station.

According to equation (2) the maintenance and operation cost is expressed[16] as a function "m" of the initial cost, while an annual increase of the cost is also taken into account via the M&O cost mean annual inflation rate "g_Σ". Finally, "i" is the mean capital cost of the economy and "e" is the mean annual rate of change of energy production market price.

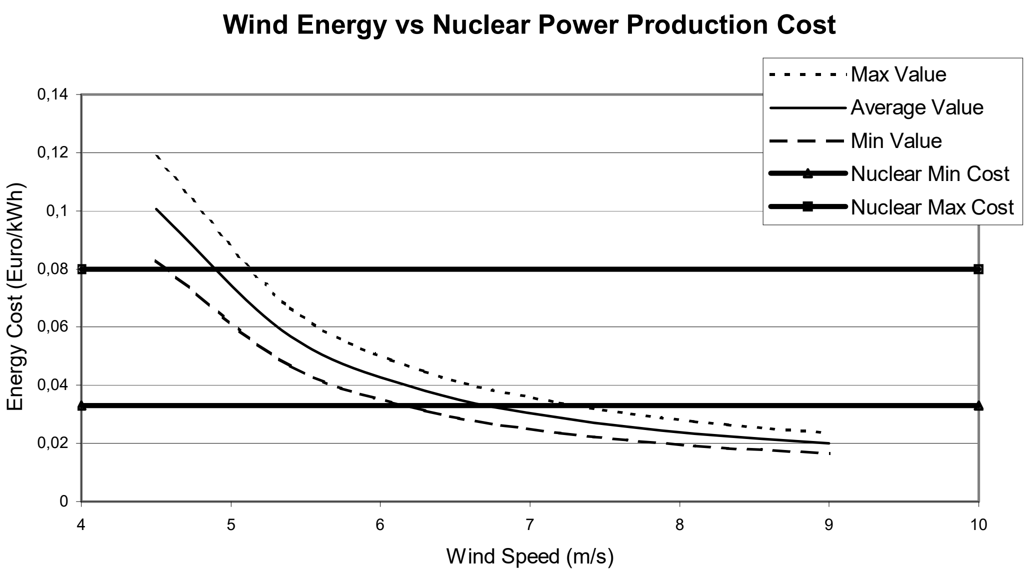

Figure 6: Energy Production Cost Comparison between Nuclear and Wind Power

Applying the above described analysis on a wind-farm installation with variable wind speed at hub height, properly operating for twenty years, taking also into account the typical values[19] of the primary cost prediction parameters, Table I, the calculation results are summarized in figure (6). Note that -for comparison purposes- the inflation free capital cost is taken equal to 5%, while "g_Σ" and "e" are assumed zero. It is important at this point to repeat that the wind farm capacity factor is strongly depended on the available wind potential (i.e. yearly average wind speed value)[20].

Table I: Energy Production Cost Parameters Proposed Numerical Values

Energy Source	First Installation Cost (Euro/kW)	M&O Cost (Euro/MWh)	Fuel Cost (Euro/MWh)	Capacity Factor (%)
Nuclear Power	1200-2000	8-10	7-9	90
Wind Energy	700-1000	6-15	0.0	20-40

In the same figure (6) the nuclear power station energy production cost range is also sited. As it is obvious from this figure, at wind speeds over 5.5m/s wind energy falls within the price range of nuclear power. On top of that, for wind speed values of the order of 6.5-7.5m/s the wind energy is the cheapest option for electricity production. For a more realistic energy production cost picture, a closer look needs to be taken in each particular situation, since nuclear energy cost varies also with plant size and location.

Recapitulating, one may conclude that despite the low "CF" values realized by wind power stations, the competitiveness of wind energy versus nuclear power is well established, on a pure techno-economic basis. In the following, the main social-environmental impacts of both technologies under investigation are also examined.

5. Social-Environmental Impacts of RES & Nuclear Power Applications

Fission reactors are extremely complicated devices, thus they need adequate organization, as well as industrial, staffing and technological infrastructure, in order to properly operate. The effects of nuclear reactors can be divided into those occurring from an accident and those, which are a result of the normal operation.

Hence, with any nuclear reactor, there is a diminutive possibility of a random malfunction, which could cause the chain reaction in the core to run out of control, resulting in very high temperatures and a core "meltdown". Meltdowns that breach reactor containment vessels could potentially release huge amounts of radiation into surrounding environment, as seen by the accident at Chernobyl in 1986. Following a major accident, along with the initial radiation exposure, the land and water covering a large area around an accident site could become contaminated, and unfit to human habitation for thousand of years. Human or animal exposure to high levels of radiation can result in death, cancer or birth defects in future generations. Additionally, transported by the environmental media (air and water), the different fission products may have negative effects on flora, fauna and mankind in relatively long distances from the accident location. Finally, according to numerous studies[21][22], the probability of a major nuclear accident is in the range of 2000 to 20000 operational years (each year is set equal to 6000 hours at nominal load). The Chernobyl accident happened after 3000 operation years of nuclear power plants worldwide or equivalently the corresponding electricity production per major accident is 15000 to 150000 TWh.

Subsequently, the normal operation of a nuclear power plant also results in the release of small amounts of radiation into the environment. Bear in mind that radioactivity from nuclear electricity generation is not only released from nuclear power plants, but also from other processes of the nuclear fuel cycle. Besides power plants, the main elements of the nuclear fuel cycle are uranium exploration, mining, uranium enrichment, fuel element production, reprocessing of used fuel elements and final deposition of radioactive waste. The major problem at this level is the inability to safely dispose nuclear waste along with the continuous danger of the uncontrolled proliferation of fissile materials. Another serious problem for the ascription of damages resulting from radioactivity is the fact that these damages usually occur only after extensive time lags, making impossible to trace the damages back to specific sources of radioactivity.

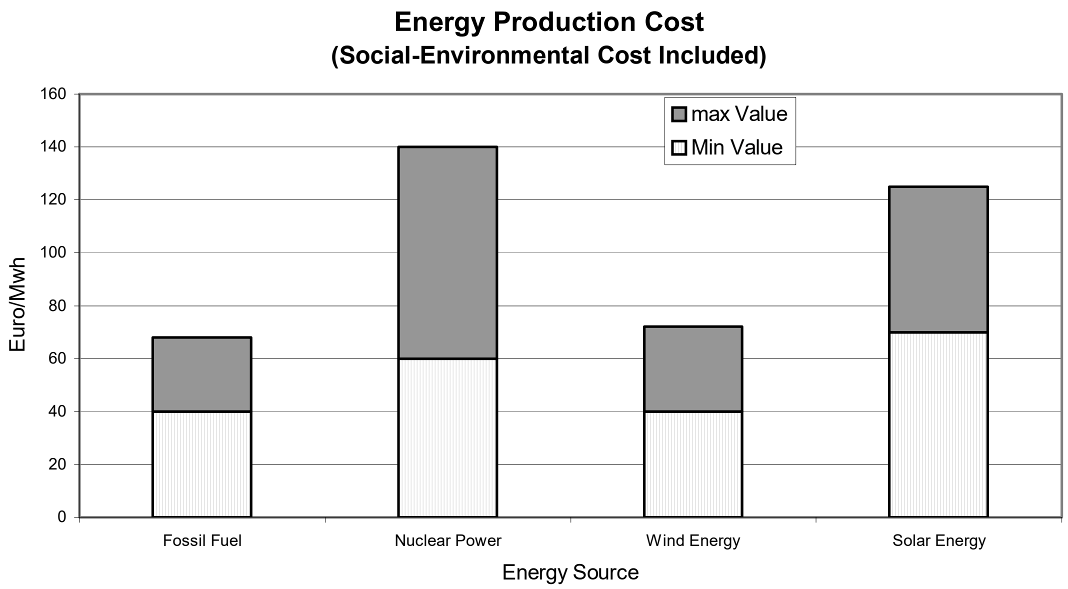

Figure 7: Energy Production Cost Comparison, Social-Environmental Cost Included

On the other side, electricity generated by nuclear power results in almost none of the greenhouse and acid gas emissions associated with fossil fuel power plants. For this reason, supporters of nuclear power have called[14] for a widespread increase in the number of nuclear plants worldwide in order to combat global warming and acid raid impacts. However, it is really important to repeat that the entire RES applications for electricity production is almost completely free from air pollutants emissions, while their energy production installations are not inclined to melt down or produce highly hazardous waste products lasting millions of years.

More precisely, the most important environmental impacts of RES applications[23] are noise emissions, visual impact, extensive land-use and, in special occasions, bird mortality. As it is obvious from this comparison, the major environmental surcharges of RES -if any- are at least two orders of magnitude lower than the corresponding ones of nuclear power[4][24].

In addition to those environmental effects, the energy production power station type adopted creates a sum of general economic effects, like technology dependency, balance of trade and national added value changes, as well as nuclear weapon proliferation risk. Although all these important subjects are beyond the scope of a techno-economical analysis, one cannot easily neglect them, especially because the development choices of each country will strongly affect the future of the whole area, since the consequences of a negative evolution may cross the local frontiers.

Recapitulating, in figure (7) the estimated by the authors[4] market price of electricity production from various alternative solutions is presented, social-environmental cost and benefits included. The results obtained are also validated by several similar studies[24][25], proving that wind and solar energy production stations do have a competitive advantage in comparison with nuclear power and fossil fuel systems. This conclusion is particularly true especially for the Aegean Sea region, not only due to the high quality available RES potential but also due to the dispread electricity consumption that zeroes any scale economies favoring nuclear reactors.

6. Conclusions

The unquestionable need for extra electrical energy dictates the development of new power plants in all East Mediterranean European countries. In this frame the idea of creating nuclear power stations is seriously examined by some countries of the area, in an attempt to meet the urgent energy requirements of their economies, disregarding that the entire region possesses excellent wind, solar and high enthalpy geothermic potential.

Thus, in the present work, the capability of available renewable energy sources versus nuclear power stations so as to fulfill the electricity demand of local societies is examined, on an integrated techno-economic basis, social-environmental cost included. It is important at this point to mention that the development choices of each country will strongly influence the energy management equilibrium of the region, especially under the strong possibility that these countries should shortly belong to the same Union. According to the results obtained, one may support that by seriously investing on renewable sources energy production plants there is no need neither to increase oil imports nor to introduce outdated nuclear power technology in our region. Hence, the cancellation of the first nuclear power plant building near Akkuyu, on the Mediterranean coast a year ago, was another implicit proof that the role of nuclear power on the twenty-first century energy economy of the area is restricted.

Consequently, it is the author's belief that nuclear reactors, belonging to the "mega" plants category, are gradually out of step with the world of modular power generation -comparable to the shift from mainframes to personal computers- that is now sweeping the power industry. Therefore, the best solution for the urgent electricity demand problem of the area should be based on modular, decentralized power supply generators, such as wind turbines, photovoltaics, fuel cells and not on huge facilities suspected for major nuclear accidents and producing radioactive byproducts lasting for thousands of years.

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RISK IN THE GREEK ELECTRICITY PRODUCTION SECTOR

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Abstract

It is generally accepted that there is an electric energy shortage in our country these days; however, the cases where the establishment of an energy production plant has been rejected and opposed by the local people are remarkable. This paper examines the risk evaluation and communication process in two cases -Atherinolakkos in Crete and Milos island, a conventional electric energy production facility and a geothermal plant- in order firstly, to locate the factors that explain the difficulty in siting electric energy production plants in Greece, and secondly, to look into the influence the use of renewable energy sources has on risk evaluation. The paper concludes with some policy proposals regarding the risk communication process.

Keywords: Risk Evaluation; Electricity Sector; Plant Siting; Policy Proposals

1. Introduction

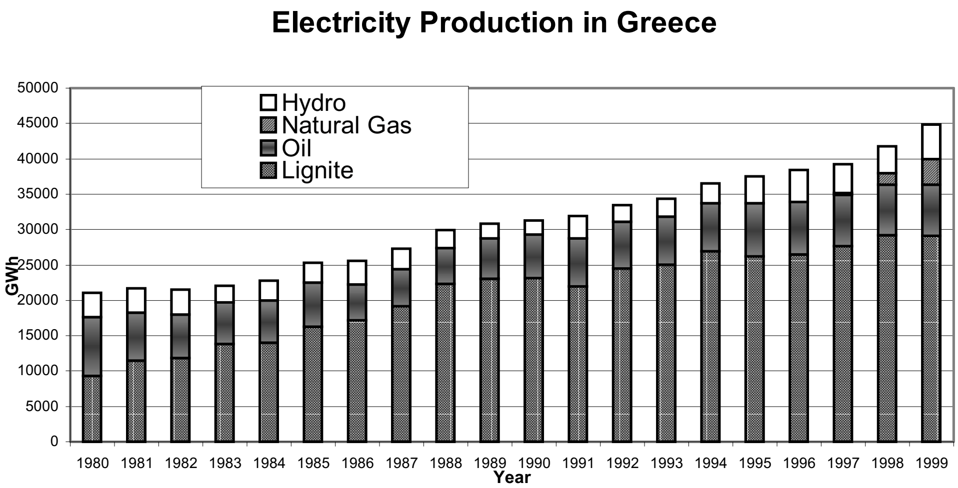

Figure 1: Evolution of electricity production profile in Greece

Energy consumption and demand have significantly increased in Greece in the recent decades approaching the 28,000 ktoe in 2000. In this context, the electricity consumption increase has approximated 4% per annum (see figure (1)), while the maximum (peak) load increase of the mainland electrical grid is much more abrupt (6%), (see figure (2)). For this purpose, the establishment of new electricity production plants is characterized as an extremely urgent problem, in order to protect the national electrical grid from several problems, like voltage and frequency instability or even total black out.

The continuous increase of electrical energy consumption in Greece has so far been primarily covered by either imported oil or locally extracted lignite (figure (2)), thus strongly contributing to

Marouli Chr., Kaldellis J.K., 2001, "Risk in the Greek Electricity Production Sector", 7th International Conference on Environmental Science and Technology, Conference Proceedings, Vol. A, pp.460-469, University of Aegean, Global-NEST, Syros, Greece.

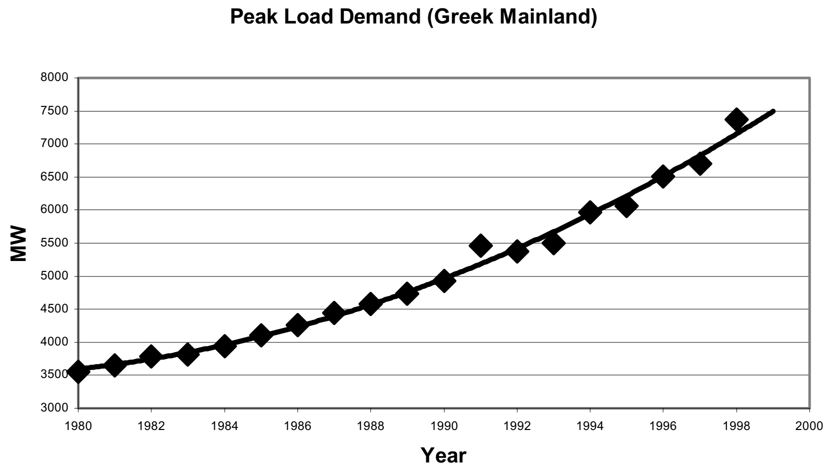

Figure 2: Evolution of Peak Power Demand in Greece

environmental deterioration[1]. The use of renewable energy sources has not been much considered, although often proposed by several authors[2][3].

The problem of inadequate electric energy supply becomes more obvious after the electricity market liberalization in Greece (law 2773/99), becoming effective on 19.02.2001, which ends the PPC monopoly in the local electricity market[4]. From now on, any individual can create a new electricity production plant, based either on fossil or on renewable energy sources, and make the electrical energy available to the market, via the central electrical network. On top of that, the RAE[5] chooses, using international tenders, which companies have the ability to develop their own power stations on the basis of economic criteria.

In view of this unquestionable need for energy in Greece, an important issue for the economic and social development of the country, the Public Power Corporation (PPC) has repeatedly tried to site new energy production facilities, an activity which has often caused serious local opposition, as it involves risk analysis and management. Taking into account the generally up to now negative attitude of the local societies towards the attempts of Greek Public Power Corporation to establish new electricity production plants, it is very interesting to observe the reaction of the same communities in the cases that international private enterprises are going to propose similar projects.

2. Risk Acceptability and Relevant Theoretical Issues

Opposing the establishment of an energy plant at a specific location indicates that the public has judged the risk(s) unacceptable. Risk unacceptability hints to the fact that there are *different definitions of "riskiness*". Experts and lay people use different definitions of risk as several researchers have shown[6]. As Marris et.al.[7] write that, when assessing risk, "experts focus on quantitative assessments of likelihood and consequences, whereas the general public incorporated a number of additional "qualitative" dimensions...". According to the psychometric model which Fischhoff, Slovic and others proposed, the full characterization of risks is multidimensional and involves the qualitative characteristics of the relevant hazards (e.g. natural vs. unnatural, controllable vs. uncontrollable, familiar vs. unfamiliar, etc.), the types of risk exposure (e.g. voluntary vs. involuntary, controllable vs. uncontrollable, equitable vs. inequitable, etc.), and the nature of potential consequences and associated benefits (e.g. minor or major, known vs. unknown, reversible vs. irreversible, equitable vs. inequitable, certain vs. uncertain, etc.)[8].

Several criticisms of the psychometric paradigm have been stated pointing to the significance of the social, cultural and political context, and that of the communication procedures. Marris et.al.[7] write,

> "*risk perceptions may not be so much related to the "personality profiles" of hazards as to the characteristics of the people who perceive the risks, and to notions of trust and accountability in risk management*".

Thus, cultural theories of risk[9] have been developed investigating the *social and cultural aspects* of the risk analysis process. These theories highlight, among other things, that in the evaluation of risks as acceptable or not, issues like the following are significant:

- equitable distribution of risks (who bears the risks?)
- trust and credibility (how trustworthy are the risk information sources? How credible are the data presented?). On this issue, it has been argued that two parameters are important: the trustworthiness of the risk information sources, and the types of information the public asks for[10].
- dependability (how dependable the relevant risk management systems are?)

With such issues at hand (different definitions of risk, quantitative vs. qualitative parameters of risk, trust, etc.), the significance of *risk communication* is evident, as well as the potential - if not expected - *difficulties* in this process.

Some authors[11] have indicated that in the analysis of environmental risks technical jargon may lead to serious misunderstandings, as it is often the case that common words may have taken up a new meaning, different from the one commonly understood.

In addition, there are two technical issues[12] that may lead to misunderstandings and conflicts:

- experts work with data that refer to groups and make predictions about incidence of injury or disease within groups, while the public is often concerned about probabilities of injury for specific individuals. However, there are not adequate data for individuals.
- There are two interpretations of probability:
  - the objectivist interpretation, concerned with the relative frequency of a possible event, and
  - the subjectivist interpretation, concerned with the degree of confidence that an event may occur.

Data for one type of probability does not give (and should not be interpreted as giving) information about the other type. These two technical issues often lead to difficulties in the risk communication between experts and the public, either because of lack of clarity about these nuances, or because of inadequate explanation to the other social actors, or because of inadequate understanding of the existence of different interpretations of facts.

As Keeney[13] and other researchers suggest, disagreements and conflicts in risk evaluation and communication may result from several sources:

- different information (e.g. on different aspects of the risk, or emphasis on specific kind of data). On this issue, it is important to realize that experts and the public use and prefer different sources of information. Webler et.al.[14] indicate that

  > "*It [technical risk analysis] assumes that risk identification, assessment and management can be accomplished by relying only on objectively available scientific information and analyses*." (p.28)

  The public, on the other hand, relies on other kinds of information too, such as social and cultural.
- conflicting information (e.g. conflicting estimates of quantitative risk parameters)
- different evaluations of given information (e.g. different views of the acceptability of an estimated risk).

  Different evaluations indicate different underlying sets of social values and/or different concerns. For example, the instrumental rationality which experts use, perceives risk as an objective measure, independent of the social setting; it ignores that risk contains social parameters as well (like who bears the risks, trust in the risk management process, etc.) On the other hand, cultural rationality, characteristic of the public, relies mostly on social and cultural knowledge and understands risk within a social and value-laden context.

Depending on the source of disagreement, different communication strategies are possible. In any case, conflicts arising from different evaluations cannot be resolved and require a forum, which allows a plurality of viewpoints.

Conflict does not always pre-exist; it is sometimes a reaction to the planning process. As Webler et.al.[14] indicate often the risk communication process is manipulative; it aims to persuade the public that they should accept the risk, rather than being an equal exchange between all actors for the identification and use of the best available knowledge.

At this point it is interesting to mention the "Not in My Back Yard (NIMBY) syndrome", not a new social phenomenon, which has often been associated with the siting of landfills, hazardous waste facilities, nuclear power plants etc. According to specialists[15][16], the NIMBY syndrome refers to the tendency for people's judgments to be based on individual environmental interests rather than being guided by concern for the "public good". As a result of the NIMBY phenomenon, the "production" of a public good may prove impossible, although all individuals may need it. In our case, energy production needs may be difficult to satisfy, as there is often local opposition to their establishment at specific locations. However, as Wolsink[16] indicates, the NIMBY syndrome only explains a limited number of cases; rather, it is often the case that opposition may be generated because of a unacceptable planning process.

Thus, ideally, an effective risk communication process should have the following characteristics:

- it should be a forum for equal exchange among all actors,
- it should not include claims that risk can be reduced to zero, or that trade offs between economic costs and statistical lives are avoidable, or that any course of action is value free, and
- it should be based on the understanding that there are real conceptual differences and different concerns between experts and the public (rather than the belief that the public is irrational). Thus, the concern should be not to "educate" the public, but how to best accommodate different value judgments.

3. Risk Communication in Greece: the Electric Energy Production Sector

With this theoretical knowledge in mind, we can look into what the difficulties have been in the siting of electric energy production plants in Greece. Although in depth research of several cases -for example with possible interviews and/or focus groups- are needed, it is worthwhile and instructive to start looking into the views of the company's experts (the national electric company, PPC), and of the public (for our purposes mainly expressed by the local authorities, although it is not denied that local authorities and local inhabitants do not necessarily coincide in worldviews or interests). We recognize that there are several other views to be considered, e.g. policy makers, as well as possible diversity within the public.

Before we go on in examining the chosen two cases, it is important to realize some special characteristics of the local electrical production socio-political scene.

- In Greece, up to 19.2.2001, there was only one major energy production company -the national electric company, PPC- which is part of the public services domain. Only after the 2244/94 law private investors obtain the opportunity to produce electricity using renewable energy sources *only*.
- In Greece, there is a serious lack of trust in public administration and public services. It is believed that interests guide their actions and policymaking and that rarely do their job right.

With these observations in mind regarding the structure of the energy sector and the political culture of Greece, we can now examine the risk communication process in the siting of energy facilities with the goal to locate potential sources of conflict. We will compare two cases -one of a conventional energy production plant and one using soft/renewable energy sources- in order to see if the use of more environmentally friendly sources makes a difference in the siting process.

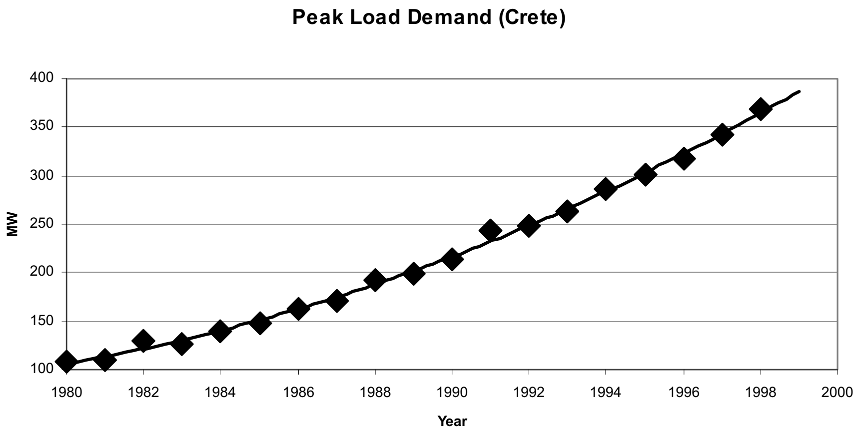

Figure 3: Evolution of Peak Power Demand in Crete

In the discussion of the two cases, we will look for indications of the three potential sources of conflict (different information, conflicting information, different evaluations of the information), as well as of the possibility and the way in which the planning process has contributed to (or even caused) the conflict.

3.1 Case 1: Atherinolakkos in Crete

In the case of Atherinolakkos, the PPC proposed the establishment of a conventional (thermal) energy plant in that location in order to resolve the acute energy problems of Crete, figure (3). Regarding the history of the case, several (13) efforts had been unsuccessfully initiated by the PPC before Atherinolakkos with the aim to locate an energy plant in Crete. In the case studied, the company asked the regional authorities to propose a location, they proposed Atherinolakkos and the PPC accepted it. Then, the PPC communicated with the local populace in order to inform them about the planned plant. There was opposition by local inhabitants; the prefecture asked the expert advice of a local scientific institution, whose opinion was not against the proposed plant. Public opposition continued and was strengthened. The local municipality was involved too. In the meantime, an independent scientist publicized scientific data, which supported the rejection of the plant as proposed, or the need for specific additional safety measures.

Looking into public documents and correspondence between the PPC, the political leadership, scientists, environmental groups (Greenpeace) and the regional and local authorities, we can observe the following for the risk communication process:

i The planning process was such that it could only lead to a "manipulative communication process"[14]. The PPC asked the regional government to propose a site for the establishment of an energy production plant, much needed for Crete; the regional government proposed Atherinolakkos in Lasithi; and the PPC adopted the location as the site for the proposed plant. Then, PPC experts, with the help of selected scientists, communicated with the public. At later stages of the process, the letters and opinions of the local government are treated as nuisances by the company, rather than as chances for communication.

ii The prefecture of Lasithi asked for expert advice from a local scientific institution regarding the proposed plant, indicating that they need and value scientific information for the support of their position. This initiative also indicates the prefecture's mistrust of the presented scientific data.

iii At the local level, the municipality (Municipality Lefkis, 17-3-1999), at a letter addressed to the PPC, expresses

   a. mistrust in the intentions of the PPC, indicating that their choices were based on "the logic of political party interest [loss of votes] and not on long term planning".
   b. concern for the equitable distribution of risks ("we do not accept to bear the greatest part of pollution from the production of energy in Crete…")

c. mistrust for the PPC's environmental impact assessment.
d. concern for the local environment which is characterized as "virgin", and
e. opposition to the planning process which intends to impose solutions on them.

All these indicate that there is a conflict in the evaluations of the given information, with socio - cultural parameters being important in the public's evaluation (such as mistrust in the public services sector (and the company), and concern for the equitable distribution of risks). Furthermore, the risk communication process did not provide a forum for equal exchange of information and opinions among all actors, thus leading not only to failure but also to the aggravation of the conflict between the company's experts and the public.

iv The different actors seemed to have different logics:

a. The PPC used instrumental logic, valuing only scientific facts, seeing risk as "a scientific and technical issue", one that can be managed as long as it is within accepted EU standards. Their arguments are guided by regional, if not national, concerns - e.g. energy availability for Crete, tourism, etc.; local concerns seem to be at least of secondary importance.
b. The local community -as expressed by the municipality- used a cultural rationality, being concerned about the inequitable distribution of environmental risk.
   They also seemed to give a special value to the local environment, indicating that local inhabitants usually have a bond with "their place" which guides their value judgements and often cannot be understood by remote observers.
   Mistrust in the public services and administration seems to have played an important role in this process.
c. The regional government continued to pressure for the establishment of an energy plant in Crete, even after the local opposition, highlighting differences in the stances and criteria of the different levels of government.

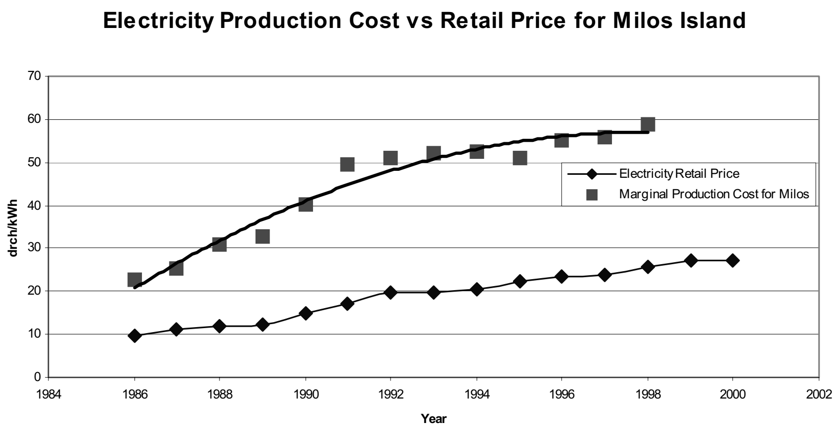

Figure 4: Time Evolution of Electricity Production Cost in Milos Island

3.2 Case 2: Milos Island

Milos is an island with considerable mining activity and a valuable geothermal potential. There was always a significant energy need in the island, while the present peak load demand is over 6000kW. Like the vast majority of the remote Greek islands, the energy production cost in Milos is extremely high (three times the corresponding marginal cost for PPC), due to the aged oil-fired internal combustion engines that are used by the local autonomous thermal power station (see figure (4)) and the difficult fuel transportation, especially during the winter. In the summer, the electricity demand often exceeds the maximum power of the local grid, leading to electrical black outs. To face this serious problem, PPC decided to exploit the existing local high enthalpy geothermal potential, starting with a pilot power station. The pilot operation started in 1987 without a clear agreement between the PPC and the local society about the necessity to build this energy production plant on the island. Although PPC made this pilot station to cover the electricity needs of Milos, soon an extension of the plant was possible in order to contribute to a solution of similar problems in the rest of the central Cyclades islands. Local opposition was aggravated when the PPC started looking into the establishment of a commercial sized power station, which would provide energy to other Cyclades islands nearby.

Looking into people's views[17] and expert documents, we can identify the following points as important in the risk communication process in the case of Milos island:

1. The PPC decided on the establishment of a geothermal energy production plant on Milos, on the basis of scientific studies that showed that the geothermal field of the island was usable for energy production. It did not consult with the local community for it. It simply informed the public about initially the establishment of a pilot operation, and later their intention to establish a commercial plant
2. There was no local opposition to the pilot operation as
   - 2.1 the local community, with its long experience with mining and industrial activities, could understand the technological, economic and social value and problems of the use of the local geothermal field.
   - 2.2 The local community shares the view that it is significant to use the local geothermal energy. They are concerned, however, about the way it should be utilized.
3. Local opposition started at the second stage, the consideration of a commercial geothermal energy production plant. The local community expresses concern about:
   - 3.1 the use of the produced energy for local uses (like mining activities, agriculture, house uses, production of potable water from sea water, etc.)
   - 3.2 the balanced development of the island (balance between mining and other activities).
   - 3.3 the way the negative environmental effects of this plant (of which they had direct experience from the pilot operation) will be addressed.
   - 3.4 the institution which will be responsible for the management and control of the new facility. No matter what the version supported, the local community expects and demands to have a say in the decision-making and management process. This indicates the lack of trust that exists towards public services, or positively, the need of the community to share in the decision making process about a plant that will inevitably affect their life and environment.

From the above discussion, we can suppose that the main reasons of the conflict include:

- the planning process, which was manipulative and aiming to impose on the people a decision the PPC had made without them
- differences in the evaluation of the facts for two reasons:
  - a) local concerns had a special significance for the local community, while the PPC and experts used other national or regional criteria, and
  - b) the interpretation of the facts concerning the negative environmental impacts of the pilot operation might have differed between the public and the experts or the PPC.

4. Similarities and Differences Between the Two Cases

From the two cases discussed above, we can identify the following similarities:

- in both cases, a manipulative risk communication process was adopted. The PPC and their experts at best informed the public about their decision and expected their agreement. In the case of Milos, the given information might have also been inadequate or inappropriate. There was no democratic forum for the local community to share their concerns and special knowledge and to share in the decision making process (something they ask for at the stage of the management of the facility, if it were established)
- in both cases, the public on the one hand and the PPC with the experts on the other employ different sets of criteria:
  - a) the local community uses local criteria (e.g. quality of the local environment in Atherinolakkos; priority in the employment of the energy produced for local uses in the case of Milos)

b) the PPC employs national or regional criteria.
Their worldviews are different.
- in both cases, lack of trust in the public services and administration is expressed. For this reason, they demand that they also participate in the control and/or management of the plant.

The main difference in the two cases seems to be that in the case of Milos, the local community did not initially oppose the establishment of the geothermal energy plant. Actually, it operated as a pilot case for several months. The local opposition started only later, when the plant would become commercial (probably highlighting the significance of local concerns vs. regional and may be national concerns: will the energy needs of Milos be satisfied or will the needs of the Cyclades islands will be addressed sometimes at the expense of the local community?). Possibly, this initial acceptance of the facility in Milos can be attributed to the renewable/soft energy source employed for the production of energy.

5. Conclusions: Policy Lessons for the Greek Energy Sector

In conclusion, from these two cases, we can learn some important policy lessons regarding the best process needed for the establishment of energy production plants (and for other environmental issues, like waste treatment sites) as well as the elements that are important in risk analysis and communication.

1. the risk communication process is very significant and it should be a process which provides a democratic forum for all actors to express their concerns and to share their knowledge on an equal basis. Webler, et.al.[14] wrote:
   " Regardless of the outcome, risk communication must move toward the goal of the ideal speech situation [Habermas' concept, referring to an egalitarian communicative process] not for ideological reasons, but to improve the competence of risk analysis activities." (p.35)
2. The PPC, as a public service and administration, is not trusted by the public. Thus, it should not be the actor who communicates scientific information about the risks related to the proposed facility. Another, more trusted actor, should have this role in the risk communication process.
3. There is indeed a difference in the evaluation of environmental risks between the public on the one hand, and the company and experts on the other. The public emphasizes local concerns and concern for individual (rather than statistical) lives. The experts and the PPC use national or at best regional criteria and scientific, probabilistic data. This difference is real and it cannot be overcome by undervaluing the logic of the public. Neither can it be explained away by the NIMBY syndrome. The local community's logic is equally valid and there should be a place for it in the planning process of new energy facilities. As Webler et.al.[14] indicate,
   "When social, psychological and cultural variables are left out of the risk identification, assessment and management, the results cannot be as competent as if these aspects were included." (p.35)
4. As there is an increased concern for the environment, the use of renewable energy sources might provide a good starting point for possible agreement between the public and the company and experts. Conversely, conventional energy production plants may face increased local opposition in the future as information -accurate or not, complete or not- regarding their environmental impacts is now being widely available.

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THE "NIMBY" SYNDROME IN WIND ENERGY APPLICATION SECTOR

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Abstract

In excess of five years of inactivity, a significant increase of the existing wind power has taken place during the last two years, suddenly pushing the installed wind capacity of our country definitely over 100MW. Unfortunately, almost all new installations are concentrated in two geographical regions, i.e. E. Crete and S. Euboea. In similar cases concerning other European countries, a drastic change of the public attitude towards wind power has been encountered and the Not In My Back Yard (NIMBY) syndrome has appeared. To face such a problem, the impact of these new installations on the local societies is investigated. In this study, data from relative opinion surveys on both sides of Atlantic, along with data collected from our country are analyzed to help any future decision taken in the area of local energy planning.

Keywords: Wind Energy; NIMBY; Public Attitude; Energy Planning

1. Introduction

During the last decade, wind energy has been the fastest growing energy sector for electricity production in various European countries (figure (1)), achieving annual expansion rates in the order of 30%[1]. At the same time, the continuous increase of electrical energy consumption in Greece[2] is so far mainly covered either by imported oil or locally extracted lignite (figure (2)), thus strongly contributing to environmental deterioration[3].

It is interesting to mention at this point that in many Greek regions extremely high wind potential

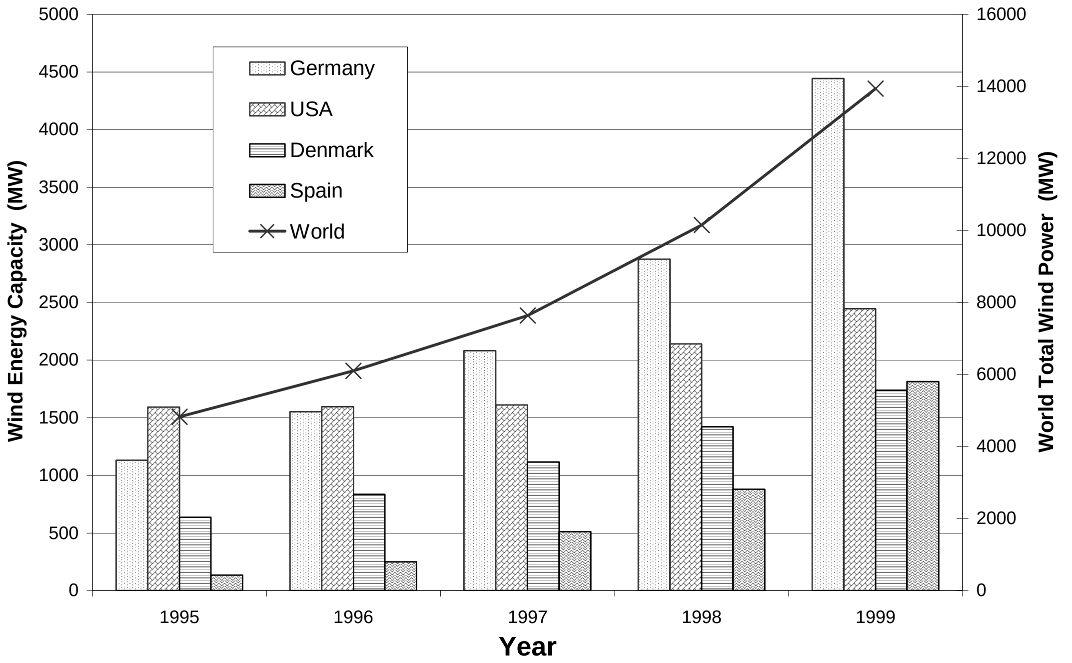

Figure 1: Wind energy installations around the world.

***Kaldellis J. K., 2001**, "The NIMBY Syndrome in the Wind Energy Application Sector", International Conference on "Ecological Protection of the Planet Earth I", Conference Proceedings, Vol. II, pp.719-727, Xanthi, Greece.*

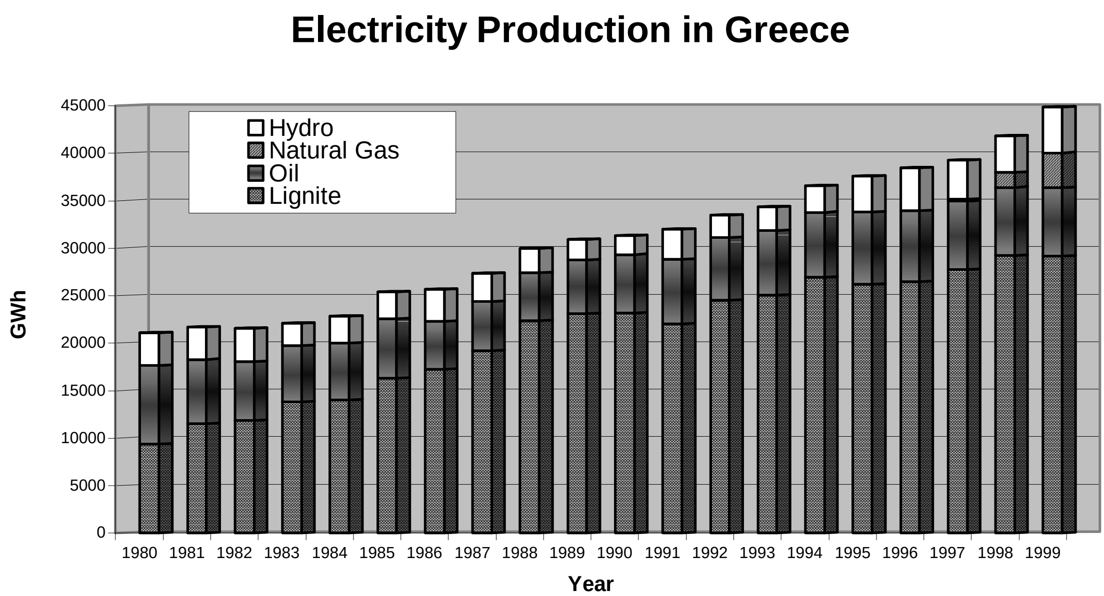

Figure 2: Evolution of electricity production profile in Greece.

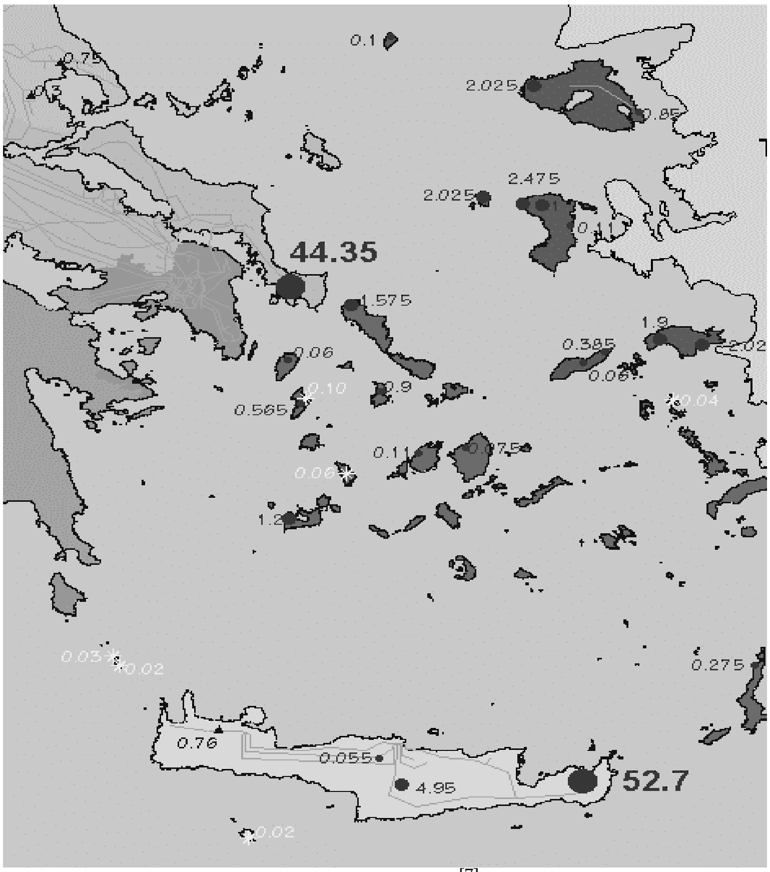

Figure 3: The locations of new wind parks[7].

values are encountered, as in many cases the annual mean wind speed at 10m height is up to 10m/s[4]. For all these reasons, the Greek State voted in October 1994 for the new Renewables law (2244/94), ending the monopoly of Greek PPC in the local energy market[5]. One of the most positive aspects of this law is that private investors are allowed to produce electricity by renewable sources and PPC is "obliged" to purchase electricity at a fixed percentage (e.g., 90%) of the market price. In addition, according to the recent 2601/98-development law, a 40% subsidy is provided to private investors, in the area of wind energy applications.

Despite all these positive incentives, only 15MW of wind power were added during the last five (94-99) years in Greece, reaching the modest result of 40MW installed capacity[6]. In the meantime, total Europe wind power capacity approaches the 8GW, the vast majority installed during the 1994-99 period. Nevertheless, during the last year a significant increase (by more than 150%) of the existing wind power has taken place, suddenly pushing the installed wind capacity in Greece over 100MW[7]. Unfortunately, almost the totality of the new wind parks is concentrated in two geographical regions (i.e., East Crete and S. Euboea), while a remarkable number of new installations are scheduled for the area of Peloponnisos.

This significant concentration of remarkable-sized wind turbines (diameter between 35m and 70m) in a relatively small geographical area could possibly change the traditional picture of the Greek landscape and create negative public attitudes towards wind turbines[8]. For this purpose, an extensive study is now prepared in order to examine the impact of the existing wind parks on the local environment-societies, in view of the “Not In My Back Yard” (NIMBY) syndrome. Data from several relative opinion surveys on both sides of the Atlantic, along with preliminary data collected from our country (area of S. Euboea) are analyzed, in order to obtain a clear-cut picture of the NIMBY syndrome in the area of Wind Power applications.

The conclusions drawn from the present analysis may be found useful in any decision taken in the area of regional wind energy planning in our country.

2. The Status of Wind Energy Market in Greece

According to the existing official data (Summer 2000) in Greece there exist approximately 330 wind turbines, 140 of them belonging to PPC and the rest 190 to private investors. The nominal power of PPC wind parks is 26.6MW while the corresponding power of private companies is 94.7MW. What is presently interesting to mention is that less than two years ago[5] the total power of PPC wind parks was almost the same while the private investors' wind parks contributed with less than 15MW.

This significant power increase was anticipated by the authors in previous studies[9], though almost all the new wind parks have been concentrated in only two geographical regions of the country, i.e. South Euboea and East Crete (figure (3)).

The new wind turbines installed are of medium to large-scale group of machines, since their nominal power is greater than 500kW. The size of new wind turbines (WTs) is in accordance with the European tendency to install bigger and bigger wind turbines (figure (4)), so as to take advantage of scale economies. More precisely, in N. Europe and in the USA-Canada the new wind parks are created using MW-scale machines, while the 2.0MW and 2.5MW wind turbines are the most popular models for 2000 and 2001.

Analyzing the data of the existing wind turbines in Greece one may assert that during the last two years more than 160 machines -with nominal power between 500kW and 750kW- were installed (figure (5)). The diameter of these new machines is greater than 40m. Additionally, almost all these machines are placed on, at least, 50m high towers. In figure (6), one may compare the size evolution of commercial wind turbines installed all over the Europe. As it can be easily concluded, the size of the new generation wind turbines is much bigger than the previous one, and it is highly questionable if these "small giants" can be smoothly incorporated into the Greek landscape, and especially in the traditional pictures of the Aegean Archipelago islands.

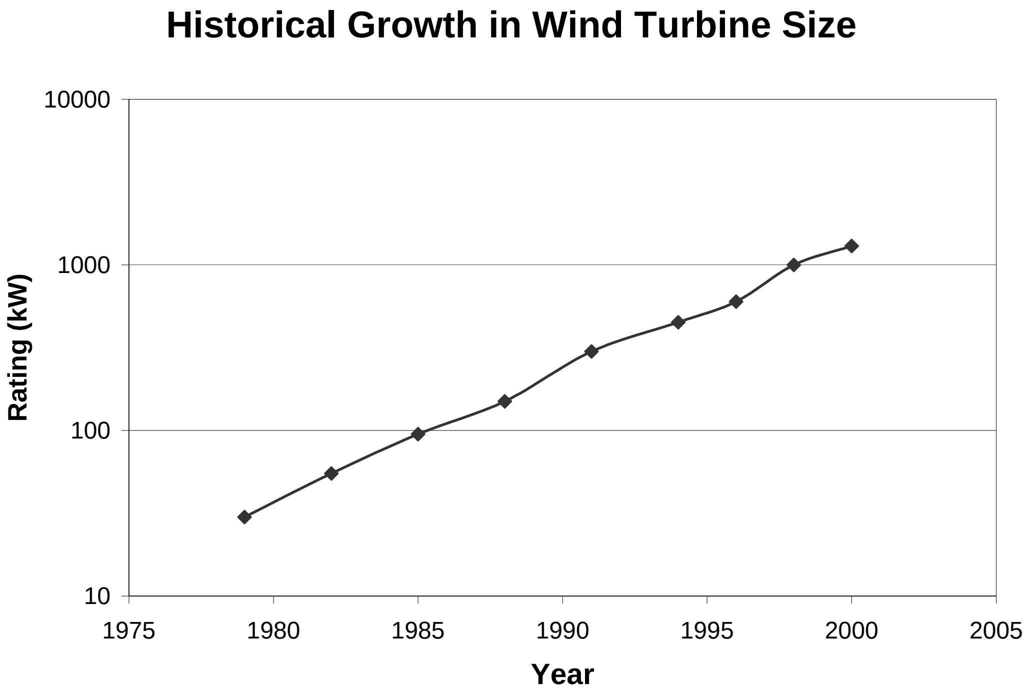

Figure 4: The size evolution of WTs.

3. The NIMBY Syndrome and its Relation to Wind Energy

The NIMBY phenomenon is not a new one. It has also appeared in several other cases, such as the sitting of landfills, hazardous waste facilities, nuclear power plants and even conventional thermal power stations (e.g. the case of Atherinolakos in Crete)[10].

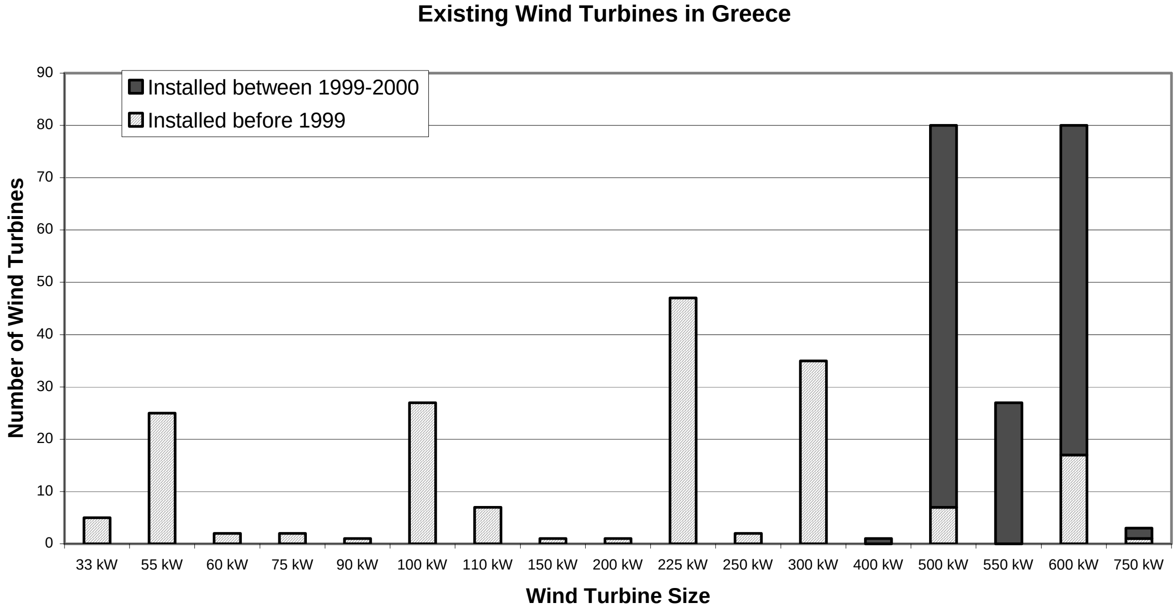

Figure 5: The size of the existing wind turbines in Greece.

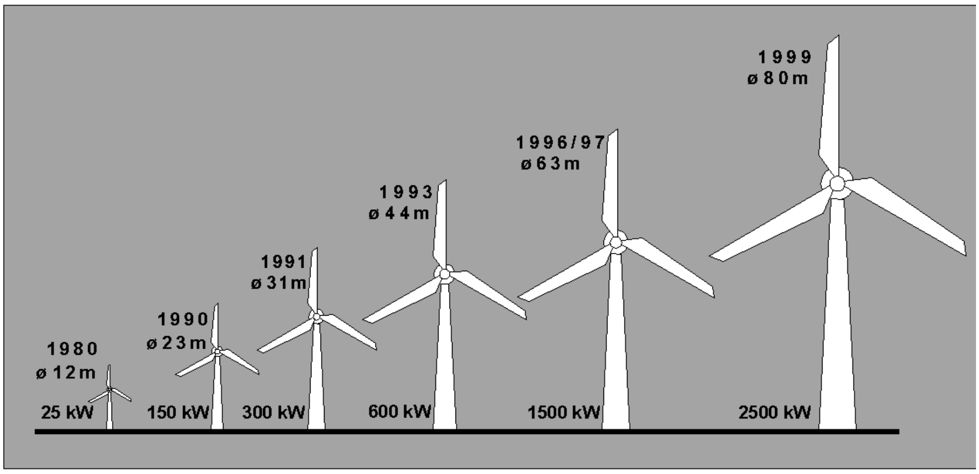

Figure 6: Comparative size of commercial wind turbines.

According to specialists[11][12] the NIMBY syndrome is a specific type of social dilemma. Thus, the application of social dilemma theory[13] shows that a public good may not be produced although all individuals need it.

In the present study, the public good is electricity provided by large wind parks instead of thermal power stations[3]. In this case it is common belief that the wind energy contributes to the diminution of several dangerous air pollutants and at the same time to the minimization of exchange loss for imported oil[14].

However, although the public opinion is definitely in support of wind power, a remarkable part of the society is opposed to wind turbines in their own living environs (e.g., distance less than 5km from their residence). Subsequently, according to the NIMBY-concept, the people living there oppose individual locations, that fulfill the minimum requirements for wind turbine installations[4]. The local habitants try to maximize their own individual utility of the environment, minimizing the impact of wind turbines by not allowing them to be built.

If all the appropriate locations face similar contradictions, no wind power plants are eventually going to be built. Therefore, wind power is not currently being used as a source of energy, despite the fact that almost everybody believes it should. Summarizing, in similar cases we face the primary concern with individual environmental interests over and above the logic of the "public good"[13].

According to several opinion surveys data, the negative view of wind turbines on the landscape is the major factor determining opposition to wind energy[15]. On top of that, people unconsciously realize that conflict on aesthetic ground is subjective, therefore, they rationalize their opposition by citing concerns as noise, shadow flicker and bird mortality, which can be objectively evaluated.

Modern wind turbines, with a hub height and a rotor diameter of 35m at least, form a dominant landscape element, especially because they are located in highly visible locations in order to exploit the existing wind potential. The reaction to the sight of a wind farm is highly subjective. Many people see them as a welcome symbol of clean energy, whereas some find them unwelcome surcharges to the landscape.

The negative attitude of the residents of a future wind park location is also based in other factors, such as the fear that the wind turbines will harm the habitants of the region or the disbelief that the wind turbines will make a difference in improving air quality. Finally, another significant factor for the negative attitude against new wind parks is opinions about interference such as noise, shadow flicker and impact on birds and nature.

Opposition to wind power projects can be defined in terms of a negative attitude and resistance actions. The most common resistance acts against wind power projects include contacting local authorities, attending protest meetings, writing letters, signing petitions etc. On top of that, a small number of wind energy opponents are ready to take legal action to stop the installation of wind turbines in their area.

Although the existing data indicate that only a small minority considers actions against wind projects, the active opposition can cause serious problems and drawbacks. Keep in mind that legal procedures against permits given by local authorities can often be initiated by only one opponent. A relative recent example is the case of PPC Wind Park in the area of Eressos-Sigri in West Lesvos. In this case, the 9x225kW wind park of PPC was delayed by more than five (5) years after legal actions taken against this project by the former president of the Sigri village council.

4. Opinion Surveys Concerning the NIMBY Syndrome for Wind Power Plants

Public opinion surveys on both sides of the Atlantic[16][17] have consistently shown strong support for the development of wind energy. Typically, two-thirds to three-fourths of those polled supports wind development even in areas with existing wind turbines. On the other hand, there also exist other groups that find wind turbines "*huge and noisy industrial machines damaging local amenity*".

According to our opinion public attitude surveys of wind power are of a very varied and frequently uncontrollable quality. They have not often been performed according to scientific standards and there is little co-ordination between studies. This makes it difficult to make reliable comparisons between them. During the last years, surveys on wind power acceptance have mainly been done in countries like Britain, USA, Germany, Denmark and Netherlands. In all these countries an important penetration of wind power is encountered during the same period (figure (1)).

In the following we are going to summarize[17] the results of the most well known public surveys, taking also into account some interesting comparative studies of other researchers[16][18]. Thus, one of the most interesting public opinion surveys is the one carried out by professor J. Palmer of State University of New York for the Green Mountain Power Corp's (GMP). The study was carried out in view of a new wind farm in Searsburg Vermont. The survey was written and was mailed to a random

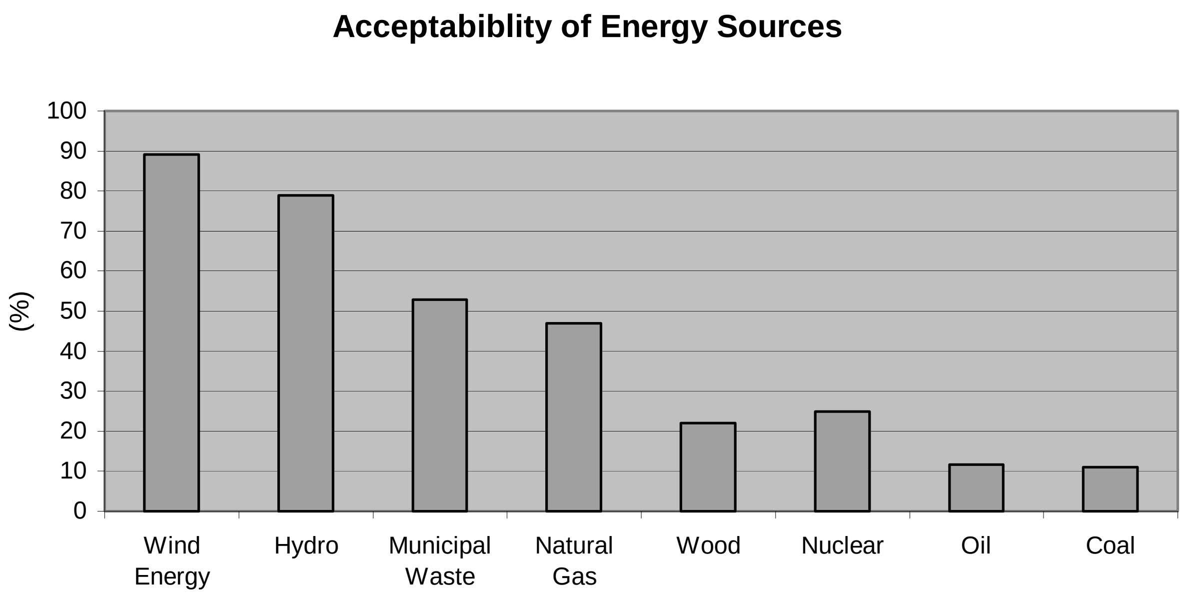

Figure 7: Acceptability of energy sources, USA.

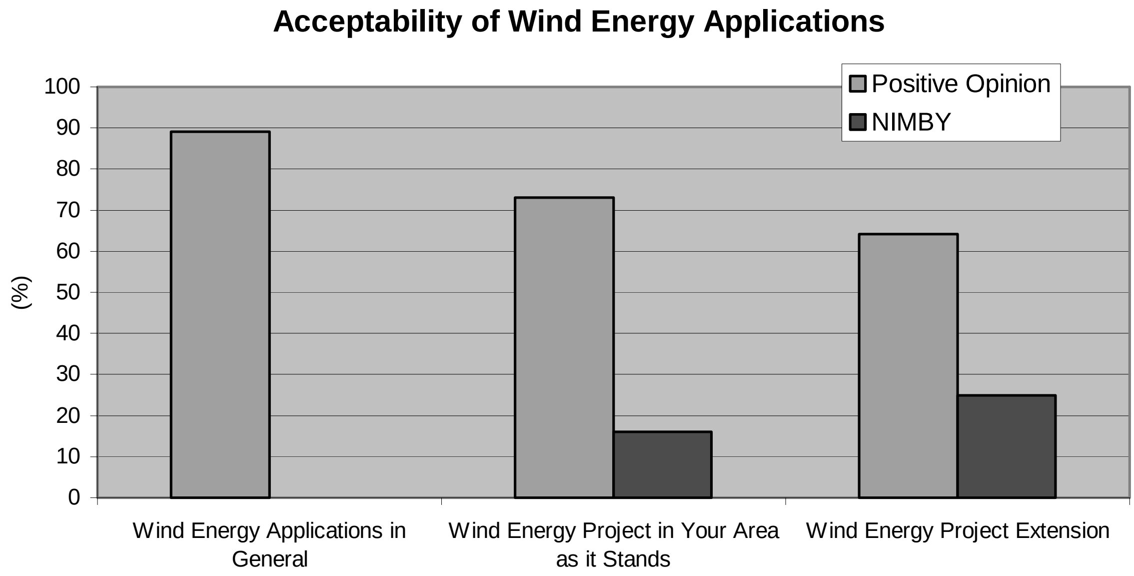

Figure 8: NIMBY syndrome in the USA.

sample of residents in Searsburg and surrounding towns. Sixty-three percent of those receiving the questionnaire completed and returned it. Respondents were first asked whether they would like to see an increase or decrease use of eight different energy sources, i.e., wind, hydro, municipal waste, gas, wood, nuclear, oil and coal, to generate electricity. Wind power was placed first, since 89.1% of respondents favoring increased use in comparison to 11.6% for oil and 11.0% for coal (figure (7)).

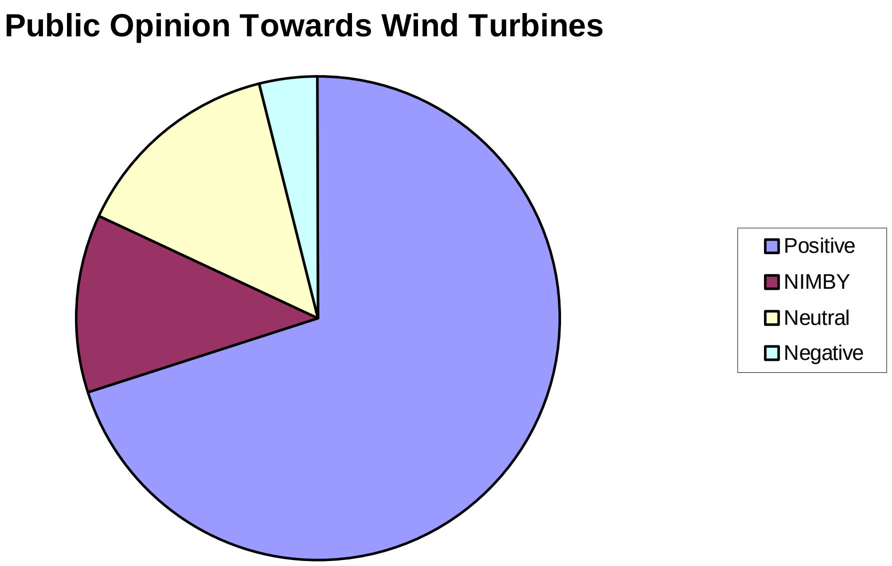

Figure 9: NIMBY syndrome in Wales.

In the second part of the survey, emphasis was laid to examine the strength of the NIMBY sentiment. Residents were questioned, among others, about their support of the Searsburg project as it stands and how supportive would be of doubling the size of the project. In both questions a decrease of the positive answers was encountered, however 73.1% still supported the existing project (16% is assumed the NIMBY percentage) and 64.2% remained in support of the project extension (24.9% NIMBY) (figure (8)).

The second survey presented here is the one carried out by the University of Wales during February 1994. In this case 457 interviews were taken into account in four survey areas around Llandinam. In

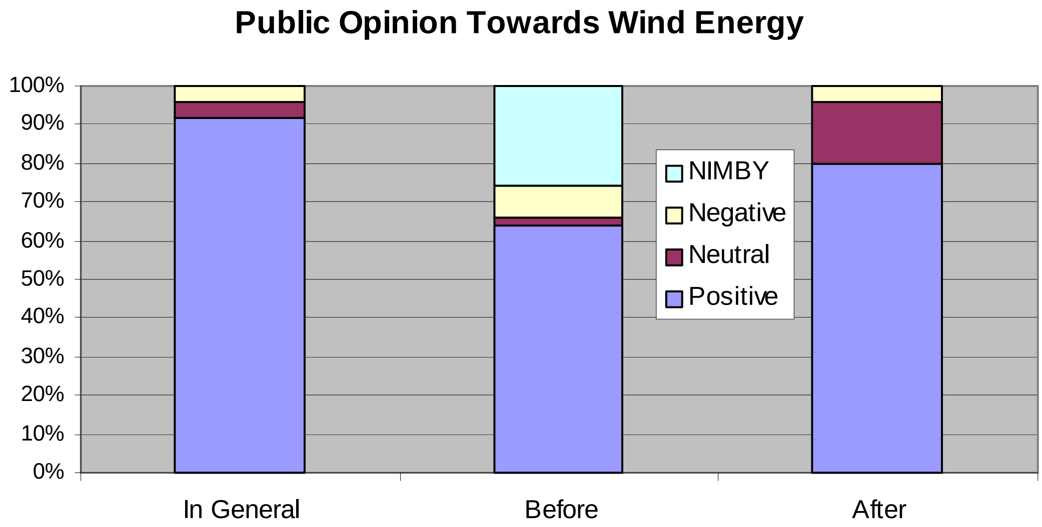

Figure 10: NIMBY syndrome in the UK.

three of them wind farms already existed. The majority of respondents (four out of five, ≈82%) expressed favourable opinions about the development of wind power stations, and among them the 70% was in favour of further construction in their neighborhood (figure (9)). Comparisons with the control area suggest that attitudes towards wind farm developments are more favourable where and when they actually take place, and residents are less likely to adopt a NIMBY position than the control sample.

The last survey included here (see also [17]) concerns the attitude of local people towards the wind farm at Coal Clough Lancashire and it was carried by the Liverpool University on May 1996. During the survey the questionnaire was completed with the interviewer present. The corresponding sample was 50 persons. According to the results obtained, 92% of the sample supported wind farm production and only 4% strongly opposed it. However, only 64% of them said that they felt positive about the proposal to built a new wind farm in their neighborhood, whilst 8% were strongly against it (figure (10)). When the survey conducted, after some months of living with the wind farm, 80% felt positive about the wind farm and 4% were against it. In this case, like other similar cases, it is validated the phenomenon, that in studies in which opinion was canvasses at the time of construction and some months afterwards, respondents were more positive at the second stage than the first one.

5. Public Attitude Towards Wind Energy in Greece

As mentioned above, a remarkable wind power has been installed during the last two years in our country. This positive, in general, evolution seems having two weak points. The first one is related to the size of the wind turbines selected (Figures (5) and (6)). Since these wind farms are private investments, the investors select machines of the order of 500kW to 750kW in an attempt to minimize the initial installation, maintenance and operation cost, and maximize the energy production. However, these machines form a dominant landscape addition, especially when they are located in relatively closed areas.

The second point to be analyzed is that almost all the new wind power installed is concentrated in two small geographical regions (figure (3)). Therefore, the problem of negative public attitude towards wind turbines is expected to be more serious in these two areas than in regions where a small number of medium or small size machines were installed. For this purpose, an extensive study concerning the public acceptance of wind parks in Greece is in preparation. The first stage of this survey is focused in the area of S. Euboea. In this windy area of the Aegean Archipelago there already exist more than 150 wind turbines, while new wind parks are also under development (figure (11)). Due to the remarkable

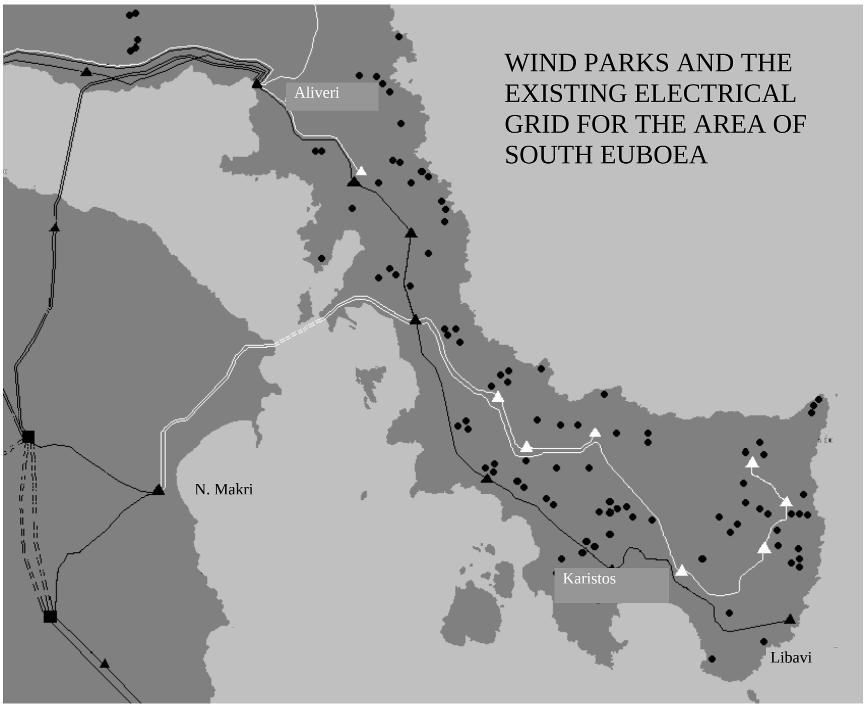

Figure 11: The Wind Parks Location in S. Euboea.

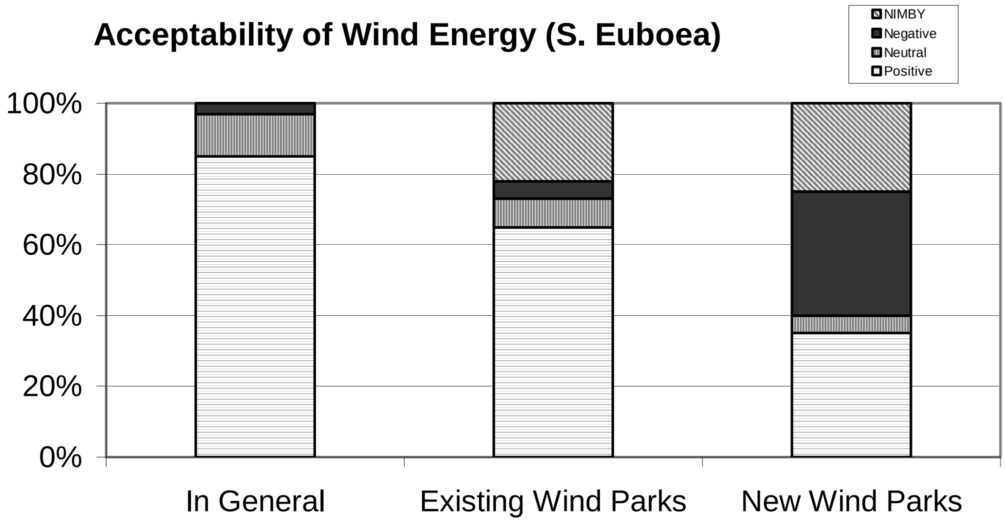

Figure 12: NIMBY Syndrome in S. Euboea.

concentration of wind power, a negative attitude towards these *private* wind power installations is possible to appear.

According to the preliminary results of our survey (sample of 47 respondents), the public opinion is no more positive (figure (12)), although the vast majority (85%) of residents accept the necessity of clean energy production and diminution of imported oil using wind power. More precisely, the 65% of the respondents agree with the development of the existing wind parks. However, only 35% are still positive to creation of new wind parks, while almost 35% of the sample is strongly opposite to this enlargement.

At this point it is important to note that the public opinion towards wind energy in this specific region under investigation starts to change against the wind energy, mainly due to the speculative exploitation of wind potential by private companies. The main target of all these companies is the profit maximization, thus the environment protection is no more a priority. The opinion of the authors is that if this situation is not properly analyzed and amended, the future of wind energy in the area of S. Euboea is not bright. Keep also in mind that if this phenomenon starts in a region of our country it is very possible to expand all over the country (e.g., the fiasco of Milos project that cancelled all the application of geothermy in our country), decelerating the wind energy penetration in the local energy market.

6. Conclusions

A critical evaluation of the existing local wind power market situation is presented. Emphasis is laid on the necessity to use wind power instead of imported oil or locally extracted lignite in order to minimize the negative environmental impacts, e.g., the huge amounts of air pollutants emitted. However, the vast majority of new wind parks are situated in only two restricted geographical areas. Thus a remarkable change of the public opinion towards wind energy is possible to appear, a common phenomenon in almost all European countries. In order to prevent such a negative evolution, the impact of these new installations on the local societies is investigated here, in view of the NIMBY syndrome. Also data from relative opinion surveys on both sides of the Atlantic, along with preliminary data collected from our country, are analyzed in order to obtain a clear-cut picture of the NIMBY syndrome in the area of wind power applications. According to the authors' opinion, if this uncontrollable situation is not properly analyzed and handled, the future of wind energy applications - in these specific regions investigated- is questionable. Thus we hope that the results presented may be utilized in any future decision taken in the area of local energy planning.

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ESTIMATING THE VISUAL IMPACT OF WIND PARKS IN GREECE

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Abstract

During the last years, a significant number of remarkably sized contemporary wind turbines have been installed in few relatively restricted geographical areas, provoking serious local population reactions on the basis of important environmental impacts. In this context, "visual intrusion" is found to be one of the major factors determining opposition to wind energy. In order to examine these problems an extensive study is carried out concerning the visual impact of the existing wind parks in Greece. In the first part of this study, each wind turbine is being photographed, along with the entire machine arrangement in every wind park. Accordingly, a public opinion survey is carried out all over Greece, concerning the local habitants' attitude on a wind park, as far as the "visual intrusion" of existing wind turbines is concerned. The results collected are analyzed in view of the machines general acceptability. The conclusions drawn are characteristic of the public attitude towards wind power applications and may be found necessary to everybody related to the local energy planning procedures. Finally, the photo-data collected are analyzed in an attempt to ameliorate the wind turbine incorporation in the traditional Greek landscape.

Keywords: Wind Park; Visual Impact; Public Opinion Survey; Landscape

1. Introduction

During the last three years the installed wind power in Greece has been significantly increased from 40MW to 270MW, after a long period (1993-1998) of stagnation, mainly due to the incomplete legislation frame[1][2]. Bear in mind that this important wind power increase was based on remarkably sized contemporary wind turbines, concentrated[3] in few relatively restricted geographical areas, i.e. mainly on NE. Crete and S. Euboea. On top of that, an increased number of wind projects is under development for the Peloponessos area, in an attempt to take advantage of the existing electrical network capabilities and the available infrastructure[4]. Unfortunately, this noteworthy wind power penetration provoke in some areas serious local population reactions, which in several cases lead even to the complete wind power projects cancellation, by claiming important environmental impacts[5]. More specifically, noise emission and visual impact are the most commonly used complaints against wind turbines by local people.

Thus, the present work analyzes the visual impact of wind parks in Greece, since according to several public surveys "visual intrusion" is one of the major factors determining opposition to wind energy[6][7]. On top of that, many researchers believe that people unconsciously realize that opposition on aesthetic grounds is subjective and thus they rationalize their opposition by rising objectively evaluated[8] concerns like noise, shadow flicker and birds.

In order to examine the above-mentioned problem, an extensive study is carried out concerning the visual impact of the existing wind parks in Greece. This study is divided in two parts. In the first part a public opinion survey is carried out all over Greece, concerning the local habitants' attitude towards a wind park, as far as the "visual intrusion" of existing wind turbines is concerned. The results collected are analyzed in view of the machines general acceptability by the local communities. Accordingly, a new database is created, comprising the main characteristics along with the picture of each wind turbine operating in Greece. Besides, the entire machine arrangement in every wind park is also included. By analyzing the photo-data collected, one has the opportunity not only to evaluate the existing wind turbines visual impact but also suggest modifications in order to ameliorate the wind turbines incorporation in the traditional Greek landscape.

2. Registration of Local People Attitude

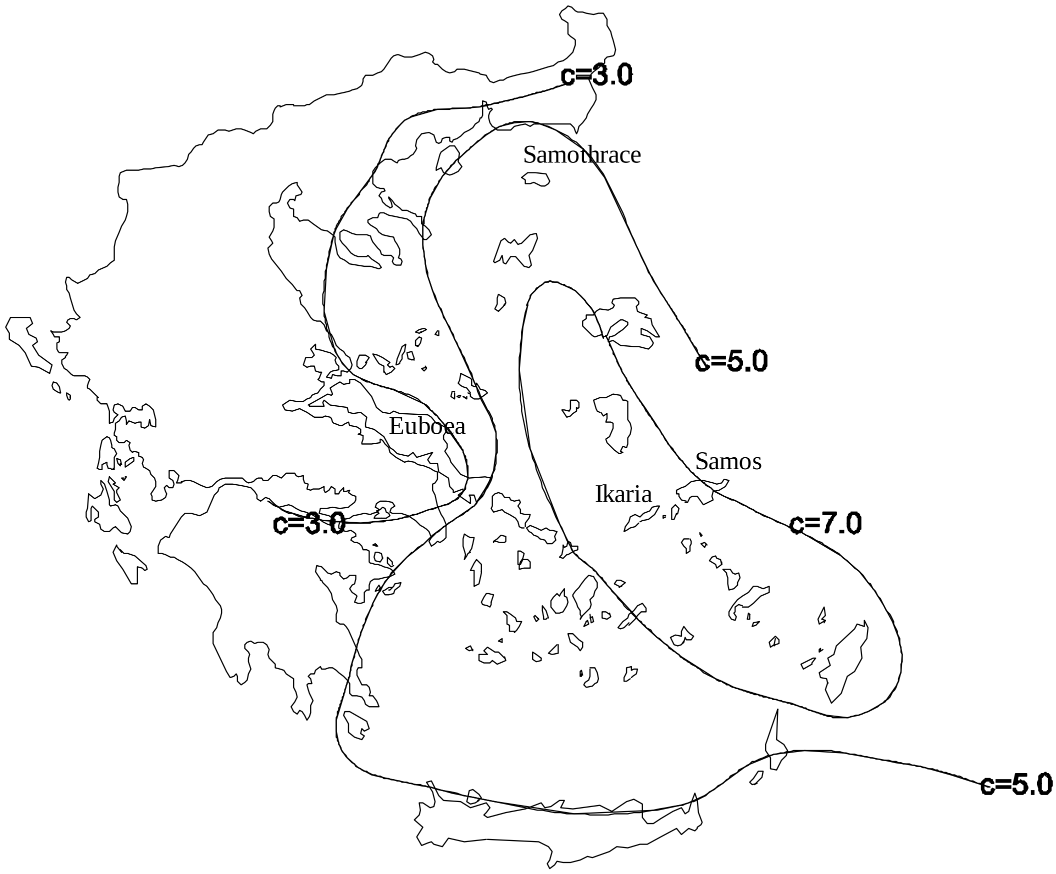

Figure 1: Wind Parks Location in Greece

In view of these negative reactions encountered, concerning specific Greek communities, the Soft Energy Applications and Environmental Protection Laboratory of TEI Piraeus has undertaken (since 2000) an extensive study about the public acceptance of wind parks all over Greece[4]. The first stage of this survey is focused on the S. Euboea area along with Samos and Andros islands, three windy Aegean Archipelago regions (see also figure (1)) where a remarkable number of wind converters have been installed.

Keep in mind that the first stage of this survey is conducted[10][11] in two separate phases (during the 1st and 2nd semester of 2001) by different research groups, while the complete public opinion investigation and the results analysis validates the necessary scientific criteria[12].

In the questionnaire, a general question was posed about the acceptability of the operating wind parks in the neighborhood, along with a more specialized question concerning the "visual intrusion" of these wind power installations.

2.1 S. Euboea Results

According to the results obtained (sample of 128 respondents), the public opinion is actually divided, figure (2). 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[13] of the public attitude towards wind turbines encountered in S. Euboea may be the remarkable concentration (≈80MW) of numerous large wind converters, in a relatively short time.

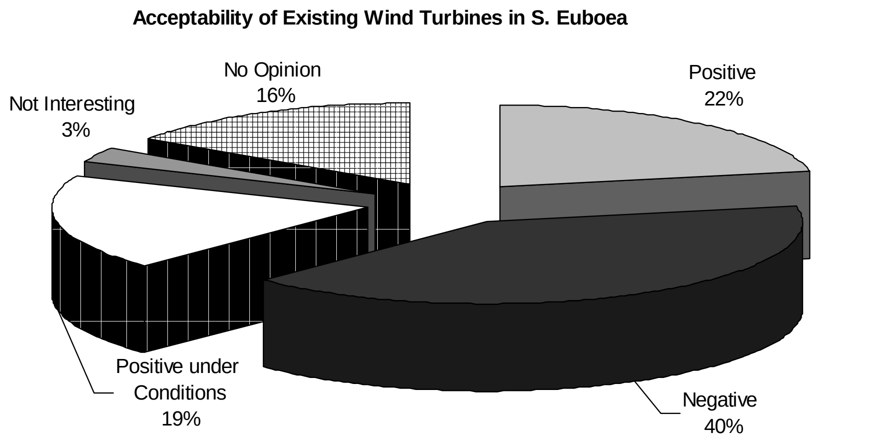

Figure 2: Public Opinion Towards Wind Parks

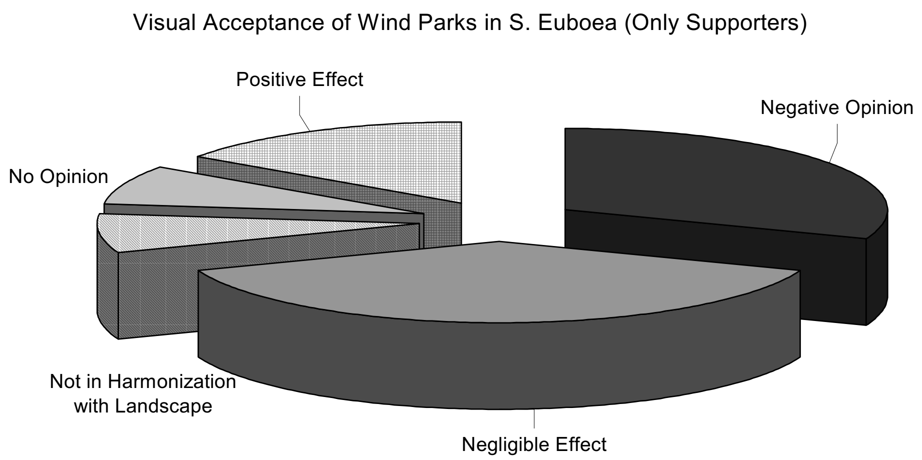

Figure 3: Wind Turbines Visual Impact, Supporters Sample

Another interesting outcome of this double-phased public survey is the inhabitants negative -by almost 46%- visual impact of wind turbines, while another 16% believe that the existing machines are not in harmonization with the landscape. On the other hand only 6% like the sight of these machines whereas 19% do not mention any visual intrusion. Analyzing now the attitude of the respondents, expressing negative opinion towards existing wind turbines, almost their entirety (93%) declare visual impact of existing machines. What seems more perturbing is that almost 40% of the habitants being supportive to the wind energy applications in their region state strong (32%) or mild (8%) negative visual impact of wind turbines, figure (3).

2.2 Samos Island Results

Samos is a medium-sized island of East Aegean Sea, possessing excellent wind potential. In this island, since 1991, there exist several private or PPC-owned medium-sized wind parks. Local habitants' general attitude (sample of 196 interviews) towards wind turbines is completely different from the S. Euboea one. More specifically, the respondents' vast majority (64%) was positively expressed for the development of wind power stations, while another 14% supported wind farms under the precondition of proper operation, figure (4). Only a small minority (5%) were negatively expressed for the existing wind converters.

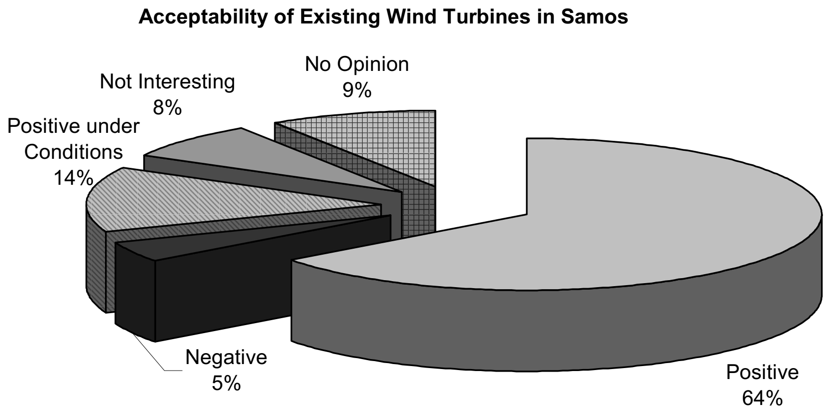

Figure 4: Public Opinion Towards Wind Parks

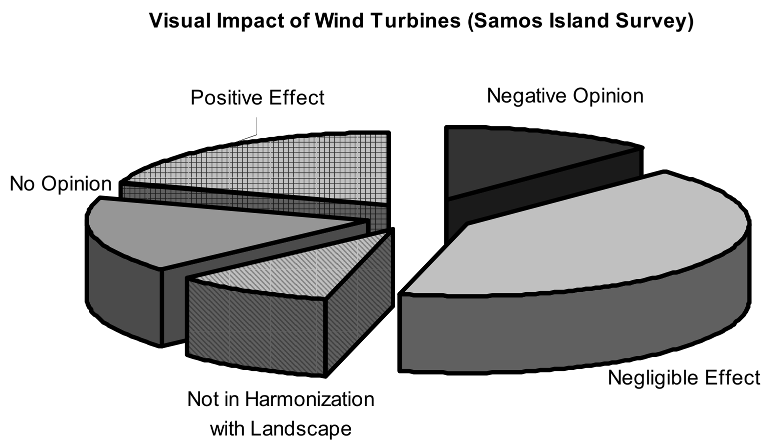

Figure 5: Visual Impact of Wind Turbines

Even in this positively reacting society, 12% of the sample mentions negative visual impact of wind turbines, while another 9% declares that these machines are not in harmonization with the landscape, figure (5). On the other side, the vast majority of the local people do not point out any visual intrusion, while 2 out of 10 are fond of wind energy installations.

2.3 Andros Island Results

Andros is a medium-sized island (the second biggest one) of the Cyclades complex, located in the middle of the Aegean Sea. The local terrain is very intense, including several rocky mountains with relative sharp slopes. The island has one of the best wind potential in Greece (mean annual wind speed ≈10m/s), while a PPC (Greek Public Power Corporation) owned wind park of 7x225kW wind turbines exists in the island, operating with outstanding results since 1993.

In Andros island the local people are quite familiar with the existence of wind turbines in their region. Thus they do not present any serious opposition against these machines, especially in cases of proved proper operation, figure (6). At this point it is important to clarify that the sample of Andros is quite lower (30 respondents) than the one used in Samos or Euboea, since the public survey in this area is not yet completed.

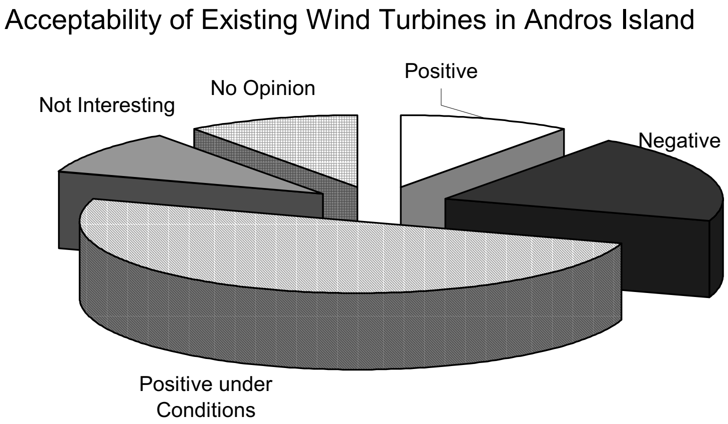

Figure 6: Public Opinion Towards Wind Parks

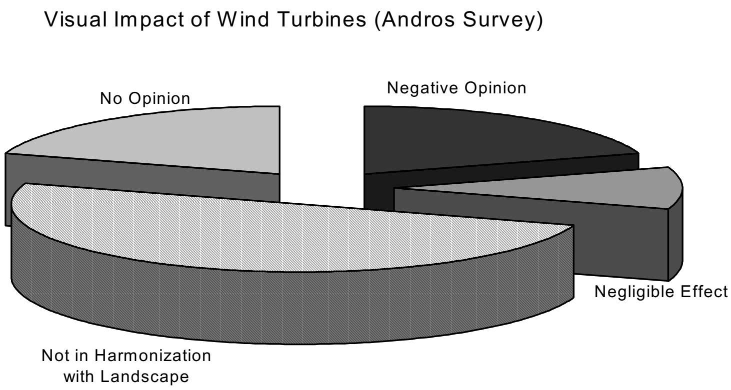

Figure 7: Visual Impact of Wind Turbines

However, despite the general positive attitude towards wind power, a remarkable portion (50%) of the habitants state that wind turbines are not in agreement with the landscape, while 20% of local people declare visual annoyance, figure (7).

Recapitulating, according to the assessed results of three recent public opinion surveys, realized during 2001 (total sample 354 respondents) about the social attitude towards existing wind parks, one may conclude that a remarkable part of the respondents declare significant visual impact of existing wind turbines in the landscape, especially in S. Euboea, where the wind power concentration is much more intense. On top of that, even wind parks supporters often report visual impact of the wind converters. The conclusions drawn are in accordance with several parallel works suggesting that "visual impact" is one of the major factors determining opposition to wind energy.

3. "WIND-PHOTO" Database Development

"WIND-PHOTO" is the second version of a new database originated in 1998. The current version is developed in "Access 8.0", mainly for Windows-98 compatibility reasons. Additionally, "WIND-PHOTO" is fully collaborating with "Windbase II", containing operational characteristics[14] of commercial wind turbines since 1988.

Table I: Information about Wind Parks Analyzed

Location	Turbine Type	Start Up	Rated Power (kW)	Owner
Pithagorion Samos	9xV-27	1992	9x225	PPC
Marathocambos Samos	9xWM19S	1991	9x100	PPC
Ikaria	7xWM15S	1991	7x55	PPC
Samothrace	4xWM15S	1990	4x55	PPC
Polipotamos Euboea	20xJACOBS	2000	20x600	Priv

In this "WIND-PHOTO" version, the available information for each wind turbine consists of:

a. Wind Turbine type and Rated Power
b. Engine Location
c. Engine Photo
d. Annual energy production throughout its operation
e. Major engine failures history
f. Machine arrangement in the corresponding wind park

Up to the end of 2001, more than 150 wind converters were registered in this database, totaling rated power of almost 120MW. However, in the present work emphasis is laid on the entire wind park appearance related to the landscape.

In this context, one has the opportunity to evaluate the visual impact of several wind parks, using the information included in "WIND-PHOTO" database. In the following typical results are presented with reference to the degree of selected wind parks integration in their surroundings. The general characteristics of wind parks under investigation are included in Table I.

Considering the public opinion surveys presented in the previous chapter, various wind parks located in S. Euboea and Samos Island are embraced in this analysis. On top of that, two PPC wind parks located in the islands of Samothrace and Ikaria are also included.

Figure 8: Pithagorion Wind Park 9x225kW

More specifically, the first wind park investigated (figure (8)) is the one located near Pithagorion, a historic small town at the south of Samos Island. This wind park belongs to PPC and consists of nine famous wind converters (of the 2nd generation), i.e. nine V-27 wind turbines (rated power 225kW), installed since 1993, approximately producing 6000MWh/year. As it is clear from the available photos, e.g. figure (8), all wind converters are sited on a plateau near the sea, far from houses and public areas. V-27 machines belong to the most popular type of the 2nd generation wind turbines, operating with a fair annual energy production under the unfavorable conditions of a remote island.

Accordingly, the next wind park examined is the PPC wind park located near Marathocambos, a small town at the center of Samos Island. This is one of the oldest wind parks in Greece (erected in 1990-91), based on nine small wind converters (of the 1st generation), i.e. 9 Windmatic 19S (or Aiolos-100)

Figure 9: Marathocambos Wind Park 9x100kW

machines, rated power 9x100kW. As it results from the available photos, figure (9), all nine-wind converters are sited along a hillcrest, distant from houses and public areas. Additionally, first generation machines are quite small (see also Table 1), although their rotor blades are unusually large in comparison to the contemporary blades.

The third wind park examined is the Ikaria wind park, erected by PPC in 1991. Ikaria is a medium-sized island of East Aegean Sea, situated 240km from Athens, nearby Samos. The mean annual wind speed exceeds 9m/s. The Ikaria wind park is one of the smallest Greek wind parks, consisting of seven old-fashioned (1st generation) wind converters, i.e. 7 Windmatic 15S (or Aiolos-55) machines, rated power 7x55kW. According to the photos collected (figure (10)), this wind park is sited on a plateau, at a large distance from public areas. The engines used are microscopic in comparison to the wind turbines applied nowadays.

The fourth wind power station analyzed is the one of Samothrace, the well-known small island of N. Aegean. It has been the first commercial installation in Greece, operating since 1990. The wind park analyzed, figure (11), employs only 4 Windmatic 15S engines -exactly the same model as in Ikaria case. This tiny wind park is located on a small natural neck of land at the island's main port. Despite their insufficient tower maintenance, the wind park production is acceptable, while it is well approved by local community.

Finally, one of the most recently built wind parks of S. Euboea is being surveyd, figure (12). This medium-sized private establishment in Polipotamos -operating since 2000- includes 20 Jacobs wind turbines of 600kW each. Due to their size and painting, these machines -although located in the open

Figure 10: Ikaria Wind Park of 7x55kW

Figure 11: Samothrace Wind Park 4x55kW

space- form a far-sighted addition to the landscape. These 20 machines -being only a part of the approximately 300 wind converters scheduled to be installed in the area- provoke serious contradiction with local people. However, all wind turbines are carefully sited in order to exploit the maximum wind potential, while the wind park has a flawless operation, producing enough electricity to fulfill the annual demands of almost 7000 families.

The results obtained are typical examples concerning the information included in "WIND-PHOTO" database. This information can be used in an attempt to evaluate the existing machines impact degree in the traditional Greek landscape.

Figure 12: Polipotamos Wind Park 20x600kW

4. Preliminary Evaluation of Analyzed Wind Parks Visual Impact

Among the parameters affecting a wind power station visual impact[5][13] on the surrounding, one may comprise visual uniformity, wind turbine mechanical situation, machine proximity to dwellings etc. In this context, a specific committee of sector experts studies all the available visual material, ranking the above-described installations on pure visual impact terms, by using the following criteria:

i. Relative size of construction compared to the surrounding landscape and the existing skyline
ii. Engines micro-sitting and uniformity
iii. Adaptation of wind parks in the area character
iv. General aesthetics of the installation, including design, colour, engine status (aging), external appearance due to maintenance level etc.

The evaluation data are summarized in Table II. As it is evident, the ranking given is more or less subjective, although the authors believe that it is generally correct.

The overall conclusion of this examination is that all the wind parks examined are well incorporated in the landscape, while only the big wind parks induce a dominant intrusion on the landscape. The major defect of old wind parks is their inappropriate external maintenance, forming a negative picture of individual turbines, figure (13).


Figure 13: Old Wind Turbine in Kithnos

Table II: Wind Parks Evaluation on Aesthetics Basis

Relative Size	Micro Sitting
Samothrace	Pithagorion
Marathocambos	Polipotamos
Ikaria	Ikaria
Pithagorion	Samothrace
Polipotamos	Marathocambos

Adaptation	General Aesthetics
Marathocambos	Pithagorion
Ikaria	Polipotamos
Samothrace	Marathocambos
Pithagorion	Ikaria
Polipotamos	Samothrace

Recapitulating, the existence of the recorded wind parks in "WIND-PHOTO" is not disturbing the landscape aesthetics, at least according to the current concentration degree. On the other hand, a significant wind turbine surcharge in restricted areas may feed the inhabitants' precautious attitude[9][13], as far as the wind power stations visual impact is concerned.

5. Conclusions

An extensive public opinion survey is carried out all over Greece, in order to investigate the public attitude towards wind parks, while special emphasis is laid on the visual impact of existing wind turbines. According to the information analyzed, an important part of local people (including several wind energy supporters) claim significant visual impact of existing wind turbines. In view of this result, a new database "WIND-PHOTO" is created, including, among others, photos of Greek wind turbines, along with their entire arrangement in the corresponding wind park. These photo-data collected are analyzed by experts, initially to understand the reasons of negative wind turbines visual impact on local people and secondly to suggest modifications so as to ameliorate the engine incorporation in the landscape. In the authors' opinion, the visual intrusion of existing or new wind parks should be properly analyzed and amended on the basis of "WIND-PHOTO" information. In the opposite case, any additional wind energy applications may confront serious contradictions, derived from groundless allegations of important visual annoyance.

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PART FIVE

WASTES

- Air Pollution
- Solid Wastes
- Recycling

FIFTEEN YEAR AIR QUALITY TRENDS ASSOCIATED WITH THE VEHICLE TRAFFIC IN ATHENS, GREECE

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Abstract

Air quality data obtained by the Athens air pollution-monitoring network, during the period 1986-2000, was analyzed to determine long-term trends in air quality. The analysis of the concentration measurements of atmospheric pollutants shows that decreasing trends are observed at all monitoring stations, during this period. The decreasing trends of the examined atmospheric pollutants at ground level be attributed to various improvements in pollution sources such as, the renewal of the vehicle fleet and the improvement of fuel quality. The analysis showed that decreasing trends are observed for almost all the examined air pollutants. Despite the decreasing trends, smoke and carbon monoxide concentration levels in the centre of Athens remain, for the most part of the examined period, above the EU and WHO limit values, respectively. Violations of the limits were on the decline during the greater part of the examined period. The analysis also showed that the highest nitrogen dioxide concentrations were observed in the centre of Athens. The annual percentages of hourly nitrogen dioxide concentrations that are higher than 200 μg/m^3, caused increasing trends during the examined period. Violations of this limit were on the decline during the greater part of the examined period.

Keywords: Long-term urban air quality trends; Air pollution statistics; Athens

1. Introduction

Athens, being a city of about 4,000,000 inhabitants in an area of 450 km^2, faces air pollution problems as most of the other big cities in the world do. The high population density, caused by the accumulation of industrial and commercial activities in and around the city, resulted in high pollution levels during the last 30 years. Until the mid 80's the main pollutants in the Greater Athens Area (GAA) were sulphur dioxide and smoke. Photochemical pollution followed pollution from primary pollutants and resulted in the Athens photochemical smog. In recent years, European Union (EU) and World Health Organisation (WHO) air quality standards are frequently exceeded in the GAA, especially concerning O_3 and NO_x[1] to [7].

Athens is considered as a typical example of a city suffering from an intense photochemical air pollution. In late spring and late summer the development of land/sea-breeze circulation, in conjunction with the complex topography and high solar insolation favours the appearance of extreme photochemical air pollution episodes. Because of the hazardous effect of high levels of secondary air pollutants to humans and demonstration of the air quality, this is related to the health of Athens basin inhabitants[8].

The city of Athens is located in an area of complex topography within the Athens basin (~ 450 km^2). Mountains surround the city with heights ranging from 400 to 1500 m at the west, north and east sides (figure (1)). Openings between these mountains exist at the northeast and at the west of the basin, while to the south there is the sea (Saronikos Gulf). The Athens basin has a southwest to northeast major axis and is bisected by a cluster of small hills. Most of the industrial activities emitting sulphur

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dioxide contaminants are located to the south-west of the basin, near the Piraeus harbour, consisting of textile, cement, chemical, paint and paper factories. Other sources of sulphur dioxide pollution are the ships in Piraeus harbour, at the southwest edge of the basin, and the airplanes at the Athens International Airport (Hellenikon), at the southeast edge. Moreover, outside the Athens basin and to the west of the city lies a big industrial area, with refineries, steel works, cement plants and shipyards, emitting sulphur dioxide contaminants.

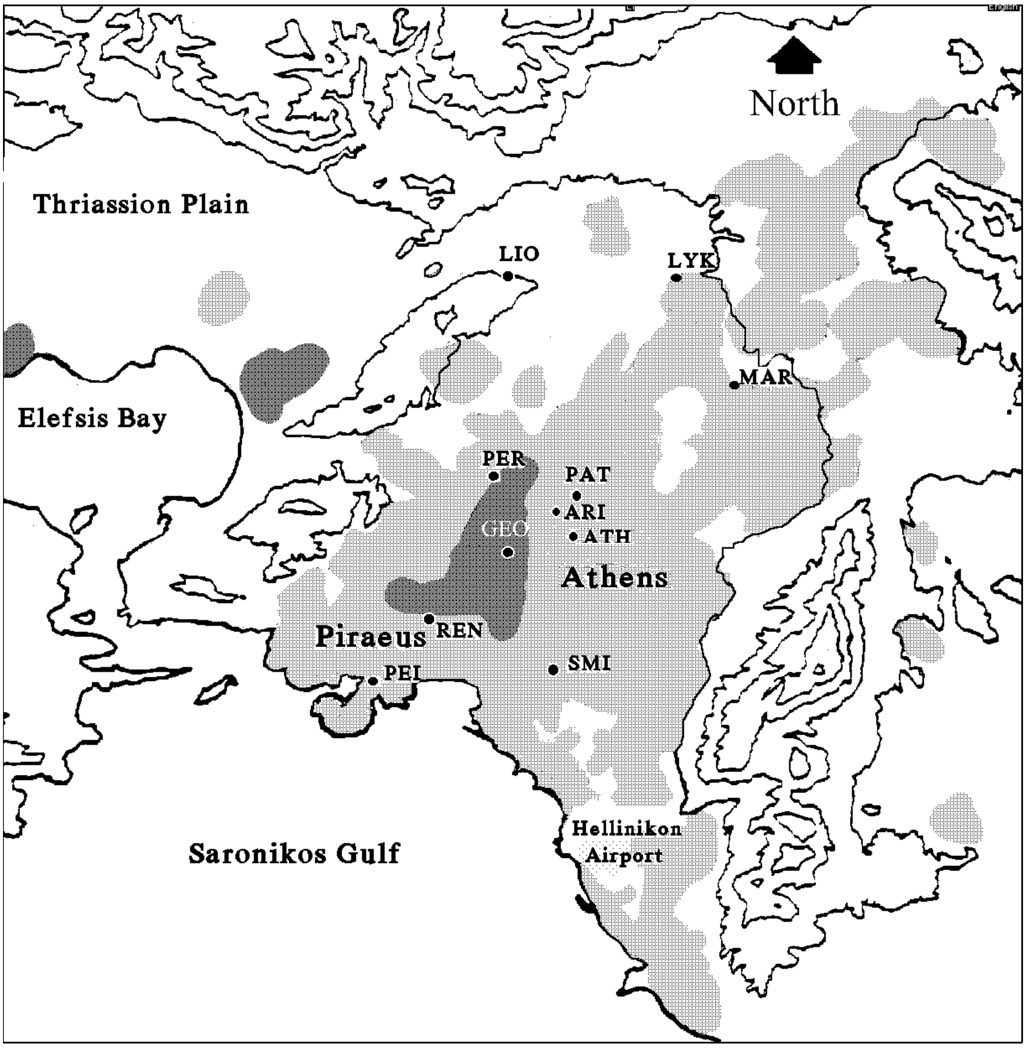


Figure 1: Map of the Greater Athens Area with elevation contours at 200 m intervals. The urban area (light shaded) and the industrial area (dark shaded) are indicated.

The climate of Athens is Mediterranean with wet, mild winters and hot, dry summers. The mean daily temperature is 10 ^{0}C and 26 ^{0}C for the winter and summer period, respectively. The Mediterranean climate is characterized by rainfall deficiency during the warm period of the year. Therefore, from the annual mean rainfall, which is 390 mm, most occurs in late fall and during the winter months. The average daily sunshine duration varies between 4.5 hours in January and 12 hours in July. The prevailing winds in the Athens basin blow from N and NE in late summer, fall and winter, and from SSW and SW in the spring and early summer. These NE and SW directions coincide with the major geographical axis of the basin. The ventilation of the basin is poor during the prevalence of local circulation systems, such as sea/land-breezes along the major NE-SW geographical axis of the basin. The vertical temperature gradient is measured at the Hellinikon Airport headquarters of the Greek Meteorological Service twice a day at 00:00 and 12:00 GMT. Various researchers determined the characteristics of inversions and the influence of various meteorological parameters on air pollution episodes[9][10].

The Greek authorities, in an effort to protect the environment from a serious air pollution problem, imposed the substitution of gasoline powered vehicles with three way catalysts vehicles. It should be noted that the vast majority of the vehicle substitution took place during the period 1989-1993. The application of this regulation was initially a satisfactory solution, especially for the heavily polluted urban areas. However, after some years the efficiency of catalysts is remarkably decreasing, therefore, their replacement is becoming essential[11].

2. Data Used

In the summer of 1983, a network of fully automated stations was established by the Ministry of the Environment, Physical Planning and Public Works (MEPPPW), in an attempt to measure CO, NO, NO_2, SO_2, and O_3 concentrations. Since 1989, the MEPPPW has been operating an air pollution monitoring system consisting of eight automatic stations, continuously measuring the above pollutants concentrations. The data obtained by the MEPPPW network has been analyzed beforehand by various researchers[2][3][4][7][12] to [18].

Maximum smoke, sulphur dioxide, carbon monoxide and nitrogen dioxide concentrations are observed at central-city residential stations (downtown Athens and Piraeus) during the cold period of the year, while at stations located in industrial and suburban areas the seasonal variations of these pollutants present a very small amplitude[12] to [17]. On the contrary, maximum ozone concentrations are observed at suburban residential stations during the warm period of the year, while at central-city residential stations located at long streets with heavy traffic the seasonal variation of this pollutant presents a very small amplitude[12][13].

The air pollution data used in this study originates from nine of the eleven monitoring stations of the MEPPPW network for the 15-year period 1986-2000, are studied to estimate the observed trends and to examine their cases. Table I provides some additional information about the automated stations that are taken into consideration in this study, because each one of these stations represents the located area.

Table I: List of stations and related information.

ID	Station	Abbreviated station name	Area
1	"Patission"	PAT	Centre City - Residential
2	"Aristotelous"	ARI	Centre City - Residential
3	"Piraeus"	PIR	Centre City - Residential
4	"Athinas"	ATH	Centre City - Residential
5	"Nea Smyrni"	SMI	Suburban - Residential
6	"Peristeri"	PER	Centre City - Residential
7	"Geoponiki"	GEO	Suburban - Industrial
8	"Maroussi"	MAR	Suburban - Residential
9	"Lykovrissi"	LYK	Suburban - Residential

3. Results and Discussion

The main pollution sources related with anthropogenic activities in the GAA are auto traffic, industry and central heating. The main source of carbon monoxide, nitrogen oxides, hydrocarbons and smoke in the Athens basin is exclusively the automobile traffic[18][19].

The analysis showed that decreasing trends are observed for almost all the examined air pollutants. The annual variation in carbon monoxide concentrations, shown in figure (2) (left panel), is characterized by a continuous decreasing trend during the examined period. More over the annual course of carbon monoxide concentrations, shown in figure (2) (right panel), is characterized by a

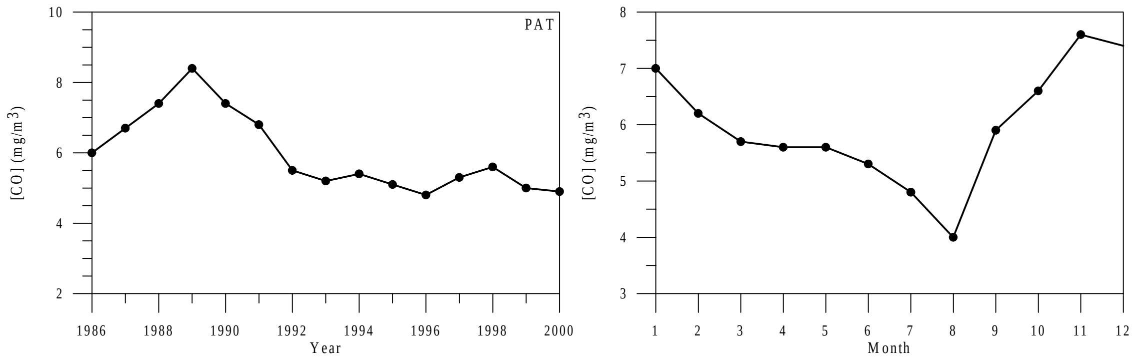


Figure 2: Annual means (left panel) and seasonal variation (right panel) of carbon monoxide concentrations for "Patission" station, for the period 1986-2000.

maximum during the cold period of the year and a minimum during the warm one. The main factor affecting the levels of carbon monoxide concentrations is the monthly variation in traffic load. Traffic emissions at Patission Street, near by the measuring site "Patission", contribute to the seasonal variation of carbon monoxide concentrations in that station (figure (2), right panel)[16]. Especially during summer months (July-September) when most people are on vacation, traffic is much less, leading to a decrease in carbon monoxide concentrations. Another factor affecting the levels of carbon monoxide concentrations during the cold period are attributed to the cold start emissions for all the non-catalyst gasoline fuelled vehicles[16][20].

Table II: Annual mean carbon monoxide concentrations and summary of smoke linear trends for the main stations of the air pollution monitoring network in GAA.

Station	**Operating period**	**Mean (mg/m^3)**	**St. Dev. (mg/m^3)**	**ASV[1] (mg/m^3)**	**Change per year (%)**	**Change per winter (%)**	**Change per warm period (%)**
PAT	1986-2000	6.0	1.1	3.6	-2.3 (*)	-2.5 (*)	-2.3 (*)
ATH	1988-2000	4.0	1.0	2.7	-2.6 (*)	-2.9 (*)	-2.8
PIR	1986-1998	3.4	1.1	2.5	-4.1 (*)	-2.8 (*)	-4.0(*)
GEO	1986-2000	1.6	0.3	1.3	1.9	1.5	1.6
SMI	1987-2000	1.8	0.2	1.4	-0.3	-0.3	-1.0
MAR	1990-2000	2.0	0.5	1.4	-1.2	0.2	-0.1
PER	1990-2000	2.2	0.7	1.5	-4.7 (*)	-3.5 (*)	-4.5
LYK	1994-2000	1.3	0.2	1.2	5.0	-1.9	10.8

[1] ASV: amplitude of seasonal variation, (*): statistically significant at the 95% confidence level.

In Table II the annual mean carbon monoxide concentrations for all the available stations of the air pollution-monitoring network in GAA for the period 1986-2000, are presented. As it can be seen, a continuous decrease of the carbon monoxide annual mean concentrations is observed. This is due to the increased percentage of substitution of gasoline-powered vehicles with vehicles equipped with three way catalysts[16]. It can be easily deduced that the carbon monoxide concentration levels of central-city residential stations (downtown Athens and Piraeus) are significantly higher than the rest of the examined stations. More over the seasonal variation of carbon monoxide concentrations at central-city residential stations reveals more acute variation (Table II). The carbon monoxide concentration levels are higher at "Patission" as compared to "Aristotelous", "Athinas" and "Piraeus" throughout the year, because of the higher emissions from traffic in the more densely populated area at "Patission".

For comparison with the urban case, the seasonal variation at one residential station located about 10 km from downtown Athens or Piraeus is shown in Table II. Both the mean value and the ASV of the carbon monoxide concentrations are several times larger at the urban densely populated areas as compared to the suburban residential area at "Nea Smyrni", "Peristeri" and "Lykovrissi". From Table II it appears that the ASV of carbon monoxide concentrations is reduced as we move from urban to suburban locations.

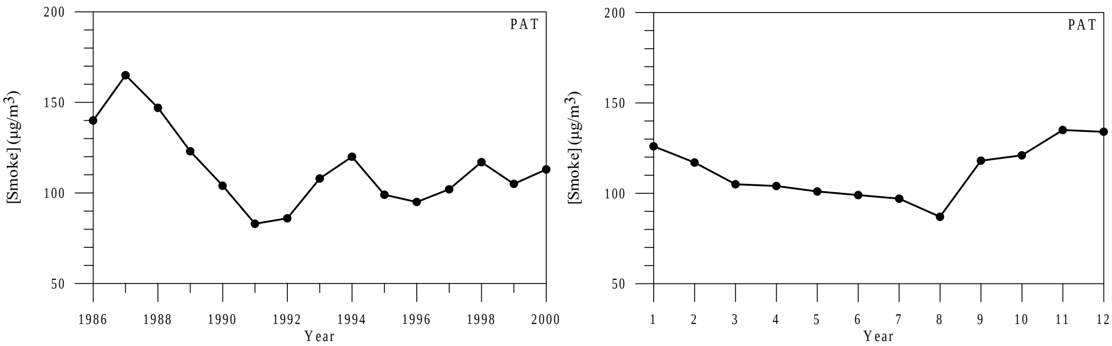


Figure 3: Annual means (left panel) and seasonal variation of smoke concentrations (right panel) for "Patission" station, for the period 1986-2000.

Table II also summarizes the linear trends observed at all available stations. The overall linear trends seen in this table for each station are also calculated separately for the winter (December-January-February) and warm (April-May-June-July-August-September) period. All trends tested by the Mann-Kendall rank statistics[21]. During the period 1986-2000 the overall trends range from -4.7% to 5.0% per year, while the winter trends range from -3.5% to 1.5% per year and the warm period trends range from -4.0% to 10.8%.

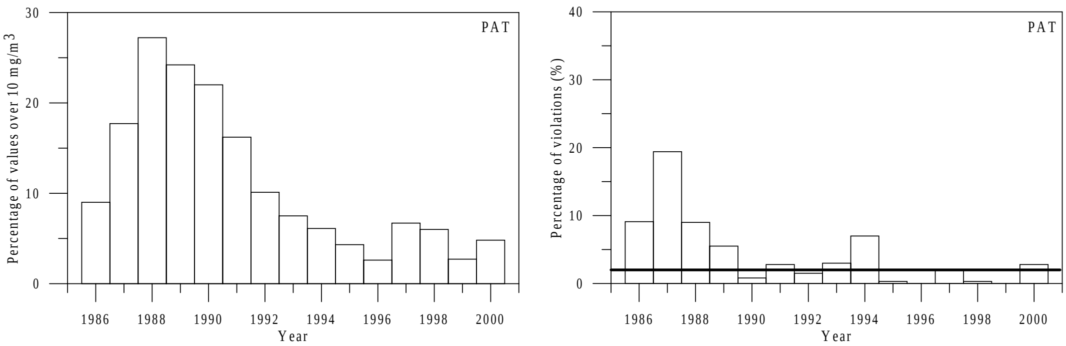
The annual mean variation of smoke concentrations in the centre of Athens ("Patission"), shown in figure (3) (left panel), is characterized by a continuous decreasing trend during the examined period. More over the seasonal variation of smoke concentrations at "Patission", shown in figure (3) (right panel), is characterized by a maximum during the cold period of the year and a minimum during the warm one. The higher discharge rates from central heating systems (about 30 m above ground) during winter in combination with the shallow atmospheric mixing layer observed during the same period are responsible for such smoke variation[9][17]. Traffic emissions at Patission Street, near by the measuring site "Patission", contribute to the seasonal variation of smoke concentrations in that station (figure (3), right panel). The relatively higher value in September at "Patission" may be attributed to the frequent temperature inversion incidence in the area during this month[9].

In Table III the annual mean smoke concentrations for all the available stations of the air pollution-monitoring network in GAA for the period 1986-2000, are presented. It can be easily deduced that the smoke concentrations levels of central-city residential stations (downtown Athens and Piraeus) are significantly higher than the rest of the examined stations. More over the seasonal variation of smoke concentrations at central-city residential stations reveals more acute variation (Table III). The smoke concentration levels are higher at "Patission" as compared to "Aristotelous", "Athinas" and "Piraeus" throughout the year, because of the higher emissions from traffic and central heating in the more densely populated area at "Patission".

Table III: Annual mean smoke concentrations and summary of smoke linear trends for the main stations of the air pollution-monitoring network in GAA.

Station	**Operating period**	**Mean (μg/m³)**	**St. Dev. (μg/m³)**	**ASV[1] (μg/m³)**	**Change per year (%)**	**Change per winter (%)**	**Change per warm period (%)**
PAT	1986-2000	113	15	48	-1.9	-3.1*	-1.2
ARI	1986-2000	65	13	39	-3.9*	-4.6*	-3.9*
ATH	1988-2000	49	11	33	-0.2	-1.6	0.8
PIR	1986-1998	45	13	34	-3.1	-3.1	-3.4
SMI	1988-2000	26	11	32	-1.9	-2.0	-1.5
PER	1990-2000	27	11	33	-3.8*	-3.9	-1.4

[1] ASV: amplitude of seasonal variation,
* statistically significant at the 95% confidence level.



(a) (b)

Figure 4: (a) Percentage of 8-hour values of carbon monoxide concentrations higher than 10 mg/m^3 at "Patission" for the period 1986-2000 (left panel) and (b) percentage of daily smoke concentrations higher than 250 μg/m^3 at "Patission", for the period 1986-2000. Horizontal line indicates EU limit (right panel).

For comparison with the urban case, the seasonal variation at one residential station located about 10 km from downtown Athens or Piraeus is shown in Table III. Both the mean value and the ASV of the smoke load are several times larger at the urban densely populated areas as compared to the suburban residential area at "Nea Smyrni" and "Peristeri". From Table III it appears that the ASV of smoke concentrations is reduced as we move from urban to suburban locations. This result emphasizes the importance of local sources on the measurements at these stations and the effect of monthly means in reducing the effect of the seasonal variation of atmospheric processes, which, on a daily basis, control, together with the emissions, the smoke amounts in the atmosphere, at ground level.

Table III also summarizes the linear trends observed at all available stations. The overall linear trends seen in this table for each station are also calculated separately for the winter period and warm ones. All trends tested by the Mann-Kendall rank statistics[21]. During the period 1986-2000 the overall trends range from -3.9% to -0.2% per year, while the winter trends range from -4.6% to -1.6% per year and the warm period trends range from -3.9% to 0.8%.

Despite the decreasing trends, carbon monoxide and smoke concentration levels in the centre of Athens remain, for the most part of the examined period, above the EU and WHO limit values, respectively. Violations of the limits were on the decline during the greater part of the examined period.

The annual percentages of 8-h carbon monoxide concentrations that are higher than the WHO long-term goal (10 mg/m^3)[22], for the period 1986-2000, are shown in figure (4) (left panel). The increase in number of violations of this goal that is mainly observed during the fall season should be attributed partly to the increased number of surface inversions in fall[17]. Violations of the WHO long-term goal were on the decline during the greater part of the examined period. The observed reduction can be attributed to the renewal of the vehicle fleet[11][12][17]. Although, for the period 1997-2000, the observed delay in the declination rate of WHO long-term goal violations may be attributed to the low rate of catalysts replacement[23].

The reduction of smoke concentrations levels is attributed to the various government measures and regulations concerning controls and restrictions in the consumption of oil, which have been gradually applied to all pollution sources, as well as to the improvement of oil quality after 1986[14] to [17]. In spite of these decreasing trends, the levels of smoke in the centre of Athens remain, for the most part of the examined period, above the EU limit values[24]. According to the requirements of the EU directive 80/779 only 2% of smoke concentrations can exceed 250 μg/m^3. Figure (4) (right panel) shows the percentage of daily smoke concentrations higher than 250 μg/m^3 at "Patission". Violations of the EU limits were on the decline during the greater part of the examined period.

In Table IV the annual mean nitrogen dioxide concentrations for all the available stations of the air pollution-monitoring network in GAA for the period 1986-2000, are presented. It can be easily deduced that the nitrogen dioxide concentrations levels of central-city residential stations (downtown Athens and Piraeus) are significantly higher than the rest of the examined stations. More over the ASV of nitrogen dioxide concentrations is higher at "Patission, as compared to the rest stations of the MEPPPW network, because of the higher emissions from traffic in this area. This station is situated about 8 m from the ground level at the edge of a street with high traffic. The street has six lanes of traffic (three for each direction) with one of them (on the site of the station) devoted for public mass transportation (busses and trolleys). This result, once more, emphasizes the importance of local sources on the measurements at "Patission". For comparison with this case, the seasonal variation at any other station of the MEPPPW network is shown in Table IV.

Table IV: Annual mean nitrogen dioxide concentrations and summary of nitrogen dioxide linear trends for the main stations of the air pollution-monitoring network in GAA.

Station	Operating period	Mean ($\mu g/m^3$)	St. Dev. ($\mu g/m^3$)	ASV[1] ($\mu g/m^3$)	Change per year (%)	Change per winter (%)	Change per warm period (%)
PAT	1986-2000	105	10	35	-1.3*	-1.0*	-1.5*
ARI	1994-2000	78	13	17	-5.3*	-5.6*	-4.3*
ATH	1988-2000	78	9	16	-1.0	-0.3	-1.3*
PIR	1986-2000	73	9	10	-1.5*	-0.8	-1.4
GEO	1986-2000	51	10	18	-1.7	-2.1	-2.1
SMI	1986-2000	44	9	15	4.8	7.7	2.0
PER	1990-2000	56	7	22	-1.5	-2.7	-1.4
MAR	1990-2000	35	4	16	-0.6	-1.5	-0.8

[1] ASV: amplitude of seasonal variation
* statistically significant at the 95% confidence level.

Table IV also summarizes the linear trends observed at all available stations. The overall linear trends seen in this table for each station are also calculated separately for the winter period and warm ones. All trends tested by the Mann-Kendall rank statistics[21]. During the period 1986-2000 the overall trends range from -5.3% to 4.8% per year, while the winter trends range from -5.6% to 7.7% per year and the warm period trends range from -4.3% to 2.0%. The observed rather light amelioration of the air pollution situation, as far as nitrogen dioxide concentrations are concerned, may be attributed to the low rate of catalysts replacement as well as to the inertness of gasoline powered vehicles substitution, with three-way catalyst vehicles[12][23].

The annual mean variation of nitrogen dioxide concentrations in the centre of Athens ("Patission"), shown in figure (5) (left panel), is characterized by a continuous decreasing trend during the examined period. More over the seasonal variation of nitrogen dioxide concentrations at "Patission", shown in figure (5) (right panel), is characterized by a maximum in late spring and early summer, while the winter values of nitrogen dioxide are almost similar with the summer ones. It is well known that

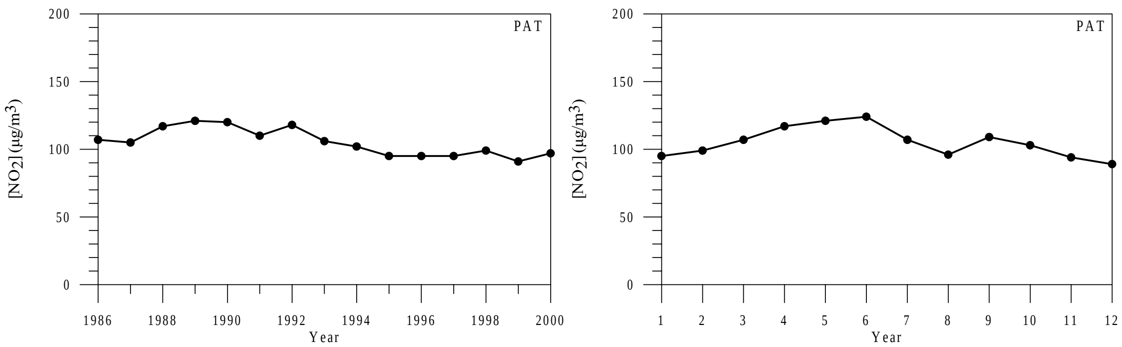


Figure 5: Annual means (left panel) and seasonal variation of nitrogen dioxide concentrations (right panel) for "Patission" station, for the period 1986-2000.

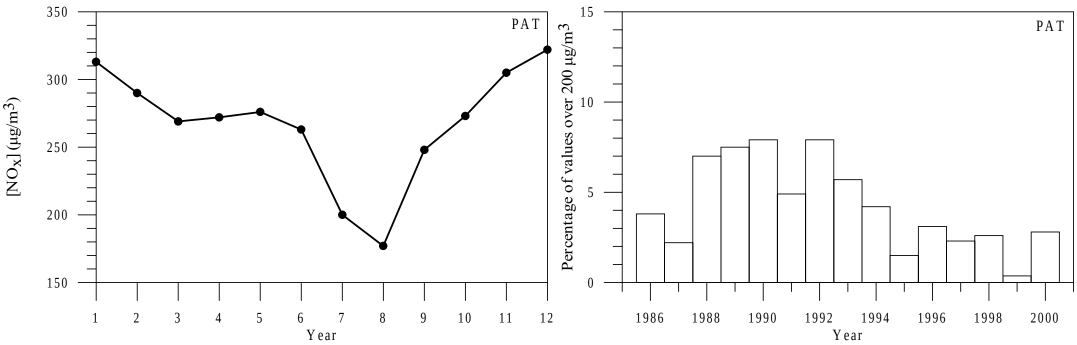


Figure 6: Seasonal variation of nitrogen oxides concentrations for "Patission" station (left panel), and percentage of hourly nitrogen dioxide concentrations higher than 200 μg/m^3 at "Patission" (right panel), for the period 1986-2000.

during summer, although the nitrogen oxide concentrations are lower than the winter ones, however the mechanism of photochemical transformation from nitrogen oxide to nitrogen dioxide is more intense. The almost similar values of nitrogen dioxide in winter and summer and the high nitrogen dioxide values in late spring and early summer may be attributed to this photochemical transformation[12][25].

The seasonal variation of nitrogen oxides concentrations at "Patission", shown in figure (6) (left panel), is characterized by a maximum appeared in winter and a minimum in summer. The average winter values are by about 70% higher than the summer ones. The summer minimum is mainly due to the reduced auto traffic because of July-August vacations but is also enchanced by the blow of the "Etesians" winds. Also another possible reason is the nitrogen oxides oxidation because of the intense solar activity during summer[25].

The annual percentages of hourly nitrogen dioxide concentrations that are higher than 200 μg/m^3, for the period 1986-2000, are shown in figure (6) (right panel). The increase in number of violations of this goal that is mainly observed during the spring season should be attributed partly to the increased number of photochemical pollution episodes[2]. Violations of this long-term goal were on the decline during the greater part of the examined period. The observed reduction can be attributed to the renewal of the vehicle fleet[11][12][17]. Although, for the period 1996-2000, the observed delay in the declination rate of WHO long-term goal violations may be attributed to the low rate of catalysts replacement[23].

4. Conclusions

The analysis of atmospheric concentrations of air pollutants, associated with the vehicle traffic, from all stations obtained by the Athens air pollution-monitoring network that have continuously been monitored during 1986-2000, were examined in order to study both the observed trends and the seasonal variation of atmospheric pollutants in the GAA. From this analysis the following conclusions can be outlined:

(i) Decreasing trends are observed in all the carbon monoxide concentration records. This is due to the increased percentage of substitution of gasoline -powered vehicles with vehicles equipped with three way catalysts. Despite the decreasing trends, the carbon monoxide concentration levels remain high in the centre of Athens and over the EU and WHO limit values during the greater part of the examined period.

(ii) Decreasing trends are observed in almost all the smoke concentration records, caused by the enforcement of some control measures over emission sources. Despite the decreasing trends, the smoke concentration levels remain high in the centre of Athens and over the EU limit values during the greater part of the examined period.

(iii) The seasonal variation of nitrogen dioxide concentrations presents a maximum in late spring and early summer, while the winter values are almost similar with the summer ones. This variation is mainly due to the reduced auto traffic because of July-August vacations but is also enhanced by the blow of the “Etesians” winds. Also another possible reason is the nitrogen oxides oxidation because of the intense solar activity during summer.

(iv) Decreasing trends are observed in almost all the nitrogen dioxide concentration records. Despite the decreasing trends, the nitrogen dioxide concentration levels remain high in the centre of Athens and over the 200 $\mu g/m^3$ values during the greater part of the examined period.

(v) The interannual variations of carbon monoxide and nitrogen oxides show quite the same pattern, indicating influence from the same source (auto traffic).

(vi) The significant improvement of the air pollution situation, taken place during the 1986-200 period, is practically inverted as far as the carbon monoxide and nitrogen dioxide concentrations are concerned. In order to have full harmonization with the air quality standards further measurements should be taken. The emphasis should be put first on both the low rate of catalysts replacement, and the substitution of gasoline powered vehicles with three-way catalyst vehicles.

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THE IMPACT OF FOSSIL FUEL CONSUMPTION ON AIR POLLUTION PROBLEM IN GREECE

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Abstract

The continuous rise of several air pollutants emissions in Greece is strictly connected to the corresponding fossil fuel consumption amplification. This fact is verified by an integrated elaboration of available atmospheric pollutants emissions data. To confront such a problem, an analytical model concerning the prediction of the main air pollutants emission distributions has been developed, on the basis of energy-consumption time-evolution records of each local economy sector. The main target of this study is to realistically simulate the upcoming evolution of the primary air pollutants, using a wide-range of energy market scenarios.

Keywords: Air Pollution; Fossil Fuels; Analytical Model; Energy Consumption

1. Introduction

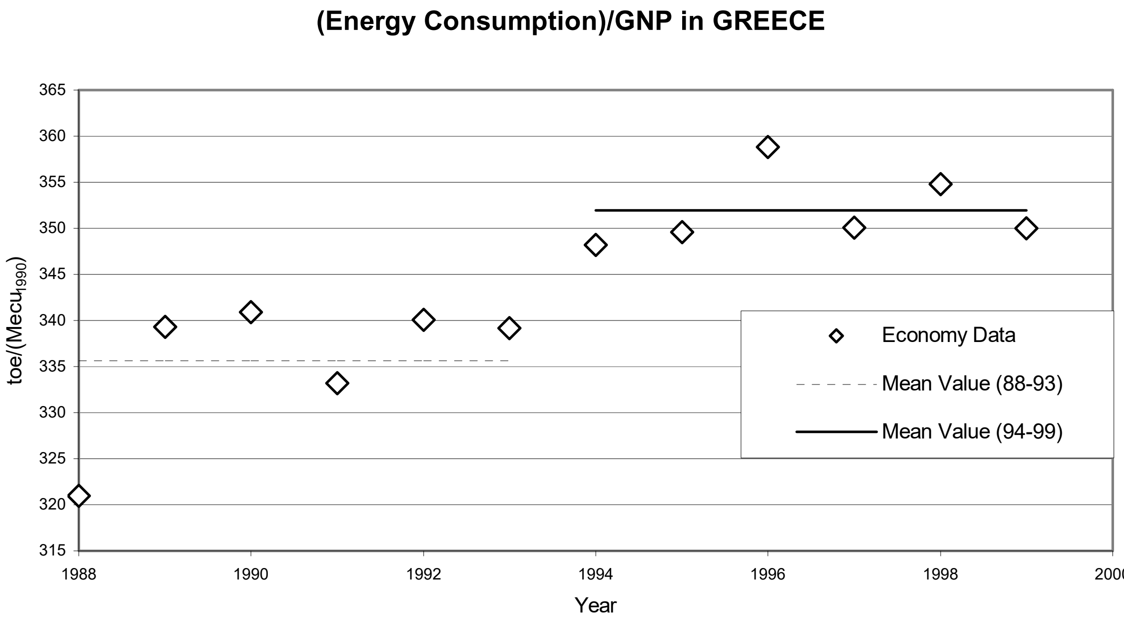

Figure 1: Reduced Energy Consumption Changes in Greece during Last Decade

Greek economy keeps on presenting an energy consumption increase during the last twenty years. This increase is higher than the corresponding GNP increase of local economy, since the specific energy consumption per GNP for (1994-1999) period is by almost 6% greater than the corresponding one of the 1988-1993 period, figure (1). Unfortunately, this excessive energy demand is mostly covered mainly by fossil fuels, despite the fact that non-renewable energy resources are mainly responsible for serious air-pollution problems[1][2].

More precisely, the electricity consumption increase has approximated 4% per annum during the last decade, while it has so far been primarily covered by either imported oil or locally extracted lignite,

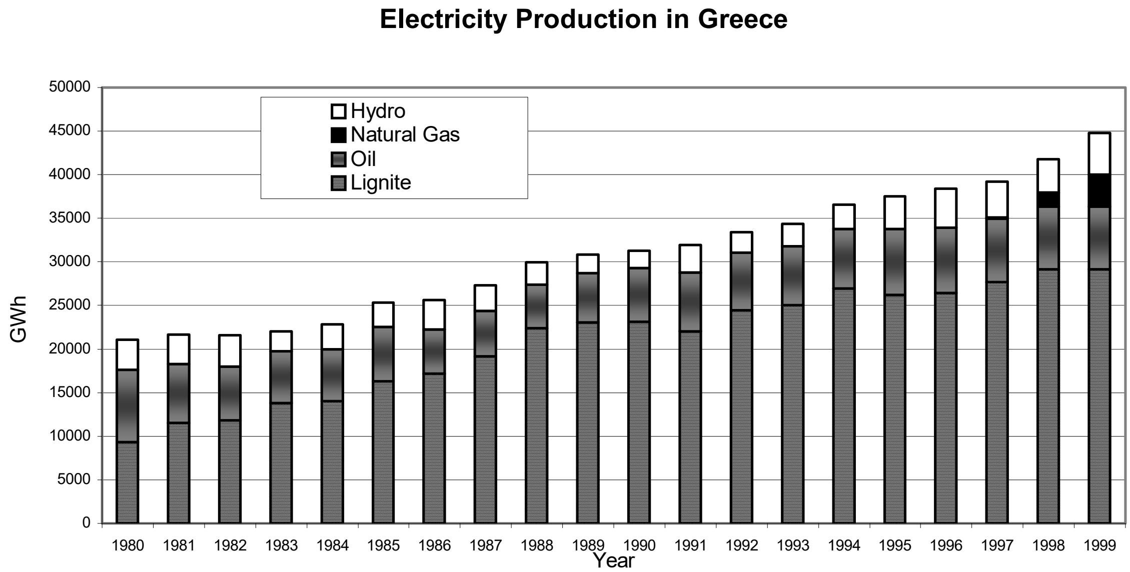

Figure 2: Time Evolution of Electricity Production Profile in Greece

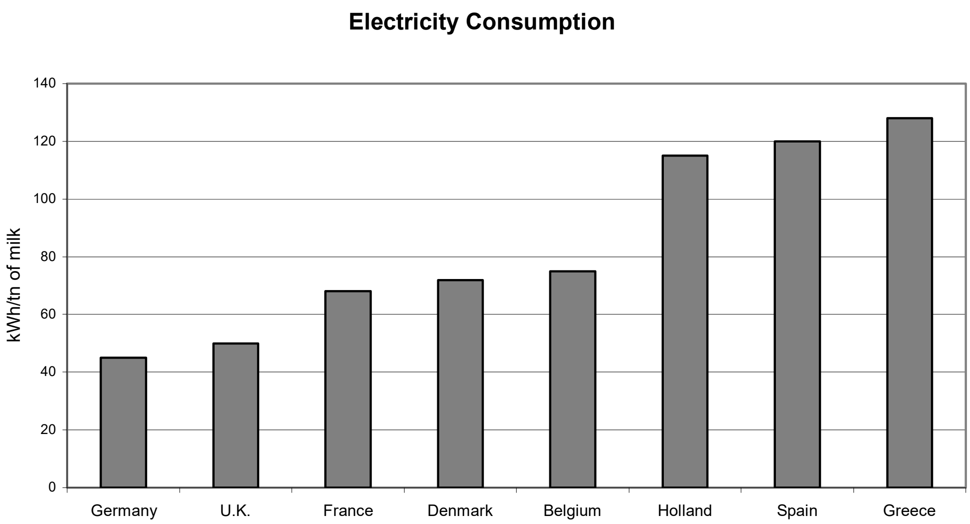

Figure 3: Energy Consumption in Milk Industry[3]

figure (2). Thus, the hydropower stations contribution on the local electricity consumption is less than 10%, while only during the last two years a remarkable natural gas quantity -imported by Russia- is also used for electricity production. Accordingly, the Greek industry -although declining- spends the 29% of the domestic energy consumption. The main characteristic of the local industry[3] is the excessive energy expenditure per unit product, see for example figure (3). Rough estimates for E.U. state that the specific energy consumption of Greek industry is almost twice the corresponding average of the 15 country members of the Union. Finally, the local transportation sector is also responsible for a great deal of the amplified imported oil consumption, since the number of existing private cars exceeds the 2,000,000 (figure (4)), while a serious problem arises by no-substituting the aged auto catalytic converters[4].

On the contrary, the majority of E.U. country members make serious efforts to reduce the usage of fossil fuels, either by limiting the energy waste or replacing conventional energy sources by renewable ones. In this context, the E.U. seems to stabilize the fossil fuel consumption, although the original targets by the European White Paper for Energy are not realized[5].

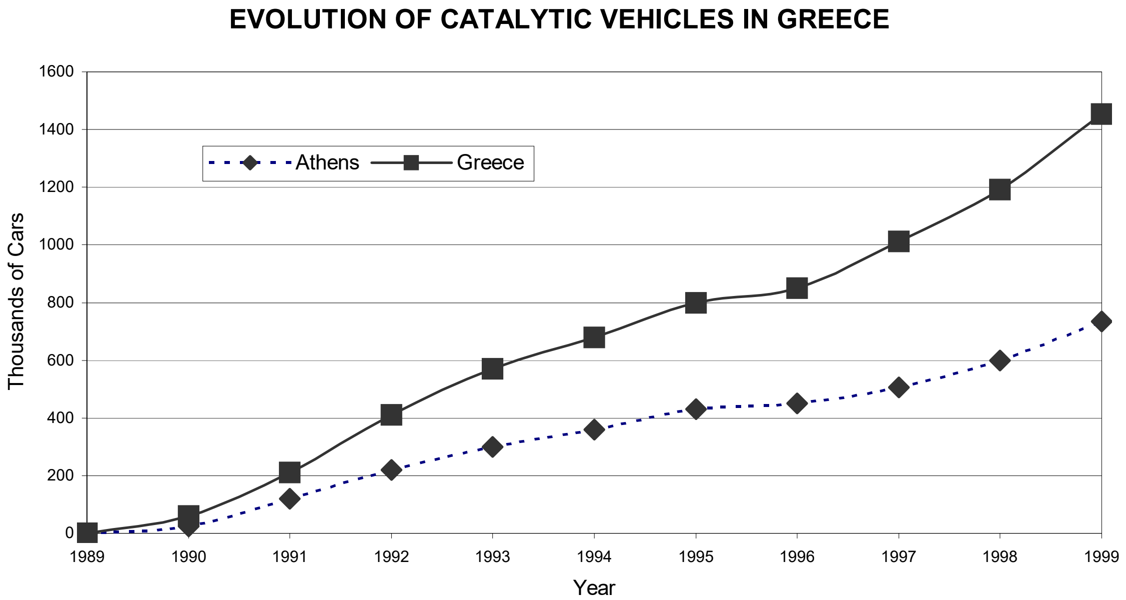

Figure 4: Evolution of Catalytic Vehicles in Greece[12]

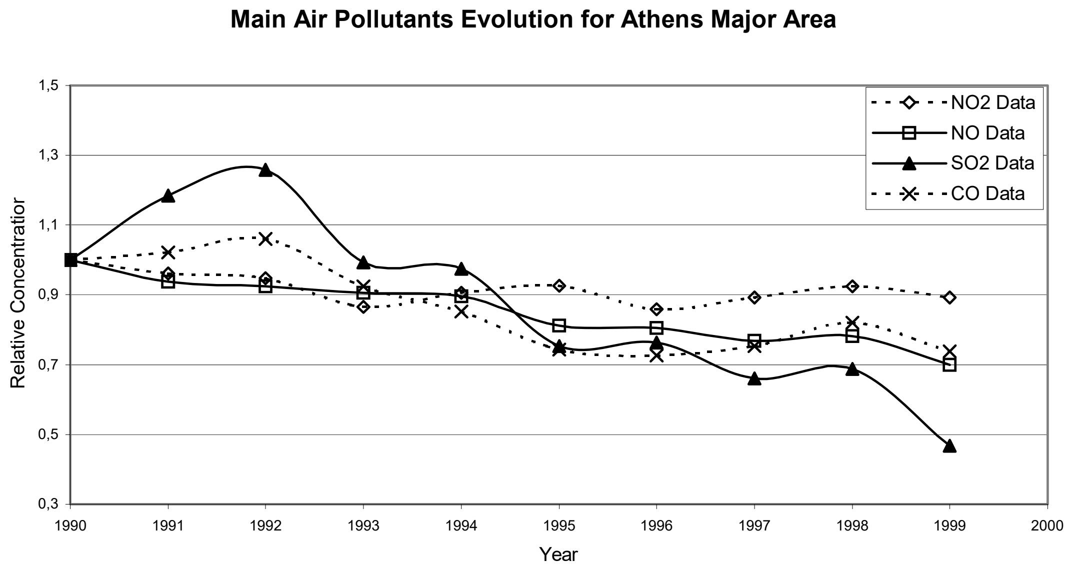

Figure 5: Time Variation of Main Air Pollutants Concentration for Athens Major Area

According to recent research and official data[1][6], every toe of conventional energy consumed in Greece is considered responsible for almost 60gr of CO, 7gr of NO_x, 20gr of SO_2 and 3200kg of CO_2 or equally every Greek citizen contributes annually to the air pollution by 7800kg of CO_2 and 7300kg of equivalent CO[2][7]. This significant environmental surcharge is directly connected to the continuous fossil fuel consumption in order to meet the amplified energy requirements of Greek society[8].

2. Evolution of Atmospheric Pollutants in Greece

In this context, the air-pollution problem should shortly become critical not only for the Greek society but also for Greek Authorities, due to the forthcoming Athens 2004 Olympic Games. In an attempt to get an unambiguous picture concerning the evolution of the primary air pollutants concentration in

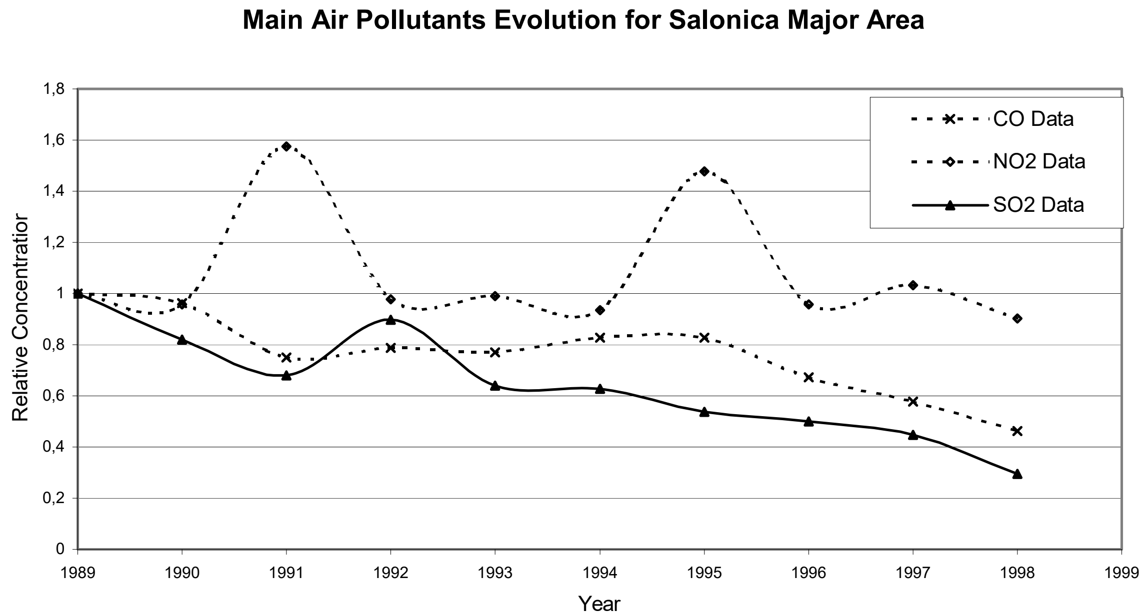

Figure 6: Time Variation of Main Air Pollutants Concentration for Salonica Major Area

Greece during the last years, data collected by local air-pollutants monitoring networks[9][10][11] are hereby analyzed.

More precisely, in figure (5) the weighted average annual values of "CO", "SO_2", "NO" and "NO_2" are presented in a non-dimensionalized form for the major Athens area. As it results from this figure, the main air pollutants concentration practically remains high, despite an assortment of anti-pollution measures, like old vehicles substitution by new -equipped with catalytic converters- ones or fuel quality improvement, e.g. sulphur reduction.

A similar picture arises for Salonica area as well, figure (6), although the values achieved are quite lower than the corresponding for Athens ones. According to the existing data, the "NO_2" concentration remains remarkably high, while a gradual decrease for "CO" and especially for "SO_2" is encountered.

Finally, official data[11] concerning the entire country are also presented from the Greek Regulatory Authority for Energy (RAE) in figure (7). According to these data, there is a significant increase of "NO_x" and "CO" emissions, mainly attributed to the transportation sector[12]. Similarly, the "SO_2" emissions elevation is in contrast to the fuel quality amelioration realized during the last years, ascribed possibly to the low quality lignite overexploitation and the increased mazut consumption by domestic navigation.

Recapitulating, all three air-pollution data collection sources underline the remarkable environmental surcharge resulting from the extensive and continuous usage of fossil fuels in our country during the last thirty years. On the contrary, the penetration of renewable energy sources in the local energy production balance still remains limited, despite the excellent wind, solar and geothermic potential availability.

3. Energy Related Factors for Greek Economy Major Sectors

The environmental destruction because of the flue gases due to fossil fuels is an immediate and imminent threat to the life conditions of the contemporary societies. In the existing Greek energy production frame, diesel oil and mazut represent a remarkable portion of the imported crude-oil products used[13].

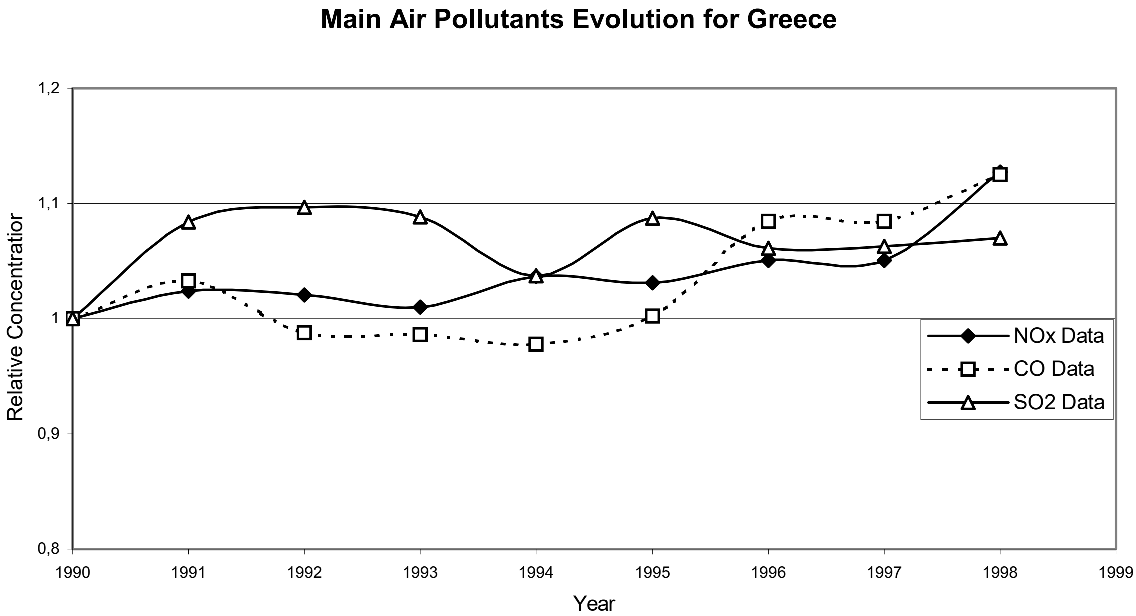

Figure 7: Time Variation of Main Air Pollutants Concentration for Greece

More specifically, diesel consumption has been significantly increased (almost by 40%) during the last ten years, figure (8). Similarly, mazut consumption is also amplified after a remarkable diminution taken place between 1992 and 1994, figure (8). At the same time, the unleaded gasoline consumption has been presenting an almost linear increase since 1991, which is not counterbalanced by the slight decline of leaded gasoline utilization. Eventually, the aircraft fuel consumption has almost remained

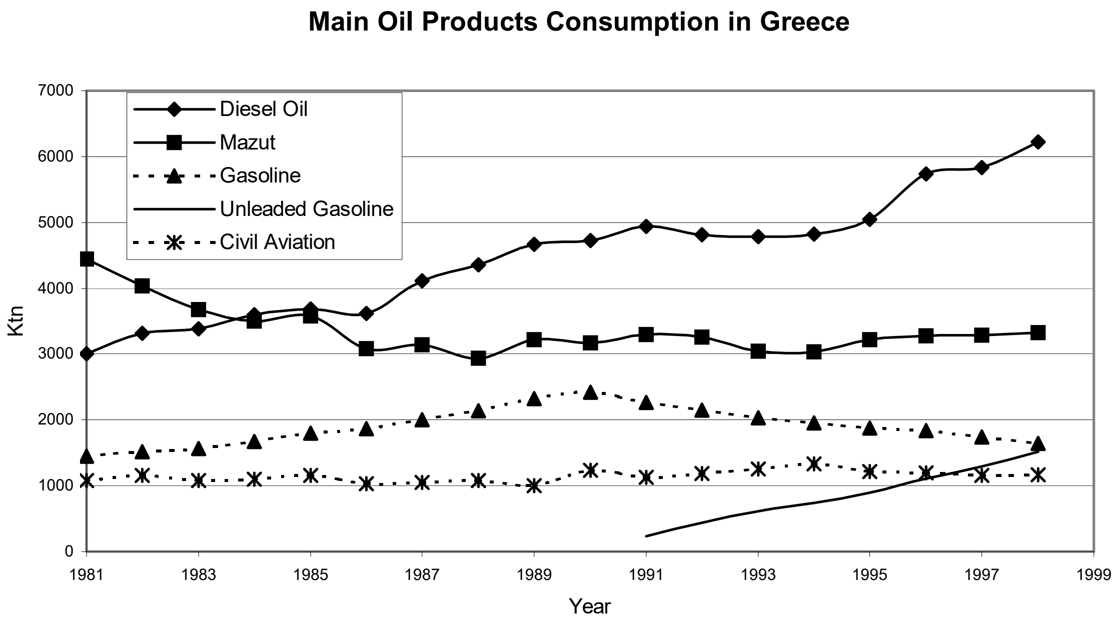

Figure 8: Main Oil Products Consumption in Greece

constant for the entire period examined, figure (8).

On the other side, a continuous increase is being observed for the usage of local (low quality) lignite, figure (9). To be more precise, during the last decade the lignite production at the Megalopolis

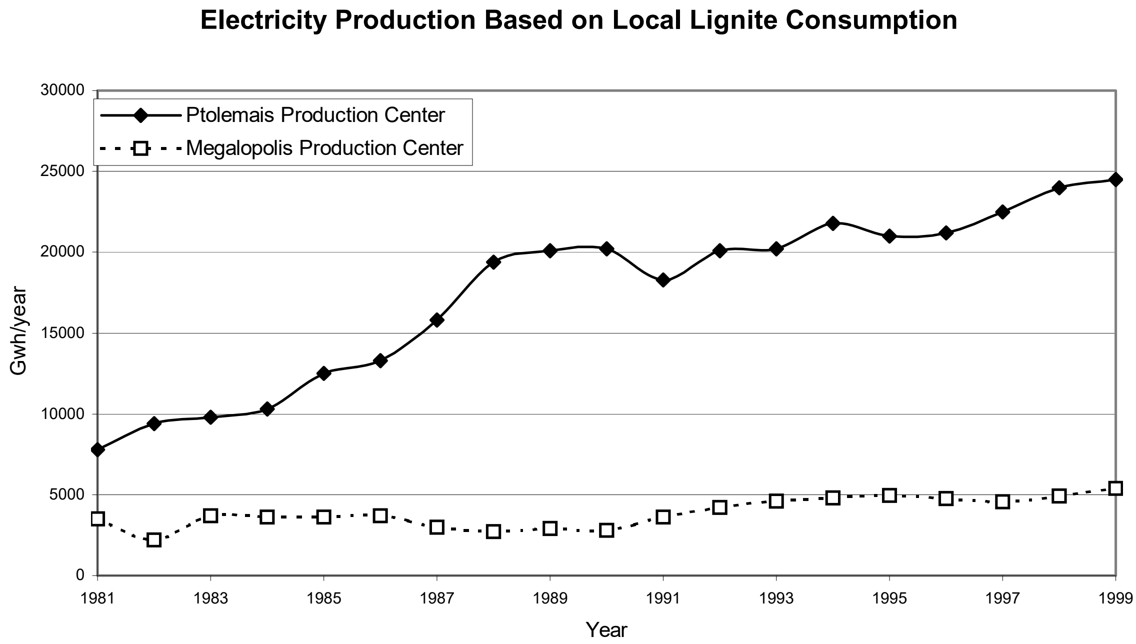

Figure 9: Local Lignite Consumption Evolution in Greece by Public Power Corporation

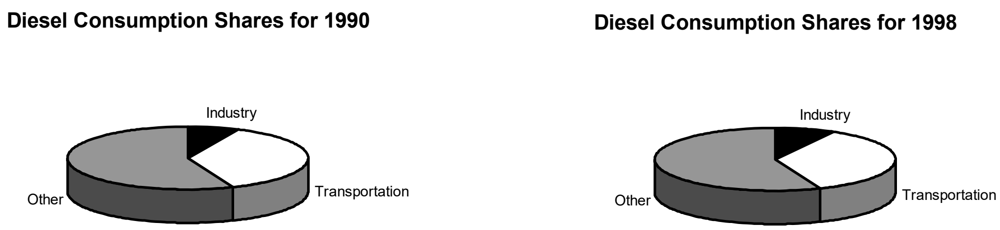

Figure 10: Diesel Consumption Shares Values for 1990 and 1998 in Greece

Production Center has been increased by almost 90%, while the corresponding outcome of Ptolemais Production Center has also been expanded over 20%, despite the deterioration of quality due to the existing reserves overexploitation.

Accordingly, for each fossil fuel used, a detailed analysis is carried out in order to define the specific fuel consumption of every major sector of local economy[2][13]. Thus, in figure (10) the local economy diesel consumption shares are sited for 1990 and 1998. Keep in mind that during the entire decade analyzed there is no remarkable change of the diesel consumption shares, since the diesel oil is mainly used by the tertiary sector (≈56%) of the economy as well as by the local transportation sector (≈36%).

One of the most interesting results of the above-presented approximation is the calculation of the corresponding fuel consumption factors for each sector of Greek economy, "$\varepsilon_{i,j}$", where:

$$\varepsilon_{i,j}(t) = \frac{E_{i,j}(t)}{E_i(t)} \quad (1)$$

with "j" expressing the economy sector and "i" the specific fuel type (e.g. diesel, mazut, gasoline, lignite-Megalopolis, lignite-Ptolemais, etc.). As it is obvious from equation (1) the following relation is valid:

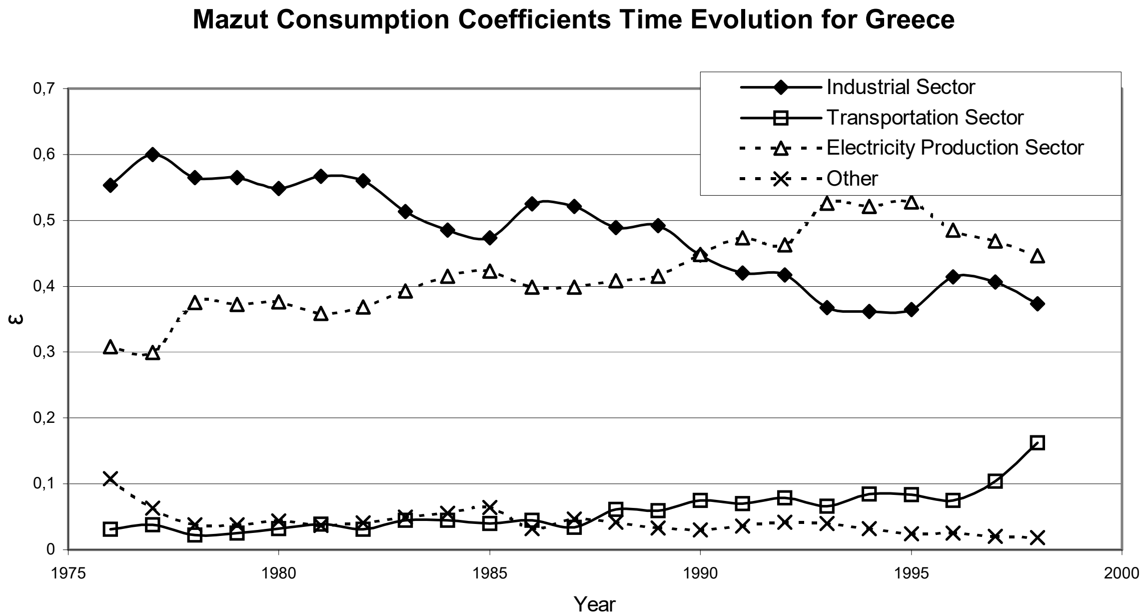

Figure 11: Mazut Consumption Coefficients Time-Evolution for Greece

$$\sum_j \varepsilon_{i,j}(t) = 1.0 \quad (2)$$

since

$$\sum_j E_{i,j}(t) = E_i(t) \quad (3)$$

In figure (11) the calculation results concerning the "$\varepsilon_{i,j}(t)$" variation for the 1975-2000 period is given for mazut (j=mazut) and for the major Greek economy activities (i.e. industry, transportation, domestic-agriculture usage, electricity production). According to the data of figure (11), mazut is mainly consumed by the local electricity production sector (ε≈0.5) and domestic industries (ε≈0.4). Recently, the corresponding "ε" value for transportation sector exceeds 0.15, mainly due to the significant mazut consumption increase by the domestic navigation sector. Generally speaking, the industry share on mazut consumption has been decreased by almost 40% during the last 25 years, while -on the contrary- a remarkably rising trend is valid for the electricity production sector.

The second part of this research is devoted to the estimation of atmospheric pollutants emissions coefficient "e(t)" for every economy sector and every fuel type, i.e.:

$$^k e_{i,j}(t) = \frac{^k P_{i,j}(t)}{E_{i,j}(t)} \quad (4)$$

where "$^k P_{i,j}$" is the emitted quantity of pollutant "k" by the "j" sector of local economy using the "i" fuel type. Finally, "$^k \xi_j(t)$" is the overall emission factor, taking into consideration the entire air pollutant "k" quantity produced by all fuels consumed in the energy sector "j", thus one may write:

$$^k \xi_j(t) = \frac{\sum_i {^k P_{i,j}(t)}}{\sum_i E_{i,j}(t)} = \frac{\sum_i {^k e_{i,j}(t) \cdot E_{i,j}(t)}}{\sum_i E_{i,j}(t)} \quad (5)$$

In Table I, the corresponding preliminary results for the local industrial sector are summarized for the 1996-1998 period concerning the "CO", SO_2", NO_x" and "CO_2" emissions. Bear in mind that in the present paper the "CO_2" emissions are not examined in details, since this important for the climate changes flue gas is separately treated in a parallel work.

Table I: Specific Emission Coefficients (tn/toe) for the Industrial Sector in Greece (1996-98)

Year	**CO**	**NO_x**	**SO_2**	**CO_2**
1996	0.0046	0.0069	0.0236	3.1301
1997	0.0045	0.0064	0.0222	2.9935
1998	0.0048	0.0062	0.0245	3.0381

4. Analytical Model for Energy Related Air Pollutants Emissions Prediction

Up to now the main air-pollutants emissions are estimated, using available information resulting from various economic activities. Subsequently, the corresponding energy consumption by fuel type for every major fiscal sector is predicted within a remarkable wide time-period.

In the following, an analytical model has been constructed in order to contribute on accurately predicting the expected main air pollutants emissions time evolution. The proposed model takes into consideration the energy consumption of each sector of local economy, including also the fuel-mix used, along with projected technological improvements concerning the economy sector under investigation.

Thus, the total annual emitted quantity "${}^kP_i(t)$" of air pollutant "k" due to the usage of fossil fuel "i" may be predicted as:

$$ {}^kP_i(t) = \sum_j {}^kP_{i,j}(t) \tag{6} $$

and using equation (4) as:

$$ {}^kP_i(t) = \sum_j {}^ke_{i,j}(t) \cdot E_{i,j}(t) \tag{7} $$

or

$$ {}^kP_i(t) = \sum_j {}^ke_{i,j}(t) \cdot \varepsilon_{i,j}(t) \cdot E_i(t) \tag{8} $$

Equivalently, the total annual emitted amount of air pollutant "k" attributed to economy sector "j" due to all fossil fuels used in the sector can be estimated according to the following relations:

$$ {}^kP_j(t) = \sum_i {}^kP_{i,j}(t) = {}^k\xi_j(t) \cdot \sum_i E_{i,j}(t) \tag{9} $$

or

$$ {}^kP_j(t) = \sum_i {}^ke_{i,j} \cdot E_{i,j}(t) \tag{10} $$

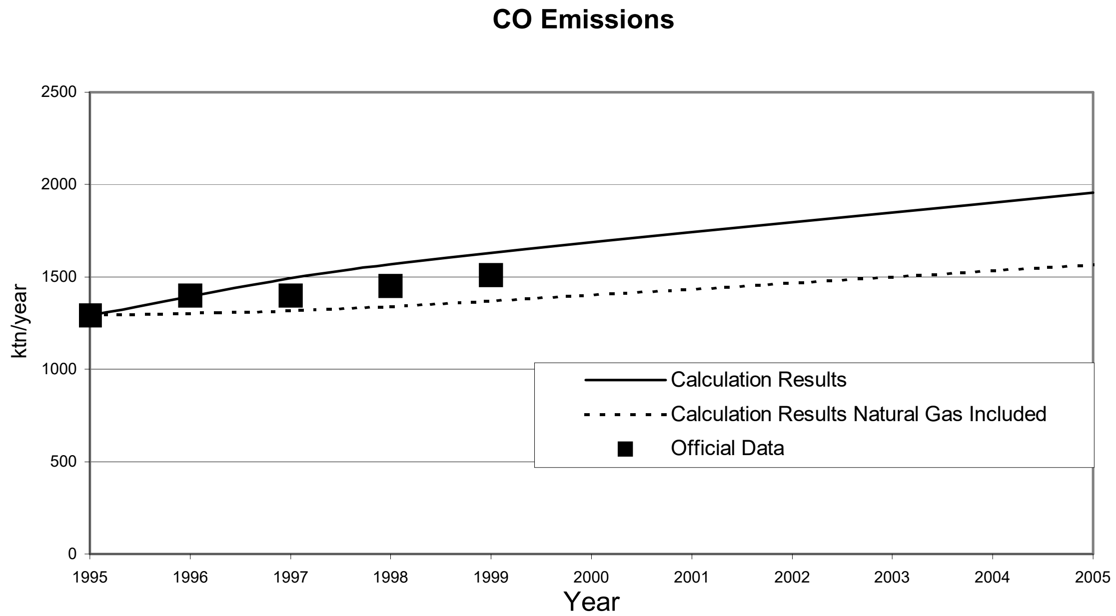

Figure 12: Comparison Between Calculation Results & Official Data, CO Annual Emissions

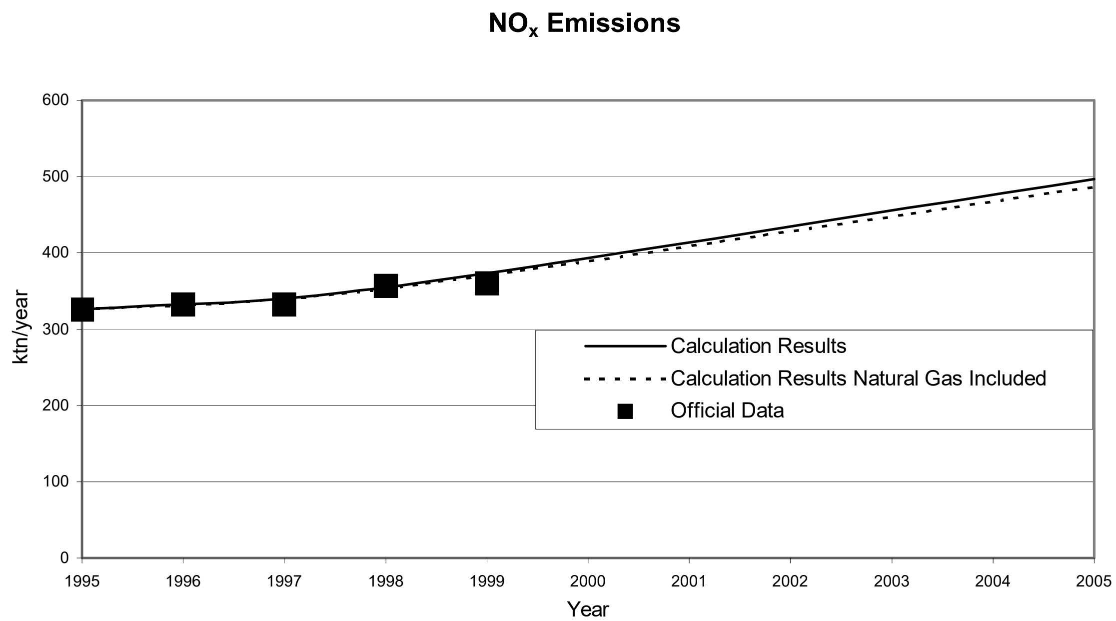

Figure 13: Comparison Between Calculation Results & Official Data, NO_x Annual Emissions

Hence, for example, the calculation of the "CO" emissions in Greece is based on the emission coefficient "${}^{CO}e_{i,j}$" of "CO" for each economy sector and every fuel type used, as well as the fuel consumption factor for any sector of local economy "$\varepsilon_{i,j}$". Bear in mind that both coefficients are time depended, since "$\varepsilon_{i,j}$" takes into consideration the fuel mix changes of every sector of economy and "${}^{k}e_{i,j}$" is strongly influenced by any technological change concerning the utilization of each fossil fuel type by the major economic sectors.

5. Application Results

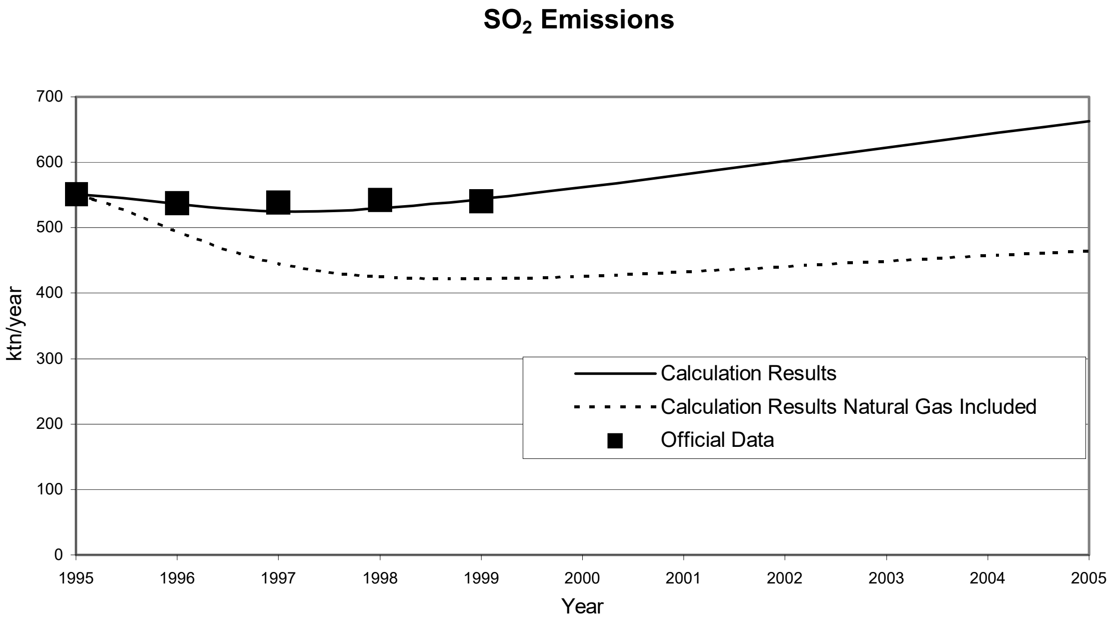

Figure 14: Comparison Between Calculation Results & Official Data, SO_2 Annual Emissions

Using the above-described analytical frame, it is possible to estimate the emissions of the main air pollutants for the period 1996-2005, using only the corresponding data of the previous decade (1986-1995) and the energy consumption values for the time period under investigation (1996-2000).

The results obtained for "CO", "NO_x" and "SO_2" are presented in figures (12), (13) and (14) in comparison with the official values given by the local authorities[11]. At this point it is important to mention that the calculation results validate the existing historical data, while the maximum discrepancy encountered is in the order of 10%.

Accordingly, the proposed model is used to estimate the expected air pollution emissions decrease in case the natural gas gets established in the local market according to the initial plan[14]. In this case, 60% of the natural gas imported every year should be spent to replace local lignite used in Ptolemais thermo-electrical power station, while another 30% should be absorbed by the local industry in place of mazut. Finally, the remaining 10% should equally substitute the diesel used by local industry (5%) and central heating systems (5%).

The corresponding calculation results are also included in figures (12) to (14). Thus, the dangerous air pollutants emissions are fairly modified by the usage of natural gas. This is not the case for the "NO_x" emissions, since the transportation sector, assumed the main responsible for "NO_x" emissions, is not seriously affected by the introduction of natural gas in the local economy. More precisely, a reduction of almost 200ktn of "CO" along with 250ktn of "SO_2" emissions should have been realized, if the natural gas penetration in the local market has followed the original plan for the entire 1996-1999 period.

On top of that, the developed analytical model forecasts a remarkable increase by 40% for "NO_x", 25% for "SO_2" and 35% for "CO" by the year 2005, in comparison with the quantities emitted in 1998. This undesirable evolution can be successfully confronted by well-organized and persistent efforts based not only on accelerated renewable energy sources and natural gas penetration in Greek fuel-mix but also on the reorganization of local energy consumption market on the basis of improved energy saving strategies[15].

6. Conclusions

The continuous rise of several air pollutants in Greece is strictly connected to the corresponding fossil fuel consumption amplification. For this purpose an extensive local market energy consumption time-evolution research is carried out, along with an integrated elaboration of available atmospheric pollutants emissions data, obtained by local air-pollution monitoring networks.

Accordingly, using the experience acquired by the above-mentioned analysis, an analytical model has been developed in an attempt to predict the expected main air pollutants emission time evolution. The proposed model takes into consideration the energy consumption of each local economy sector, including also the fuel-mix used, along with projected technological improvements concerning the fossil fuel utilization industry. The accuracy of the preliminary computational results is encouraging, compared with existing historical data.

The main scope of the complete investigation is to realistically simulate the upcoming evolution of the primary air pollutants, using a wide-range of energy consumption scenarios. Although additional work is necessary, such a computational tool may greatly elucidate the local energy sector authorities about the impact of their choices and, therefore, encourage them to adopt all appropriate measures, in order to minimize not only the financial but also the corresponding environmental cost related to the continuous increasing energy demand.

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THE MANAGEMENT OF DEVALUATED AUTOCATS AND AIR QUALITY VARIATION IN ATHENS

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Abstract

Air quality data obtained by the Athens air pollution monitoring system from the twelve year period started in 1988, is analysed to determine time variations on air quality by carbon monoxide, nitrogen oxides and ozone. The seasonal variation in carbon monoxide concentrations, for three year sub-periods, is characterised by a maximum during the cold period and a minimum during the warm period. The analysis showed a continuous reduction of the amplitude in carbon monoxide seasonal variation, for the first three sub-periods, in contrast to the increase of the last sub-period's amplitude. One of the factors which can explain this amplitude's reduction is the delayed replacement of spent catalysts from the unleaded gasoline-powered vehicles. The analysis of the seasonal variation in nitrogen oxides concentrations, for all the three year sub-periods, showed a continuous reduction of their seasonal variation amplitude. Despite to this significant improvement, the analysis of the seasonal variation in ozone concentrations, for all the three year sub-periods, showed a continuous increase of their seasonal variation amplitude, which can be related with the Athens photochemical air pollution problem.

Keywords: Devaluated Autocats; Air Quality Variation; Vehicle Emissions; Environmental Efficiency;

1. Introduction

Athens, being a city of about 4,000,000 inhabitants, faces air pollution problems as most big cities in the world. The rapid increase of population in conjunction with the continuously increasing motorized fleet, has resulted in high pollution levels during the last 25 years. Until the mid 80's the main pollutants in the Greater Athens Area (GAA) were sulphur dioxide and smoke. Photochemical pollution followed pollution from primary pollutants and resulted in the Athens photochemical smog. In recent years, European Union (EU) and World Health Organisation (WHO) air quality standards are frequently exceeded in the GAA, especially concerning CO, O_3 and NO_x[1][2]. The variability of the physiographic characteristics and the complex topography of the GAA cause the formation of local atmospheric circulations that negatively affect the pollutant transportation and dispersion. The GAA is located in Attica peninsula and includes the Athens basin, the Thriassion Plain and the area of Mesogia. A detailed description of the Athens area may be found in various publications[2].

The Greek authorities, in an effort to protect the environment from a serious air pollution problem, imposed the substitution of gasoline powered vehicles with three-way catalyst vehicles. It should be noted that the vast majority of the vehicle substitution took place mainly during the period 1989-1993. The application of this regulation was initially found to be a satisfactory solution, especially for the heavily polluted urban areas. However, after some years, the efficiency of catalysts is remarkably decreasing, therefore, their replacement is becoming essential[3].

__Paliatsos A.G., Kaldellis J.K., Viras L.G., 2001__, "The Management of Devaluated Autocats and Air Quality Variation in Athens", 7th International Conference on "Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes", Conference Proceedings, Vol. A, pp.474-478, Belgirate-Italy.

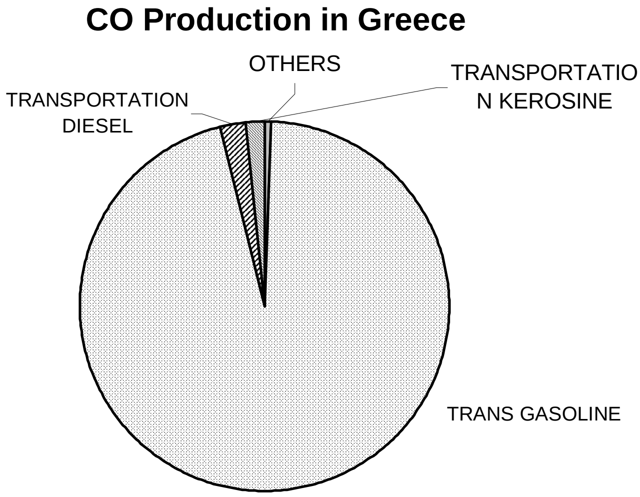

Figure 1: CO Production according to fuel used

2. Position of the problem

In summer 1983, a network was established by the Ministry of the Environment, Physical Planning and Public Works (MEPPPW) in order to measure -by automatic stations- CO, NO, NO_2, SO_2 and O_3 concentrations. The data obtained by the MEPPPW network has been analysed in the past by various researchers[1][2][4][5][6]. The first automatic station ("Patission") -starting operating in 1986- was situated at the headquarters of the public service responsible for the air pollution monitoring system. This station is located at a heavily polluted urban site in the centre of Athens, at the edge of a high-traffic street. The station "Maroussi" –starting operating in 1989- is located in the north east of Athens, about 7 km from the centre of Athens. Nearby -about 300 m- is one of the biggest GAA avenues. Around the station, a few-storied houses with open spaces and some small gardens and greens are situated.

Take into account that gasoline-powered private cars are by far (figures (1) and (2)) the most important factor, contributing to the increased concentration of several primary air pollutants[7][8]. It is also important to note the rapid evolution of private catalytic vehicles (figure (3)) encountered in Athens during 1989-1999[9].

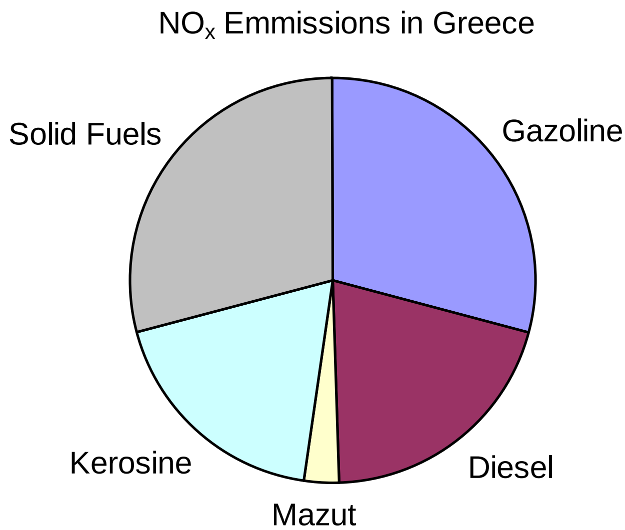

Figure 2: NO_x production according to fuel used

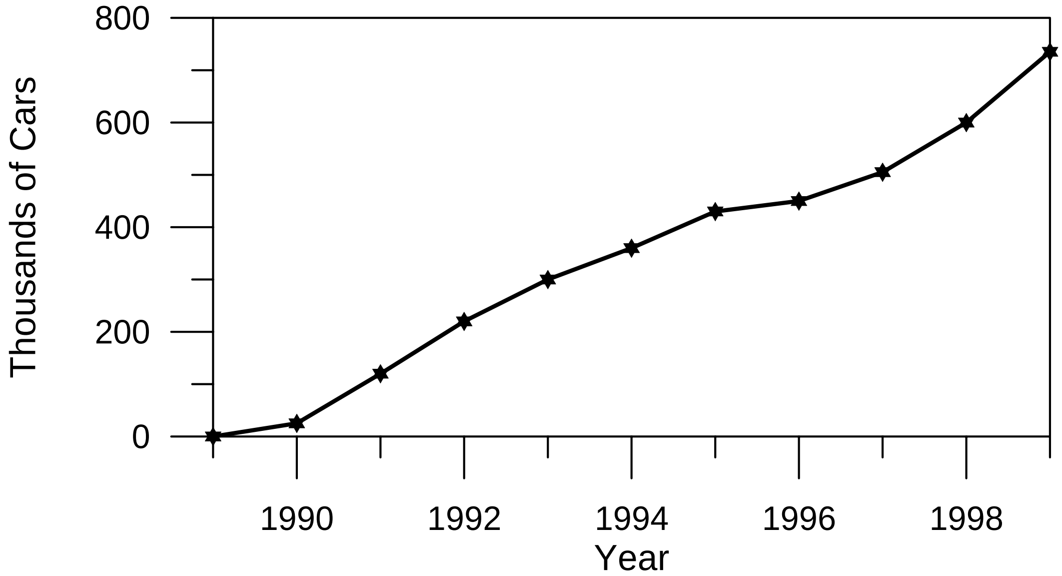

Figure 3: Evolution of catalytic vehicles in Athens

In order to more precisely estimate the air quality variation in Athens before and after pollution abatement measures, the basic pollutants (CO, NO, NO_2 and O_3) three-year averages (1988-1990, 1991-1993, 1994-1996 and 1997-1999), for the "Patission" and "Maroussi" stations, were compared. These averages are presented in Table I (see also figures (4) and (5)), while the changes (%) between the successive three-year means are presented in Table II.

According to the existing data, the NO and NO_2 levels -examined at both stations- demonstrate a decelerated reductive trend, almost zeroed during the last three years. The ozone increase at "Maroussi", during the period examined, may be attributed to the NO levels reduction at the same site (figures (4) and (5)).

Although a gradual CO levels degradation at "Patission" was recorded, late measurements indicate quite the opposite. This fact might be attributed to the corresponding variation observed in the three-year mean percentage values of 8-h carbon monoxide concentrations[10], that are higher than the WHO long term goal (10 mg/m^3) for the period 1988-1999 (Table III).

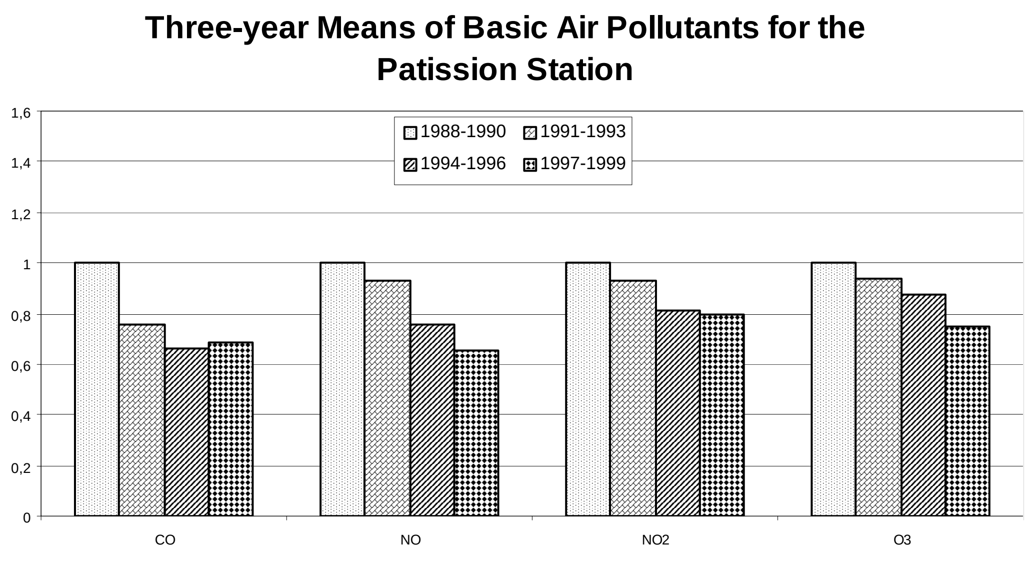

Figure 4: Time evolution of basic air pollutants for “Patission” station (relative values)

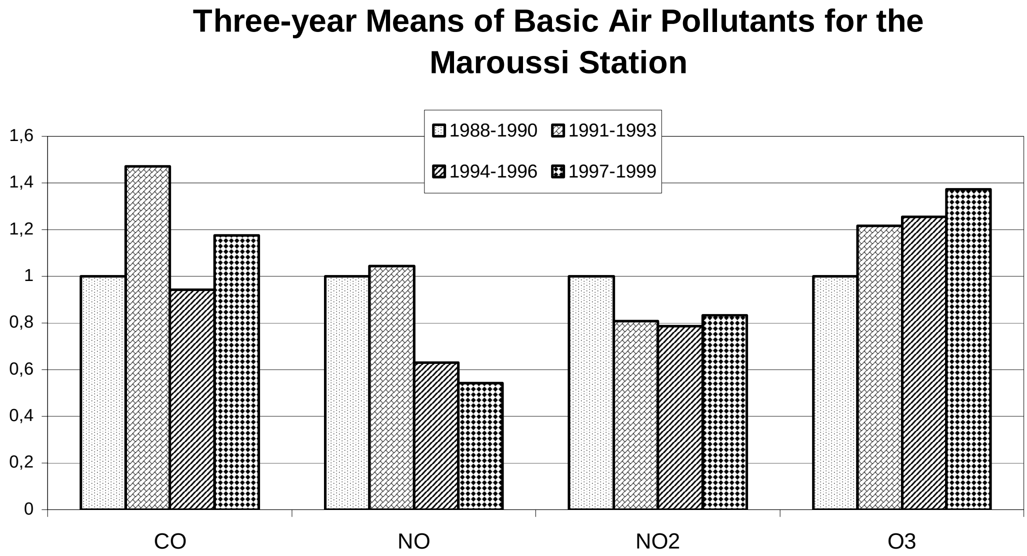

Figure 5: Time evolution of basic air pollutants for "Maroussi" station (relative values)

Table I: Three-year means of basic air pollutants for "Patission" and "Maroussi" stations

Period	**CO** (mg/m^3)	NO (μg/m^3)	NO_2 (μg/m^3)	$\mathbf{O_3}$ (μg/m^3)
1988-1990	7.7 / 1.7	198 / 46	119 / 42	32 / 51
1991-1993	5.8 / 2.5	184 / 48	111 / 34	30 / 62
1994-1996	5.1 / 1.6	150 / 29	97 / 33	28 / 64
1997-1999	5.3 / 2.0	130 / 25	95 / 35	24 / 70

Table II: Counterbalanced changes (%) of basic air pollutants for GAA

Period	CO	NO	NO_2	O_3
1988-1990				
	-5.8	-2.6	-5.3	6.5
1991-1993				
	-10.1	-12.7	-5.4	0.1
1994-1996				
	4.2	-2.3	0.1	1.0
1997-1999				

Table III: Changes (%) of CO concentrations that are higher than 10 mg/m^3 in "Patission"

Period	1991-1993	1994-1996	1997-1999
1988-1990	-73.7		
1991-1993		-89.7	
1994-1996			17.0

Recapitulating, one may conclude that during the first six years of the previous decade, a remarkable decrease of several air pollutants has been recorded, before this situation being inverted during the last four years[3].

3. Environmental Behaviour of Spent Catalysts

What has really happened? One of the most rigid explanations for this significant change is that after some years of service, the three-way catalysts of cars imported after 1990 lose their activity, either due

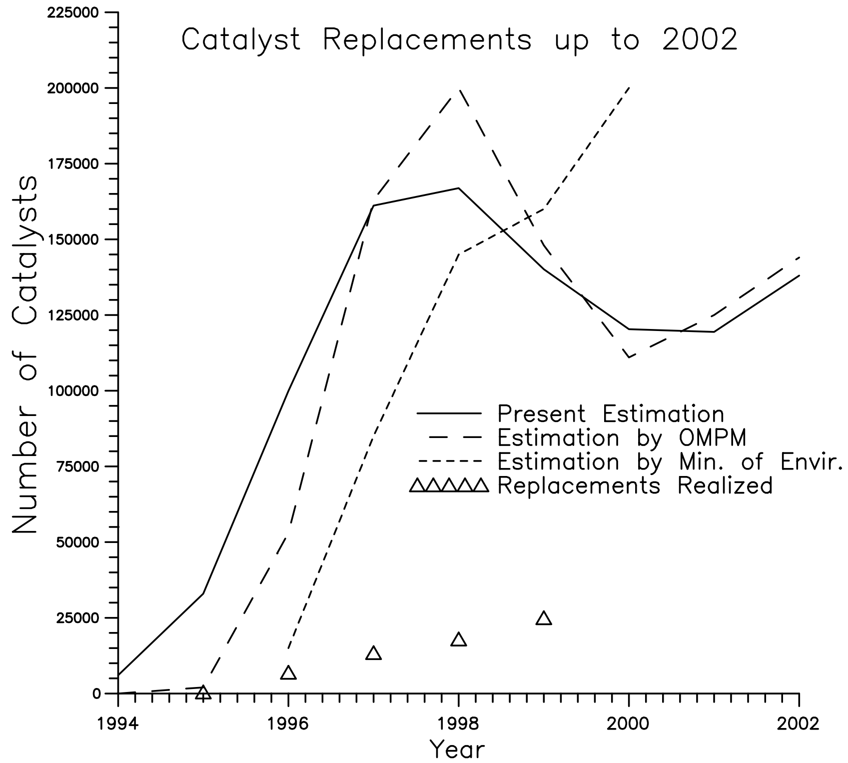

Figure 6: Estimated and realized number of autocats replacements

to thermal impacts or poisoning by contaminants in exhaust. These effects result in gradual decrease of the autocats efficiency. On the other side, the owners of old autocats do not substitute them (figure (6)) by new ones, mainly due to their replacement cost, contributing thus to a remarkable deterioration of the air quality level. This situation is going to worsen, taking into account the gradual degradation of the already existing 1,500,000 autocats in Greece.

In order to estimate the impact of aged autocats on the evolution of atmospheric pollution, the definition[11] concerning the environmental efficiency "η" of an autocat (A/C) is hereby used, expressed as:

$$\eta = \sum w_i \cdot \eta_i \qquad (1)$$

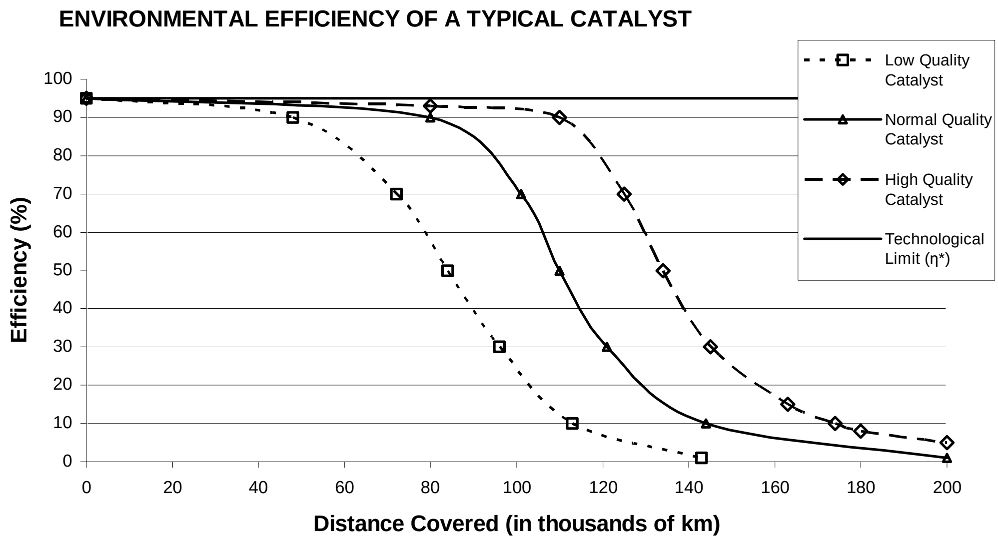

Figure 7: Proposed efficiency distribution of a typical commercial autocat

Keep in mind that "η_i" is defined as:

$$\eta_i = 1 - \frac{\text{quantity of pollutant (i) at the outlet of A/C}}{\text{quantity of pollutant (i) at the inlet of A/C}} \tag{2}$$

and "w_i" is the corresponding weight factor related to the air pollutant "i". The "w_i" depends firstly on the mass flow rate and secondly on the toxicity factor of each pollutant, produced by an internal combustion engine. A typical new catalyst converts approximately 96% of total hydrocarbons "THC", 90% of carbon monoxide "CO" and 96% of nitrogen oxides "NO_x" produced by the engine into less harmful carbon dioxide "CO_2", nitrogen and water vapour.

Using the available experimental data from several sources[12][13] one may conclude that the environmental efficiency of a commercial catalyst is decreased; gradually in some cases, more rapidly in others. Therefore, the distribution of a typical commercial autocat (figure (7)) is proposed by the authors. For example, according to this semi-empirical profile, the environmental efficiency of an autocat after an 80,000 km distance covered is between 0.55 and 0.94, while the minimum (EU-2000 limits) environmental acceptable efficiency "η_{min}" is 0.8.

4. Conclusions

Air quality data -obtained by the Athens air pollution monitoring system, from the twelve-year period started in 1988- are investigated in order to determine time variations of selected air pollutants, mainly attributed to the transportation sector of the economy. According to the proposed analysis, the amelioration of the air pollution situation, taken place during the 1990-1996 period, is practically inverted, especially as far as the CO and NO_x emissions are concerned.

One of the main factors explaining this negative evolution is the low replacement rate of spent catalysts from the unleaded gasoline-powered vehicles. In fact, an integrated statistic analysis model is under development, in order to establish a quantitatively relation between air pollution changes and gradual degradation of existing autocats. Taking into account all above information, we believe that the local authorities have the necessary data to determine the future of spent autocats in our country, in view of the encountered air quality variations in the GAA.

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THE IMPACT OF AUTOMOBILE CATALYTIC CONVERTERS DEGRADATION ON AIR QUALITY

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Abstract

The gradual decrease of autocatalyst efficiency, either due to thermal impacts or poisoning, is responsible for a significant contribution of the transportation sector to the air quality deterioration for the majority of urban areas. In the present work autocatalyst degradation procedure is analyzed both theoretically and experimentally. For this purpose, experimental measurements carried out by several European Organizations are included in order to establish quantitative relations between autocatalyst environmental efficiency and their service period. According to the results obtained, a statistically validated relation between air pollution changes in the main urban areas and gradual degradation of the existing 1,500,000 automobile catalytic converters (ACC) can be established.

Keywords: Air Quality; Automobile Catalytic Converters; Environmental Efficiency

1. Introduction

Catalysts have been widely used since 1980 to lower the emissions of carbon monoxide (CO), hydrocarbons (HC) and nitrogen oxides (NO_x) in the exhaust of automobiles all over Europe. In this antipollution frame, the introduction -by Greek State- of catalytic converters in cars, at the beginning of the 90's, was a positive movement to control the dramatically increased air pollution[1] in the main urban areas (e.g., figure (1)). In fact, during the first half of this decade, a decrease of several air pollutants has been recorded, before this situation being inverted in the last years[2].

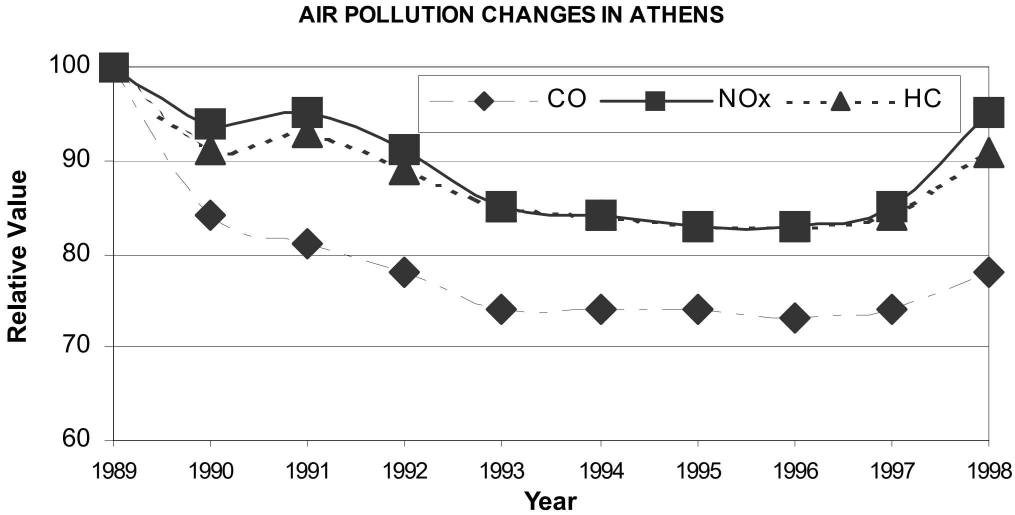

Figure 1: Air pollution changes in the Athens Region

What has really happened? One of the most rigid explanations for this significant change is that after some years of service, the three-way catalysts of the cars imported after 1990 lose their activity, either due to thermal impacts or poisoning by contaminants in the exhaust. These effects result in gradual

***Kaldellis J. K., Konstantinidis P., Charalambidis P., 2001**, "The Impact of Automobile Catalytic Converters Degradation on Air Quality", International Conference on "Ecological Protection of the Planet Earth I", Vol. II, pp.633-641, Xanthi, Greece.*

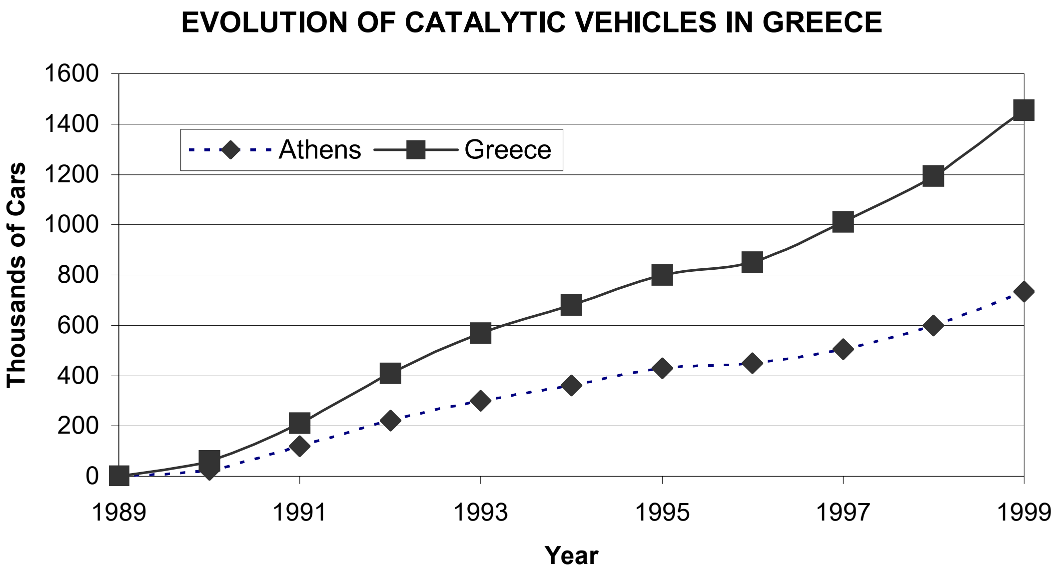

Figure 2: Evolution of catalytic vehicles in Greece

decrease of the automobile catalytic converters (ACC) efficiency[3]. In addition, the owners of old ACC do not substitute them by new ones, mainly due to their replacement cost[4], contributing thus to a deterioration of the air quality level for the majority of urban areas. This situation is going to become worst, taking into account the gradual degradation of the already existing 1,500,000 ACC in these areas. At the same time an increasing number of new cars (figure (2)) enters the local market without, having the old ones replaced.

To facilitate the solution of this extremely urgent problem, the ACC degradation procedure is analyzed in the present survey, both theoretically and experimentally. For this purpose data concerning thermal effects and phosphorus-lead and sulfur poisoning are investigated, taking into account that interactions among poison species complicate deterioration studies.

Additionally, experimental measurements carried out by several European Organizations, in order to estimate the emission level of aged ACC, are also included. These results are statistically analyzed so as to establish quantitative relations between the environmental efficiency of ACC and their service period.

Finally, the establishment of a relation between the air pollution changes in the main urban areas and the time-evolution of the catalytic vehicle number in Greece, extracting the replaced aged ACC, is examined and statistically analyzed as far as its confidence intervals are concerned.

2. Automobile Catalytic Converters Degradation

It has been established that three-way catalysts gradually lose activity both due to thermal effects and poisoning. Besides these procedures the chemical-thermal deactivation is another complicated reason contributing to the efficiency decrease of the ACC.

More precisely catalytic converters are designed to withstand occasional high temperature operation. On top of that the efficiency of a catalytic converter significantly increases[3] over 300 to 400°C, while the light-off temperature of the main air pollutants is at temperatures higher than 350°C. However, prolonged and repeated exposure to temperatures above 800-1000°C leads to a considerable deterioration of catalytic performance.

According to existing studies[5][6], commercial catalysts' exposure to oxidizing conditions at high temperatures results in changes in activity for NO_x reduction and CO oxidization, which are generally attributed to Rh deactivation. Thus, repeated oxidization may permanently damage the ACC. Additionally, Pt and Pd used in contemporary catalysts are susceptible to sintering and loss of active metal area. In general, Pd is less susceptible to thermal deterioration than Pt.

As mentioned above, phosphorous, lead and sulphur are the main contaminants assumed responsible for ACC poisoning. Keep in mind that phosphorous in fuel along with phosphorous derived from engine oil additives are potential sources of ACC phosphoric contamination. Of course the phosphorous level in unleaded regular gasoline is very low compared to the engine oil one. Studies illustrate that 93% of P is derived from engine oil while only the rest 7% from the fuel used. Experimental studies indicate that the existence of P in oil additives lowered the conversion of NO_x, CO and HC compared to no usage of them. Besides, the effect of poisoning with phosphorus on the conversion efficiency of the catalyst revealed a greater loss in CO than in NO_x conversion.

The so-called unleaded gasoline used by the catalyst-equipped vehicles currently contains about 1-2mg/l Pb (and in no case greater than 5mg/l). It is well established that any notable increase in lead usage would accelerate the deterioration of three-way catalysts. Several comparisons[7] with similar catalysts aged on clear fuel showed that HC and NO_x conversion was lowered by exposure to lead-containing fuel, whereas CO conversion was not. Generally speaking, one may assert that lead is a less dangerous poison of three-way catalyst activity than phosphorus.

Sulfur dioxide is present in exhaust gas at a concentration of about 20ppm arising from 0.03% sulfur in typical unleaded regular gasoline. Laboratory studies demonstrated that a 0.0 to 0.03% increase of gasoline's sulfur content resulted in lower CO, hydrocarbon and gross NO_x conversions, but a further increase in fuel content to 0.09% did not result in any additional activity drop. Subsequently, sulfur dioxide has been found to suppress the reduction of NO_x to NH_3 by Pt catalysts as well as the oxidization of propylene. On the other side, SO_2 does not significantly poison the NO_x reduction activity of Rh. Therefore, SO_2 has not been perceived as a severe poison of Pt-Pd oxidization catalysts[8].

Finally, an important part of ACC degradation is attributed to their micro-structural changes. According to electron microscopy analysis (TEM/STEM/EDS) of a standard commercial three-way catalyst surface composition, the fresh catalyst showed highly dispersed precious metal particles with quite homogeneous distribution[9]. The particle size distribution measured shows diameters in the range of 1-10nm with an average between 3-4nm. The aged sample showed large sintering of metal particles. Their sizes ranged from 20nm to several microns, significantly decreasing the precious metal dispersion on the catalyst surface. Additionally, EDS analysis showed a smaller relative amount of rhodium compared to platinum (12:1) than the fresh sample did (5.5:1), while the theoretical values are 5.1:1. This is mainly due to the much higher surface mobility of Pt in comparison to Rh. Lastly, photoelectron spectroscopy (XPS) measurements indicated a higher degree of rhodium oxidization in the aged sample than in the fresh catalyst. This dramatic change on precious metal used dispersion on the catalyst surface[10] is assumed responsible for the lower conversion levels of NO_x and HC of the aged catalyst in comparison to the fresh one. The CO emissions behaviour cannot clearly be determined[11], due to the additional (secondary) carbon monoxide creation by the incomplete hydrocarbon oxidization, taken place in an aged ACC.

In summary, it is easy to conclude that it is almost impossible to develop a reliable theoretical model concerning the time-depending degradation of an ACC, mainly due to the complicated procedures taken place during its operation and also due to the lack of extensive measurements. In the next chapter the available experimental measurements realized by several independent research groups are analyzed in order to validate the corresponding analytical model proposed by the authors some years ago[3].

3. Time Depending ACC Efficiency Deterioration

As far as the environmental efficiency η_i of an ACC is concerned, the following definition given by Konstantinidis and Kaldellis[3] is adopted here:

$$\eta_i = 1 - \frac{\text{quantity of pollutant (i) at the outlet of autocatalyst}}{\text{quantity of pollutant (i) at the inlet of autocatalyst}} \quad (1)$$

where the index i is related to the air pollutant i. A typical new catalyst[2] converts approximately 96% of total hydrocarbons THC, 90% of carbon monoxide CO and 96% of nitrogen oxides NO_x produced by the engine into less harmful carbon dioxide CO_2, nitrogen and water vapour.

As mentioned above, it is not possible at this moment to define a theoretical distribution of the time-evolution of the environmental efficiency of an ACC. Thus, we are going to use any reliable existing experimental information in order to develop an analytical semi-empirical profile of typical catalyst efficiency. For this purpose, measurements from lab ageing tests as well as measurements of on road ageing procedures are used[13][14]. Both data sets present important disadvantages, while, on the other side, one should take into consideration that accessibility on similar information is very difficult. In order to evaluate the artificial ageing procedures data, one should keep in mind that in these tests the experimental conditions are usually perfectly controlled. However, it is almost certain that the results of such an ageing procedure during a 50h, 100h or even 200h of experiments are not the same with a normal operation ageing results of a catalyst, which normally takes place during a ten to fifteen years period. Accordingly, on-road measurements may be influenced by several uncontrollable parameters, like the fuel used quality, the operational situation of the vehicle's engine, the circulation status, the atmospheric conditions, any mechanical problems of the ACC or even the driver personality. On top of that, detailed experiments are very rare in the bibliography and in most cases critical information is missing.

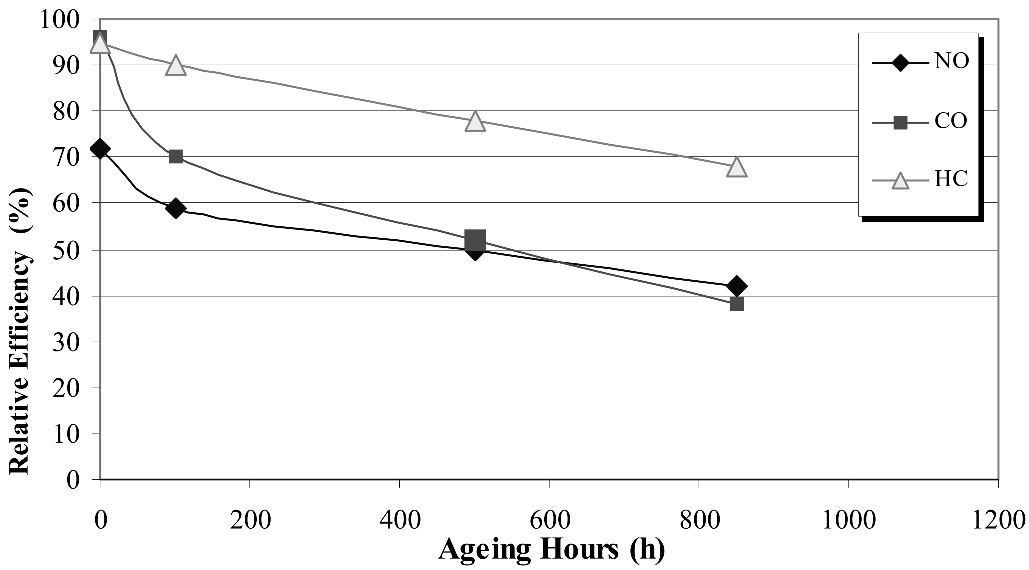

Figure 3: ACC artificial aging results[12]

Under these circumstances, we have collected several lab test results concerning the artificial ageing of various commercial catalysts. During the first case analyzed (figure (3)), the catalyst was aged[12] for 800-850 hours (roughly equivalent to 90,000 km). The catalyst inlet temperature at the higher engine speed was 760°C and at the lower engine speed 593°C. As it is clear from figure (3), a significant decrease of the catalyst efficiency is observed, especially as far as the CO and NO_x emissions are concerned.

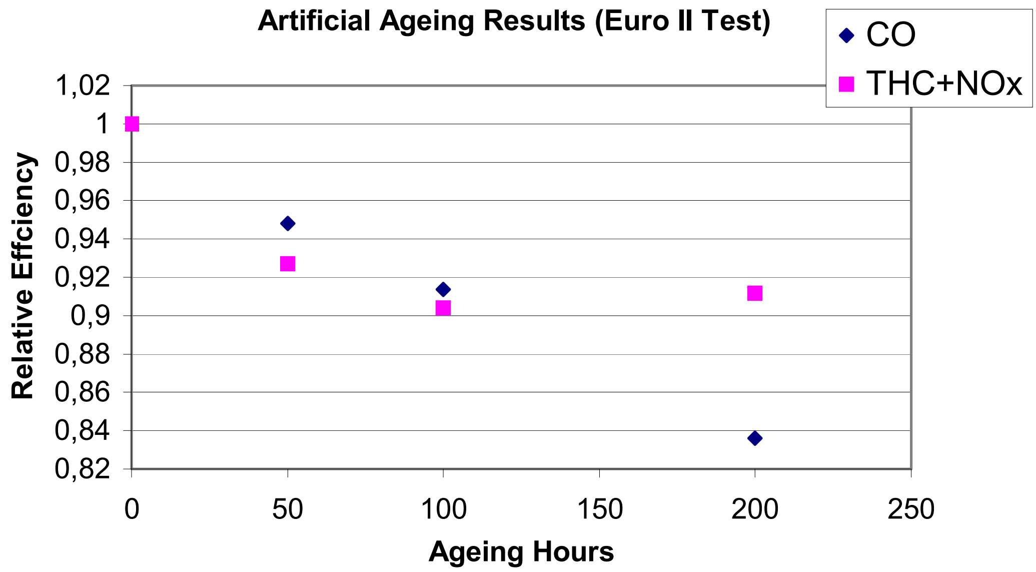

Figure 4: ACC artificial aging results[13]

The second test case investigated here is a more recent one (figure (4)) concerning the results of artificial ageing according to RA-A2 Euro II test procedure. The catalyst was aged[13] for 200 hours (50h are roughly equivalent to 80,000km). The catalyst inlet temperature was 850°C and the vehicle used was an "Opel Corsa 1.6GSi." The ACC volume was 1.8lit and its weight was almost 3.6kg. The results of the ageing procedure are summarized in figure (4), where a significant decrease of the catalyst environmental efficiency is observed, especially as far as it concerns the CO emissions.

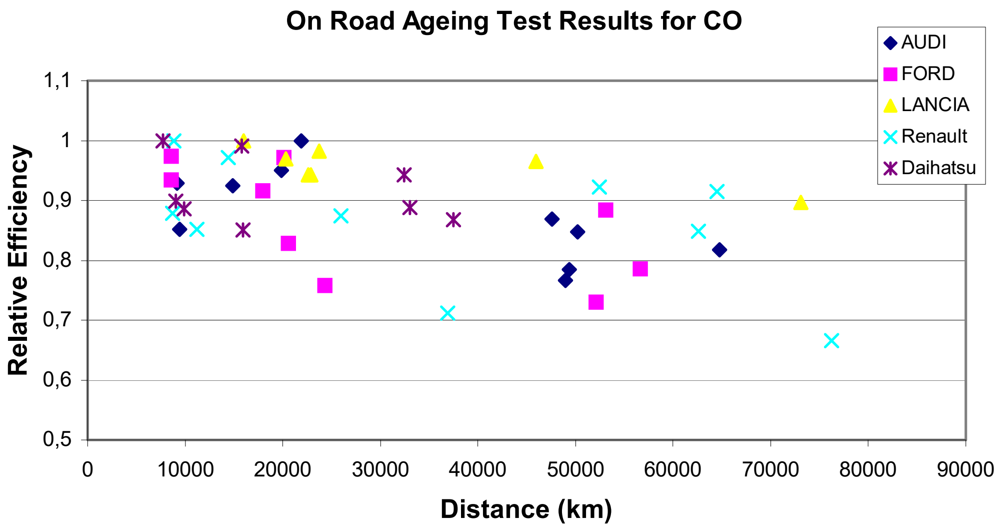

Figure 5: ACC on-road aging results[14]

Subsequently, the experimental measurements concerning the on-road ACC ageing results are presented. Keep in mind that the first series of data are based on[14] the annual reports of the Ministry of Housing, Physical Planning and Environment of the Netherlands, and the sample used consists from at least five different vehicles of the same model. The second set of data is based on measurements[13] concerning one car for every model tested. According to the data of figures (5) and (6) a significant diminution of the ACC environmental efficiency, regarding the CO emissions, is encountered. Almost

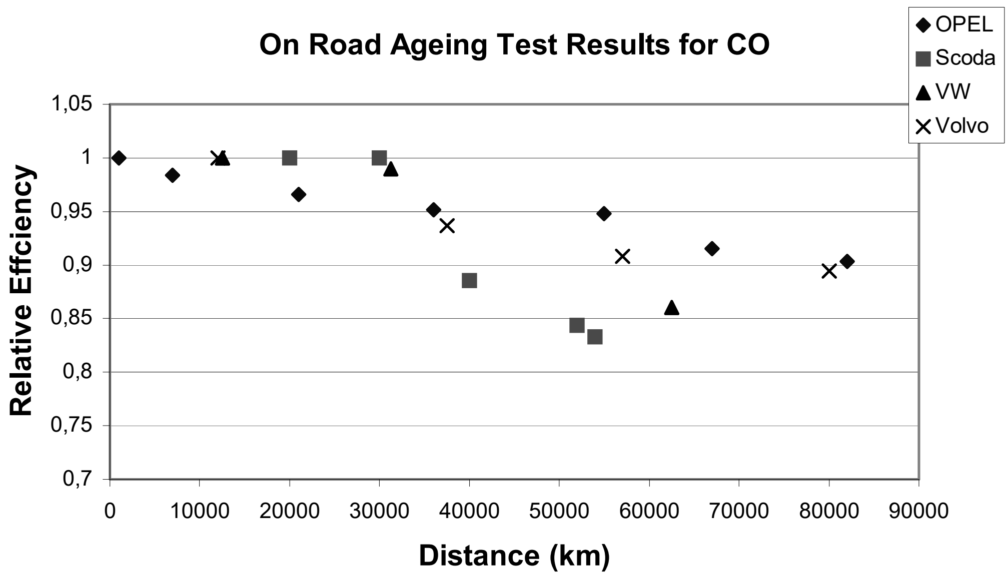

Figure 6: ACC on road aging results[13]

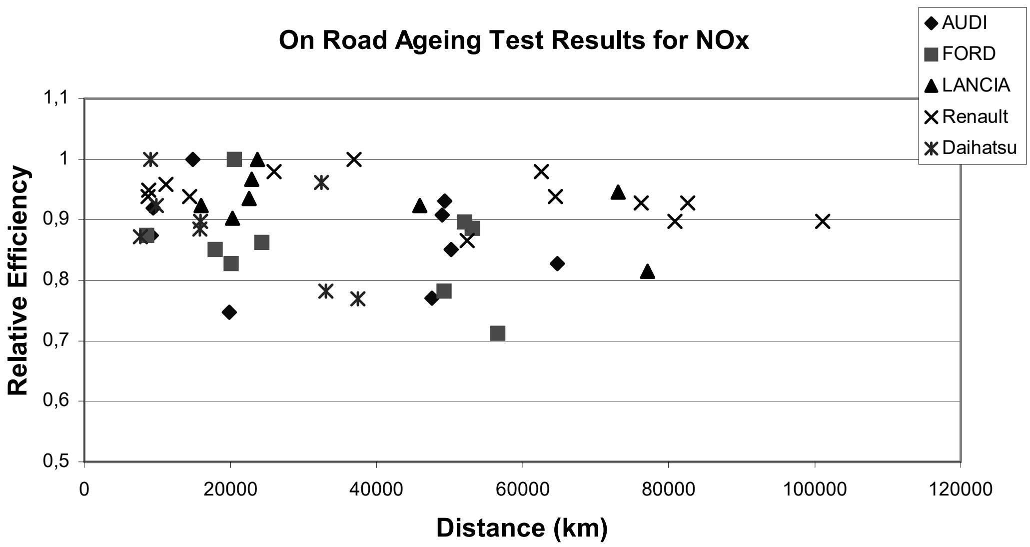

Figure 7: ACC on-Road aging results[14]

all tests present a considerable efficiency decrease (by approximately 15%) before the distance of 80,000km. This ACC degradation is more obvious after the 40,000km.

A similar picture is also applicable for the NO_x environmental efficiency of the catalysts (figures (7) and (8)). The efficiency distributions of the second series of measurements present a more typical shape than the ones of the first series, since the first set of data is based on more than a single car operational behaviour. However, all tests show a significant ACC efficiency degradation (of the order of 20%) regarding the NO_x emissions.

In summary, we can assert that for all the tests analyzed here (on road and artificial aging ones) an important degradation of catalysts environmental behaviour is detected, which usually starts after the first 30,000 to 40,000km, being also much more pronounced after 80,000km of operation of the ACC.

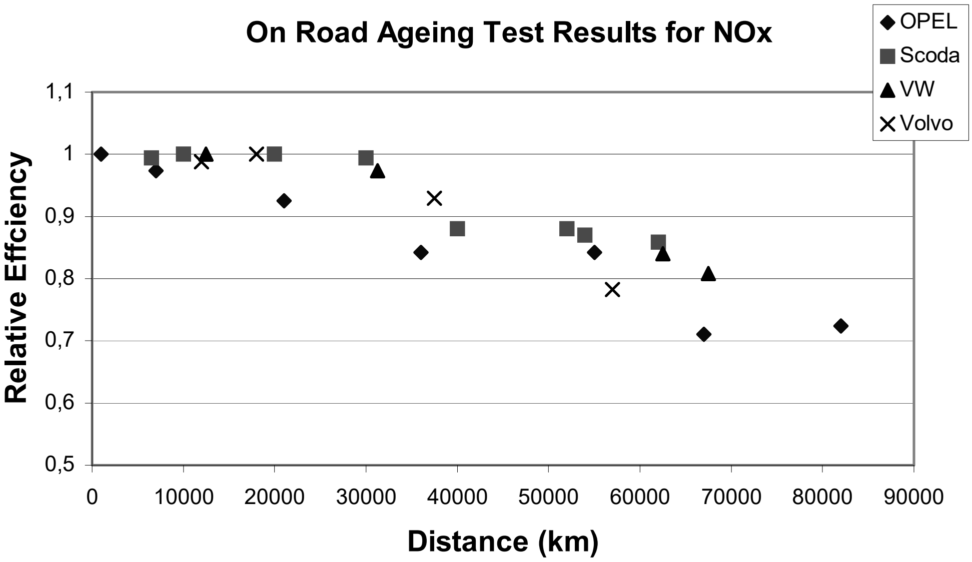

Figure 8: ACC on road aging results[13]

4. Proposed Analytical Model

Using the experimental information of the previous section, one may conclude that the environmental efficiency of a commercial catalyst is, gradually in some cases and more rapidly in others, decreased.

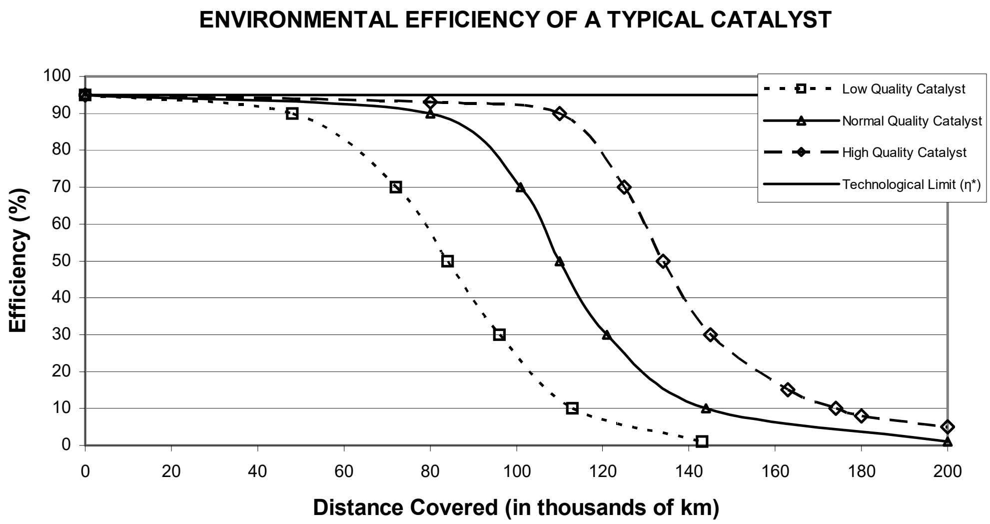

Figure 9: Proposed efficiency distribution of a typical commercial ACC

Therefore, the distribution already proposed by the authors may be used (figure (9)). For example, according to this semi-empirical profile, the environmental efficiency of an ACC after an 80,000km distance covered is between 0.55 and 0.94, while the minimum environmentally acceptable (EU-2000 limits) efficiency η_{min} is 0.8.

Using the beta-distribution[15], regarding the probability density function "f=f(η)" of an ACC efficiency, we get:

$$f(\eta) = \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\cdot\Gamma(\beta)} \cdot \eta^{\alpha-1} \cdot (1-\eta)^{\beta-1} \tag{2}$$

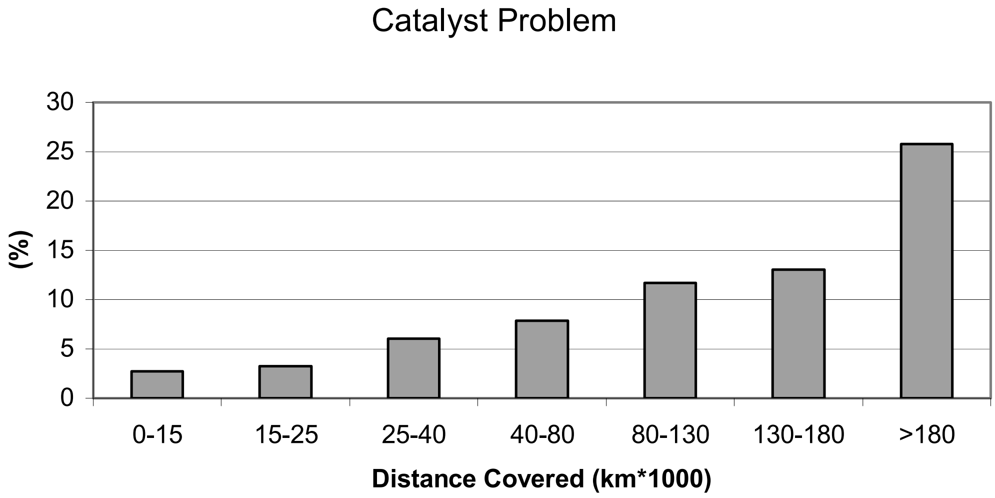

Figure 10: Results of catalyst controls[16]

where Γ(x) is the well known gamma function and the parameters α and β are defined using the mean value and the corresponding deviation of η=η(x).

For a more reliable estimation of the f(η) function parameters, the results concerning the on-road emission controls (1996-99) of catalytic vehicles by the corresponding department[16] of the Ministry of Environment, Physical Planning and Public Works are taken into account (figure (10)), based on an almost 10,000 samples.

For the calculation of the total production of pollutant i by the $j_{max}(n)$ catalytic vehicles, imported during an –n year period starting from 1991, the following expression may be used:

$$P_j^n = \sum_{j=1}^{j=j_{max}(n)} P_{i,j} = \sum_{j=1}^{j=j_{max}(n)} \int_o^{x_j} (1 - f_{i,j} \cdot \eta_{i,j}) \cdot m_{i,j} \cdot dx_j \qquad (3)$$

where $m_{i,j}$ is the mass flow rate of the pollutant i produced by the engine of the catalytic vehicle j at the inlet of the ACC and x_j is the distance covered by the vehicle j during the time-period used after its entry in the local market.

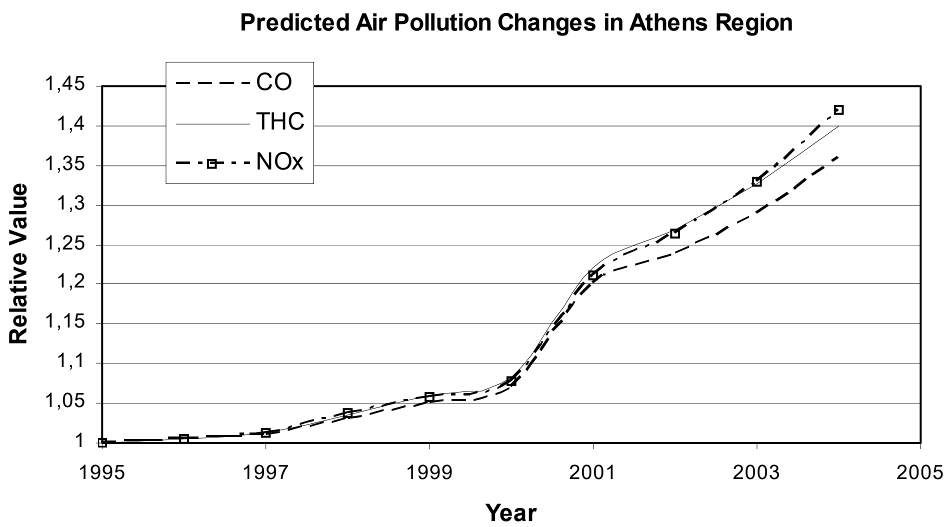

Figure 11: Calculated air pollution changes

Finally, in case of estimating the expected increase of the air pollutant i emissions between two successive years (e.g., (1991+n-1) and (1991+n)) due to the catalytic vehicles used, one may write:

$$\delta P_i^{(n-1,n)} = \frac{P_i^n - P_i^{n-1}}{P_i^o} \tag{4}$$

5. Air Pollution Changes-Calculation Results

Using the above presented mathematical model -in a more simplified form, *i.e. for the estimation of the air pollutants production of every engine-size group (e.g. 1400÷1600cc) the emissions of only one representative typical engine are used. Accordingly, the results are multiplied by the population of the group of that year (e.g. 35237 new vehicles of 1400÷1600cc for 1997)*- and adopting a log-normal probability distribution concerning the annual distance covered by a typical catalytic vehicle (mean value 14,600km, standard deviation 3,300km) the corresponding changes of CO, NO_x and THC emissions are computed and presented in figure (11). Keep in mind that the replacement rate of aged ACC, although very small (5,000-10,000 replacements per year), is also taken into account.

By comparing the measurements concerning the air pollution mean annual values in the major region of Athens and the calculation results by the proposed model, the similarity of the corresponding NO_x, CO and THC profiles is obvious and statistically validated. Thus, the 1-RMS correlation factor values (RMS→0%, best correlation) are 58% for NO_x, 43% for THC and 71% for CO, respectively. On top of that, by extrapolating the calculation results up to year 2004 and by neglecting the additional air pollutants production by any imported between 2001 and 2004 vehicles, an increase of the air pollution is expected in the Athens area, if the devaluated ACC are not replaced. In this case, if the problem is not properly faced and solved, the air pollution increase would be one of the major problems of the Greek State during the next few years, especially in view of the Athens 2004 Olympic Games.

6. Conclusions

The impact of the aged ACC efficiency gradual decrease on the major urban areas air quality level is investigated. For this purpose, the ACC degradation procedure was analyzed both theoretically and experimentally. Experimental measurements -carried out by several European Organizations so as to estimate the aged ACC emission level- are taken into account. These results along with any available theoretical information are analyzed, in order to establish quantitative relations between the environmental efficiency of ACC and their service period. Accordingly, a first attempt to estimate the expected air pollution changes (NO_x, THC, CO) is presented, based on the statistical model developed. The results obtained fairly correlate to the existing experimental measurements concerning the Athens region for the 1995-99 period. Finally, by extrapolating the calculation results up to 2004, a remarkable deterioration of the air quality level is expected, if the aged ACC are not replaced within the next two or three years.

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RECYCLING OF ELECTRICAL AND ELECTRONIC WASTE IN GREECE: POSSIBILITIES AND PROSPECTS

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Abstract

The continuous progress of technology and the high living standards of our times have increased the electrical and electronic equipment used in everyday life. As a result, a new waste type appears: the Waste of Electrical and Electronic Equipment. The present paper elaborates information concerning the quantity of the imported electrical and electronic equipment, along with the estimated number of the so-called "white machines", consumed by the Greek market during the last decade. Accordingly, the main problems -related to the way of handling these materials- are described. Finally, the proposed solutions and obligations of manufacturing companies, traders and other relevant parties are presented.

Keywords: Electrical Waste; Electronic Waste; Recycling; White Machines

1. Introduction

The continuous progress of technology, along with the high living standards of our times, has significantly increased the electrical and electronic equipment used in everyday life. More precisely, the life quality level of a typical family in industrial world strongly depends on number and technological status of its household's electrical and electronic devices. A parallel evolution takes also place in business and industrial sector, where the introduction of automatic control systems and personal computers constitute a major competitive advantage, in many occasions replacing human contribution.

At the same time, a remarkable change of manufacturers' viewpoint is encountered, abandoning the strategy of "high initial cost-big service period" of the equipments produced. On top of that, the vast majority of electronic and electrical equipments manufacturers are focusing (their efforts) on persuading their consumers into the advantages and relatively low prices of their products, neglecting their disposition after the end of their service period.

In this context, the present paper elaborates information concerning the quantity of the imported electrical and electronic equipment in our country, along with the estimated number of the so-called "white machines", consumed by the local market during last decade. Accordingly, the main problems -related to the up to date way of handling these materials after their service period- are described.

Finally, the proposed solutions and obligations of manufacturing companies, traders and other relevant unions are presented. One of the essay's major aims is to propose integrated national measures, like the establishment of a national council, mainly dealing with electric and electronic equipment waste recycling.

2. Waste of Electrical and Electronic Equipments

As mentioned above, the extremely fast technological improvements in the area of electrical and electronic devices during the last twenty years result in a new waste type, named Waste of Electrical and Electronic Equipment (WEEE), which -at the same time- may contain both dangerous and useful

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prime materials[1][2]. The WEEE stream differs from the municipal waste stream for several reasons, like:

i The rapid growth of WEEE, since the amount of WEEE is doubled every ten to twenty years.
ii Their hazardous content. This leads to a considerable input of harmful materials into the disposal or recovery routes.
iii The disharmony between the volume and the weight of WEEE and their chemical substances. However, even these small amounts of chemicals may seriously affect the environmental quality, while their impact will increase in the future.
iv The environmental burden due to the production of electrical and electronic products exceeds by far the environmental burden due to the production of materials constituting the other sub-streams of the municipal waste stream. As a consequence, enhanced recycling of WEEE should be a major factor in preserving resources, particularly energy[3].

The most important preliminary factors concerning the successful management of WEEE are focused on the following subjects:

a. The definition of electrical and electronic equipments along with their content
b. The estimation of the operational life of every electrical and electronic equipment
c. The definition of WEEE and the devices that this term should include

2.1 Definition-Classification of EEE

Up to now there is not a simple, theoretical rigid, practical and useful definition, including one hundred percent (100%) of the existing electrical and electronic equipments (EEE). The E.U. study group for the management of WEEE has not propose a single EEE definition[4], finally concluding that electrical and electronic equipment "*means equipment which is dependent on electric currents or electromagnetic fields in order to work properly and equipment for the generation, transfer and measurement of such currents and fields failing under specific categories and designed for use with a voltage rating not exceeding 1000 Volt for alternating current and 1500 Volt for direct current*".

According to this definition, the E.U. classification of EEE is summarized in Table I.

Table I: Proposed Classification of EEE

1.	Large household appliances
2.	Small household appliances
3.	IT equipment
4.	Telecommunication
5.	Radio, Television, Electro–acoustic
6.	Lighting equipment
7.	Medical equipment systems
8.	Monitoring and control systems
9.	Toys
10.	Electrical and electronic tools
11.	Automatic dispensers

2.2 Service Period of EEE

In addition to the inconsistencies regarding the definition of EEE, the service period definition of EEE is another obstacle in the WEEE management process. More precisely, it is quite difficult to set the accurate time period after which the EEE is finally transformed to WEEE[5]. This is mainly due to:

a. The large diversity of operational life of several existing EEE
b. The remarkable difference between the time proposed by the manufacturer and the real time of equipment practical degradation
c. The economic situation of the equipment owner

For example, manufacturers give 15 years duration of life for a kitchen and 5 years for personal computers. However, the innovation cycle for the kitchen is 6 years in the UK and 10 years in Greece, while the corresponding values for the PC varies between 6 and 18 months. Recapitulating, the service period of EEE is assumed to be the total operational period of the equipment, from the moment that is sold up to the moment that is rejected. In order to obtain a first estimation about the numerical values of the service period of EEE, data from E.U. are summarized in Table II.

Table II: Service Period and Number of Appliances in E.U. Households

Appliances	**Number of Appliances per Household**	**Life Cycle (years)**
Washing Machine	0.91	8
Clothes Dryer	0.35	10
Dish-Washing Machine	0.19	10
Refrigerator	0.44	10
Freezer	0.39	10
Microwave	0.7	10
Kitchen	0.87	15
Vacuum Cleaner	0.98	10
TV Set	1.3	13
Video Recorder	1	10
Hi-Fi Recorder	0.8	15
Radio Set	1	15
PC	0.3	5
Electric Stove	0.3	20
Electric Iron	1	10
Electrical Drill	0.8	20
Hair Dryer	0.5	15
Telephone	1	5

2.3 Annual Generation of WEEE in E.U.

Before analyzing the annual production of WEEE in the countries members of E.U. it is important to define what is characterized as waste electrical and electronic equipment in E.U. Therefore, according the Directive 75/442/EEC "*waste electrical and electronic equipment or WEEE means electrical or electronic equipment which is waste within the meaning of Article 1(a) of Directive 75/442/EEC, including all components, sub-assemblies and consumables, which are part of the product at the time of discarding*". Thus, the EEE is transformed to WEEE at the moment that it is assumed devaluated and it is introduced in the waste stream.

During the last years the mean annual increase rate of WEEE in E.U. takes values between 3÷5%, while the total annual generation of WEEE in E.U. is estimated to be 16kg/habitat. In Table III the annual WEEE production of a typical European household is given, including the most common EEE used[4].

2.4 Environmental Impact of WEEE

Although the annual production of WEEE is relatively limited in comparison to others Waste sub-groups, they often demand special treatment, due to the hazardous content of their components. However, currently WEEE scrap is considered a Green list waste[6] and will not be classified as hazardous waste when moving for recovery within the OECD member countries.

The most serious environmental impact of WEEE is related to the following materials and components:

- The printed circuit boards (PCB) and the mercury in them, mainly from the early appliances

- Plastic containing brominated flame retardants in the cables and in the printed circuit boards sub-systems
- The unspecified (by the manufacturers) materials, utilized in liquid crystal devices (LCD) and in computer flat screens
- The cadmium from the batteries and the printed circuit boards
- The lead of the cathode ray tubes

As it is obvious from the above-mentioned materials, the impact of WEEE on the environment should be seriously evaluated in the near future, especially in view of the expected remarkable increase of WEEE production, since the majority of the early EEE approaches the end of its service period.

Table III: Annual WEEE Production of a Typical European Household

Appliances	Annual Weight of WEEE per Household (kg)	Replacement Times in 20 Years
Washing Machine	8.0	2.5
Clothes Dryer	1.2	2
Dish-Washing Machine	1.0	2
Refrigerator	1.5	2
Freezer	1.4	2
Microwave	1.8	2
Kitchen	3.9	2.3
Vacuum Cleaner	0.8	2
TV Set	2.5	1.5
Video Recorder	0.5	2
Hi-Fi Recorder	0.8	1.3
Radio Set	0.1	1.3
PC	1.8	4
Telephone	0.1	1

3. WEEE Management Techniques

The WEEE treatment steps almost coincide those management procedure of typical solid wastes, although WEEE material cycles cannot usually be fully closed. Due to lack of space the main WEEE management stages are summarized in figure (1).

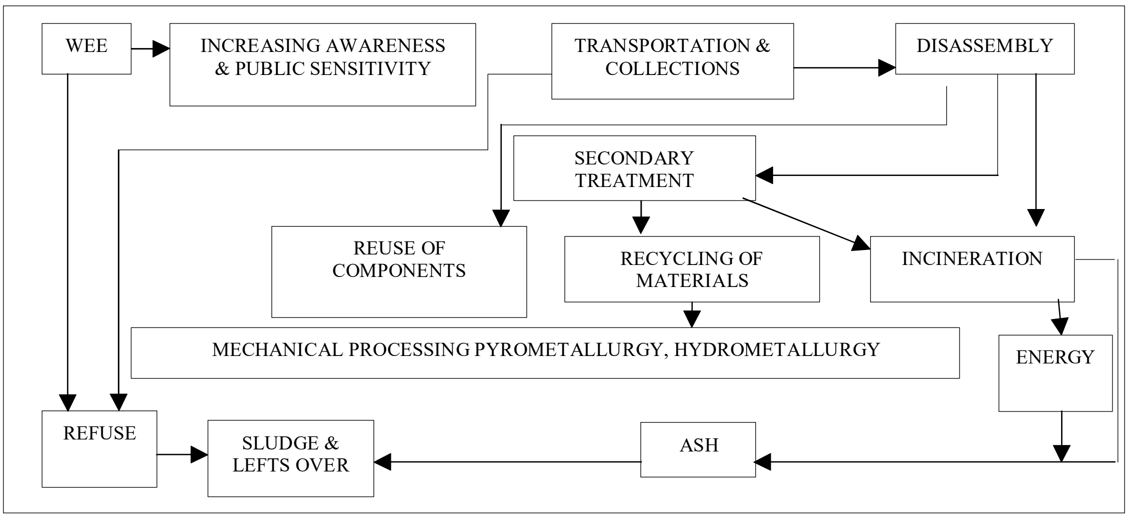

Figure 1: Main Stages of WEEE Management

Common delivery systems include:

- collection at municipal depots or recycling centers
- take back by retailers, on an old for new basis
- second-hand shop, collecting goods on request from the householder
- small chemical waste route (especially in rural areas)
- kerbside collection or collection on request from the householder

The transportation of WEEE is the major factor influencing the whole procedure success. It is realized using every available vehicle, depending mainly on the type and size of the waste.

Recovery and recycling[7] will have to be carried out by qualified specialist firms, while the approaches that are commonly used for recycling include:

- manual disassembly and recycling
- coarse sorting followed by automated recycling
- fully automated recycling of mixed materials

Incineration[8] is characterized as an old-fashioned treatment method, mainly used for PVC and plastic parts of EEE, in an attempt to remove harmful substances and reduce the WEEE volume. This technique leads to a considerable input of hazardous materials (e.g. mercury and cadmium) into the disposal routes. Furthermore, the incineration of non-hazardous wastes has been identified as the largest source of dioxins and furans emissions to air in Europe.

Landfilling[6] is usually the last stage of WEEE treatment process, applied to inappropriate for secondary treatment materials. This requires social consensus also at community level. The risks relating to the landfilling of WEEE are due to the variety of substances contained in them. The main problem in this context is the leaching and evaporation of hazardous substances.

4. International Experience Concerning WEEE Treatment

In E.U. there exist about twenty large multinational companies and several thousands of medium or small sized enterprises belonging to the electrical and electronic production sector. Despite the remarkable weight of EEE produced, the EU electrical and electronic industry generates a very small part of the overall EU waste, i.e. 6.5÷7.5 million tons/year or less than 1% of total EU waste. Today, more than 90% WEEE is landfilled, incinerated or shredded without any pre-treatment. Usually small WEEE, being disposed of with the ordinary household waste, go directly to incineration or landfill.

The main problems encountered[9] during the various WEEE treatment procedures applied in European countries are related to:

i **the EEE and WEEE definitions**. More precisely the existing official description of EEE does not include the 100% of the existing devices, since new products are manufactured every day, which are not included in the official catalogues. On top of that, the WEEE definition is not completely accepted by the entire OECD countries, thus it is possible a WEEE of one country to be characterized as EEE for another and vise-versa. Additionally, such a deviation minimizes the hazardous wastes control procedures between the countries members of OECD. Finally, the different national applications of the principle of "producer responsibility" lead to substantial disparities in the financial burden for economic operators.

ii **the collection procedures adopted**. Generally speaking, the utilization of multi-collection strategies increases the efficiency of the WEEE treatment project[7]. Among the methods used, municipal depots are normally well accepted, if they are easy to reach for the consumers and have long opening hours, while Saturday is the busiest collection day. Finally, the programs records show the year-end holiday season to be the best time for collecting consumer electronics. On the contrary, the intermediate storage is no solution. It is acceptable only if appropriate recycling plants are already under construction. According to the available data from several pilot projects, the minimum collection target must be 4kgr of WEEE per inhabitant.

iii **the transportation procedures utilized**. Keep in mind that this WEEE treatment stage is responsible for the highest cost contribution (fuel consumption) of the whole project, mainly depending on the type of the waste transferred along with the distance covered, Table IV. In Germany the 40% of the household WEEE collection and transportation is realized by municipal undertakings, while private companies treat the remaining 60%.

iv **the WEEE treatment cost**. The total net costs of meeting the collection and reuse /recycling requirements for household WEEE of the proposed draft Directive on WEEE are likely to be in the range of Euro 500÷900 million / yr for the EU15. The requirements for commercial equipment might, according to a rough estimate, add around 20% to this figure. So far it is estimated that recycling of EEE when all costs are considered, could be four to six times more costly than landfilling the equipment. The least-cost for highest collection rate pilot projects is about 300÷500Euro/tn or 1.5÷2.5Euro/person/yr[10]. Recapitulating, the up to now investigation results clearly declare that the WEEE management procedures cannot be economically viable, if they are supported only by private companies or manufacturers. In the course of time, it is almost certain that the consumer will finally pay an important part of this cost. Thus, if all these costs pass directly to the consumer through he product price[2], this would lead to an average price increase of 1% for most electrical and electronic goods, but could be as much as 2÷3% for some product categories, such as refrigerators, televisions and other monitors. In this case the cost must be transparent for the consumer.

Table IV: Mean Transportation Distances According to E.U. Report

COLLECTION		**DISTANCE (in km)**
FROM	**TO**	
Households	Collection Center	22,5
Collection Center	Recycling Center	135
Households	Dealers	0
Dealers	Recycling Center	135
Working Place	Collection Center	22,5
IT Collection Center	Recycling Center	140
Everywhere	Landfill	85

Summarizing the international experience related with the relatively recent WEEE treatment projects all over Europe, the major efforts are concentrated in households and enterprises sector[1]. Although the main target of these projects is to deteriorate the environmental impacts of WEEE, the opportunity of energy saving and materials recycling cannot be neglected. On top of that, a remarkable number of new jobs are created mainly in collection-transportation (46.6%) and WEEE dismantling of (53.4%) sector.

Another interesting result of the studies carried out underlines the fact that many EEE are discarded not because they are worn out or broken, but because a new model appears. For example, a company, accepting discarded telephone apparatus for reprocessing, estimates that more than 80% of the telephones received is in perfect working order. Most likely, the devices have been discarded in order to be replaced by a different-color model or a new-featured one.

Finally, it has recently become common belief that in business world, good environmental practice keeps up with business efficiency and can provide new business opportunities. Thus, the official proposals-results for the management of the five WEEE sub-groups are shown in Table V.

Table V: Proposed Management Techniques of WEEE Sub-Groups

WEEE Sub-Group	**Management Technique**
1. Refrigerators & Freezers	Need for safe transport (without destruction) and subsequent separate treatment
2. Others Large White Goods	Will normally be sent to shredders for ferrous metals recovery
3. TV Sets & Monitors	Need for safe transport (without destruction) and subsequent separate treatment
4. Light Sources	Need for special recycling or recovery processes
5. Others WEEE	All remaining WEEE (office and IT equipment, brown goods & small appliances) is expected to go into very similar recycling or recovery operations

5. Existing Situation in Greece

Greece, being a country member of EU, also participates in the contemporary technological evolutions of the electrical and electronic sector, thus a remarkable increase of WEEE is encountered as well. According to the official data by Greek National Statistics Agency, the main devices imported in our country include TV and VCR sets, Hi-Fi systems, Personal Computers and Printers, Copying Equipments, Electrical and Electronic Typewriters, Pocket and Desk Calculators. In figure (2) data concerning the weigh of imported EEE by the main manufacturing countries are presented, with emphasis on the origin of the equipments. As it is obvious from this figure the vast majority of EEE imported in our country comes from E.U. and NE Asian countries. Additionally, the EEE imports from E.U. have increased by almost 60% during the 1993÷1997 period, partially at dispense of the imports from the rest of the world.

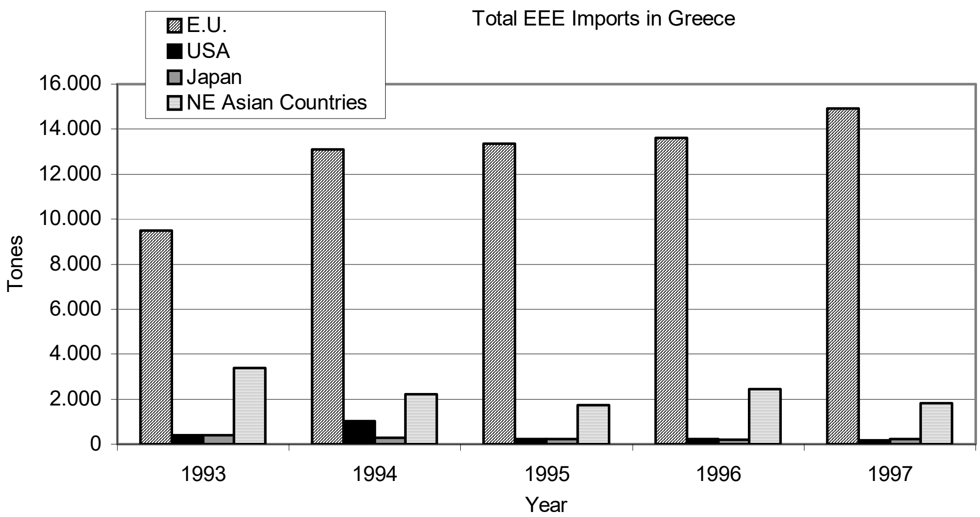

Figure 2: Total Weight of Imported Electrical and Electronic Equipment in Greece (1993÷1997)

Accordingly, in Table VI we present the estimated quantities[11] of the existing materials in the EEE imported in Greece during the 1993÷97 period. As it is obvious, all these materials are finally transformed to waste that should be managed. In Greece there is almost no systematic effort for the management of WEEE and only a few measures have been introduced to control the generation of waste. The most commonly used deposition of WEEE is landfilling, while in some cases the reuse of special parts of devaluated EEE is experienced. At the same time individual second-hand dealers collect white goods in order to sell their metallic parts as scrap material.

Unfortunately, even after the 113944/1997-law acceptance by Greek Parliament, concerning the national strategy for solid waste management, there is no remarkable improvement in the WEEE treatments, while this type of wastes are completely ignored by the corresponding legislative frame.

Table VI: Estimated Quantities (kg) of Materials Existing in Imported EEE, Greece (1993÷1997)

Materials	1993	1994	1995	1996	1997	TOTAL
Metals	2799536	5595701	4215003	5011518	5524328	23146086
Copper	161196	81503	252995	248553	280920	1025167
Glass/Ceramics	950022	1338199	1677950	1968390	1931140	7865701
Plastics	1540649	1932386	1168520	2653445	2545007	9840007
PCB	164388	228481	254397	304217	293009	1244492
Wood	59386	92490	52591	100482	87329	392278
Electrical Connections	103725	186657	129297	190727	159475	769881
Others	261155	453924	409124	534889	484390	2143482
TOTAL	6040057	9909341	8159877	11012221	11305598	46427094

6. Proposed Solution Guidelines

Taking into account the above-presented information concerning WEEE treatment in E.U. we suggest[12] the following proposals for our country:

- Responsibility for WEEE treatment must be shared by -and clearly identified for- all players including corporate and domestic users
- The manufacturers should increase the utilization of recycled or used material in new electrical and electronic products
- The electrical industry should supply the products specific know-how to be used for new recycling technologies development or further development of the existing ones.
- The manufacturers should also provide basic data for the recovery capacities planning, such as the products life duration, quantities and species of their components. These data also include disassembly instructions, materials lists, storage recommendations, transport instructions
- The Greek State must adopt the following policies:
  - ✓ Encourage pilot projects for the WEEE management
  - ✓ Contribute to increasing public awareness
  - ✓ Buy environmental friendly products or products with recycled content
  - ✓ Offer all obsolete federal computers to public schools
- Different possibilities must be accessible on choice concerning the ways of used electrical and electronic appliances take back/collection (like local and regional communities, traders, recycling firms, manufacturers / importers etc). This parallel and combined existence of long–established and well–tried solutions must be preserved for market–economy reasons
- Small domestic appliances liable to be dropped in rubbish bins must be collected close to households if a high coverage rate is to be achieved
- Medium appliances should be brought to municipal collection points
- Major domestic electrical appliances, as well, must keep on being taken back via municipal collection systems (non-destructive bulky–goods collection and delivery at the recycling–yard.)
- In case of products already placed in the market, an extra collection fee should be added on new products

7. Conclusions

Greece as a member state of E.U. must take measures to endeavor a minimum rate of separate collection of 4 kgr/person/year of WEEE from private households no later than 1 January 2006. Also, our country should take the necessary measures to ensure that the minimum recovery rate of several categories of WEEE will reach specific targets during the same period. Finally the Government Authorities should provide information on an annual basis for the quantities and categories of electrical and electronic equipment put on the market, collected and recycled within the Country, both by numbers and by weight. This information must be transmitted to the Commission by 1 January 2007 and on a three-year basis thereafter.

Only by imminently adopting the above-described measures and by establishing of a national council, mainly dealing with WEEE recycling, it is possible for our country to meet successfully the E.U. targets. Keep in mind that all suggestions made are based on the experience and strategies of numerous other countries around the world. Finally, the proposed management plan can be successfully accomplished only if it is financially and technically supported by producers, importers and private recycling companies. Recapitulating, the work presented here is the first part of an integrated study concerning the WEEE management opportunities in our country and a great deal of supplementary work should be carried out soon, under the basic idea that in the future the contribution of EEE in global waste production should be continuously increasing.

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