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

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3. ***Applications of Renewable Energy Sources*** **(RES II)**	***6th ″***
4. ***Energy Mechanics & Management of Natural Sources*** **(EM-MNS)**	***4th ″***
5. ***Environment & Industrial Development*** **(ENV-ID)**	***2nd ″***
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., Kavadias K.A., Filios A., Garofallakis S., 2004**, "Income Loss due to Wind Energy Rejected by the Crete Island Electrical Network: The Present Situation", to appear in the *Journal of Applied Energy*, APEN 936, on-line available in www.ScienceDirect.
- **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.

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

Published Results:

- **Kaldellis J.K., Kavadias K.A., 2004**, "Evaluation of Greek Wind Parks Visual Impact: "The Public Attitude" to appear in *Fresenius Environmental Bulletin*, F23-156, vol.13/5.
- **Kaldellis J.K., Kavadias K.A., Paliatsos A.G., 2003**, "Environmental Impacts of Wind Energy Applications: Myth or Reality?" *Fresenius Environmental Bulletin*, Vol. 12 (4), pp.326-337.
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3. "Technological Progress in Wind Energy Market"

Published Results:

- **Kaldellis J.K., 2004**, "Investigation of Greek Wind Energy Market Time-Evolution", *Energy Policy Journal*, Vol.32/7, pp.865-879.
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4. "Technological Progress in Solar Energy Market"

Published Results:

- **Kaldellis J.K., Koronakis P., Kavadias K., 2004**, "Energy Balance Analysis of a Stand-Alone Photovoltaic System, Including Variable System Reliability Impact", *Renewable Energy Journal*, Vol.29/7, pp.1161-1180.
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5. "Flow Field Prediction for High Speed Turbomachines"

Published Results:

- **Kavadias K.A., Kaldellis J.K., 2003**, "An Integrated Aerodynamic Simulation Method of Wind Turbine Rotors", *Applied Research Review* Journal of the TEI of Piraeus, Vol.8(1), pp.221-242.
- **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*, pp.19-33, Volume18 (2).
- **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., 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.
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7. "Combined Wind-Photovoltaic Stand-Alone Applications"

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- **Kaldellis J.K., 2004**, "Parametric Investigation Concerning Dimensions of a Stand-Alone Wind Power System", *Journal of Applied Energy*, Vol.77/1, pp.35-50.
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8. "Evaluation of Energy Storage Systems"

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9. "Air Pollution Analysis"

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

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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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14."Waste Water Treatment Applications"

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

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- **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.

Research Projects under Development

Participation in Research Programs (2002B-2003)

1. "***Maximum Energy Autonomy of Greek Islands on the Basis of Renewable Energy Sources***" Research Program "Archimedes" supported by the Greek Ministry of Education
2. Hellenic/French Collaboration Research Program "Platon" entitled "***Advanced Techniques of Automation in Wastewater Treatment Plants***". (Accomplished)
3. "***Development of an Experimental Hybrid Plant based on a Wind Turbine - P/V Station Collaboration***", supported by T.E.I. of Piraeus (Accomplished)
4. "***Reorganization of Mechanical Engineering Department - New Sector Development in the area of Soft Energy Applications & Environmental Protection Technologies***", supported by EPEAEK-Greek Ministry of Education (Accomplished)
5. Program "***RENES-Unet***", for the Diffusion of Renewable/Soft Energy Applications in Greece and European Union
6. "***Techno-economic Study of Small Hydro Power Stations***", supported by the private company EMPEDOS SA
7. "***Water Pumping Storage Systems for Crete Island***", in collaboration with the Technical University of Crete and the Enercon Hellas SA
8. "***Desalination System Based on Gas-Turbines Exhausted Gases***" supported by PPC and Crete Municipalities Union
9. "***NATURA-2000***", supported by the Greek Ministry of Environment, Physical Planning and Public Works
10. "***Natural Gas Cogeneration Opportunities in Urban Areas***", in collaboration with the Municipality of Nikaia
11. "***Energy Saving in TEI Buildings***", supported by TEI of Piraeus

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PART ONE

WIND ENERGY

- Technology
- Feasibility Evaluation
- Aerodynamics

INVESTIGATION OF GREEK WIND ENERGY MARKET TIME-EVOLUTION

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Abstract

An integrated, time-depending computational frame concerning the economic behaviour of wind energy applications in Greece is developed. This frame is accordingly used to analyse the local wind energy market situation during the last fifteen years. According to the results obtained, one may -on pure economic basis- explain the evolution of wind energy applications in the three major Greek sections presenting interest for wind power stations construction, i.e. the small-medium sized Aegean Archipelago islands, the Crete Island and the windy sites of mainland. Furthermore, the proposed model predicts no additional wind parks in the Aegean Sea Islands and Crete. The only solution to this negative evolution is the development of additional energy storage systems, e.g. wind-hydro stations. On the contrary, the Greek mainland opportunities in selected windy sites are more encouraging under the precondition of strengthening the existing electricity transportation networks and properly handling the increasing public annoyance towards new large wind turbines erection in relatively few closed areas.

Keywords: Wind Energy Market; Time-Dependency; Economic Behaviour

Nomenclature

BCR_n	benefit to cost ratio of the investment after a n year period
c	wind energy-electricity price (Euro/kWh)
CF	wind turbine capacity factor
C_n	total investment cost in current values over a n year period (Euro)
e	electricity price escalation rate
f_o	first installation cost coefficient for ten (10) wind turbines
FC_n	fixed maintenance and operation cost over a n year period (Euro)
g	local market inflation rate
g^k	annual change of the price for the k-th major component of the installation
G_n	investment gains in current values over an n year period (Euro)
i	return on investment index
$i^/$	capital cost index
IC_o	initial investment cost (Euro)
m	annual fixed M&O cost coefficient
N_o	wind turbine nominal (rated) power (kW)
Pr	specific ex-works price of a wind turbine (Euro/kW)
r_k	replacement cost coefficient for the k-th major component of the installation
R_n	investment savings in current values over a n year period (Euro)
t	time
VC_n	variable maintenance and operation cost over a n year period (Euro)
Y_n	residual value of the investment in current values after a n year period (Euro)
z	number of wind turbines
α	own capital invested (%)
β	loan capital invested (%)
γ	State subsidization (%)
Δ	technical availability
η_n^*	economic efficiency of the investment after a n year period

***Kaldellis J.K., 2004**, "Investigation of Greek Wind Energy Market Time-Evolution", Energy Policy Jr, Vol. 32, pp.865–879.*

ρ^k annual level of technological improvements for the k-th major component
Φ_n tax paid in current values over a n year period (Euro)
$\Phi_{(j)}$ tax paid during only the year j (Euro)
ω wind turbine mean power coefficient

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 height exceeds the 10m/s. Additionally, the electricity production cost of almost all the autonomous power stations (APS) used to fulfil the electricity demand of the local societies in the Aegean Archipelago regions is extremely high, while the mean production cost of Greek APS approaches the 0.15Euro/kWh, figure (1). Finally, Greece's significant dependency on imported fuel (i.e. the 65%-73% of its domestic energy consumption is imported), leads to a considerable exchange loss, especially with countries outside the E.U.[1].

Considering the above-presented reasons associated with the encouragement of the E.U. (expressed via important financing), the Greek State began its wind energy development plan in early eighties[2]. On top of that, the Greek government voted for several "Development Laws" since 1982, see Table I, defining a remarkable subsidization (γ=40%-60%) for the wind power applications in Greece. Finally, in October 1994, the Greek parliament approved the new Renewables' law (2244/94) allowing the private investors to produce electricity by wind parks, while Greek PPC is "obliged" to purchase this electricity production at a fixed percentage (e.g. 90% for the islands) of the corresponding market price.

Table I: Development Laws Subsidization Opportunities for Selected Areas of Greece

Development Law	Validation Period	Aegean Sea Islands		Crete & Selected Mainland Areas	
		α	γ	α	γ
1262/82	1982-90	≥15%	55%	≥25%	45%
1892/90	1990-94	≥25%	45%	≥35%	40%
2234/94	1994-98	≥30%	45%	≥40%	40%
2601/98	1998 up today	≥30%	40%	≥30%	40%

Despite all these positive incentives the wind power increase during the 1994-1999 period was discouraging, while at the meantime total Europe wind power capacity annual expansion rates exceed the 30%. Only recently (2000) a remarkable acceleration of new wind park installations is encountered, although the expected electricity market liberalization is going to drastically change the situation in the local market[3].

Even so, this explosion of new installations is focused in only two distinct regions, i.e. East Crete and S. Euboea. Thus, the maximum wind penetration is achieved, in order not to jeopardise the local grid stability, while the NIMBY (Not In My Back Yard) syndrome appears due to the remarkable number of "huge" wind turbines concentrated in relatively closed areas[4].

In order to obtain a realistic explanation of this unexpected time evolution of the local wind energy market and to forecast the near future changes of the sector, an extensive feasibility analysis is carried out, based on time-dependency of the corresponding parameters.

2. The Status of Wind Energy Market in Greece

According to the existing official data (end of 2000) in Greece, there exist approximately 350 wind turbines, 156 of them belonging to PPC and the rest 190 to private investors, figure (2). The nominal power of PPC wind parks is 36.6MW, while the corresponding power of private companies is 94.7MW.

More precisely, the Greek wind energy programme[2] started in 1982, when PPC installed the first wind turbines 5x20kW (M.A.N.) on a research wind park on the island of Kythnos. Since then, a number of wind projects were undertaken by PPC, most of them realized during the 1990-93 period, via the E.U. financing. During the 1993-98 period, the amendment of Greek wind power capacity was practically zero, figure (3). In October 1998, the first private wind park officially started its operation (17x600 Bonus Mk-IV) in the East Crete, figure (2). Finally, during the last two years (mainly on 2000) a drastic increase of private investors' wind power installations is encountered (80MW increase), while the PPC's wind power remains almost unaffected. The questions arising from this brief historical presentation of the Greek wind power market in relation to the corresponding situation in the rest of Europe (E.U., 1999) are:

a. What is the time-evolution of the economical results of wind parks created between 1985 and 2000?
b. Are the basic reasons that delay the wind energy expansion in Greece during 1990-1998 simply economic?
c. Is the official position of PPC satisfactory, claiming that wind parks are not economically viable? If not why the corresponding wind energy plan is practically cancelled?
d. What is the expected modification of the local wind power market up to 2005, in view of the total electricity market liberalization?

Attempting to give some realistic answers to the questions set, we proceed in presenting an integrated time-depending feasibility study concerning the wind energy investments in Greece, during the last twenty years.

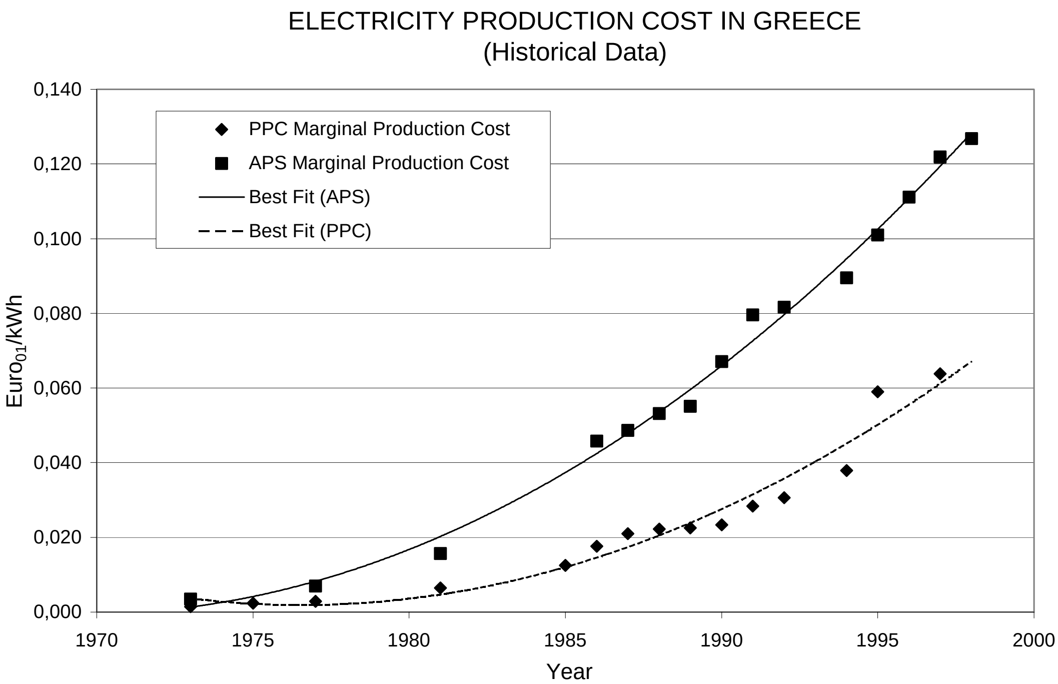

Figure 1: Electricity Production Cost in Remote Islands (APS)

3. Proposed Computational Frame

The proposed survey is based on an improved economic viability model[3][5] concerning the wind turbine installations in the local market, taking into account the time evolution of the basic parameters of the problem. According to this model, the exact value of the payback period and the economic efficiency or the benefit to cost ratio can be predicted for the 1985-2005 period. All calculations are done using current values for all the quantities involved. More precisely, the pay-back period "n^*" can be estimated as:

$$G_n = R_n - C_n - \Phi_n = 0 \quad \text{for } n=n^* \tag{1}$$

where:

$$R_n = R_{n-1}(1+i_n) + R_o \cdot \frac{CF_n}{CF_o} \cdot \prod_{j=1}^{j=n}(1+e_j) \tag{2}$$

$$R_o = 8760 \cdot CF_o \cdot (z \cdot N_o) \cdot c_o \tag{3}$$

$$C_n = IC_o \cdot \left\{ \alpha \cdot \prod_{j=1}^{j=n}(1+i_j) + \beta \cdot \prod_{j=1}^{j=n}(1+i'_j) \right\} + FC_n + VC_n \tag{4}$$

$$FC_n = FC_{n-1} \cdot (1+i_n) + \frac{m_n}{m_o}(m_o \cdot IC_o) \cdot \prod_{j=1}^{j=n}(1+g_j^m) \tag{5}$$

$$VC_n = IC_o \cdot \sum_{k=1}^{k=k_o} r_k \cdot \sum_{l=1}^{l=l_k} \left\{ \left[\prod_{j=1}^{j=l \cdot n_k}(1+g_j^k) \cdot (1-\rho_j^k) \right] \cdot \left[\prod_{j=l \cdot n_k}^{j=n}(1+i_j) \right] \right\} \tag{6}$$

$$\Phi_n = \sum_{j=1}^{j=n} \Phi_{(j)} (1+i)^{n-j} \tag{7}$$

Before explicitly analysing the terms appearing in equations (1) to (7), it is important to mention that in the proposed study the time evolution of a parameter is generally decomposed in two parts. The first part is taking into account the exact time point "t_o" at which the wind power investment is realized, while the second part is characterized by the operational period "τ" of the project undertaken. Thus, one may assume that:

$$t = t_o + \tau \tag{8}$$

and any function of time "f(t)" can be analysed as:

$$f(t) = f(t_o, \tau) \tag{9}$$

The initial investment cost "IC_o" appearing in equations (4) to (6) includes[6][7] the market price (ex-works) "$P_r.z.N_o$" and the corresponding installation cost "$f \cdot (P_r.z.N_o)$" of a wind plant consisting of "z" wind turbines of rated power "N_o". Thus, the turnkey cost "IC_o" can be expressed as:

$$IC_o = P_r \cdot z \cdot N_o \cdot (1+f) \tag{10}$$

It is important to mention that, in the course of times, there is a remarkable change of the commercial size of wind turbines, varying from 15-20kW in 1980 to 1.5MW in 2000. The present analysis is based on a typical[8] wind park size of ten (z=10) wind turbines of nominal power $N_o=N_o^*(t_o)$, where "$N_o^*(t_o)$" is the optimum wind turbine size for each year; see also Appendix One.

Additionally, an important specific price "$P_r(t_o)$" (Ecu/kW or Euro/kW) diminution of the corresponding optimum wind turbine size is encountered, mainly during the '80s, which was weaker during the past decade, Appendix One. Of course for the Greek market analysis, the relation between Ecu (or Euro) and drachmas should also be taken into consideration. Finally, the installation cost coefficient "$f(t_o)$" depends mostly[3] on the peculiarities of the exact location of wind park erection, taking values between 0.15 and 0.6 (typical value f=0.35) for the optimum commercial model of each year[5].

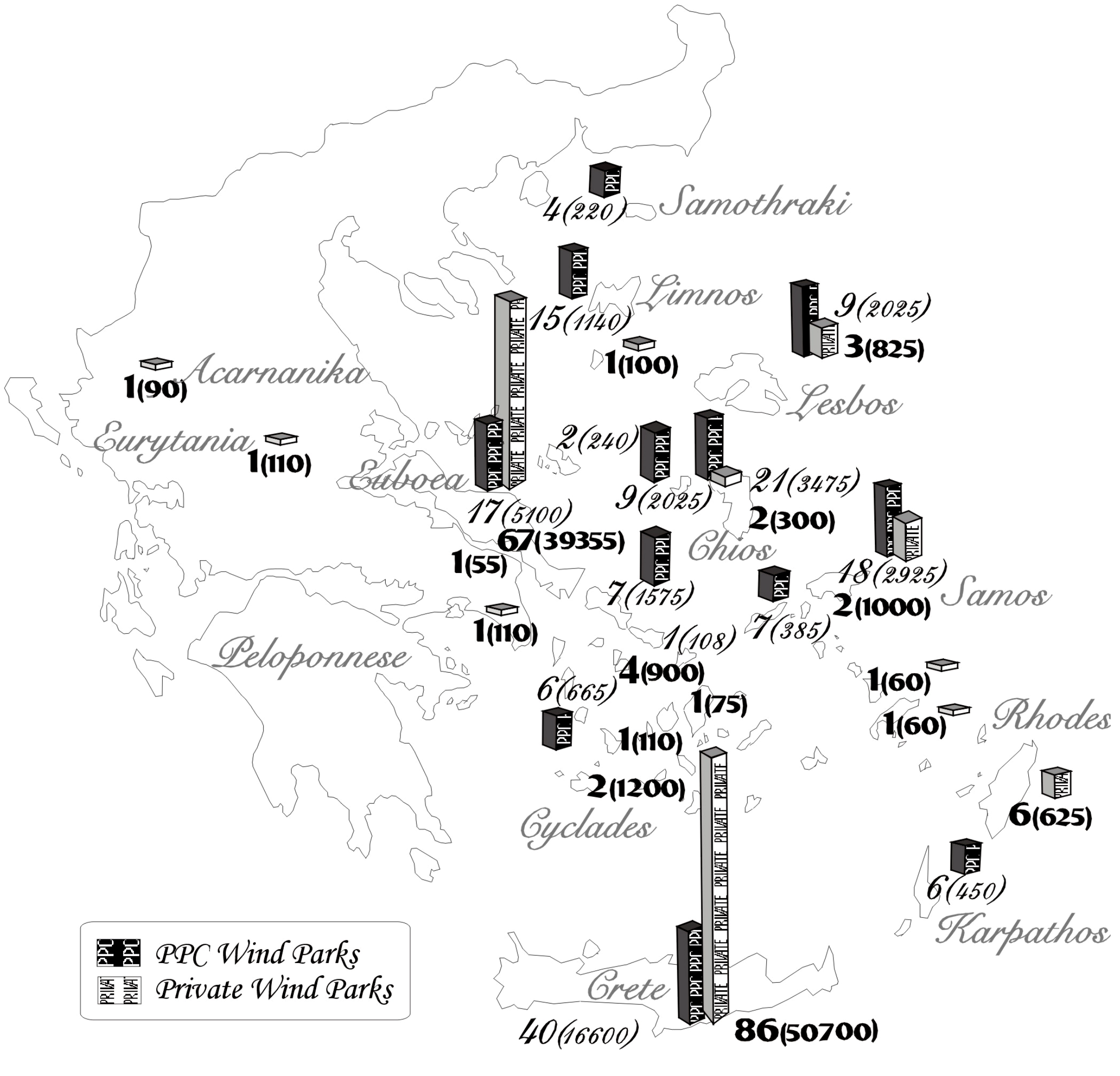

Figure 2: Existing Wind Parks in Greece (end 2000)

Subsequently, the term "$\alpha.IC_o$" describes the invested capital ("i(t)" the return on investment index), while the "$\beta.IC_o$" term expresses the loan capital ("i´(t)" the capital cost index). According to various development laws, valid since 1982 for the renewable energy applications in Greece, the Greek State subsidizes by "100xγ%" the corresponding investments; see Table I. Thus one may write:

$$\alpha(t_o) + \beta(t_o) + \gamma(t_o) = 1.0 \qquad (11)$$

Therefore, 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 "$m_o(t_o)$" of the initial capital invested, considering an annual increase of the cost equal to "g^m" (i.e. the M&O

annual inflation rate). An additional increase of the M&O cost, related to the aging[9] of wind converters, is expressed by the term "$m_n(\tau)/m_o$".

In Appendix One the "$m_o(t_o)$" and the "$m_n(\tau)/m_o$" functions are estimated according to data taken from the local and the European wind power installations[6].

Finally, the variable maintenance and operation cost depends on the replacement of "k_o" major parts of the installation, which have a shorter lifetime "n_k" than the complete installation[10]. The symbol "r_k" describes the replacement cost coefficient of each one of the "k_o" major parts (rotor blades, gear boxes etc) of the installation and "l_k" is the integer part of the following equation:

$$l_k = \left[\frac{n-1}{n_k} \right] \tag{12}$$

Note also that "$g^k(t)$" and "$\rho^k(t)$" describe the annual change of the price and the corresponding level of technological improvements for the "k-th" major component of a wind converter[11].

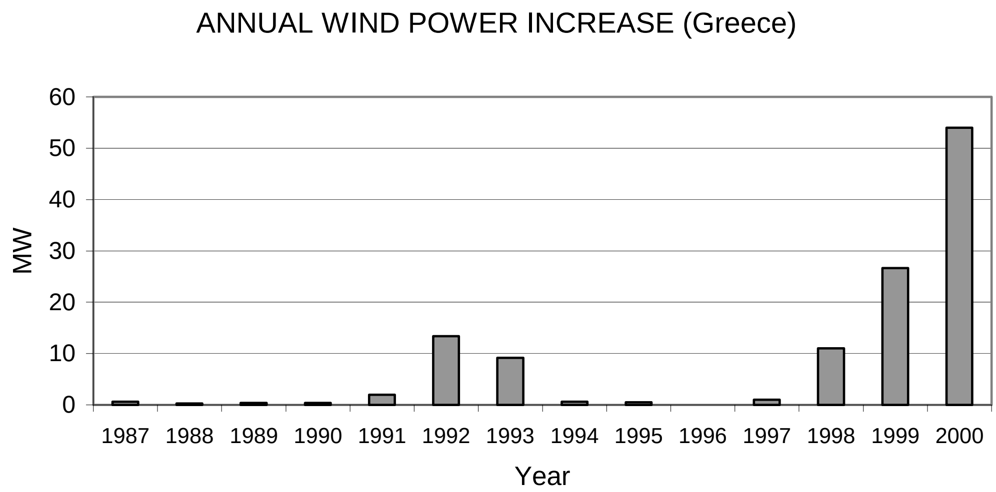

Figure 3: Annual Change of Wind Power in Greece

On the other hand, the total (tax-free) savings "R_n" of the installation during a n-year period, due to the energy production by the wind power station depend on "$R_o(t_o)$", on the capacity factor "CF(t)" time evolution, on the return on investment index "i(t)" and on the electricity price escalation rate "e(t)". Bear in mind that the capacity factor is the product of the technical availability "$\Delta(t)$" with the mean power coefficient "$\omega(t)$" of the installation, i.e:

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

More precisely, "ω" can be computed[12] as:

$$\omega = \int_0^\infty \frac{N(V)}{N_o} \cdot f(V) \cdot dV = \int_{V_c}^{V_F} \frac{N(V)}{N_o} \cdot f(V) \cdot dV \tag{14}$$

with "V_c" and "V_F" the corresponding cut-in and cut-out wind speeds of the wind turbine analysed, 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. In cases that no detailed wind speed data exists for the area under investigation, the well-known Weibull distribution "f(V)" is used[13]. However, this is not the case in the proposed analysis, since the calculations are based on available experimental data of the wind potential for various regions of Greece[14].

Similarly, the technical availability factor "$\Delta(t)$" can be expressed as:

$$\Delta(t) = \Delta_o(t_o) \cdot \frac{\Delta_n}{\Delta_o}(\tau) \cdot \Delta_w(t) \cdot \Delta_G(t) \qquad (15)$$

Generally speaking, the "$\Delta_o(t_o)$" mainly depends on the technological status during the period of time that the investment is realized. In early 80's, the technical availability of the first wind parks was approximately 60% maximum value, while at the beginning of past decade this value exceeded 90%. Nowadays, the contemporary wind turbines achieve a high quality level; obtaining a technical availability of the order of 99%, see Appendix One. However, it is also essential mentioning the accessibility difficulties -due to bad weather conditions- of almost all Greek islands, especially during the winter. For this purpose, a modified form of the analysis[15] concerning offshore installations may be used to estimate the "Δ_w" function, Appendix One.

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 the grid stability[16]. More specifically, this limit results from the selected operation point and the maximum permitted output of the local diesel engines, 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 should be reconsidered towards higher values. From the existing law-defined restrictions (8295/95), the maximum grid connected total wind power installed in an autonomous electrical system is defined as 30% of the peak load demand of the grid under investigation during the previous year. Therefore, the wind energy absorption by the local grid "Δ_G" is strongly decreased[17] as the wind power penetration in the local grid is increased, Appendix One.

Usually, wind turbines are constructed to operate for a period of twenty (20) years at least. 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. Based on real data evaluations[6][18][19][20] it can be asserted that the reliability of most wind turbines is characterized by early failures until the third operational year. This phase is generally followed by a longer period of "random failures" before the failure rate through wear and damage accumulation "wear-out failures" increases with operational age, function "$\Delta_n(\tau)/\Delta_o$" of Appendix One.

Accordingly, the electricity price escalation rate "$e(t)$" is defined as:

$$e_j = \frac{c_j}{c_{j-1}} - 1 \qquad (16)$$

where "c_j" is the effective cost coefficient (drch/kWh or Euro/kWh) of the replaced conventional energy by the wind energy during the year "j".

Finally, "$\Phi_{(j)}$" describes the tax paid during only the "j" year, mainly due to the revenues of the previous year. According to the Greek tax-law, the "$\Phi_{(j)}$" depends on the law-defined tax-coefficient, the net cash flow of the "j-1" year, the investment’s depreciations, as well as the financial obligations of the enterprise.

In order to obtain a clear-cut picture of the economic behaviour of a wind power installation, the economic efficiency "η^* " and the corresponding benefit-cost ratio "BCR" of the wind plant are also computed, further to the pay-back period of the investment. Using the definitions by the authors[6][3], one gets:

$$\eta_n^* = \frac{\tilde{G}_n}{IC_o \cdot (1-\gamma) - \tilde{Y}_{(n)}} \tag{17}$$

and

$$BCR = \frac{\tilde{G}_n}{IC_o \cdot (1-\gamma)} \tag{18}$$

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

$$\tilde{x}_j = \frac{x_j}{\prod_{k=1}^{k=j}(1+g_k)} \tag{19}$$

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, Appendix One.

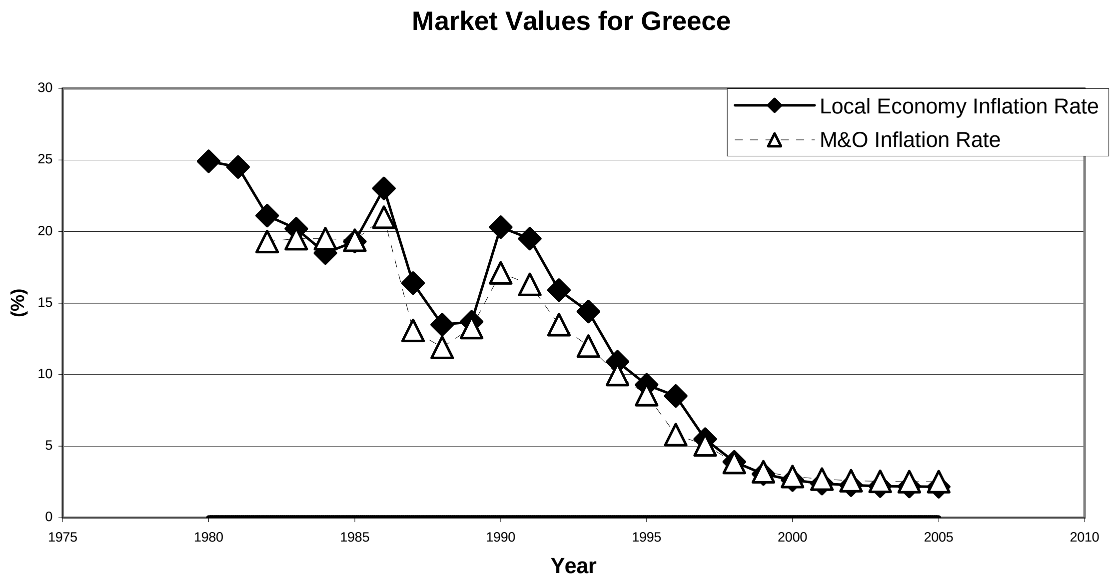

Figure 4: Market Values for Inflation Rate in Greece

In order to accomplish the analysis of all the parameters involved on the feasibility study of a wind power installation in Greece, the time-evolution of the main economic variables[5][21] are to be analysed. More precisely 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. According to the data given in figure (4) the inflation rate of the local economy is gradually decreasing during the last ten years, while in the 80's its value was quite high achieving values of the order of 20%. Similarly, the wind turbine M&O inflation rate "g^m" describes the annual change (increase) of the M&O cost, taking into account the annual changes of labour cost and the corresponding spare parts, figure (4).

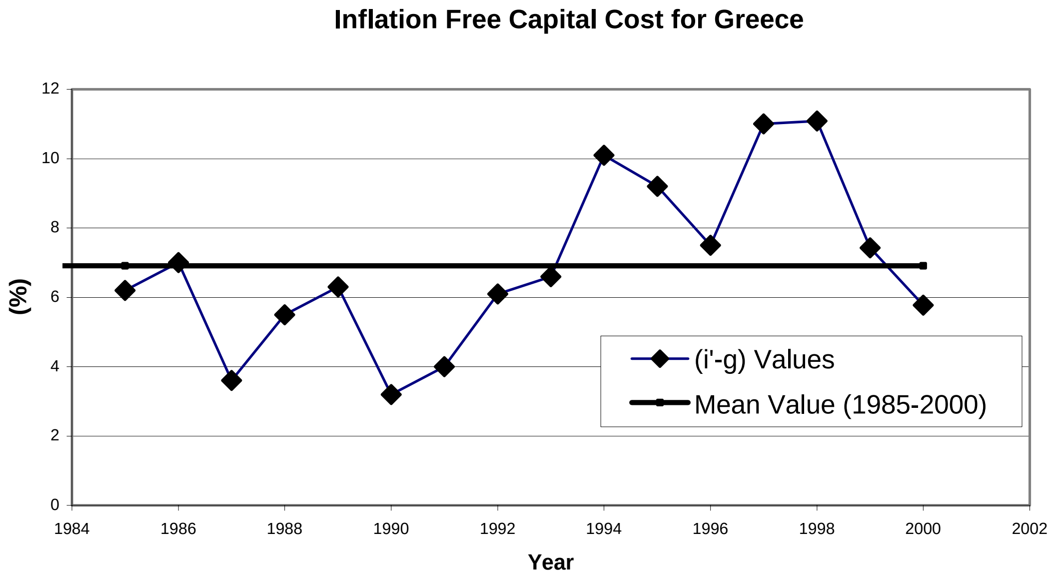

Figure 5: Inflation Free Capital Cost Index for Greek Economy

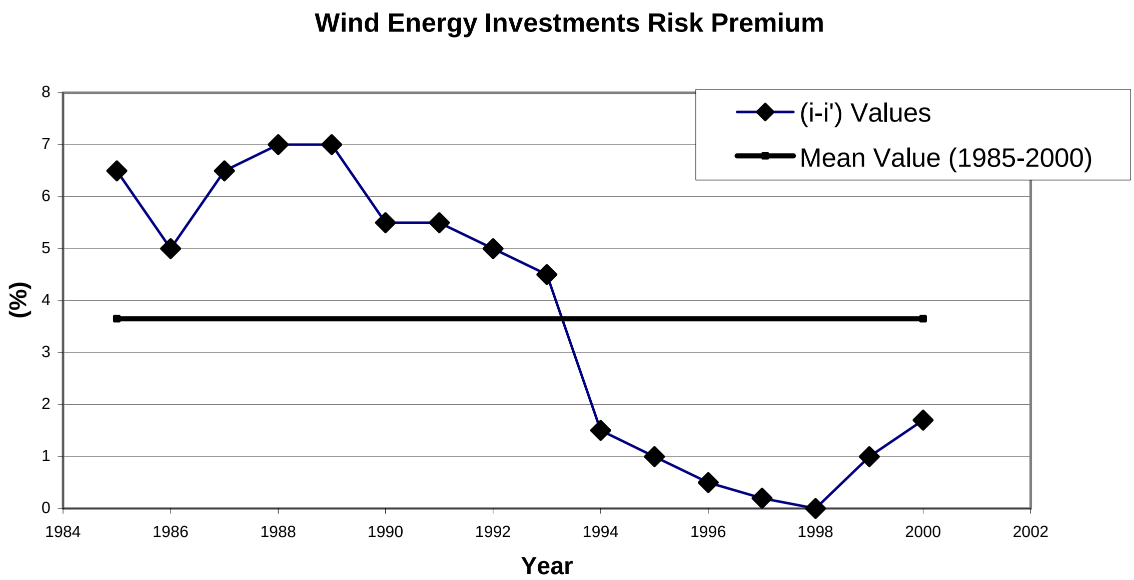

Figure 6: Wind Energy Investments Risk Premium for Greek Economy

In general, the capital cost index "$i^{/}(t)$ " mainly depends on local market economic wealth and more precisely on the existing investment opportunities, the repayment timing, the investment risk and any State or European subsidies. Additionally, the value of the capital cost index varies with the inflation rate of the economy, so as to obtain positive inflation-free capital return, figure (5). Furthermore, any capital investment process is based on the idea of spending money at a time period, expecting a prompt reimbursement. The annual amount of money, that investors require in order to invest their own capital, is defined as "return on investment". This economic parameter "i(t)" depends on the same factors as the above mentioned 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 hereby presumed that the variation of return on investment follows the capital cost index, plus the risk premium defined[11] according to the risk value assumed by the single investor, figure (6).

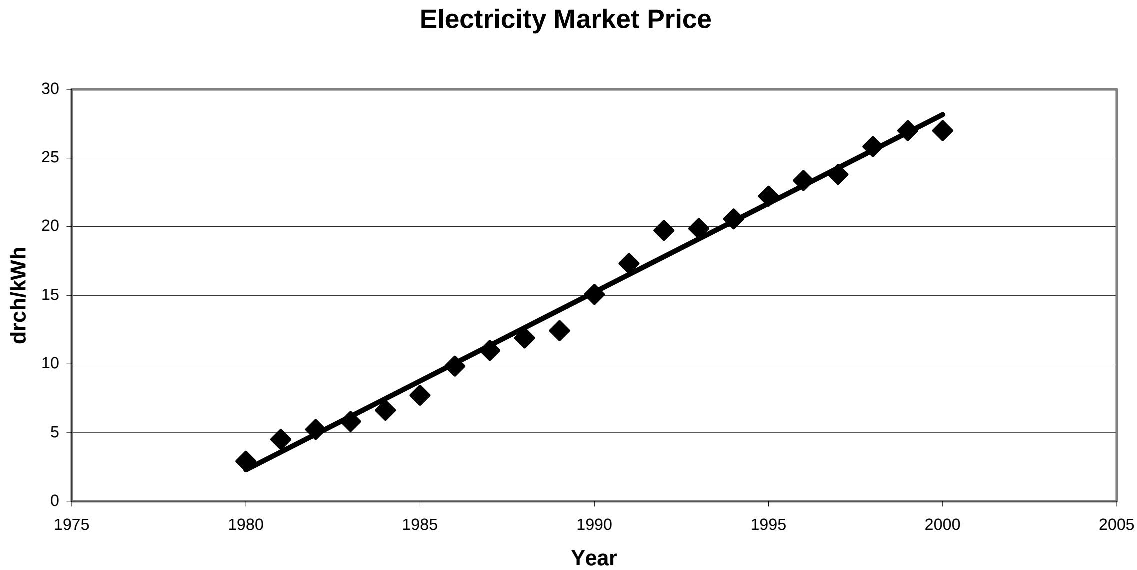

Figure 7: Electricity Retail Price in Greece

Finally, the term "electricity price escalation rate", replacing here the more widely used term of "fuel escalation rate", describes (figure (7)) the annual rate of change of the electric energy market price "c(t)", since the wind energy produced is finally sold to the local PPC grid at a price directly related to the corresponding retail price, according to the 2244/94 existing law. In general, the exact value of this parameter "e(t)" 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). According to figure (7) data, based on the market price of electricity during the 1980-2000 period, one may consider that "e(t)" values cannot be easily estimated by a single parameter function, since they present an intense wavering undulation during a small time period. Summarizing, it is important to mention that in the proposed computational frame the time-dependency of the governing economic parameters is based on twenty-years real data from the local market records, while after 2001 expected values are used[21].

4. Wind Park Feasibility Analysis as a Function of Investment Realization Time

Based on wind power installations history[1] of the last fifteen years, the local wind market is divided in the following regions:

A. The small and medium sized Aegean Archipelago Islands
B. The island of Crete
C. The windy sites of mainland (e.g. Euboea, S. Peloponnessos, etc)

The developed computational frame is going to be applied for each case separately, taking into account the advantages and disadvantages of each region, in order to attain rigid and validated conclusions.

4.1 Wind Energy Applications Status in Aegean Archipelago Islands

As already mentioned, this region includes all the Aegean Sea islands, except Crete. In almost all of these islands there exists a local autonomous power station (APS) and the electricity production is based on aged internal combustion engines, while the local electrical grid is usually small and weak, Table II. Furthermore, the electricity production cost is extremely high, mainly due to imported fuel cost. Finally, the infrastructure of these areas is poor, significantly increasing the corresponding first installation cost ($f_o \geq 0.45$) of any commercial sized wind turbine.

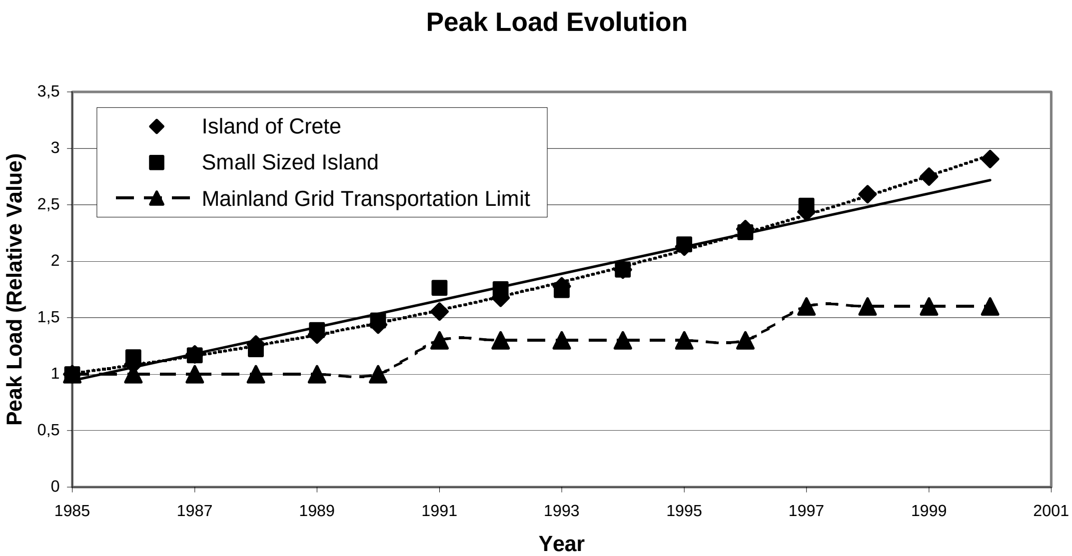

Figure 8: Evolution of Electricity Peak Demand for Selected Areas

Table II: Peak Electricity Demand and Maximum Power of Typical APS (1999)

Island	Maximum Power of Local APS (kW)	Peak Load Demand (kW)
Agathonisi	240	95
Amorgos	2650	2190
Astipalaia	1600	1350
Ikaria	6900	5400
Lesvos	49500	45700
Limnos	8900	11700
Mikonos	21200	17500
Patmos	4380	3580
Serifos	2000	1900
Siros	20000	18700
Andros-Tinos	9400	9300
Karpathos	9000	6500
Milos	7600	5970
Samos	46080	24400

On the other hand, vast majority of these islands present an excellent wind potential (several sites with annual mean wind speed greater than 9m/s, i.e. $\omega \approx 0.5$), enabling them to produce wind energy at a very competitive cost[22]. On top of that, the entire Aegean Sea region has been identified as a first priority one for financial support by European Union and Greek State. Therefore a remarkable subsidization percentage (γ=55% initially, γ=40% now) is defined for any investment in the wind energy application sector, according to the various existing development laws since 1982, Table I.

On top of that, according to the current Renewables law (2244/94), the electricity produced by wind parks is "obligatory" engaged by the local electricity utilities (Greek PPC) at 90% of the corresponding low voltage retail price. This situation will not drastically change before 2005, despite the electricity market liberalization process that is taking place all over Europe[23]. However, the basic problem for significant wind power installation in these islands is the grid capacity limitation[16], since the grid stability should be maintained[17]. According to available information, the annual peak load demand development of a typical Aegean Sea island is almost linear, figure (8), while the commercial wind turbines rated -power- increase with time is practically exponential, Appendix One. Thus, remarkable wind power supplement can be accomplished only in cases that supplementary storage systems (e.g. wind-hydro stations) are going to be constructed[24].

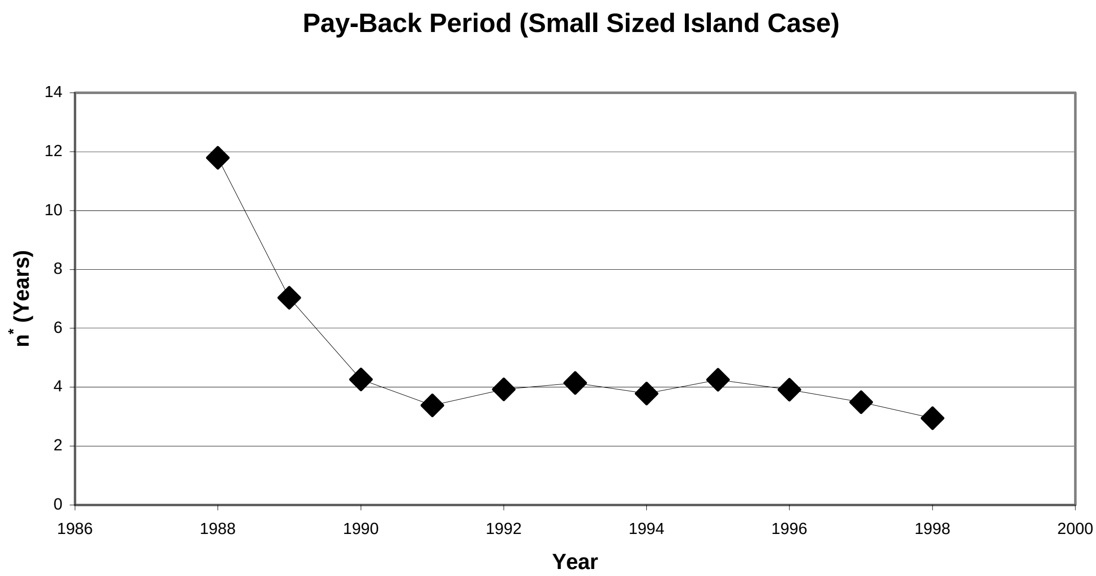

Figure 9: Payback Period for Wind Parks Installed in Aegean Sea Small Sized Islands

As it is obvious from figure (2), a remarkable number of small wind converters is spread over the Aegean Sea, most of them installed up to 1993 by Greek PPC. However, during the last years PPC installed only one 500kW wind turbine, for the demonstration of Kithnos hybrid station, while private investors installed another six machines in the islands of Samos, Milos and Siros.

In an attempt to explain this disappointing situation, the proposed time-depending calculation model is applied, for a typical small-medium sized windy island of central Aegean Sea[25], i.e. the island of Andros (10.3m/s annual mean wind speed observed at ten meters height, ω=0.55). The investigation carried out analyses the economic behaviour of typical wind parks containing ten (z=10) wind turbines of nominal power "N_o^*". Keep in mind that "N_o^*" is the optimum (best-value) wind-turbine size of each year; see also Appendix One. According to the present method, each wind power investment is accomplished at a variable time point ("t" or "t_o"), taking values between 1985 and 2000.

Thus, despite the strong incentives by E.U. and Greek State, every wind power investment realized in these islands up to 1988 was not viable, figure (9), either due to the low technical availability (rather immature technology / accessibility difficulties because of bad weather etc) of machines used or due to the high inflation rate of local economy.

For the period 1988 to 1991, there is a remarkable diminution of the payback period (almost sub-tripled) mainly due to the technical availability of commercial wind converters amelioration and the corresponding specific price decrease.

Between 1991-1998 the payback period remains approximately constant, achieving steadily low values. This payback period stabilization can be attributed to the low electricity price offered by PPC up to 1995. This is not the case for the after 1995 period, where the 2244/94 law is valid. The main problem arising during these last five years has its origin on the gradually decreasing wind energy absorption, since the local weak electricity grids cannot properly handle the remarkable wind power penetration scheduled[17]. For example, the operation of wind parks created in 1992 (rated power 2.25MW or 10x225kW) does not significantly affect the local electrical grid, while the energy production from a 10MW (10x1MW) wind power station -erected in 1998- cannot easily absorbed by any Aegean Sea island electrical network without supplementary energy storage devices.

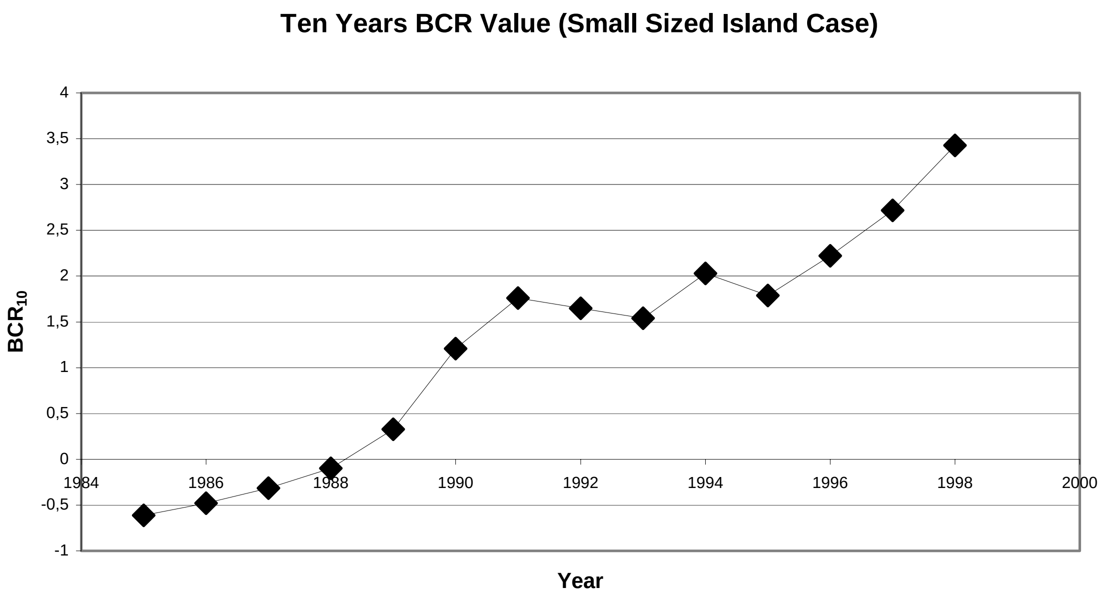

Figure 10: Ten Years BCR Value for Wind Parks Installed in Aegean Sea Small Sized Islands

Subsequently, the ten-year benefit to cost ratio "BCR_{10}" of the investment examined present similar behaviour, see figure (10). Therefore, "BCR_{10}" stays negative for any wind power investment realized up to 1988. Accordingly, "BCR_{10}" increases very fast for investments realized up to 1991. Then, for the 1991-1996 period it remains rather invariable, despite the small scattering of the computed values encountered. The increasing time distribution of "BCR_{10}" is decelerated after 1998, because -as already mentioned- the size of the proposed wind parks is not in accordance with the capacities of local grids (figure (8)), without constructing extra energy storage systems[24]. The main problem to be solved is the inability of the local network to absorb the entire wind energy production at low electricity consumption periods, in order to maintain grid stability. If this problem is not solved, the future wind power penetration will be gradually zeroed.

At this point, it is important to assert that the wind parks erected between 1989 and 1993 present definitely positive economic behaviour, a fact that comes in contradiction with the official opinion of Greek PPC relating to island wind parks viability. The only severe explanation for this statement (opinion) is due to the extremely low technical availability of these wind parks, Table III, which up to 1997 achieved the poor value of 30%[26]. The direct consequence of this unusual technical availability value (international mean value ≈90%) is the low energy production that drastically reduces the PPC wind parks annual revenues.

Table III: Mean Annual Capacity Factor (Technical Availability Included) of PPC Wind Parks

Wind Turbine Group	1993	1994	1995	1996	1997	1998
24x55kW	0.114	0.229	0.127	0.169	0.246	0.315
26x100kW	0.086	0.232	0.168	0.150	0.224	0.234
34x300kW	0.240	0.	0.	0.	0.	0.2180
45x225kW	0.290	0.334	0.313	0.311	0.291	0.280
3x500kW	-	0.319	0.267	0.311	0.303	0.253
26473kW (Total)	0.208	0.154	0.137	0.136	0.142	0.183

4.2 Case Study of Crete Island

Crete is the largest island of Greece and the fourth largest in the Mediterranean Sea. The wind energy prospects in Crete are very positive for several reasons, including:

a. The island is very windy, as average annual wind speed exceeds 8m/s in numerous locations.
b. The annual electricity demand rises 7% per year, while the peak power load -appearing exclusively during the summer season- follows a parabolic increasing function, figure (8).
c. The infrastructure of the island is acceptable (fair "f_o" values), remarkably improved during the last twenty years ($f_o \leq 0.45$).
d. The wind electricity production is purchased by PPC, at a price bordering on small islands tariff, i.e. at 90% of the consumers' sale price vs. 70% on the Greek mainland.
e. The subsidization opportunities are very good, being comparable to the ones valid for the Aegean Archipelago islands, especially after the 2234/94-development law was voted.

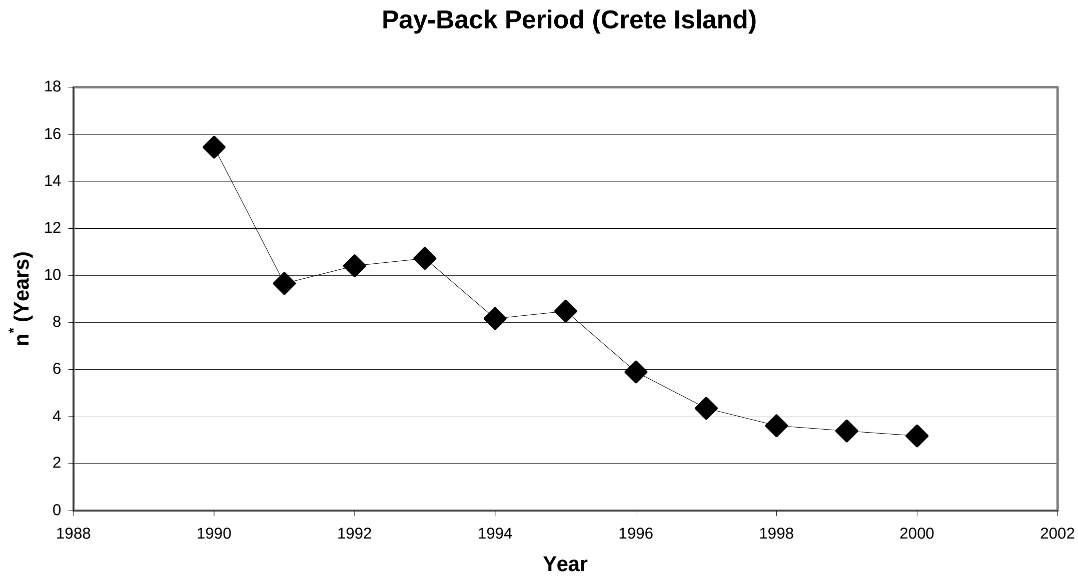

Figure 11: Payback Period for Wind Parks Installed in Crete

For all these reasons, a remarkable wind power increase was encountered[2] between 1993 and 1998, representing almost the only new wind energy installations in the whole country, during that period. After the first private wind park officially began its operation (October 1998), a significant increase (from 18MW to 60MW) of installed wind power capacity took place during the next two years. On the other hand, one should take into consideration that the local electricity network is not very rigid; therefore either major transportation problems or grid stability boundaries gradually deteriorate the wind energy absorption percentage, especially in low demand periods[27].

Above remarks are evidently supported by continuous diminution of the estimated payback period (figure (11)) of several wind parks operating after 1990. Before 1990, any investment realized in wind energy sector has been characterized as non-viable; while after 1998, the expected pay-back period tends to stabilize at approximately three to four years, with possible future increase, as a result of limited wind energy absorption capabilities.

Accordingly, the mid-term economic efficiency "BCR_{10}" of wind parks under investigation is characterized as increasingly positive, figure (12). Of course, during 1991-95 the low prices offered and the important legislative frame changes decelerate the benefit to cost ratio rise. Since 1995, the "BCR_{10}" increase has been amazing; however, after 1998 a remarkable slope change of "BCR_{10}" distribution is encountered, mainly due to the energy absorption barriers already mentioned.

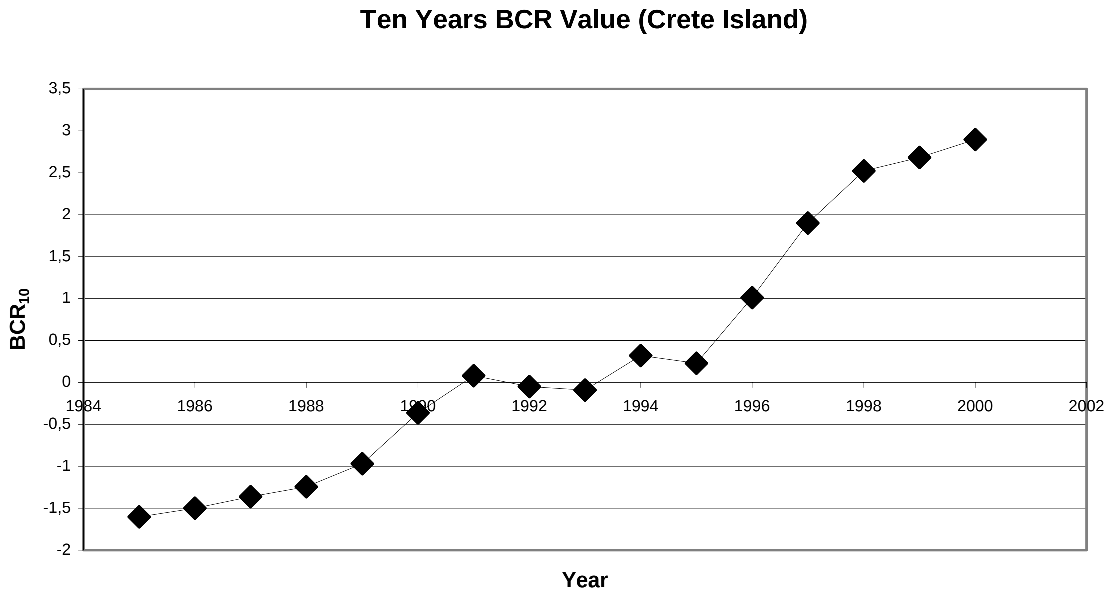

Figure 12: Ten Years BCR Value for Wind Parks Installed in Crete

4.3 Wind Energy Opportunities of Greek Mainland

According to existing long-term wind speed measurements, it is obvious that even the windiest mainland sites demonstrate poor wind potential compared to the majority of Aegean Sea islands. Additionally, the wind energy price offered and the corresponding subsidization percentages are quite lower than the ones valid for the Aegean Sea region.

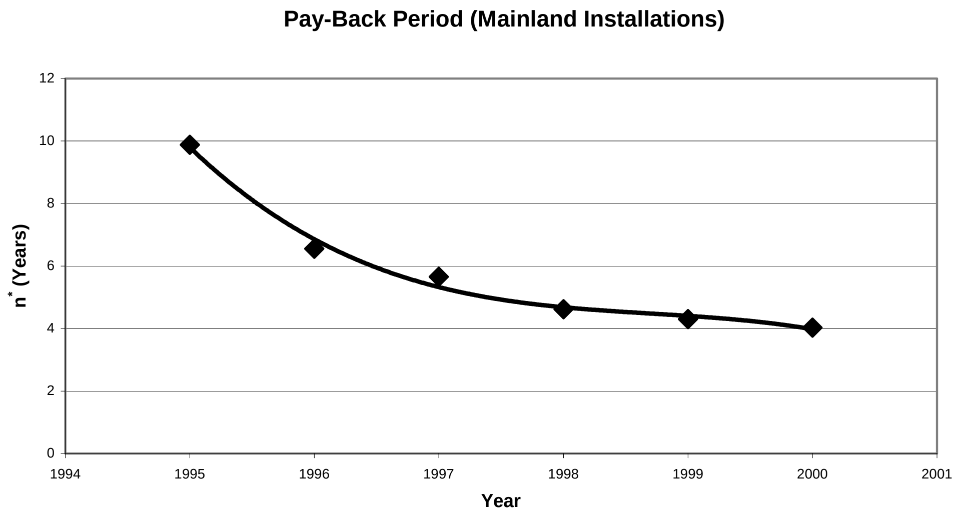

Figure 13: Payback Period for Wind Parks Installed in Greek Mainland

However, the selected mainland sites for wind power stations erection have better infrastructure ($f_o \rightarrow 0.3$), while the wind energy absorption capabilities are much higher ($\Delta_G \rightarrow 1.0$), as only the existing transportation network barriers should be respected, figure (8). On top of that, the recent development law (2601/98) equals the wind energy applications subsidization percentages for the whole country, i.e. $\gamma=0.4$.

Consequently, although wind energy projects were out of the question (not feasible) up to 1994 (strongly negative "BCR_{10}" values), after the modification of the corresponding legislative frame, the payback period has been remarkably reduced, especially between 1995 and 1998, figure (13). After 1998, the payback period diminution is milder but still cannot be characterized as constant. Finally, the "BCR_{10}" time distribution (figure (14)) is continuously increasing, especially after 1994, being however positive only for investments realized after 1995. Given that the mainland electricity grid limits are much higher than Crete's, the "BCR_{10}" is expected to increase after 2000, too.

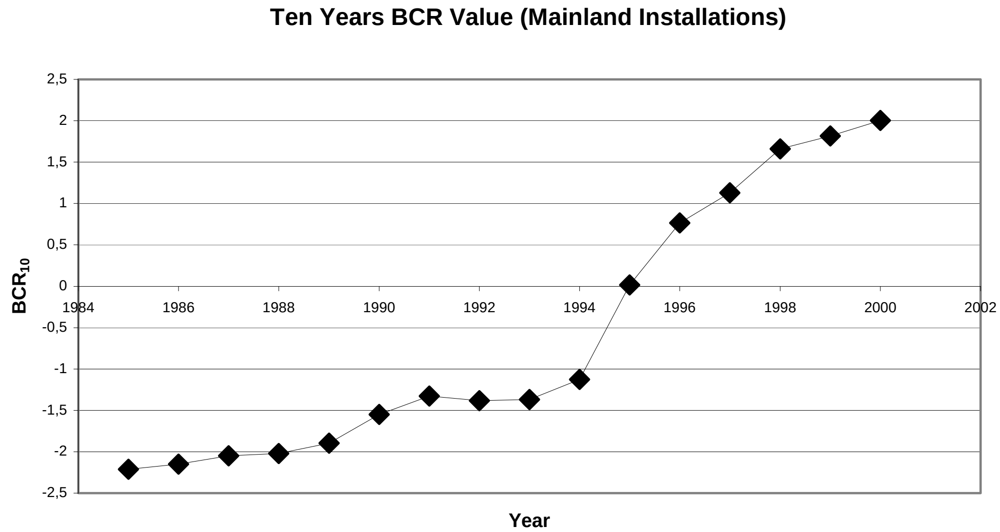

Figure 14: Ten Years BCR Value for Wind Parks Installed in Greek Mainland

Recapitulating, one may conclude that -according to the proposed model calculation results- a remarkable wind power investment pay-back diminution is observed between 1988-1991 for all the Aegean Sea region, figure (15). At the same period wind energy investments were not economically attractive in any other Greek area. During 1991 to 1995, the amortization time was stabilized at approximately four years for the Aegean Archipelago islands and at nearly eight years for Crete. According to this analysis, the totality of PPC wind parks built during this period in the Aegean Sea region should have presented very positive financial outcome. However, this never happened, obviously due to their extremely insufficient technical availability.

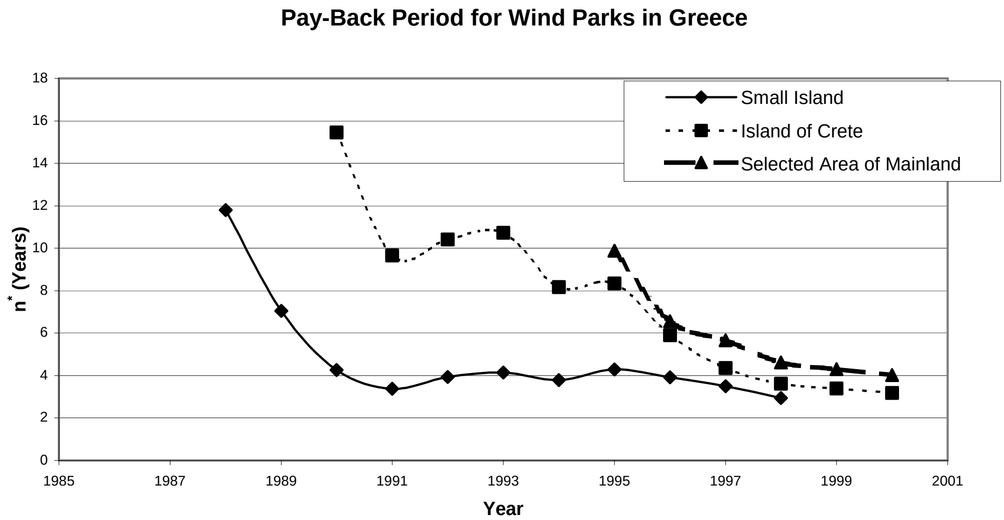

Figure 15: Payback Period for Various Wind Parks Installed in Greece

Since 1995, the economic attractiveness of island wind parks remains practically constant, as the technological improvements along with the amelioration of the local market financial situation were overwhelmed by the incorporation problems of the relatively huge contemporary wind turbines into the local weak electricity networks. On the contrary, the remarkable size of Crete electricity grid and the better infrastructure of the area encourage the installation of numerous medium-sized converters (500-750kW), since the payback period of similar investments keeps on dropping.

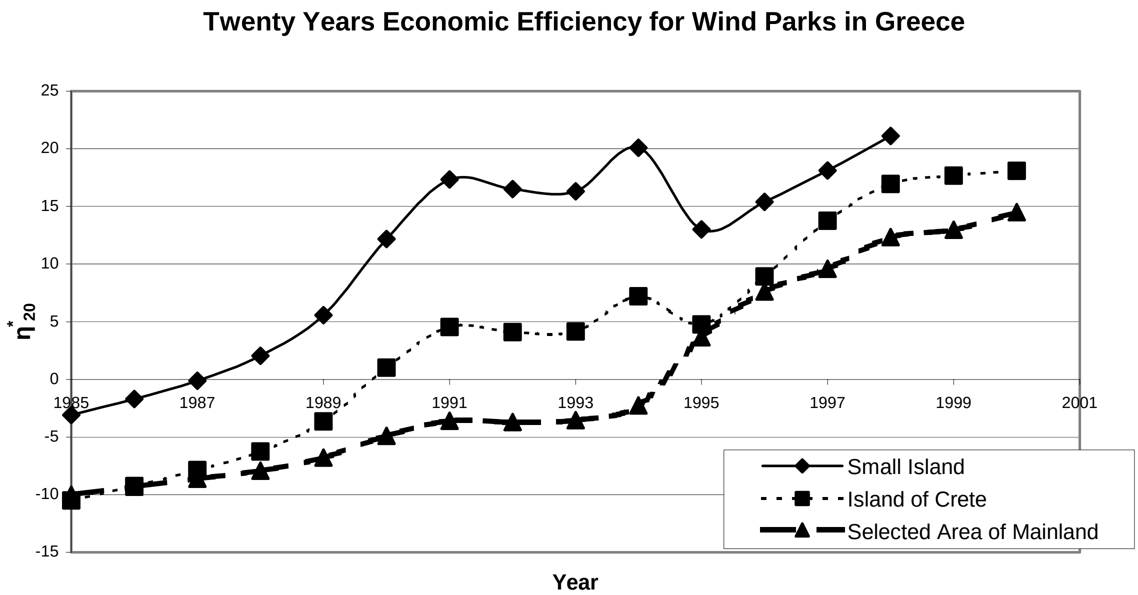

Figure 16: Long Term Economic Efficiency for Various Wind Parks Installed in Greece

At the same time, the long-term economic efficiency "η_{20}" of Cretan wind parks (figure (16)) approaches the corresponding Aegean Sea ones, despite their lower wind speed values observed. However, after 2000, the existing wind power penetration barriers -effective for the Aegean Sea islands since 1995- have also started decelerating the expected revenues of the new Cretan wind power installations.

Finally, as it is obvious from figures (15) and (16), mainland wind power stations present no financial interest before 1994. On the other hand, the new financial and legislative frame strongly encourages wind energy applications in windy sites of mainland, making them fully competitive to the corresponding installations of the isles of Greece. Subsequently, the significant grid size permits new installations' development up to the maximum grid transportation capabilities. Another quite recent and important obstacle, that should be properly handled, is the increasing contradiction of the high-wind-speed areas habitants[4], due to the unjustifiable concentration of several large-scale wind turbines in relatively few closed areas.

5. Conclusions-Proposals

An improved, time-depending computational frame concerning the economic behaviour of wind energy applications in Greece is developed. This model is accordingly used to analyse the local wind energy market situation during the last fifteen years. On top of that, the developed model is applied to predict (forecast) the expected changes of the sector, in view of the European electricity market liberalization. Bear in mind that as indicated by the new legislative frame (law 2773/99) the most cost-effective electricity production solutions should be gradually adopted in every Greek territory.

According to the results obtained, one may explain on pure economic basis the evolution of wind energy applications in Greece, taking also into account the remarkable modification of the corresponding legislative frame. Subsequently, the low economic efficiency of PPC wind parks erected in the Aegean Sea Islands, between 1989 and 1993, cannot be attributed on the market situation. The most pronounced explanation is related to the extremely inadequate technical availability of these wind parks.

Finally, one should not expect a noteworthy number of new wind parks in the Aegean Sea Islands in the near future. This situation may be remarkably ameliorated in cases that the proposed wind-hydro solution is adopted. The inconsistency between wind energy production and electricity demand is also going to zero the additional wind power stations in Crete in the next two-years, since every new wind power unit installed will decrease the wind energy absorption of the existing installations. Of course, the development of extra energy storage systems may reduce the wind power penetration problem.

On the contrary, Greek mainland opportunities may possibly be more encouraging, if two conditions are provided; the first related to the strengthening of the existing electricity transportation networks, while the second based on the public acceptance of the increasing wind turbine number and size. Our investigation results state that, at present, these two problems have not been properly solved. However, if the Greek State and the wind energy private investors seriously handle these obstacles, a significant wind power increase is expected in the near future, in several windy areas of Greek mainland.

Appendix One

$$x = t_o - 1990 \tag{A1}$$

$$N_o^*(t_o) = 226.12 * e^{0.1786x} \quad (\text{kW}) \tag{A2}$$

$$\mathbf{Pr}_{dr} = 0.0051x^4 - 0.0357x^3 - 0.9026x^2 + 11.508x + 248.5 \quad (\text{drch}/\text{W}) \tag{A3}$$

$$m_o(t_o) = 3.5045 * e^{-0.0456x} + \delta \quad (\%) \tag{A4}$$

δ (insurance annual cost)

$$\Delta_o(t_o) = 10^{-5}x^3 - 0.0009x^2 + 0.0191x + 0.8768 \tag{A5}$$

$$\frac{\tilde{Y}_n}{IC_o} = 0.0012\tau^2 - 0.0512\tau + 0.8581 \tag{A6}$$

$$\frac{m_n}{m_o}(\tau) = 1 + \frac{\delta m(\tau)}{m_o} \tag{A7}$$

where:

$$\delta m(\tau) = 0.005\tau^2 - 0.025\tau + 0.0219 \quad (\%) \tag{A8}$$

$$\frac{\Delta_n}{\Delta_o}(\tau) = 0.0022\tau^3 - 0.1053\tau^2 + 0.6711\tau + 98.875 \quad (\%) \tag{A9}$$

$$\Delta_G \geq 10^{-4} y^3 - 0.0229 y^2 - 0.4669 y + 100.37 \quad 3\% \leq y \leq 30\% \tag{A10}$$

where:

$$y = \frac{N_{w.p.}}{N_{peak\,load}} \tag{A11}$$

with "$N_{w.p}$". and "$N_{peak\,load}$" the existing wind power and the peak load of the local grid

$$\Delta_w = 0.0002\overline{V}^3 - 0.0071\overline{V}^2 + 0.0338\overline{V} + 0.9768 \tag{A12}$$

where " $\overline{V}$ " is the mean annual wind speed of the area.

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A PROBABILISTIC COMPUTATIONAL METHOD FOR THE ECONOMIC EVALUATION OF SOFT ENERGY APPLICATIONS IN COURSE OF TIME

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Abstract

Electricity market liberalization in Greece initiated in February 2001 -according to the E.U. Electricity Directive- and led to fundamental modifications of the local power industry. In view of these amendments, a remarkable growth of the renewable energy sector is expected. In this context, an integrated computational algorithm is developed, based on a well-established cost-benefit method; so as to investigate the time-evolution of energy related enterprise main financial parameters. The proposed analysis includes the usage of several (defined by the user) probability distributions of governing variables future values, while extended time-series historical data of the necessary techno-economical parameters are also incorporated. The resulting numerical code is prepared in "Visual-Basic" environment and a user-friendly computational tool is created, presenting, among others, time-depending distributions of the project net gains, economic efficiency and cost to benefit ratio. Finally, the present probabilistic analysis of the project estimates the probability profiles of its most important economic evaluation results, like the payback period, the ten or twenty years economic efficiency etc. On top of that, the probability of obtaining a desired result is also directly quantified.

Keywords: Computational Method; Probabilistic Analysis; Economic Evaluation; Soft Energy Applications

1. Introduction

Electricity market liberalization in Greece initiated in February 2001 -according to the E.U. Electricity Directive- and led to fundamental modifications[1] of the local power industry. At the same time by analyzing the existing official data of the last twenty years (1980-2000), there has been detected a remarkable electricity consumption increase from 21TWh in 1980 to almost 48.5TWh in 2000; see also figure (1). In the same figure, one may also observe the significant peak load augmentation of the mainland electrical network (from 3500MW to 8500MW), underlining the urgent requirement for new electricity production plants in the near future[2]. For this purpose, the establishment of new electricity production plants is being characterized as an extremely urgent concern[3], in order to protect the national electrical grid from several problems, like voltage and frequency instabilities or even total blackouts.

Table I: Official data by R.A.E. (2001)

Renewable Technology Used	***Electrical Capacity Requests (in MW)***
Wind Power	10707
Large Hydro	831
Small Hydro	616
Photovoltaics	7.5
Biomass	384
Geothermy	335.5
TOTAL	12881

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The inadequacy of electrical energy becomes more obvious nowadays, as the new legislative frame (law 2773/99) ends the PPC monopoly in the local electricity market[1]. From now on, any individual is capable of creating a new electricity production plant, based either on fossil or on renewable energy sources, providing thus electricity to the market via the central electrical network. On top of that, by using international tenders, the RAE (Regulatory Authority for Energy, 2001) -based on economic criteria- indicates which companies have the ability to develop their own power stations[4].

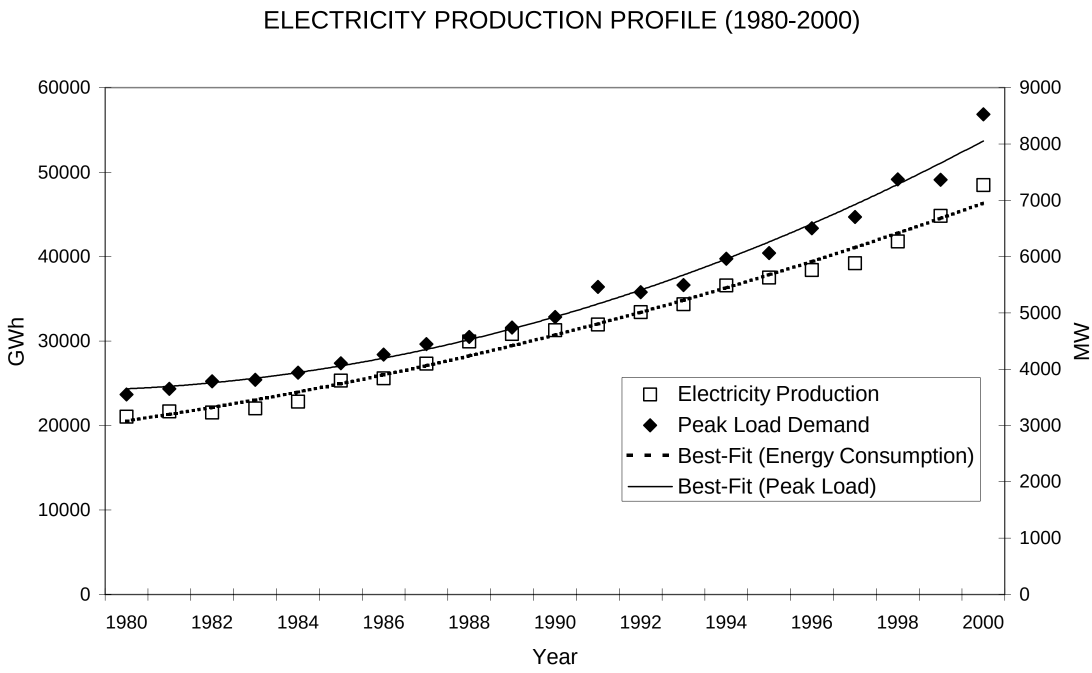

Figure 1: Electricity consumption increase in Greece

In view of these amendments, a remarkable growth of the renewable energy sector is expected. More specifically, requests for new power stations -founded on renewable energy sources exploitation of more than 13,000MW- exist (Table I) in the Ministry of Development, in an attempt to take advantage of the remarkable project total cost subsidization. That may be available either via the 2601/98-development law or the "Competitiveness Operation Program" of the Ministry of Development.

Unfortunately, soft energy electricity production applications are still characterized by relatively large initial investment costs[5], e.g. photovoltaic, hydropower and wind-power plants. For this purpose, a reliable way of evaluating the economical behaviour of a commercial project is considered necessary, in order to analyze the long-term risks involved in similar ventures, especially when new projects are scheduled.

In this context, an integrated computational algorithm is developed, based on a well-established cost-benefit method; so as to investigate the time-evolution of energy related enterprise main financial parameters. The proposed analysis includes the usage of several (defined by the user) probability distributions[6] of governing variables future values, while extended time-series historical data of the necessary techo-economical parameters are also incorporated.

The complete numerical code is prepared in "Visual-Basic" environment and a user-friendly computational tool is created, presenting, among others, time-depending distributions of the project net gains, economic efficiency and cost to benefit ratio. Finally, the present probabilistic analysis of the project estimates the probability profiles of its most important economic evaluation results, like the pay-back period, the ten or twenty years economic efficiency etc. On top of that, the probability of obtaining a desired result is also directly quantified.

2. Cost-Benefit Method

2.1 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,[7,8] the future value (after –n years of operation) of the investment cost "C_n" of an electrical power installation contains the initial installation cost "IC_o" (turnkey value), along with 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 equipment used "$P_r \cdot N_t$" and the corresponding installation cost "$f \cdot (P_r \cdot N_t)$". Keep also in mind that "N_t" is the total nominal power of the new power station, while the values of the specific ex-works price "P_r" and the installation cost factor "f" are analytically presented in parallel works,[5,9,10] see also Table II.

Table II: Typical Economical Data for Renewable Electricity Production Stations

Technology Used	*Wind*	*Photovoltaic*	*Small Hydro*	*Biomass*	*Geothermy*
Initial Specific Cost ∈/kW	650-900	3000-5000	800-1300	1000-1500	700-1200
First Installation Cost Factor "f"	0.25-0.60	0.1-0.2	0.25-0.6	0.2-0.3	0.2-0.5
M&O Cost Parameter "m"	1%-3%	0.2%-0.5%	0.5%-1.5%	5%-20%	0.5%-5%

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, 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 (Table II), 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 the equipment used, is also included. Summarizing, the fixed maintenance cost of the power station under investigation is given as:

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

Finally, the variable maintenance and operation cost mainly depends[7] on the replacement of "k_o" basic parts of the installation, which have a lifetime "n_k" shorter than the rest installation. Using the symbol "r_k" for the replacement cost coefficient of each one of the "k_o" basic parts (e.g. gear box, rotor blades, inverter etc), the "VC_n" term can be expressed using the following relation:

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

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 price change and the corresponding technological improvement level for the "k-th" basic component of the installation.

On the other hand, considering the corresponding parameters numerical value at the start of the power-station operation, the annual savings "R_o" of an energy production plant can be expressed, according to equation (6) as:

$$R_o = 8760 \cdot CF_o \cdot N_t \cdot c_o \tag{6}$$

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, since CF=Δ.ω. Consequently, the total (tax-free) savings over an n-year period "R_n", due to energy production, are given as:

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

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

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

Subsequently, the electricity 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 "$\Phi_{(j)}$" 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[11]. 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 payback period of any electrical power investment can be predicted, solving the break-even equation, thus:

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

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

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

or

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

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

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

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.

2.2 Historical Data

For the application of the above-presented analytical model one needs the historical data describing the time evolution of the main economic parameters in the local market. Capital cost, return on investment, electricity price escalation rate, local market inflation and M&O inflation are pure economic parameters in this context, hence their past time ($t \le t_{cr}$) evolution is given by official data[12], while their future time evolution can be approximated by statistically weighted distributions. Using the theoretical analysis[13] by Kaldellis (2001) one may write:

$$X(t) = X_{\mathbf{exp}} \quad \text{for } t \le t_{cr} \tag{14}$$

and

$$X(t) = \langle X \rangle \quad \text{for } t \ge t_{cr} \tag{15}$$

where:

$$X = i \vee i^{/} \vee e \vee g \vee g^{\Sigma} \tag{16}$$

The forecasting "<X>" values are accompanied by their corresponding probability density distribution "f_x".

According to previous work[7] 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 installation M&O 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. Subsequently, the capital cost "$i^{/}(t)$ " mainly depends on local market economic wealth and more precisely on the existing investment opportunities, the repayment timing, the investment risk and any State or European subsidies. Thus, the value of the capital cost varies with the inflation rate of the economy, so as to obtain positive inflation-free capital return. Furthermore, the term "return on investment" identifies the annual benefit required, in order investors to lay out their own capital. This economic parameter "i(t)" depends on the same factors as the above mentioned 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 hereby presumed that the variation of return on investment follows the capital cost, plus the risk premium defined according to the risk value assumed by the single investor. Finally, the "electricity price escalation rate" describes the annual rate of the electrical energy market price change. The exact value of this parameter "e(t)" depends on various factors (e.g. dollar exchange rate, nature of the conventional energy to be replaced, the policy of the electrical utilities towards renewable energy sources).

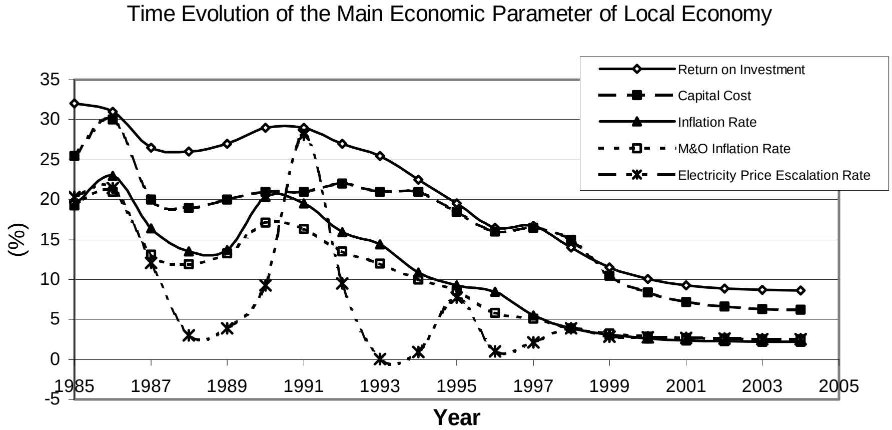

Figure 2: Local market main economic parameters time-evolution

Summarizing, it is important to mention that in the proposed computational frame the time-dependency of the governing economic parameters is based on twenty-years real data from the local market records (see also figure (2)), while after 2001 (statistically weighted) expected values are used along with the corresponding probability density distributions, i.e. "f_i, $f_{i'}$, f_e, f_g, f_Σ".

A parallel approach is also utilized to simulate the mean power coefficient time-evolution. According to previous work[14] by the authors, the mean power coefficient depends on the renewable potential of the installation site and on the output power curve of the machine used. Considering the stochastic behaviour of the wind speed, a random variation of the mean power coefficient is expected for wind power applications around an almost constant average value. However, for solar, hydro, biomass or geothermal applications the expected mean power coefficient variation is comparatively more predictable. On top of that, a time depending efficiency degradation of the equipment utilized may also be included in a similar analysis. In the proposed analysis the following expressions are taken into consideration:

$$\omega(t) = \omega_{\mathbf{exp}} \quad \text{for } t \le t_{cr} \tag{17}$$

and

$$\omega(t) = < \overline{\omega} > + \Delta\omega \cdot \mathbf{sin}\left[2\pi \cdot \frac{(t - t_{cr})}{T}\right] \quad \text{for } t > t_{cr} \tag{18}$$

where "$< \overline{\omega} >$", "$\Delta\omega$" and "T" are predicted using the existing experimental data, e.g. "ω_{exp}" values and "$< \overline{\omega} >$" is accompanied by its corresponding probability density distribution "f_ω"[11].

2.3 Presentation of Probability Distributions Used

As it is obvious, any prediction of future evolution of the above-mentioned parameters is mainly based on the existing historical data and the implicit assumption that no dramatic change of local economy status is going to be realized. Accordingly, the research team attributes a probability distribution[15] for every parameter analyzed, on the precondition that this parameter varies between specific limits.

Hence, the proposed computational method offers the opportunity of selecting the desired analytical distribution -for each parameter mentioned in equations (16) and (18)- among several typical functions, like the normal or the lognormal, the triangular or the parabolic one. Subsequently, the corresponding analytical probability density distribution can be written as:

$$f_x = f(x) \qquad \text{where } x=i \text{ or } i' \text{ or } g \text{ or } g^{\Sigma} \text{ or } e \text{ or } \omega \tag{19}$$

During the calculation process the entire combination set is examined with reference to all the above-mentioned parameters; thus the total probability value of each scenario investigated is given as:

$$p_{tot} = \left(\int_{i-\delta i}^{i+\delta i} f(i)\cdot di\right)\cdot\left(\int_{i-\delta i''}^{i+\delta i'} f(i')\cdot di\right)\cdot\left(\int_{g-\delta g}^{g+\delta g} f(g)\cdot dg\right)\cdot\left(\int_{g-\delta g^{\Sigma}}^{g+\delta g^{\Sigma}} f(g^{\Sigma})\cdot dg^{\Sigma}\right)\cdot\left(\int_{e-\delta e}^{e+\delta e} f(e)\cdot de\right)\cdot\left(\int_{\omega-\delta\omega}^{\omega+\delta\omega} f(\omega)\cdot d\omega\right) \tag{20}$$

where "δx" depends on the number of points used to simulate the probability distribution of all parameters along with the corresponding variation range of each parameter examined.

3. Presentation of the Solution Algorithm

For the application of the proposed model, there has been devised an integrated numerical algorithm able to estimate the probability density functions of the main economic parameters of a renewable energy application, along with the corresponding mean value and standard deviation. The proposed algorithm, see also figure (3), is based on the following steps:

Step 1: Define the time that the power station starts operation
Step 2: Define the size and the technology used
Step 3: Define the invested capital shares, including loan terms
Step 4: Determine tax coefficient, insurance annual cost and installation region infrastructure status
Step 5: Define the electricity production way of usage
Step 6: Define the technical availability parameters
Step 7: Define the range of values (min, max, average) and the number of points for local economy inflation rate, maintenance and operation inflation rate, local economy capital cost, return on investment parameter and electricity price escalation rate
Step 8: Select the desired analytical probability distribution for the above-mentioned five parameters
Step 9: Check (and modify if necessary) the resulting scenarios concerning the time evolution of all five parameters
Step 10: Determine any expected major power-station-components replacement during the operational lifetime of the investment, along with any anticipated technology improvements
Step 11: Define the range of values (min, max, average) and the number of points as regards the mean power coefficient of the installation
Step 12 Select the desired analytical probability distribution of the mean power coefficient of the installation
Step 13: Check (and modify if necessary) the resulting scenarios concerning the time evolution of the mean power coefficient of the installation
Step 14: Define (if necessary) the desired constraints between the local market economic parameters (inflation rate, capital cost, return on investment) in order to eliminate unrealistic combinations
Step 15: For each combination of the six parameters selected (i.e. g, g^{Σ}, e, i, i', ω) and under the validation of restrictions of Step 14, solve via an iterative procedure equations (1), (7), (9) and (10), predicting the pay-back period of the investment along with the corresponding probability value (equation (20))
Step 16: Calculate via equations (11) and (12) the corresponding ten and twenty years economical efficiency parameters along with the corresponding possibility value (equation (20))

Step 17: Repeat steps 15 to 16 up to the analysis of all the combinations available
Step 18: Estimate the mean value and the standard deviation of the parameters of steps 15 and 16.

The algorithm developed is quite reliable and stable, while the typical execution time of (11x11x15x15x15x11) combinations is less than one hour on a Pentium-III 800MHz personal computer.

Among the most interesting capabilities of the algorithm it is the opportunity to check the probability density function of every one of the six main techno-economic parameters, see figure (4), modifying interactively the analytical distribution type and its main coefficients. After the probability density function is established, one may examine the time evolution of each parameter for all the possible scenarios defined, figure (5). Besides, the computational frame developed gives the possibility to evaluate the time evolution of two additional important technological parameters, i.e. the expected technical availability and the maintenance and operational cost of the installation.

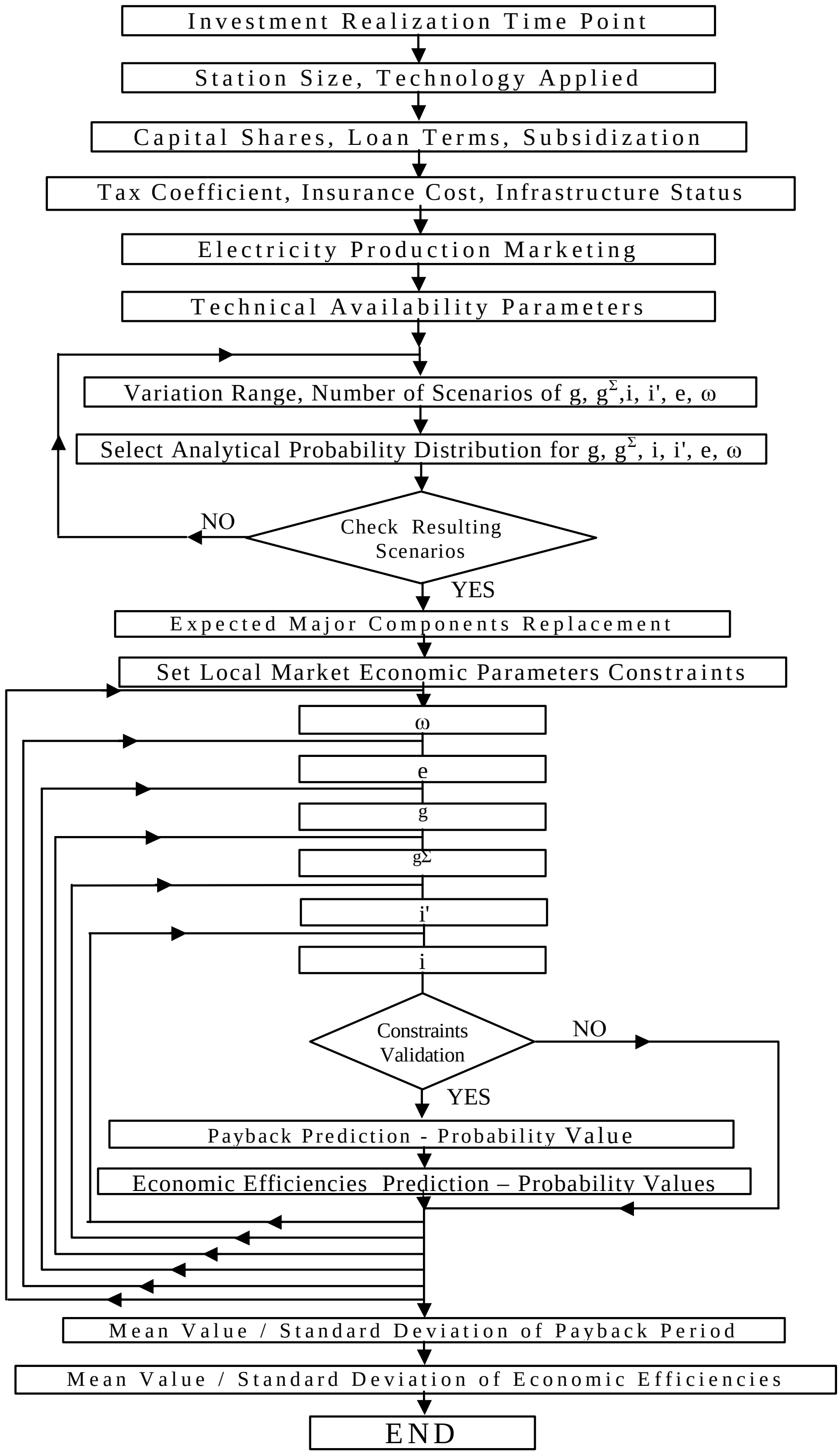

Figure 3: Logical diagram of the proposed algorithm

After the calculation is completed, one has access on the following results:

- ✓ The probability density function of the investment pay-back period
- ✓ The probability density function of the medium term (ten-years) economic efficiency of the investment
- ✓ The probability density function of the long-term (twenty-years) economic efficiency of the investment
- ✓ The total possibility of the unrealistic (according to preset constraints) scenarios
- ✓ The mean value and the corresponding

standard deviation of the predicted pay-back period of the investment

- ✓ The mean value and the corresponding standard deviation of the predicted medium term economic efficiency of the investment
- ✓ The mean value and the corresponding standard deviation of the predicted long term economic efficiency of the investment

At this point, by using the above-described information, the proposed numerical method is being applied to selected renewable energy application cases.

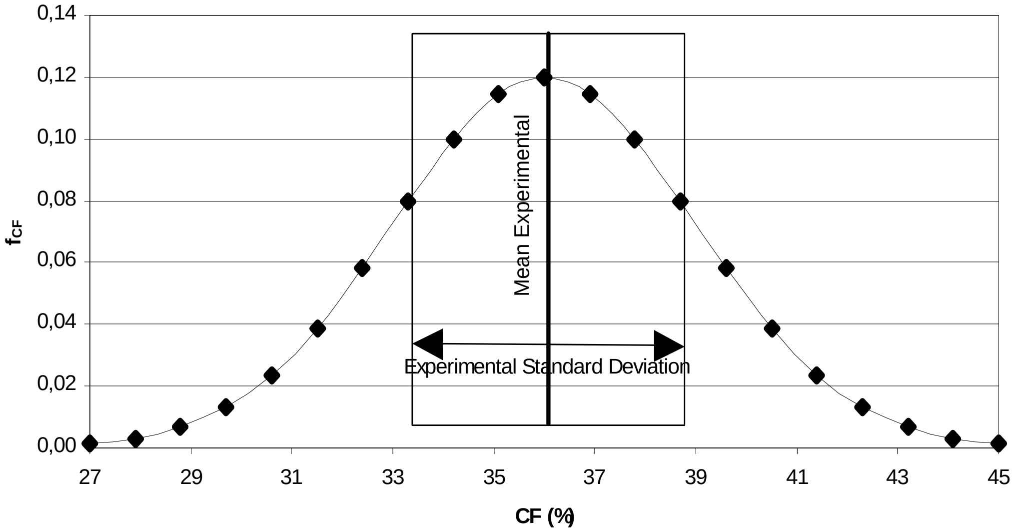

Figure 4: Probabilistic distribution of capacity factor

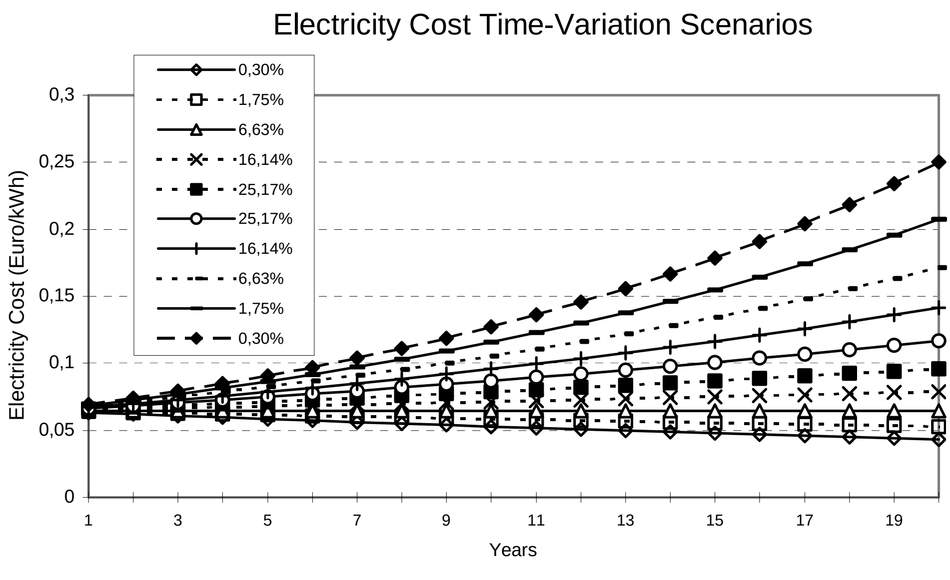

Figure 5: Electricity cost variation scenarios with time

4. Application Results

4.1 Wind Power Station in Lesvos Island

The first test case analyzed via the present numerical code is a medium-sized wind park in Lesvos Island, being compatible with the local electrical network maximum penetration limits. Lesvos is one of the biggest Aegean Sea islands -the second one after Crete- with almost 90,000 habitants. The area possesses an excellent wind potential,[16] as in several areas the local wind speed exceeds 8m/s. Two wind parks have been in operation ever since the previous decade; one of 9x225kW by PPC and a smaller one of (2x300+225)kW by municipality of Mytilene. Due to the high wind speed of the island and the sufficient infrastructure, there are several investment plans proposing the installation of significant size wind parks[4].

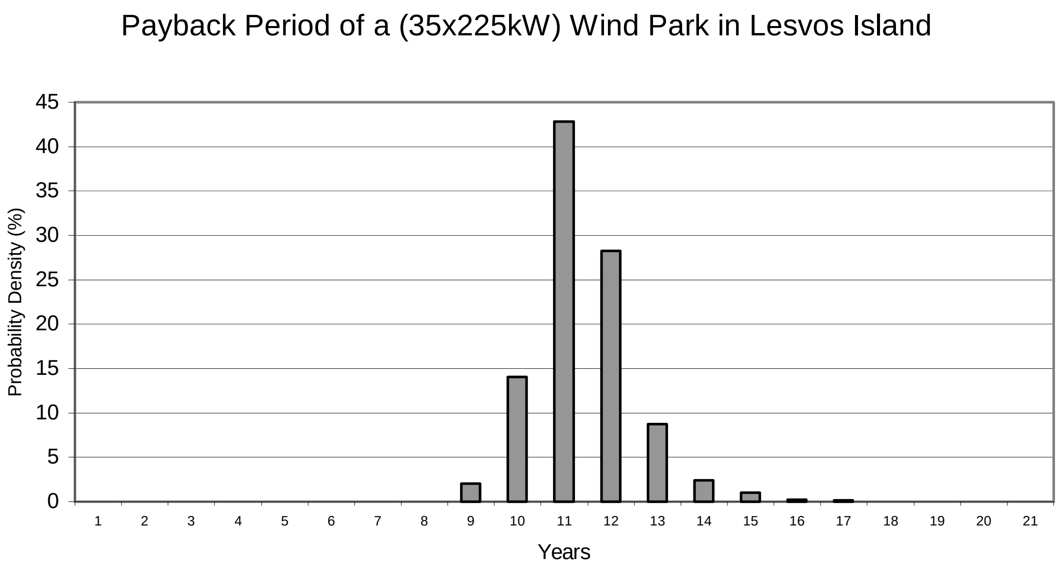

Figure 6: Payback period probability density distribution

Table III: Numerical Values of the Main Economic Parameters

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

More specifically, in the present study a wind park of 35 small-medium sized wind converters (similar to the ones already operating in the region) is analyzed, in view of the techno-economic scenarios of Table III. According to the calculation results the payback period of the investment varies (figure (6)) between 9 and 15 years, while the corresponding mean value is 10.91 years and the standard deviation is 1.08years. In figure (7) one may see the probability density function of the 20-years efficiency of the investment, which takes values in between 100% to 400%. More specifically, the long-term economic efficiency of the investment is (with reliability of 95%) between 50% and 400%. As the payback of the investment exceeds the 10 years, there is no reason to present here the 10-years economic efficiency of the investment.

Finally, in figure (8) one has the opportunity to estimate the variation of the expected payback period of a wind park in Lesvos -consisting of a variable number of 225kW wind turbines- as a function of the number of wind turbines used. In the same figure, there also exists the corresponding 95% confidence interval of the wind parks payback period. As it is obvious from the results obtained, the payback period of all the wind parks based on 225kW machines of 3rd generation varies between 8 and 14 years, for all the combinations (500,000) of Table III.

4.2 Photovoltaic Power Station in Crete Island

Photovoltaics is the most promising renewable energy technology[16] since it transforms the solar radiation directly to DC current, without moving parts. An additional advantage of this technology is the almost negligible maintenance and operation cost (m<0.5%) and the remarkably high technical availability. On the other hand, despite the impressive price diminution[17] during the last twenty years, it is characterized as the most expensive technology for electricity production, being viable only for small remote systems[18] or for large central power stations, under significant state subsidization (50-70%).

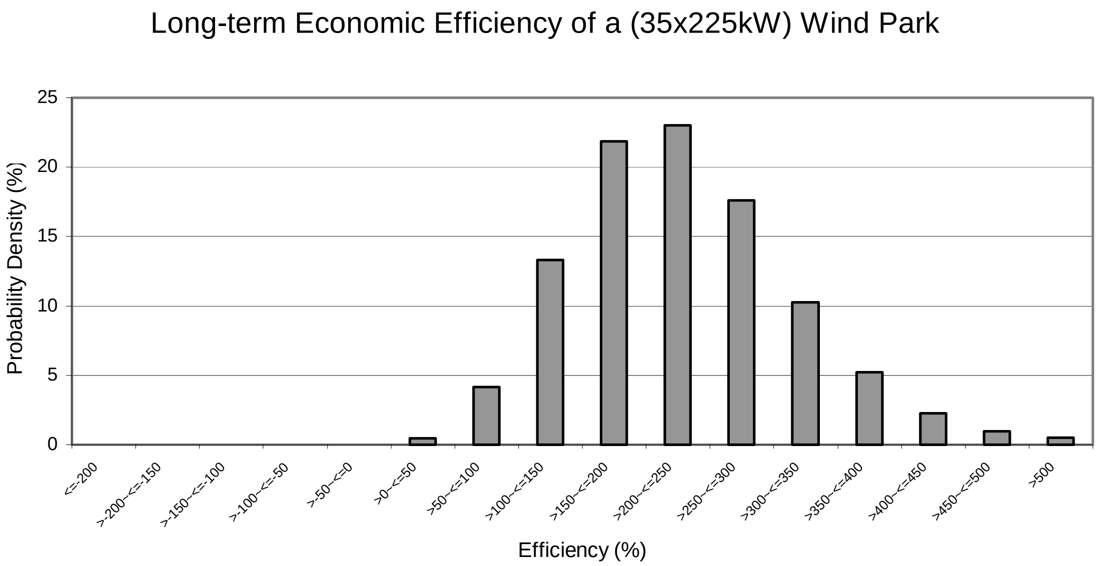

Figure 7: Economic efficiency probability density distribution

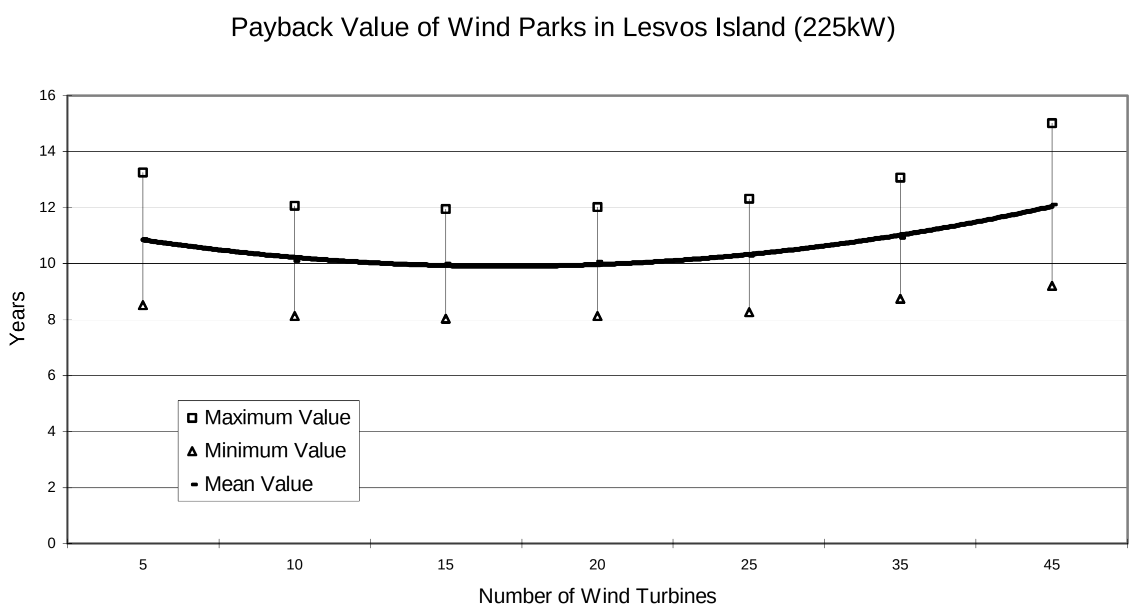

Figure 8: Wind parks payback variation

Taking into consideration the existing situation, an extensive analysis is carried out concerning the economic viability of a large photovoltaic station for Crete Island. Crete (and Gavdos) is the south limit of E.U., hence possessing excellent solar potential (more than 3000 hours of sunshine per year) and annual solar energy higher than 1750kWh/m^2. Applying the present numerical code for a photovoltaic investment in the Crete area the payback period probability density distribution is given in figure (9). According to the detailed numerical results the installation payback period mean value is 17.4 years, while the corresponding standard deviation is less than one year (0.7). Keep in mind that the service period of a typical contemporary photovoltaic station is 30 years minimum[16,17]. In the last figure (10) one may examine the probability density distribution of the 20-years economic efficiency of the investment. As it results from the data achieved, the economic efficiency is quite high (mean value 200%), although the corresponding (95%) confidence interval is large (60% up to 340%), underlining the impact of energy price changes[10] on the expected viability of similar applications.

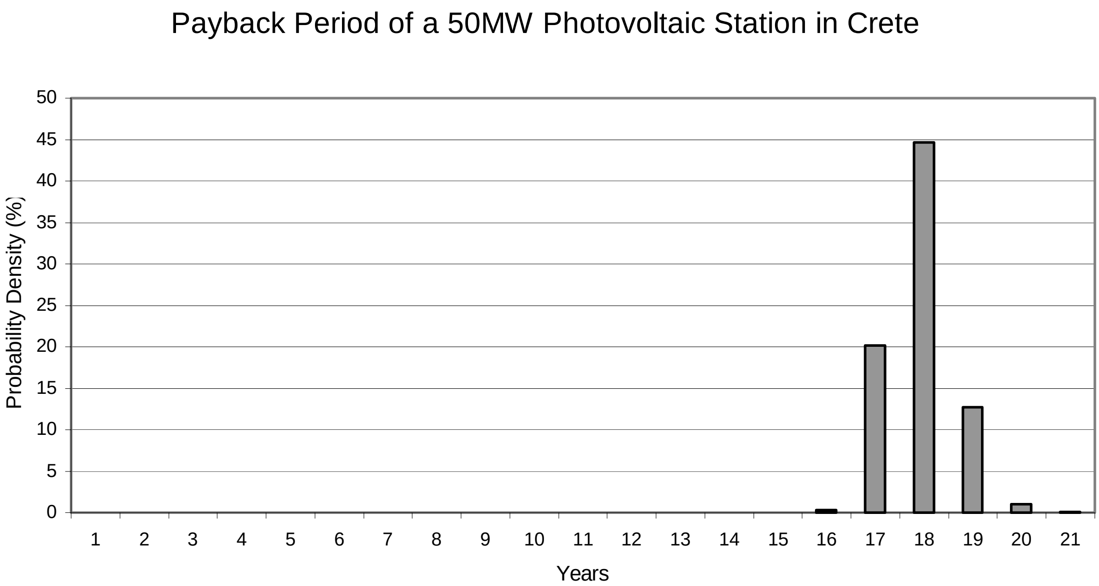

Figure 9: Payback period probability density distribution

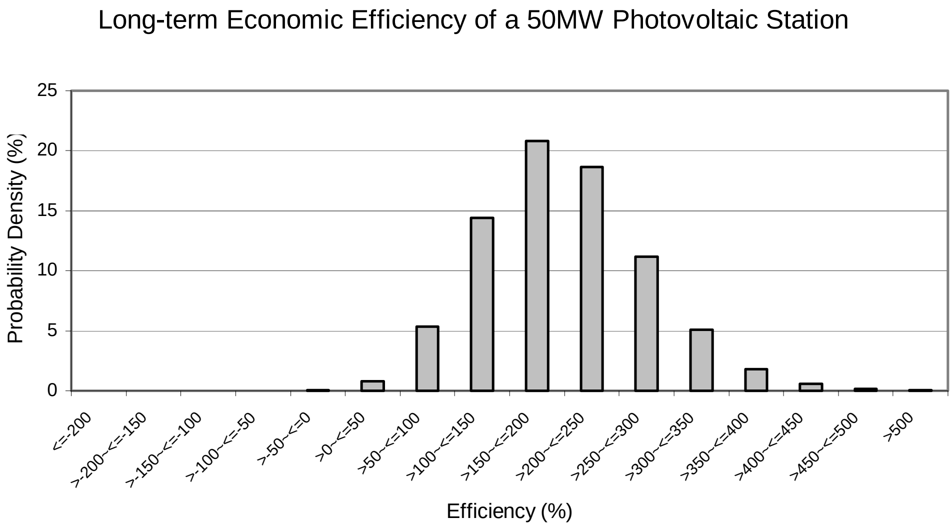

Figure 10: Economic efficiency probability density distribution

In both cases examined, one has also the opportunity to estimate the possibilities either when the payback period is less than a desired value or when the economic efficiency is higher than a specific value. Thus, for example the possibility to obtain twenty-years efficiency higher than 200% is 60% for the (35x225kW) wind park in Lesvos and 50% for the photovoltaic station of 50MW in Crete; a fact that is partially attributed to the different subsidization status of these two renewable energy applications.

5. Conclusions

An integrated computational algorithm is developed, based on a well-established cost-benefit method. The proposed numerical scheme calculates the time-evolution of any energy production enterprise main financial parameter, taking into consideration the necessary probability density distributions. The complete numerical code is prepared in "Visual-Basic" environment and a user-friendly computational tool is created, presenting, among others, the probability distribution of the main economic indexes of a project, like the pay-back period, the economic efficiency and the cost to benefit ratio. Besides, the probability of obtaining a desired result is also directly quantified.

Summarizing, as it results by the presented application examples, by applying the proposed numerical code, it is possible not only to investigate in detail the financial parameters of any energy related project, but also minimize the future investors' uncertainty; contributing thus to a remarkable penetration of renewable energy sources in the new "liberalized" local power market. For all these reasons we believe that a similar computational algorithm could be a standard tool for scientists, investors and experts of the renewable energy application sector.

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FEASIBILITY EVALUATION OF GREEK STATE 1990-2001 WIND ENERGY PROGRAM

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Abstract

An extensive financial analysis of the entire Greek State wind parks is carried out taking into account the life-long variation of every wind power installation techno-economic parameters. This investigation is based on a well-elaborated and integrated cost-benefit model developed by the authors and properly adapted to the local market situation. On top of that, the time-evolution of the local market financial parameters is included, using official data. In this context, the payback period and the corresponding BCR (Benefit to Cost Ratio) values of all wind power installations analyzed are computed. As a general conclusion, one may clearly declare that the Greek State wind power program leads to substantial financial loss, despite the existing advantageous conditions. The main reason for this unexpected financial behaviour is the unexpected low energy production of most wind power plants along with their long-term failures. In conclusion, the future of every State wind park may be redefined in view of the attempted European electricity market deregulation.

Keywords: Feasibility Study; Wind Park; State Wind Energy Program; Energy Production

1. Introduction

Wind energy is now a mature and economically attractive electricity production choice, especially in regions possessing high wind potential and sufficient infrastructure[1]. During the previous twenty years, however, several wind power applications proved financially unsuccessful, leading the investors involved to substantial loss or even bankruptcy.

In an attempt to evaluate the financial results of all Greek-State wind parks after 11-years of their operation, the feasibility analysis model developed by the authors is initially presented[2][3]. This model has recently been extended[4] to include time-variation of all the problem parameters; hence, it is adapted to analyze long-term operation of similar investments. Subsequently, the energy production data[5][6] from all the wind power stations is combined with the corresponding electricity production cost[6][7], in order to estimate the wind parks revenue in current prices. Accordingly, all the available information concerning the capital invested -including European Commissions subsidization- is also investigated, considering the local market financial situation, i.e. local market inflation, capital cost, drachmas to ecu/euro ratio etc[8].

Using the above-described data and applying the proposed analytical frame, one has the capability to estimate the payback period and the financial efficiency of all Greek State wind parks. In addition, the results obtained are directly compared with local and European market data, to deduce useful conclusions. On top of that, a general evaluation is possible regarding the financial behaviour of the entire twelve-years Greek State wind energy program. In conclusion, the future of every State wind park can be also examined, in view of the attempted European electricity market liberalization.

Nomenclature

BCR_n	benefit to cost ratio of the investment after a n year period
c	wind energy-electricity price (Euro/kWh)
CF	wind turbine capacity factor
C_n	total investment cost in current values over a n year period (Euro)
e	electricity price escalation rate
f_o	first installation cost coefficient for ten (10) wind turbines
FC_n	fixed maintenance and operation cost over a n year period (Euro)
g	local market inflation rate
g^k	annual change of the price for the k-th major component of the installation
G_n	investment gains in current values over an n year period (Euro)
i	return on investment index
$i^{/}$	capital cost index
IC_o	initial investment cost (Euro)
m	annual fixed M&O cost coefficient
N_o	wind turbine nominal (rated) power (kW)
Pr	specific ex-works price of a wind turbine (Euro/kW)
r_k	replacement cost coefficient for the k-th major component of the installation
R_n	investment savings in current values over a n year period (Euro)
t	time
VC_n	variable maintenance and operation cost over a n year period (Euro)
Y_n	residual value of the investment in current values after a n year period (Euro)
z	number of wind turbines
α	own capital invested (%)
β	loan capital invested (%)
γ	State subsidization (%)
Δ	technical availability
η_n^*	economic efficiency of the investment after a n year period
ρ^k	annual level of technological improvements for the k-th major component
Φ_n	tax paid in current values over a n year period (Euro)
$\Phi_{(j)}$	tax paid during only the year j (Euro)
ω	wind turbine mean power coefficient

2. Wind Park Cost-Benefit Analysis Model

The analysis undertaken uses the well-elaborated economic viability model[2][4] concerning the wind power stations in Greece, and considers the time evolution of the problem's basic parameters. According to this model, the exact value of the pay-back period "n^*" and the economic efficiency "η^*" or the benefit to cost ratio "BCR" of an energy production station can be predicted[9] for the 1985-2005 period using the following relations:

$$G_n = R_n - C_n - \Phi_n = 0 \quad \text{for } n=n^* \tag{1}$$

$$R_n = R_{n-1}(1+i_n) + R_o \cdot \frac{E_n}{E_o} \cdot \prod_{j=1}^{j=n}(1+e_j) \tag{2}$$

$$R_o = E_o \cdot c_o \tag{3}$$

$$C_n = IC_o \cdot \left\{ \alpha \cdot \prod_{j=1}^{j=n}(1+i_j) + \beta \cdot \prod_{j=1}^{j=n}(1+i'_j) \right\} + FC_n + VC_n \tag{4}$$

$$FC_n = FC_{n-1} \cdot (1 + i_n) + \frac{m_n}{m_o}(m_o \cdot IC_o) \cdot \prod_{j=1}^{j=n}(1 + g_j^m) \tag{5}$$

$$VC_n = IC_o \cdot \sum_{k=1}^{k=k_o} r_k \cdot \sum_{l=1}^{l=l_k} \left\{ \left[\prod_{j=1}^{j=l \cdot n_k} (1 + g_j^k) \cdot (1 - \rho_j^k) \right] \cdot \left[\prod_{j=l \cdot n_k}^{j=n} (1 + i_j) \right] \right\} \tag{6}$$

$$\Phi_n = \sum_{j=1}^{j=n} \Phi_{(j)} (1 + i)^{n-j} \tag{7}$$

and

$$\eta_n^* = \frac{\tilde{G}_n}{IC_o \cdot (1 - \gamma) - \tilde{Y}_{(n)}} \tag{8}$$

$$BCR = \frac{\tilde{G}_n}{IC_o \cdot (1 - \gamma)} \tag{9}$$

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

$$\tilde{x}_j = \frac{x_j}{\prod_{k=1}^{k=j} (1 + g_k)} \tag{10}$$

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. Keep in mind that calculations are carried out using current values for the quantities involved.

Thus, the total gains "G" of a wind park based on "z" similar wind converters of rated power "N_o" are the difference between the total (tax-free) revenues and the corresponding project cost minus the taxes paid during the entire period of operation of the wind power station.

In this context, the total (tax-free) savings "R_n" of the installation during an n-year period due to the wind power station annual energy yield "E(t)" time evolution also depends on the return on investment index "i(t)" and the electricity price escalation rate "e(t)" of the local market; see equation (2). Bear in mind that the annual energy production of a specific wind power station (zxN_o machines) is defined by the technical availability "Δ" and the mean power coefficient "ω", or the resulting capacity factor "CF" (CF=Δ.ω), i.e:

$$E = 8760 \cdot CF \cdot z \cdot N_o \tag{11}$$

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

$$e_j = \frac{c_j}{c_{j-1}} - 1 \tag{12}$$

where "c_j" is the effective cost coefficient (Euro/kWh) of the replaced conventional energy by the wind energy during the year "j".

The initial investment cost "IC_o" appearing in equations (4) to (6) includes[2][10] the market price (ex-works) "$P_r.z.N_o$" and the corresponding installation cost "$f\cdot(P_r.z.N_o)$" of the wind plant. More precisely, installation cost (or balance of plant cost) includes foundation cost, electrical interconnection cost, land purchase, planning cost, approvals, infrastructure, management of the project and grid connection cost[4]. Transportation cost is usually included in the machines' purchase cost. Thus, the turnkey cost "IC_o" can be expressed as:

$$IC_o = P_r \cdot z \cdot N_o \cdot (1 + f) \tag{13}$$

The specific price of a wind turbine can be approximated using the analytical model by the authors or using the historical data of PPC, concerning the wind park financial budget. It is worth mentioning that a significant specific price "P_r" (Ecu/kW or Euro/kW) diminution has been encountered during the '80s, although it was weaker during the past decade. As expected, the relation between Ecu (or Euro) and drachmas should also be considered for the Greek market analysis. Finally, the installation cost coefficient "f" mostly depends[4][10] on the peculiarities of the exact location of wind park erection, taking values between 0.15 and 0.6, typical value f=0.45 for the 1990-1995 period and island regions.

Subsequently, the term "$\alpha.IC_o$" of equation (4) describes the invested capital, while the "$\beta.IC_o$" term expresses the loan capital ("$i'(t)$" the capital cost index). According to development laws, valid since 1982 for the renewable energy applications in Greece[9][10], the Greek State subsidizes by "100xγ%" the corresponding investments. At the same time, wind power installations were generously supported by European Commissions funding via the corresponding 1st and 2nd Framework Support Programs. Thus one may write:

$$\alpha(t_o) + \beta(t_o) + \gamma(t_o) = 1.0 \tag{14}$$

where $\alpha \geq 0.3$ and $\gamma \leq 0.4$).

Accordingly, the maintenance and operation (M&O) cost can be split into the fixed maintenance cost "FC_n" and the variable one "VC_n"; equations (5) and (6). The annual fixed M&O cost may be estimated as a fraction "m_o" of the initial capital invested, considering an annual increase of the cost equal to "g^m" (i.e. the M&O annual inflation rate). An additional increase of the M&O cost, related to the aging[11][12] of wind converters, is expressed by the term "m_n/m_o".

Finally, the variable maintenance and operation cost depends on the replacement of "k_o" major parts of the installation, which have a shorter lifetime "n_k" than the complete installation[10][13]. The symbol "r_k" describes the replacement cost coefficient for each "k_o" major part (rotor blade, gear box etc) of the installation, while "l_k" is the integer part of the following equation:

$$l_k = \left[\frac{n-1}{n_k}\right] \tag{15}$$

where "n_k" takes values depending on the machine's specific component examined along with the technology status applied. Note also that "$g^k(t)$" and "$\rho^k(t)$" in equation (6) describe the annual change of the price and the corresponding technological improvement level for the "k-th" major component of a wind converter[4][13][14]. More precisely, the replacement cost may considerably vary, compared with normal repair cost, imposing even the abandoning of the whole project in particular cases.

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

Generally speaking, all replacement cost components tend to increase with the age of the turbine, thus the necessary reinvestments start to dominate the total M&O cost after the first ten years of the turbine life.

Following equation (7), the term "$\Phi_{(j)}$" describes the tax paid during only the "j" year, mainly due to the previous year revenues. According to the Greek tax-law, "$\Phi_{(j)}$" depends on the law-defined tax-coefficient, the net cash flow of the "j-1" year, the depreciations of the investment, along with the financial obligations of the enterprise[2].

Eventually, in order to evaluate the economic behaviour of a wind power installation, one may use the economic efficiency "η^* " (equation (8)) or the benefit to cost ratio "BCR" (equation (9)) of a wind plant, further to the pay-back period of the investment[2][4][10]. In equation (8) "$Y_{(n)}$" 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 corresponding technological know-how and the experience gained.

Conclusively, for investigating the life-time economic behaviour of Greek State wind parks, one needs the time-evolution of the local market financial parameters including the energy production cost, the annual energy production along with the corresponding initial and maintenance and operation cost values of each wind park. Using the above-mentioned information and applying the already presented analytical model, one has the capability to estimate all the necessary financial parameters of the investments under investigation.

3. Greek State Wind Parks Data Presentation

3.1 Greek State Wind Parks Energy Production

According to the existing official data (mid-2002), Greece State -via the State controlled Public Power Corporation (PPC)- is in possession of 22 wind parks including 158 wind turbines of various sizes; Table I. The nominal power of PPC wind parks is almost 37MW, while a small number of wind turbines (3 to 5) have been out of order for quite a long time, being practically abandoned.

Table I: Main characteristics of Greek State wind parks

	Name of wind park and location	**Start up**	**Wind turbine model**	**Number (z) of wind turbines**	**Rated power N_o (kW)**
1	Kithnos-I	Aug. 90	Aeroman	5	33
2	Kithnos-II	Nov. 99	Vestas V-39	1	500
3	Samothrace	Nov. 90	Windmatic WM-15S	4	55
4	Ikaria (Perdiki)	Aug. 91	Windmatic WM-15S	7	55
5	Karpathos II(Agios Ioannis)	Oct. 91	Windmatic WM-15S	5	55
6	Limnos-I (Vounaros)	Jun. 92	Windmatic WM-15S	8	55
7	Limnos II (Vigla)	Jul. 92	Windmatic WM-19S	7	100
8	Samos-I (Marathokambos)	Jul. 91	Windmatic WM-19S	9	100
9	Chios-I (Potamia)	Dec. 92	Windmatic WM-19S	10	100
10	Andros (Kalivari)	Jul. 92	Vestas V-27	7	225
11	Samos-II (Pithagorio)	Aug. 92	Vestas V-27	9	225
12	Psara (Agios Ilias)	Dec. 92	Vestas V-27	9	225
13	Chios-II (Melanios)	Jan. 93	Vestas V-27	11	225
14	Lesvos (Apolithomeno)	Nov. 99	Vestas V-27	9	225
15	Sitia-I (Moni Toplou)	Jan. 93	HMZ Windmaster 300	17	300
16	Euboea (Marmari)	Jul. 92	HMZ Windmaster 300	17	300
17	Mikonos (Faros)	Jun. 86	Micon-108	1	108
18	Karpathos I	Feb. 87	HMZ-175	1	175
19	Skiros (Aspous)	Nov. 92	-	1	100
20	Sitia-II (Moni Toplou)	Dec. 93	Tacke TW-500	2	500
21	Sitia-III (Moni Toplou)	Apr. 95	Nordtank NTK-500	1	500
22	Sitia-IV (Mitato)	Jun. 00	NEG-Micon NM600	17	600
	TOTAL			158	36993

More specifically, the commercial wind parks of PPC may be divided into six categories, i.e.:

i. 24 machines of rated power of 55kW, installed in Samothrace, Ikaria, Karpathos and Limnos since 1990. These wind turbines (WM-15S) belong to the second generation, produced during the mid 80's by Windmatic

ii. 26 machines of rated power of 100kW (WM-19S), installed in Limnos, Chios and Samos, since 1991. These wind turbines were also manufactured during late 80's by the old Danish company Windmatic, absorbed by Vestas in 1990

iii. 45 machines of rated power of 225kW, operating in Andros, Samos, Psara and Chios since 1992-93. The last nine machines were recently (1999) installed in Lesvos, almost six years later than scheduled. All these machines are the well-known V27 wind turbines manufactured by Vestas

iv. two twin wind parks of 17 HMZ/Windmaster-300 wind turbines each, situated in Euboea and Sitia of Crete respectively. Both wind parks suffered from major blade failures, since their first year of operation, thus the old blades were replaced by new ones in 1999

v. the most recent and biggest wind farm of PPC (10.2MW) erected in 1999 at Mitato of Sitia, using 17x600kW NEG-Micon stall controlled wind converters

vi. several isolated wind turbines, like the 2x500 Tacke (TW-500) and the 1x500 Nordtank (NTK-500) situated in major Sitia area, the six engines (5x33 Aeroman and 1x500 V-39) operating in Kithnos island and three abandoned wind turbines in Karpathos, Mikonos and Skiros islands

In Table II the life-long annual energy production is sited for all these installations, according to the official data announced by PPC[15]. In figure (1) the corresponding capacity factor time-evolution for each of the above subgroups is presented. A general conclusion drawn from these distributions might be the remarkable variability of the corresponding capacity factor, not justifiably explained by the annual changes of the wind potential. On top of that, between 1993 and 1998, the capacity factor of State owned wind parks has been unexpectedly low, presenting however a significant amelioration during the last three years[6][16][17].

Table II: Annual energy production (MWh) of Greek State wind parks for the (1990-2001) period

	WIND PARK	$zN_{o\,(kW)}$	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	Total
1	Kithnos-I	165	204	116	197	236	122	119	165	55	116	98	39	1467
2	Kithnos-II	500	-	-	-	-	-	-	-	-	53	679	806	1538
3	Samothrace	220	86	205	182	419	138	152	264	532	517	652	696	3843
4	Ikaria	385	205	201	338	1156	1071	760	1296	1298	1079	1145	1095	9644
5	Karpathos-II	275	5	280	267	1043	185	104	1133	1259	1203	1174	1226	7879
6	Limnos-I	440	-	218	533	612	74	0	151	553	538	809	891	4379
7	Limnos-II	700	-	-	549	733	215	359	690	731	896	951	718	5842
8	Samos-I	900	-	-	543	1997	330	1593	3146	2578	2343	2460	3021	18011
9	Chios-I	1000	-	-	540	2000	1813	1254	1015	2011	1858	1605	1248	13344
10	Andros	1575	-	2227	4830	5336	4222	4904	5003	3512	3903	4504	4800	43241
11	Samos-II	2025	-	2163	5736	6310	6348	5915	4868	4381	4575	5592	5696	51584
12	Psara	2025	-	515	4161	5300	5014	5043	5155	4943	4935	4739	4803	44608
13	Chios-II	2475	-	-	5878	6783	6597	6219	5594	7029	6390	5926	6521	56937
14	Lesvos	2025	-	-	-	-	-	-	-	-	1733	6569	4847	13149
15	Sitia-I	5100	-	-	11524	0	0	0	260	9748	14000	15193	14775	65500
16	Euboea	5100	-	-	9887	0	0	0	0	0	9398	13775	10643	43703
17	Sitia-II	1000	-	-	-	2793	2337	2720	2650	1600	1165	1333	1888	16486
18	Sitia-III	500	-	-	-	-	1147	1173	1609	1708	1522	1817	1479	10455
19	Mitato	10200	-	-	-	-	-	-	-	-	-	22267	37447	59714
	TOTAL		500	5925	45205	34858	29733	30425	32999	41938	56224	91288	102639	471734

In this context, the annual energy production of Greek State wind parks -given in figure (2)- varies between 35GWh and 103GWh, representing merely a small percentage (0.2%) of the national electricity consumption.

3.2 Local Power Stations Electricity Production Cost

The geographic distribution of Greek State wind parks, figure (3), clearly asserts that all the installations -except the Marmari Euboea wind park- are situated in windy Aegean Archipelago regions, and more precisely in island electrical networks. This fact is very important as far as the corresponding electricity production cost in these areas is concerned.

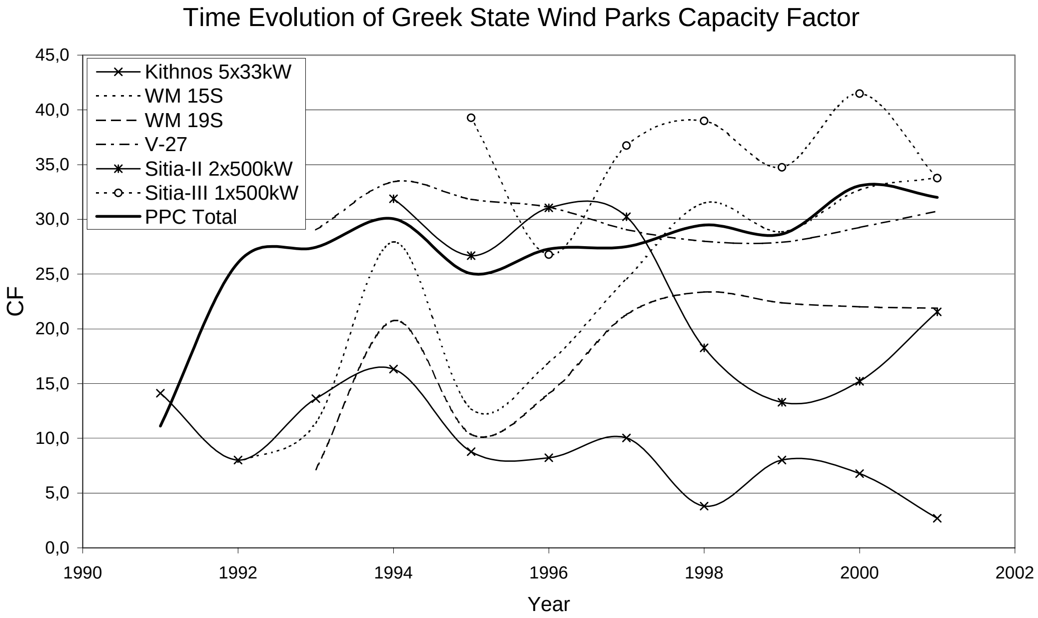

Figure 1: Capacity Factor Distribution for the Main Greek State Wind Parks

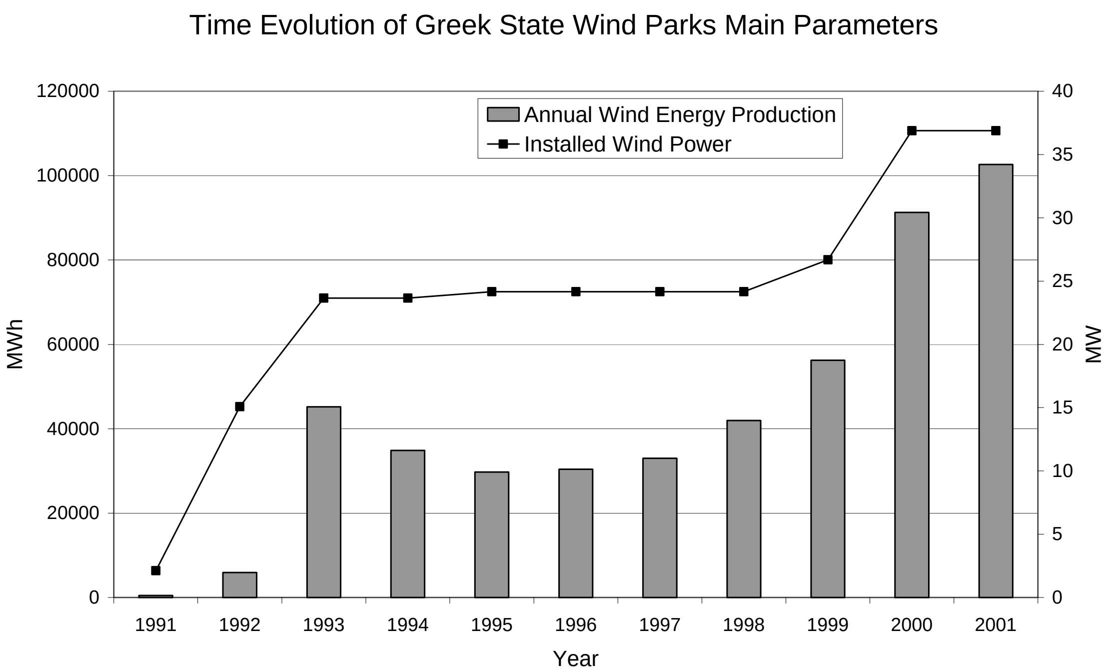

Figure 2: Annual Energy Production and Installed Wind Power Capacity Time-Evolution for Greek State Wind Parks

Figure 3: Greek State Wind Parks Locations (mid 2002)

Generally speaking, the electricity production cost for the remote Greek islands majority is extremely high[18] due to the aged autonomous (thermal) power stations "APS" used. More precisely, the mean production cost of the Greek APS is more than double the corresponding marginal cost of the Greek PPC, figure (4). Additionally, for the most islands possessing a wind park the electricity production cost is even higher -see also figure (5)- approaching values of the order of 0.25Euro/kWh, while the fuel cost is responsible[5][7] for almost 50% of this charge. According to the official data provided by PPC, the mean electricity production cost in big islands (Crete, Lesvos, Chios, Samos) is of the order of 0.1Euro/kWh, while for small islands (Kithnos, Andros, Limnos, Karpathos, Ikaria and Samothrace) approaches almost 0.3Euro/kWh.

Considering the information given in figures (1) and (5), it is possible to estimate the wind park revenues on the basis of their energy production and their local network corresponding electricity production cost; see also equations (2), (3) and (11). An alternative approximation adopted by other researchers is to utilize only the marginal cost of PPC in order to estimate the wind parks income. However, it is our belief that for every wind power station one should consider not only the particular installation and operation cost function, but also the corresponding energy production cost value.

3.3 Wind Parks Total Operational Cost Function

For the estimation of total operation cost time-distribution of equation (4), one may use the PPC historical records, concerning the expenditures of every wind park. Unfortunately, the corresponding records are not enlightening enough, as in many cases they include complex information in different time than the cost realization. On top of that, in several cases the local wind park operation and maintenance costs are incorporated into the entire APS relative cost value[5]. For this reason, the proposed examination is based on the analytical model developed by the authors for Greek wind parks[2][4][10]. Since this model describes an average financial behaviour of local wind parks, any fiscal peculiarity of all these installations encountered should be also taken into consideration.

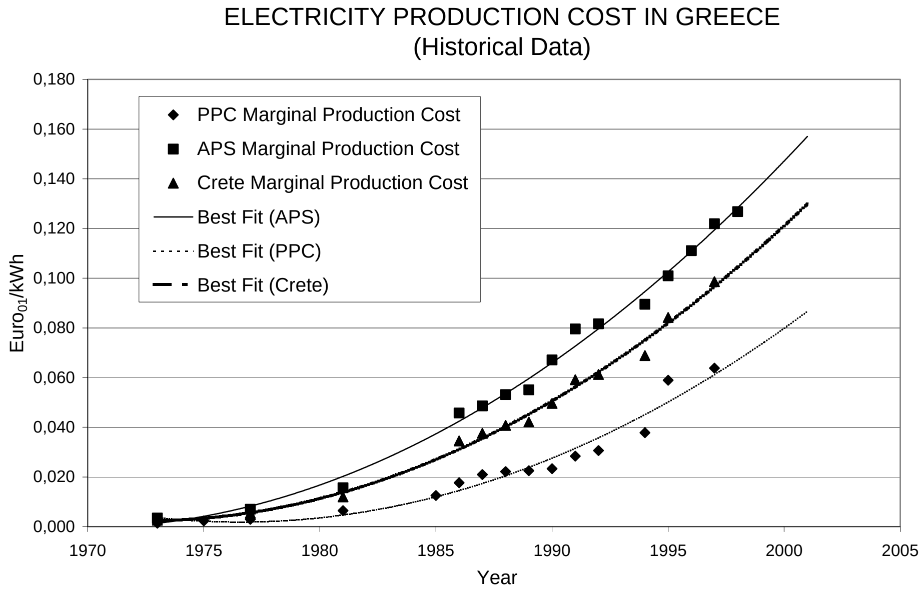

Figure 4: Electricity Production Cost Time-Variation in Greece

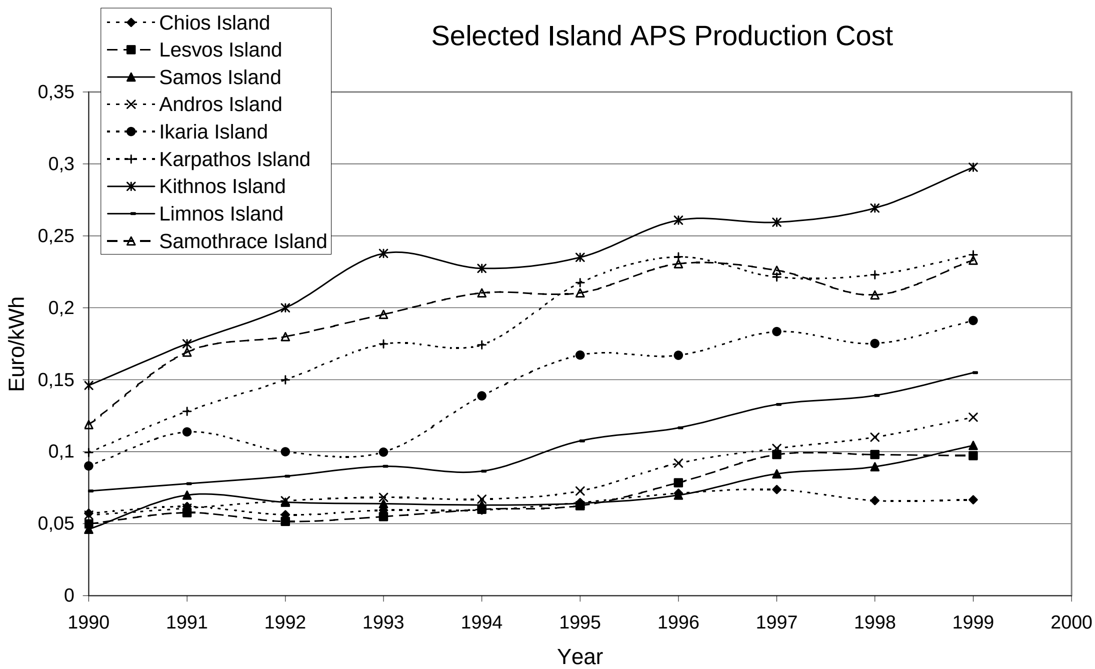

Figure 5: Electricity Production Cost for Selected Greek Islands, Official Data

In this context, using the results of a long lasting market survey by the authors[4][19], the specific ex-works price "P_r" of a wind turbine -belonging in a wind farm of "z" machines- can be approached by a function of the machine rated power "N_o" compared with the optimum commercial value "$N_o^*(t_o)$" of the wind park erection time period "t_o"; thus:

$$P_r(t_o) = \left[f_N(\nu) + c_\infty \cdot \left(1 + \varepsilon_1 \cdot e^{-\varepsilon_2 \cdot (t_o - 1990)}\right)\right] \cdot \sigma_p(z) \qquad (16)$$

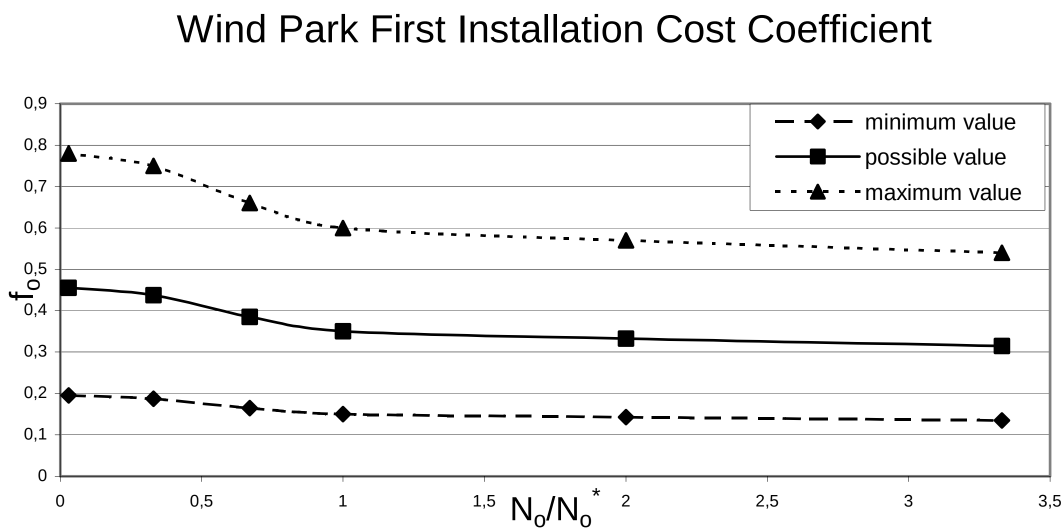

Figure 6: First Installation Cost Coefficient for Greek Market

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:

$$\nu = \frac{N_o}{N_o^*(t_o)} \tag{17}$$

where:

$$N_o^*(t_o) = A_N \cdot e^{B_N \cdot (t_o - 1990)} \tag{18}$$

and 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[4] for the local market:

$$f_N = 566 \cdot e^{-\nu/0.35} - 132.5 + 100 \cdot \nu \tag{19}$$

$$\sigma_p(z) = 1.08 - 0.08 \log(z) \tag{20}$$

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 the machines in the wind park, along with the exact location of the wind power plant, i.e. "$f=f_o \cdot \sigma_f$"; see also figure (6).

Besides, a number of items -like foundation cost, electrical interconnection cost, access tracks- decrease with the size or number of the machines. Thus, in cases of large wind farms (z>10), the site infrastructure cost "σ_f" is spread over a bigger number of machines, reducing the unit cost. On the other hand, for tiny wind parks a small balance of plant cost increase is encountered; see for example equation (21):

$$\sigma_f(z) = -0.075 \cdot (\log(z))^2 - 0.075 \cdot \log(z) + 1.15 \tag{21}$$

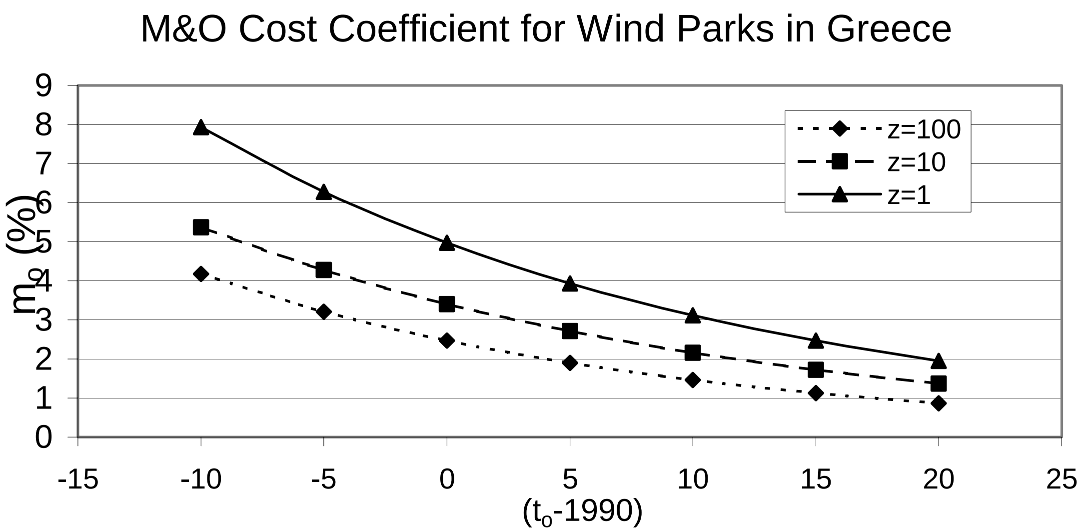

Figure 7: M&O Cost Coefficient Time Variation for New Wind Parks in Greece

Using the above-described closed analytical model, the first installation cost expressed as:

$$IC_o = z \cdot P_r \cdot N_o + (\sigma_f \cdot f_o) \cdot (z \cdot P_r \cdot N_o) \tag{22}$$

is a function of the project realization time "t_o", along with the machines' used rated power "N_o" and number "z", also depending (see value scattering of figure (6)) on the selected wind park location and the corresponding infrastructure situation.

Similarly, the cost related to maintenance, repairs, insurance, leases, management etc, significantly contributes to the total operation cost of the installation. The application of modern design and improved construction techniques, along with the experience gained during the last twenty years, lead 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.

Using the work presented by many authors see for example[10][11][12][20] the following expression is assumed valid:

$$m(t) = m_o(t_o, z) \cdot \frac{m_n}{m_o}(\tau) + \delta \tag{23}$$

where $m_o(t_o,z)$ depends on the technological status and the number of the wind turbines used, along with the accessibility of the wind park (distance, weather conditions, infrastructure, island/mainland etc.); figure (7). Accordingly, as indicated by various research groups gathered data, the time variation of "m" is to a certain extent determined by the age of the turbines "τ". More precisely, the warranty of the turbine manufacturer implies low-level expenses during the first couple of years. After the 10^{th} year, however, larger repairs are required, actually dominating the picture "$\xi(\tau)$"; see also figure (8).

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. Unfortunately, the local market does not offer any insurance contracts for wind parks until recently, thus $\delta \approx 0$. Consequently, applying the above analysis in equation (23), one gets:

$$m(t) = m_o(t_o, z) \cdot \left[1 + \frac{\xi(\tau)}{m_o}\right] \quad (24)$$

Summarizing, operation and maintenance (M&O) costs constitute a sizeable share of total annual costs of a wind power application, especially in Greek State wind parks, since their first installation cost was strongly subsidized (up to 65%) by European Commission funds.

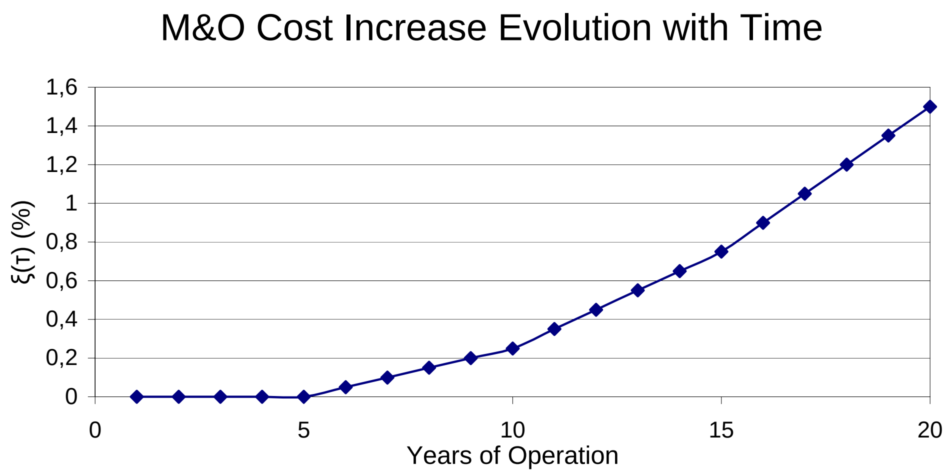

Figure 8: M&O Cost Coefficient Increase versus Operating Time in Greece

3.4 Local Market Economic Parameters Time-Evolution

As it is well accepted, the electricity price escalation rate and the capital cost are purely 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 the existing analysis[14][21], 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:

$$i' = g + i_b + \delta i(r) \quad (25)$$

In cases of soft loans, e.g. State guarantee, $r_1 \rightarrow 0$. Additionally, the annual amount of money required by the investor -so as to invest his own capital "i"- is defined as the "return on investment" and is given by equation (25). This economic parameter depends on factors similar to the capital cost parameter, although it additionally reflects the expectancies of the single investor along with his own abilities and chances to invest money. For State controlled investments gain expectancy is not the vital target, hence one may assume that $i^{/} \approx i$.

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^m" describes the annual 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, see figure (5), since the wind energy produced by the wind power station under investigation replaces electricity production by thermal power stations of PPC. The evolution of all these parameters (i, i', g, g^m) is given in figure (9), for the period 1985-2001, based on the tracks of Greek economy. Recapitulating, the time variation of all necessary parameters of equations (1), (2) and (4) has been recorded. Thus, it is possible to accurately estimate the payback period and the economic efficiency of any wind park in Greece, using the analysis of sections 2 and 3.

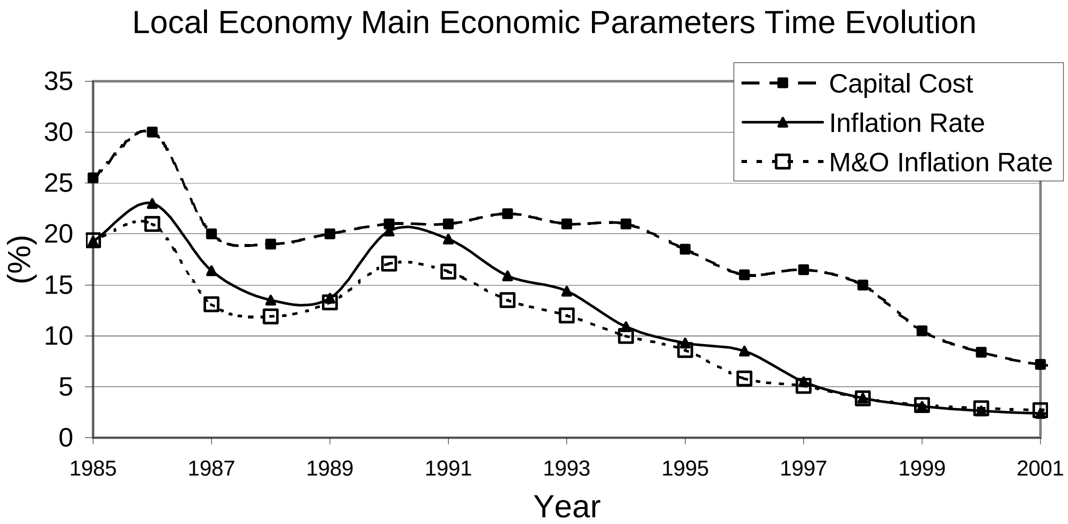

Figure 9: Time Evolution of Selected Economic Parameters of Local Market

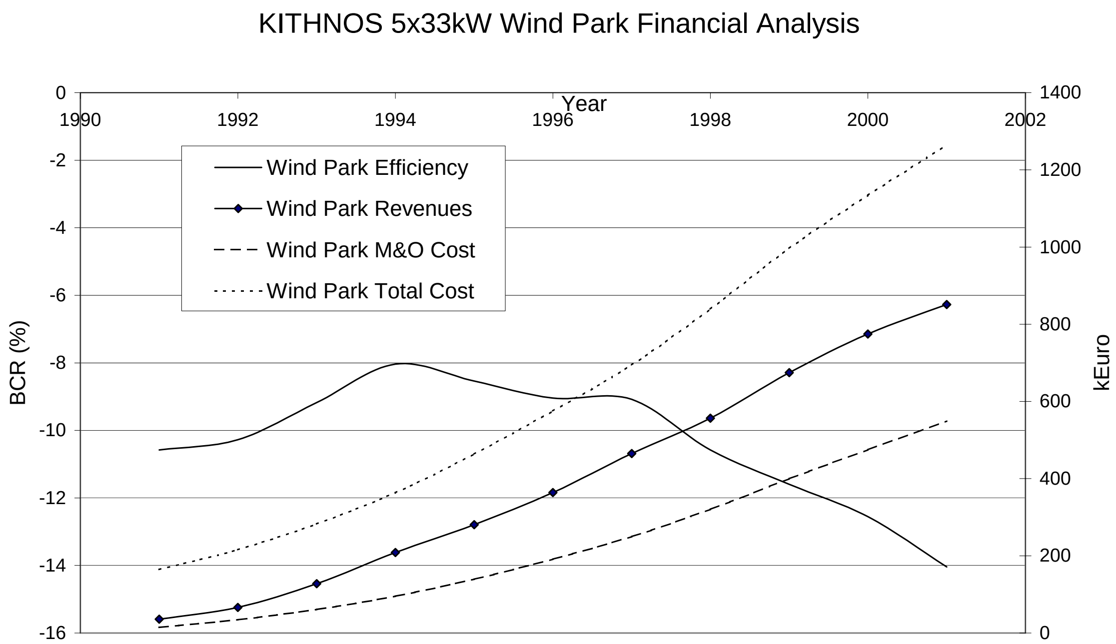

Figure 10: Time Evolution of Kithnos Wind Park Financial Results

4. Application Results

After a thorough inspection of the information given in Tables I and II, one may easily conclude the following:

- The wind turbines of Mikonos, Karpathos I and Skiros have never operated commercially, thus their revenues are practically zero
- The wind parks of Euboea and Sitia-I (17x300kW) became operative only after 1999. In these cases both projects should present significant loss, since they have been commissioned since 1992
- The wind parks of Kithnos-II (1x500kW), Lesvos (9x225kW) and Sitia-IV (17x600kW) started operating recently; hence there is not enough operational time in order to check their financial viability
- For all other installations there are sufficient data to study their financial behaviour, since they have been operating for approximately ten years.

In this context, the first wind park analysed is the Kithnos Island one, which is also the oldest Greek State wind power station, based on five 33kW two-bladed wind converters. As it is obvious from figure (10), after eleven years of operation this wind park still presents negative BCR value, which is gradually worsening after 1995. This poor financial behaviour can be mainly attributed to the unsatisfactory energy production (Table II) of the station. Bear in mind that Kithnos Island possesses medium quality wind potential and the machines used belong to the second generation, presenting thus often major failures.

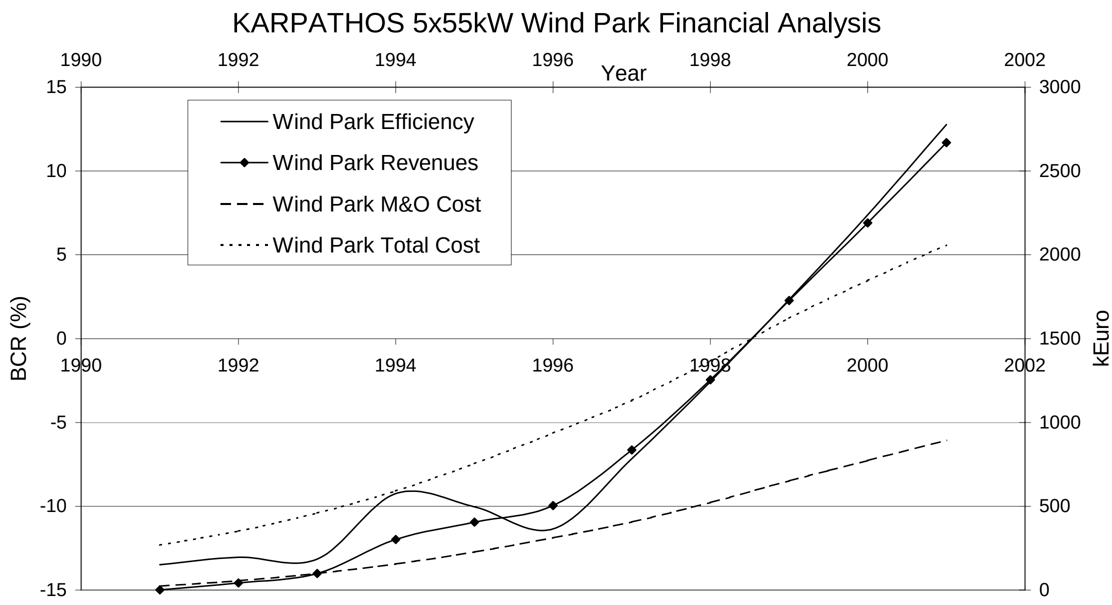

Figure 11: Time Evolution of Karpathos Wind Park Financial Results

This is not the case for the Karpathos-II 5x55kW wind power station, figure (11), which not only reimburses the initial State capital invested, but also presents significant revenues in constant terms. Hence, according to the detailed financial results of figure (11), following an unstable behaviour up to 1996, the results during the last five years are definitely positive, although the machines used are the outmoded WM-15S ones.

Unfortunately, Karpathos-II Wind Park is the only one out of the four PPC wind parks -based on 55kW machines- that clearly presents positive balance. As it results from figure (12), the other three wind parks reveal financial loss, being almost zero for Ikaria installation. The most negative evolution is encountered for Limnos 8x55kW wind farm, since the BCR is continuously dropping, exceeding the (-25%) value. After a closer inspection of its financial data, figure (13), one may observe that the wind park revenues were inferior to the corresponding maintenance & operation cost, yet from its first year of operation.

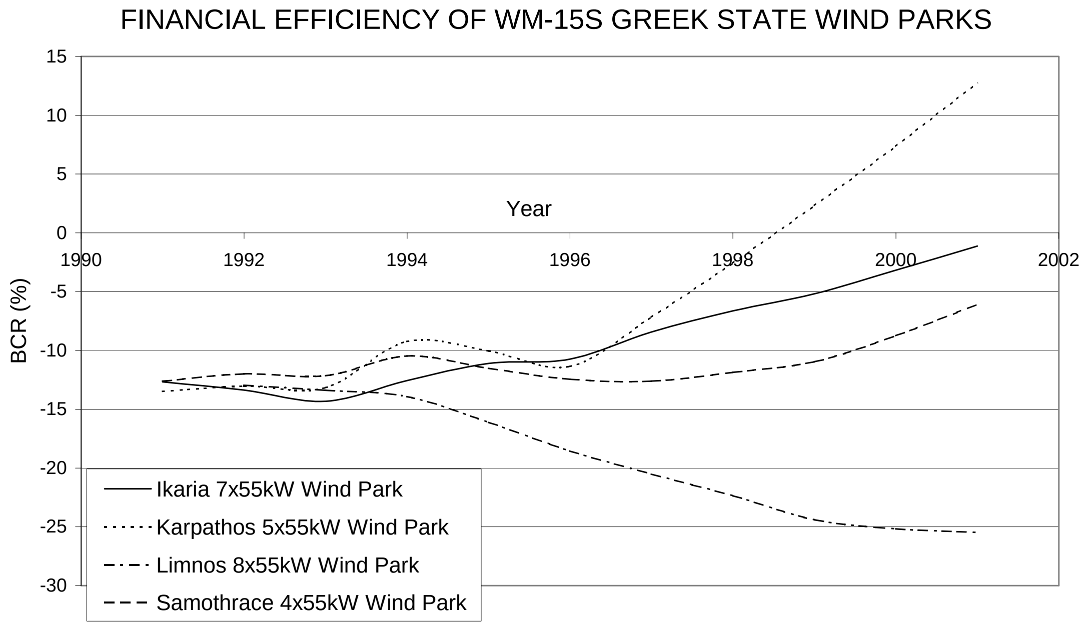

Figure 12: Time Evolution of WM-15S Greek State Wind Parks Financial Efficiency

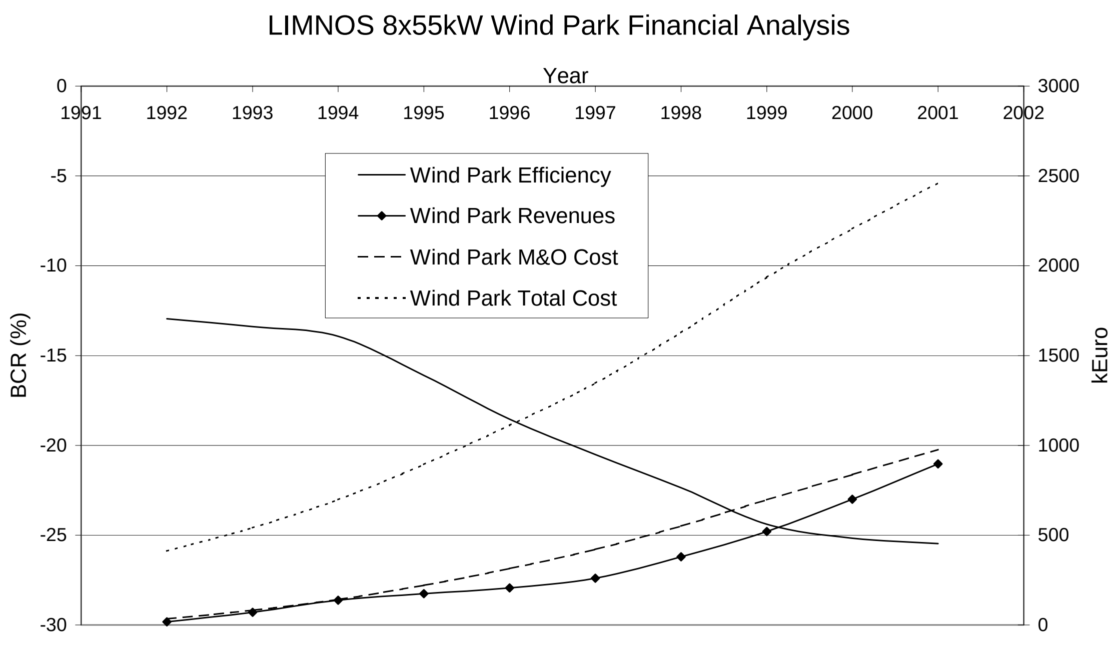

Figure 13: Time Evolution of Limnos (8x55kW) Wind Park Financial Results

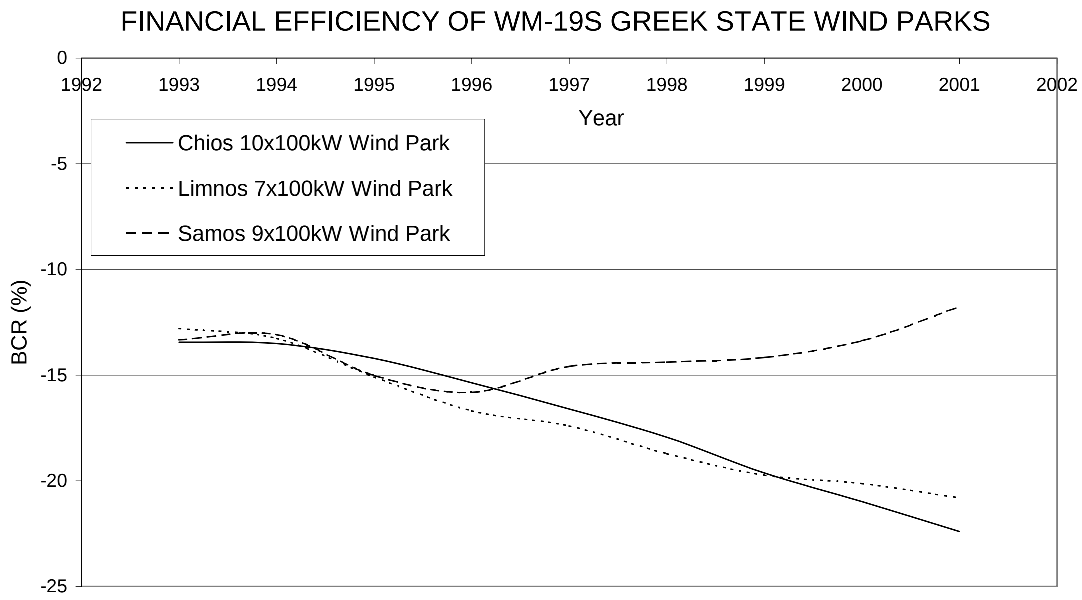

Figure 14: Time Evolution of WM-19S Greek State Wind Parks Financial Efficiency

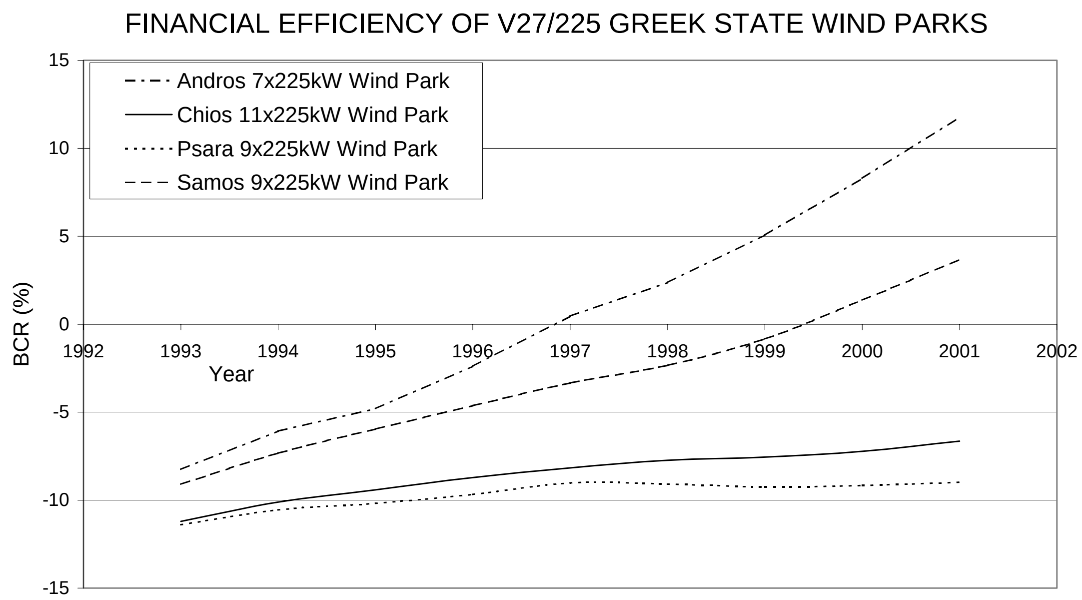

Figure 15: Time Evolution of V27/225 Greek State Wind Parks Financial Efficiency

Accordingly, the life-long financial behaviour of the three PPC wind parks based on the 100kW WM-19S wind converters is investigated, figure (14). Based on the information analyzed, all three-wind power stations present negative economic efficiency (BCR less than –12%). On top of that, the wind parks of Limnos (7x100kW) and Chios (10x100kW) present continuously increasing loss; therefore these installations have almost no opportunity to return the State capital invested (35% of the initial cost). In fact their annual maintenance & operation cost is hardly covered by the corresponding energy revenues.

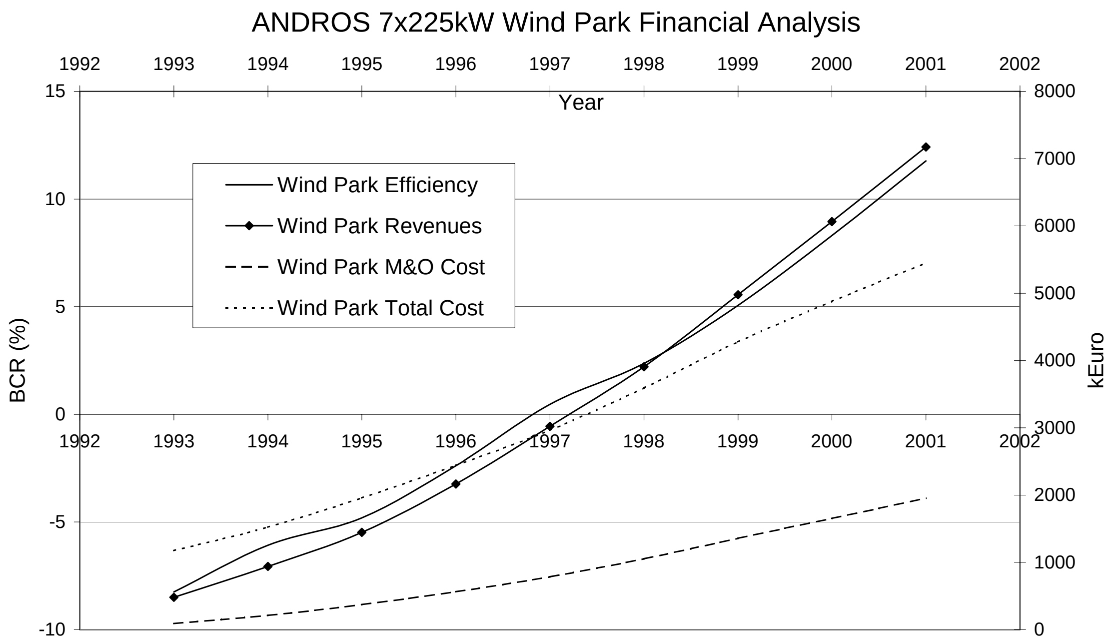

Figure 16: Time Evolution of Andros Wind Park Financial Results

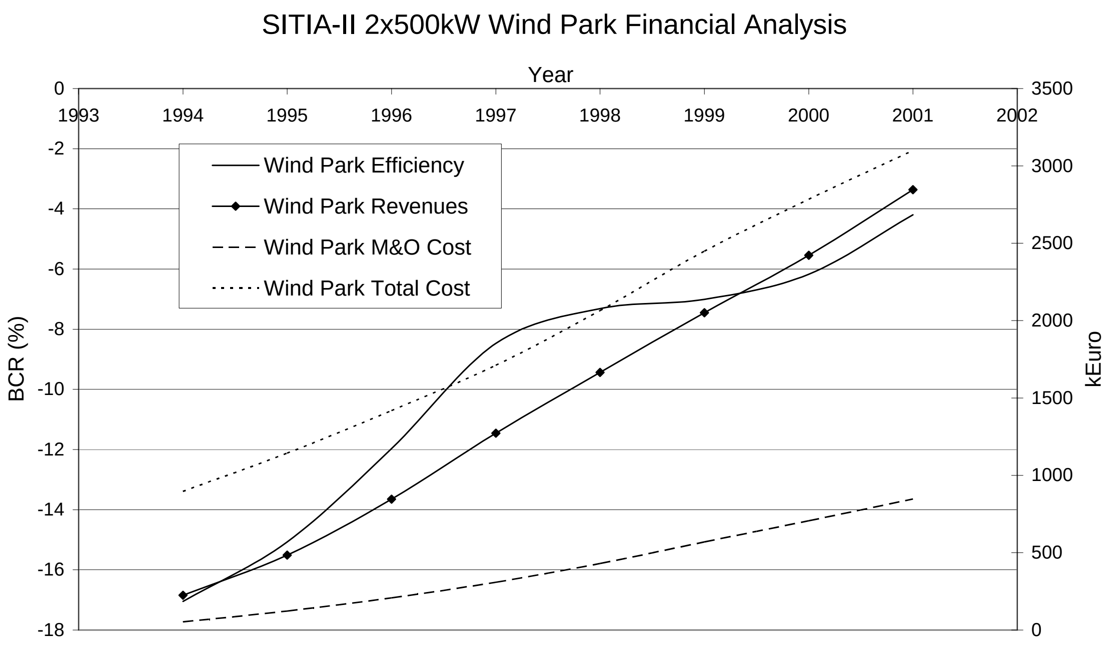

Figure 17: Time Evolution of Sitia-II (2x500kW) Wind Park Financial Results

The financial behaviour of the third State owned wind park subgroup -based on V27/225kW wind turbines- is relatively improved; figure (15). However, even for these comparatively modern machines, net gains are encountered for two of them (Andros and Samos), while the other two wind power stations (Chios and Psara) do not seem to reimburse the capital invested during their operational life. More specifically, the Andros wind park -taking advantage of the excellent wind potential of the island- has a payback period (figure (16)) of only five years; thus in 2001 the corresponding BCR value exceeds the 12%, despite the remarkable increase of the corresponding M&O cost.

The last two cases examined concern the two small installations in Sitia-Crete, based on 2x500kW and 1x500kW wind turbines. According to the results of figures (17) and (18), both investments show positive behaviour, although the 2x500kW one has not yet reimbursed the State capital invested. More precisely, for the 1997-2000 period, the BCR distribution stopped increasing, since one out of the two machines faced major problems that were not promptly confronted. On the other hand, the second installation (1x500kW) presents very positive results, since its payback period is only five years and the corresponding BCR value (in 2001) is almost 14%.

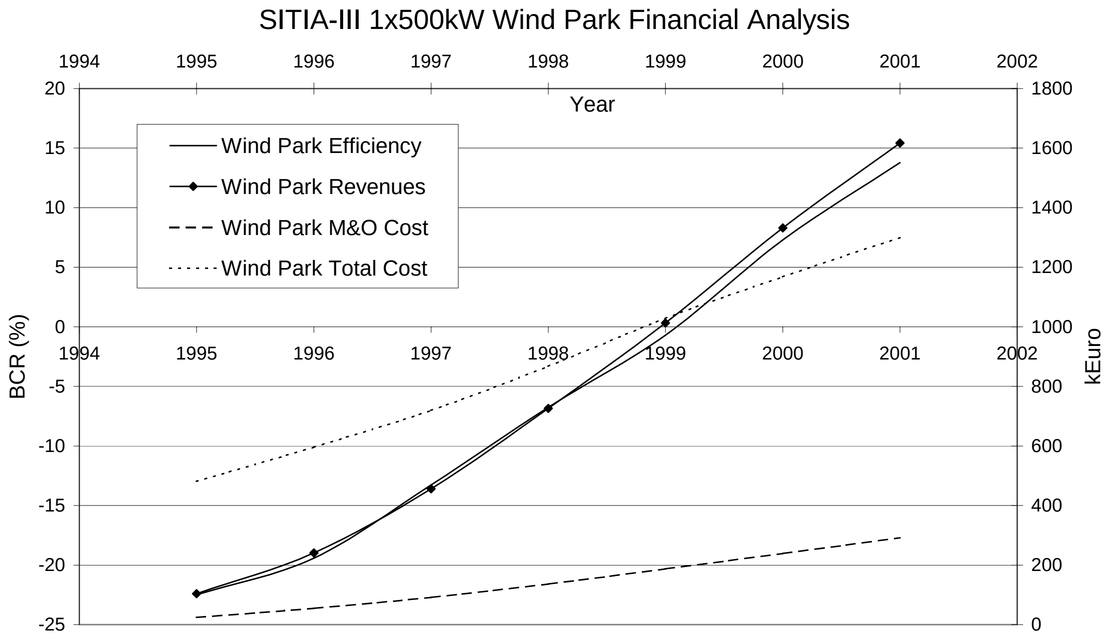

Figure 18: Time Evolution of Sitia-III (1x500kW) Wind Park Financial Results

5. Discussion of the Results

Considering the financial evaluation results of the Greek State wind parks, based on the available official information and the cost-benefit model developed by the authors, one has the opportunity to infer several conclusions. In this context, the payback period and the corresponding BCR_{2001} values of all wind power installations analyzed are summarized in Table III. As a general conclusion one may clearly declare that the Greek State wind power program lead to substantial financial loss. The problem is much more severe, as more than 50% of the capital spent in most wind power investments derive from E.U. financial support. Besides, the Greek State monopolizes[2][16][17] the energy production facilities up to 1994 (law 2244/94), while all the PPC wind parks are located in excellent wind potential areas. Therefore, in normal operation conditions capacity factors exceeding the 40% are expected; see for example figure (1). Finally, during the cost-benefit analysis, it is taken into account the local APS marginal production cost and not the quite lower marginal electricity production cost of PPC; figure (4).

More specifically, wind parks with positive BCR value in 2001 are only: the old wind park of Karpathos (5x55kW WM15S), the wind parks of Andros and Samos based on V27-225kW machines and the 1x500kW wind park of Sitia. Bear in mind that these installations have been created in different time periods, using various wind converters models. The common characteristic of these profitable investments is that they all operate in regions with mean annual wind speed exceeding the 9.5m/s at hub height. Finally, all these wind parks present continuously increasing gains, a fact that supports the continuation of their operation for the next five to ten years.

Table III: Main financial results of Greek State wind parks

	Wind park location	Start up	Payback year	BCR_{2001}
1	Kithnos-I	Aug. 90	Not Expected	-14%
2	Samothrace	Nov. 90	2003 Expected	-2.8%
3	Ikaria (Perdiki)	Aug. 91	(mid) 2002	-1.5%
4	Karpathos (Agios Ioannis)	Oct. 91	(mid) 1999	12.8%
5	Limnos-I (Vounaros)	Jun. 92	Not Expected	-25.5%
6	Limnos II (Vigla)	Jul. 92	Not Expected	-21.2%
7	Samos-I (Marathokambos)	Jul. 91	Not Expected	-11.8%
8	Chios-I (Potamia)	Dec. 92	Not Expected	-22.4%
9	Andros (Kalivari)	Jul. 92	1997	12.1%
10	Samos-II (Pithagorio)	Aug. 92	(mid) 2000	3.5%
11	Psara (Agios Ilias)	Dec. 92	Not Expected	-9.1%
12	Chios-II (Melanios)	Jan. 93	Not Expected	-6.8%
13	Sitia-II (Moni Toplou)	Dec. 93	(mid) 2003 Expected	-4.3%
14	Sitia-III (Moni Toplou)	Apr. 95	1999	13.2%

Among the rest unprofitably operating State owned wind parks, Ikaria (7x55kW) and Sitia-II (2x500kW) installations are very close to their payback period. On the contrary, Limnos-I (8x55kW), Limnos-II (7x100kW), Chios-I (7x100kW) and Kithnos (5x33kW) wind power stations operate with increasing loss, since their annual revenue is unable to cover the corresponding M&O operational cost.

Lastly, the Samothrace 5x55kW, Samos 9x100kW, Chios 11x225kW and Psara 9x225kW wind parks have a constantly unprofitable operation during the last five years and it is quite difficult to payback the State capital invested. Their energy revenue clearly covers the M&O cost, however sufficient savings to compensate their initial capital are unobtainable.

6. Conclusions and Proposals

An extensive financial analysis of the entire Greek State wind parks is carried out, taking into account the life-long variation of every wind power installation parameter. This investigation is based on a well-elaborated and integrated cost-benefit model developed by the authors and properly adapted to the local market situation. On top of that, the time-evolution of the local market financial parameters is also included, using official data.

According to the calculation results, the Greek State wind parks present substantial financial loss, despite the existing advantageous conditions. The two main reasons for this unexpected financial behaviour are the low energy production of most wind power plants and their long-lasting failures; both justified by the extremely poor technical availability (≈33%) of these installations.

Considering the European and local electricity market deregulation, there is no place for State controlled loss-making power stations. In this context, one should seriously examine the possibility to replace the old-fashioned small wind turbines with new and bigger machines that take really advantage of the excellent wind potential and the experience gained, in order to guarantee positive financial results and higher contribution of clean wind energy to the national electricity production market.

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ANALYZING THE HISTORICAL EVOLUTION OF CONTEMPORARY WIND TURBINES

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Abstract

The astonishing wind power penetration in the European energy market is also accompanied by a remarkable size increase of wind turbines used. Hence, the commercial converters dimensions have been increased by at least two orders of magnitude during the last twenty years. This continuous size expansion is dictated by the prospective positive scale economy effects, along with the difficulties in locating new wind park sites. However, considering that the wind turbines' size cannot steadily increase with time, the present paper is devoted to the time-evolution analysis of the main techno-economical parameters determining the optimum size of commercial wind turbines. More precisely, the vast majority of the widely used parameters is included here, such as the specific head mass parameter, the reduced annual energy production, the specific ex-works price, the rotor tip rotational speed, the turbine specific power, the hub height to rotor diameter ratio and the maintenance & operation cost coefficient. By analyzing the variation of the above-described parameters, it is possible to predict the optimum rotor diameter for the near future, under the precondition that the optimization function is well defined.

Keywords: Wind Turbines; Historical Evolution; Rotor Diameter; Specific Head Mass; Annual Energy Production; Specific Ex-Works Price

1. Introduction

Nowadays wind energy is the fastest growing energy sector for electricity production in various European countries[1]. In fact, the wind power market has been significantly expanded during the last ten years, presenting annual growth rates in the order of 30%. This astonishing wind power penetration in the European energy market is also accompanied by a remarkable size increase of wind turbines used. More specifically, the commercial converter dimensions have been increased by at least

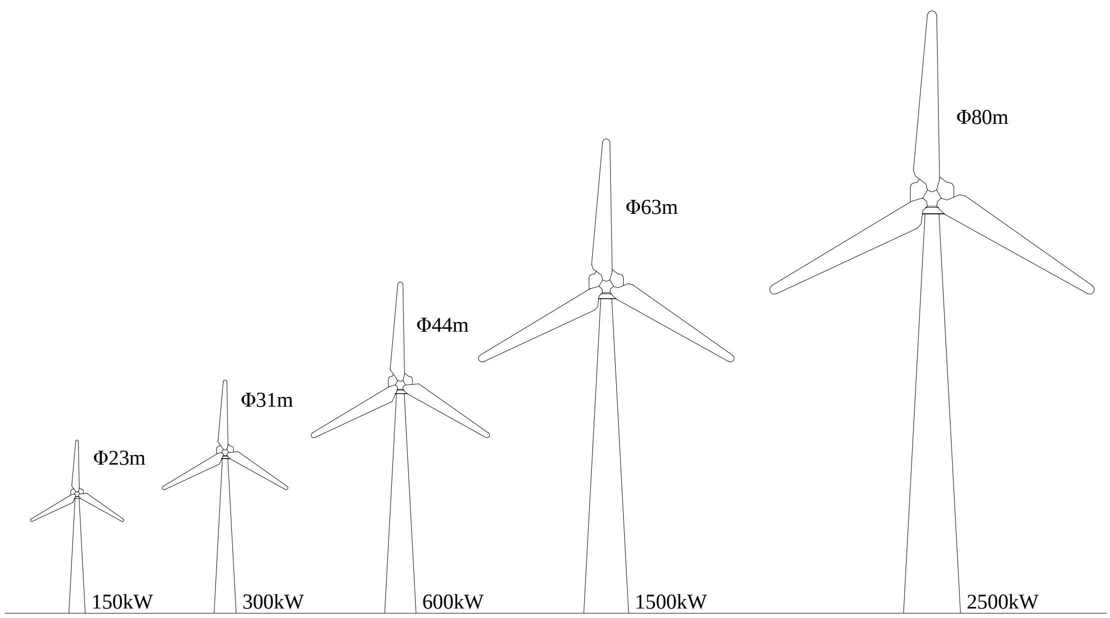

Figure 1: Size Evolution of Commercial WTs

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two orders of magnitude (25kW to 2.5MW) between 1981 and 2001[2]. This continuous size expansion (figure (1)) is dictated by the prospective positive scale economy effects, 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[3].

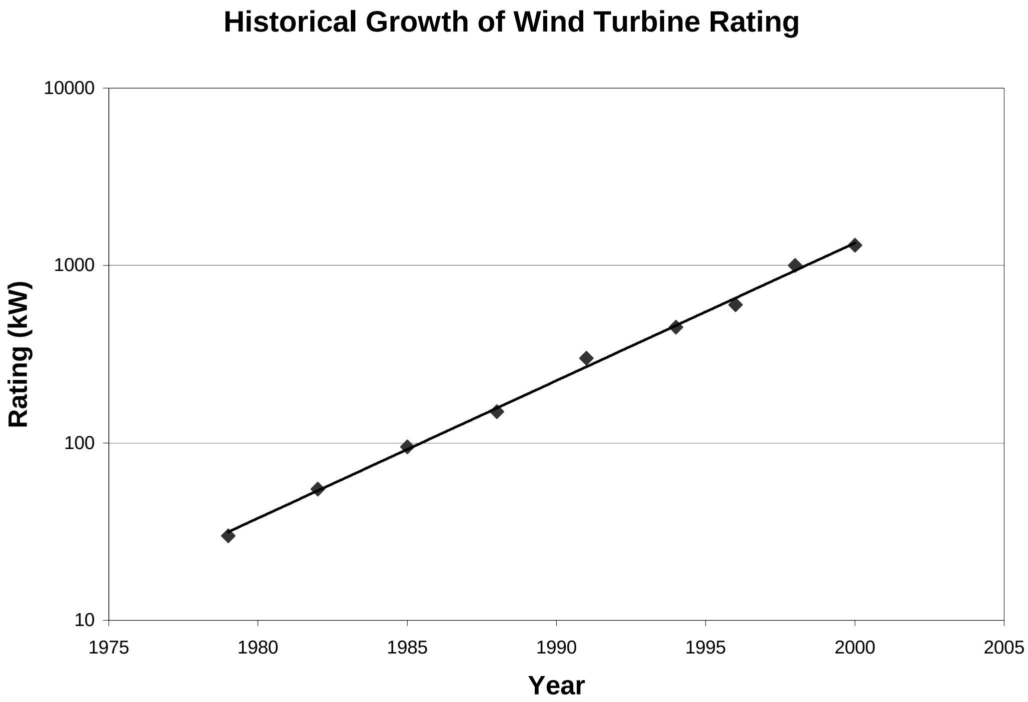

Figure 2: Time Evolution of Commercial WTs Size

However, considering that the wind turbines' size cannot steadily increase with time, the present paper is devoted to the time-evolution analysis of the main techno-economical parameters determining the *optimum size* of wind turbines (WTs) used to create an economically attractive wind power investment. Hence, in the proposed study an extensive investigation is carried out concerning the numerical values of several wind turbine parameters, expressed mainly as a function of the rotor diameter. More precisely, a vast majority of the widely used parameters is included here, such as the specific head mass parameter, the reduced annual energy production, the specific ex-works price, the rotor tip rotational speed, the turbine specific power, the tower height to rotor diameter ratio and the maintenance & operation cost coefficient. By analyzing the variation of the above-described parameters, it is possible to predict the optimum rotor diameter for the near future, under the precondition that the optimization function is well defined.

2. Analysis of Existing Information

During the last ten years a remarkable effort is exerted by the Soft Energy Applications & Environmental Protection Lab in order to collect all available information[4,5,6] concerning the existing wind turbines models. The first outcome of this study is the "Windbase II & III", including the main data of commercial wind converters[6]. Accordingly, these data are further analyzed and compared with the results of other research efforts[7,8,9] in an attempt to estimate the future evolution of wind energy sector.

By using the data collected, one may conclude that the conventionally optimum wind turbine size for each year $N_o^*(t_o)$ is an exponential function of time, figure (2) thus one may write:

$$N_o^*(t_o) = A_N \cdot e^{B_N \cdot (t_o - 1990)} \quad (1)$$

with A_N=226.12, B_N=0.1786, see also figure (2).

One of the main factors limiting the constant increase of WTs size is the corresponding weight increase, imposing remarkable strain values and serious difficulties on transferring, grounding and constructing the new technological giants.

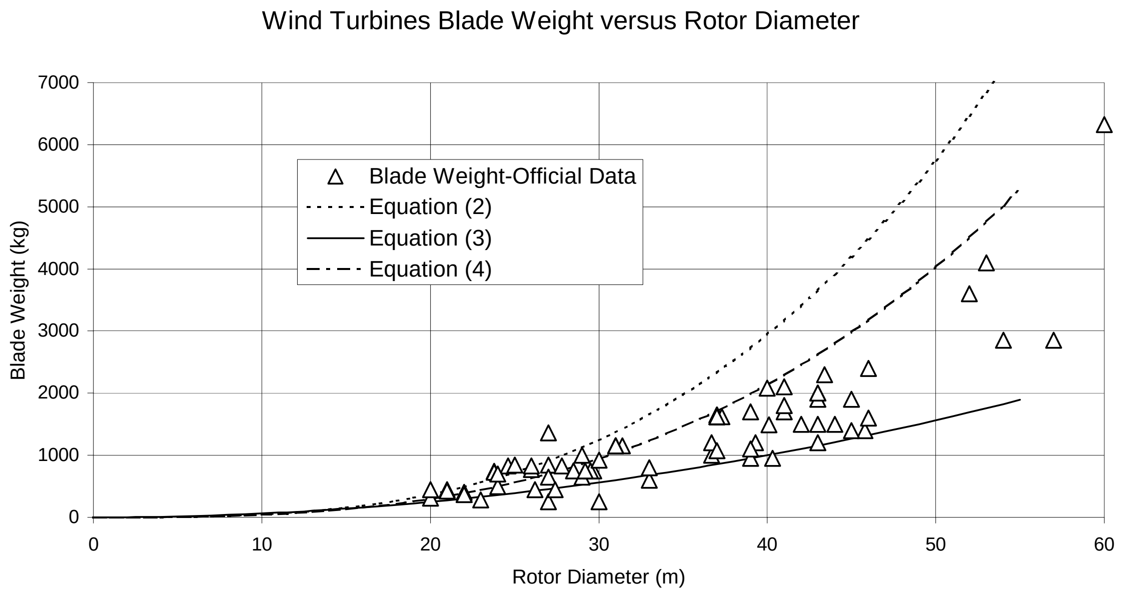

Figure 3: Wind Turbine Blade Weight vs Rotor Diameter

In this context, a preliminary analysis has been prepared on the basis of the existing official data accumulated from WT manufacturers. The first element examined is the individual blade weight "w" as a function of the rotor diameter "D", figure (3). Disregarding the conflict concerning the separation point between "blade" and "hub", one may state that the available material is included between the relation suggested by P. Molly[7], i.e.:

$$w = k_1 \cdot D^3 \quad (2)$$

and the one proposed by the Sunderland model[8], i.e.:

$$w = k_2 \cdot D^2 \quad (3)$$

As it is obvious, equation (2) is applied up to 30m diameter, while for larger blades the expression by Hau[9] can be used as the upper limit of the blade weight, i.e.

$$w = k_3 \cdot D^{2.85} \quad (4)$$

The authors use a two-phase analysis of the available information. Initially they classify the existing machines by nominal power value, finding the average value of each subgroup. Next, they elaborate the resulting data, figure (4). Therefore, the following relation is proposed for the mean blade weight "$\overline{w}$" of each WT category:

$$\overline{w} = 0.286 \cdot D^{2.35} \quad (5)$$

Using a similar analysis concerning the complete rotor weight "W_r" one may suggest the following relation between rotor weight and rotor diameter, i.e.:

$$W_r = \alpha_1 \cdot D^x + \alpha_2 \cdot D^2 \tag{6}$$

where "α_1" and "α_2" are semi-empirical coefficients resulting from the data analysis and "x" appropriate exponent taking values between 2.05 and 3.

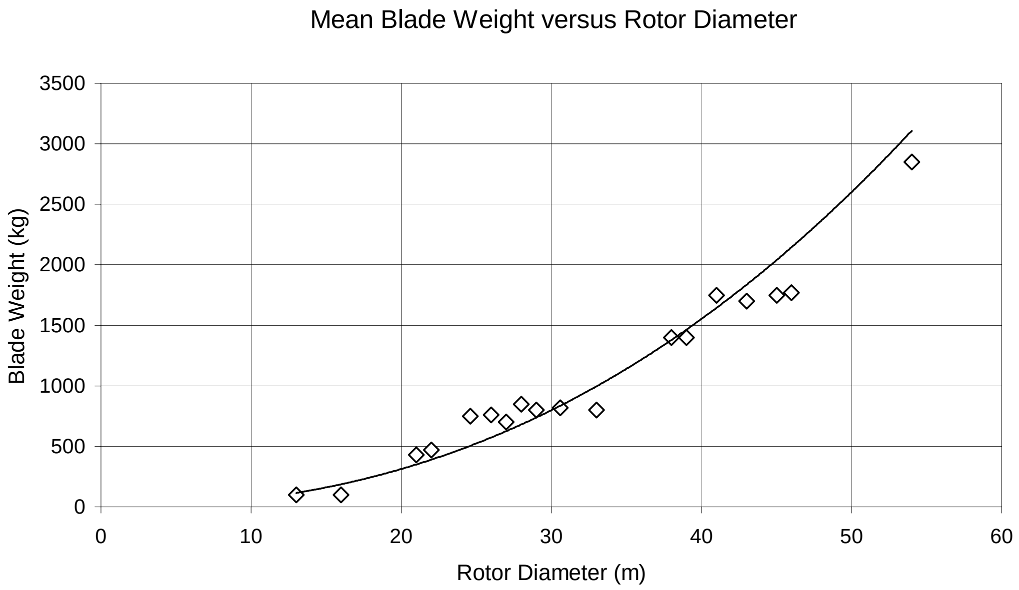

Figure 4: WTs Mean Blade Weight vs Rotor Diameter

Using, the above relations, it is possible to estimate the specific rotor weight "w_o" as the ratio between the rotor weight and the corresponding power output, i.e.:

$$w_o = W_r / N_o \tag{7}$$

Subsequently, for the rated power of a WT the following expression[3,10] is valid:

$$N_o = 0.125 \cdot \rho \cdot C_p \cdot \eta \cdot \pi \cdot D^2 \cdot V^3 \tag{8}$$

where "ρ" is the air density, "C_p" is the engine power coefficient, "η" is the electro-mechanical efficiency and "V" is the wind speed at hub height "H". However, by increasing the rotor diameter the hub height is also increased, since:

$$H = \xi \cdot D \tag{9}$$

and $0.8 \le \xi \le 1.2$. Using at this point -for simplicity reasons- the semi-empirical wind speed boundary layer profile[10] as a function of height from the ground, i.e.:

$$V = V_{10} \cdot \left(\frac{H}{10}\right)^a \tag{10}$$

one may conclude at the following relation:

$$N_o = k_o \cdot D^{2+3 \cdot a} \qquad (11)$$

where:

$$k_o = 0.125 \cdot \rho \cdot C_p \cdot \eta \cdot \pi \cdot V_{10}^3 \cdot \left(\frac{\xi}{10}\right)^{3 \cdot a} \qquad (12)$$

If one demands the minimization of rotor specific weight "w_o" and using equations (6), (7) and (11) the following expression results:

$$D^* = \left(\frac{3 \cdot a}{x - 2 - 3 \cdot a}\right)^{\frac{1}{x-2}} \cdot \left(\frac{\alpha_2}{\alpha_1}\right)^{\frac{1}{x-2}} \qquad (13)$$

thus the theoretical optimum rotor diameter is a function not only of the construction parameters of equation (6), but also of the shear exponent "a" of equation (10). On top of that, by setting x=3 (a generally applicable value) the ratio between D^* and (α_2/α_1) varies between 3 (a=1/4=0.25) and 0.175 (a=1/20=0.05). This fact underlines that the optimum rotor size cannot be determined only by the manufacturers data, since the available wind potential of an area strongly influences[11] the numerical value of equation (13).

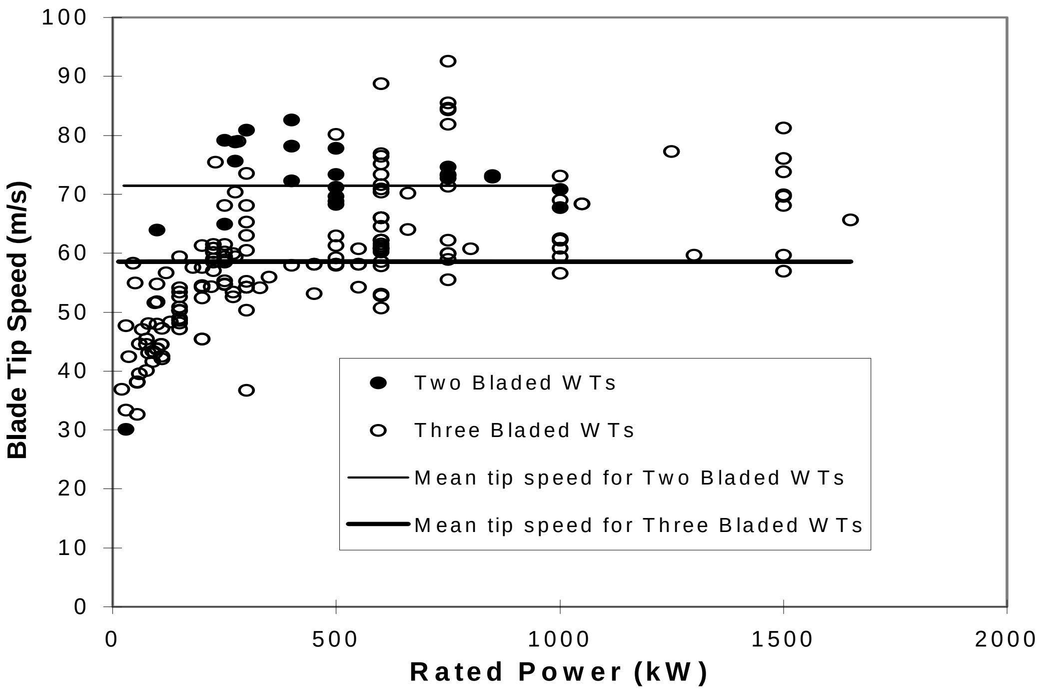

Figure 5: Blade Tip Rotational Speed

3. Investigation of Parameters Affecting the Environment Impacts

Noise emissions and visual impact are among the most important aspects, defining the social attitude towards wind power applications[12]. In this context the blade tip rotational speed is the major parameter controlling the noise level emitted by a rotor[13]. Besides, the blade tip rotational speed is also a measure of the centrifugal stresses exerted at the blade hub. Hence, by analyzing the available data (figure (5)), one may conclude that 3-bladed wind turbines up to a 40m diameter present a blade tip rotational speed lower than 70m/s. On the other side, 2-bladed machines exceed the 80m/s. This is also the case for 3-bladed machines of large rotor diameters. Under this situation, the only way to bind noise emissions is ameliorating the blade design, since the reduction of the aerodynamic noise should drastically limit the complete noise of an engine.

Accordingly, modern wind turbines -with a hub height of 40÷60 meters and a blade length of 20÷30 meters- form a visual impact on the local scenery[14]. Since visual impact is one of the major reasons making local people react[15] against new large wind farms, it is also found necessary to analyze the tower-height to rotor-diameter ratio, as both parameters define the degree of visual impact imposed on the landscape by a wind turbine.

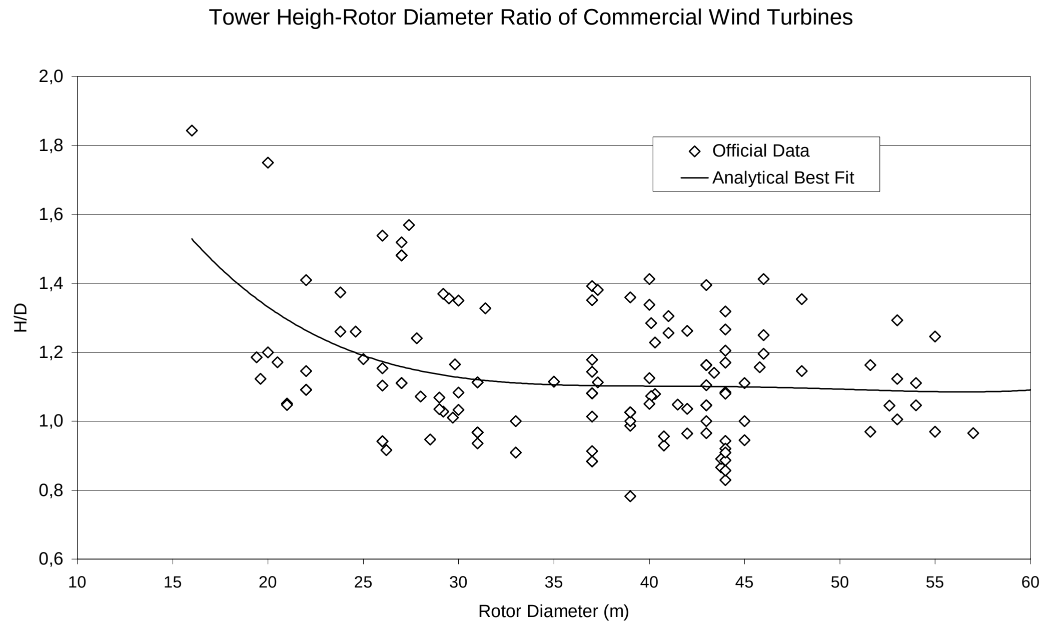

Figure 6: Tower Height Variation vs Rotor Diameter

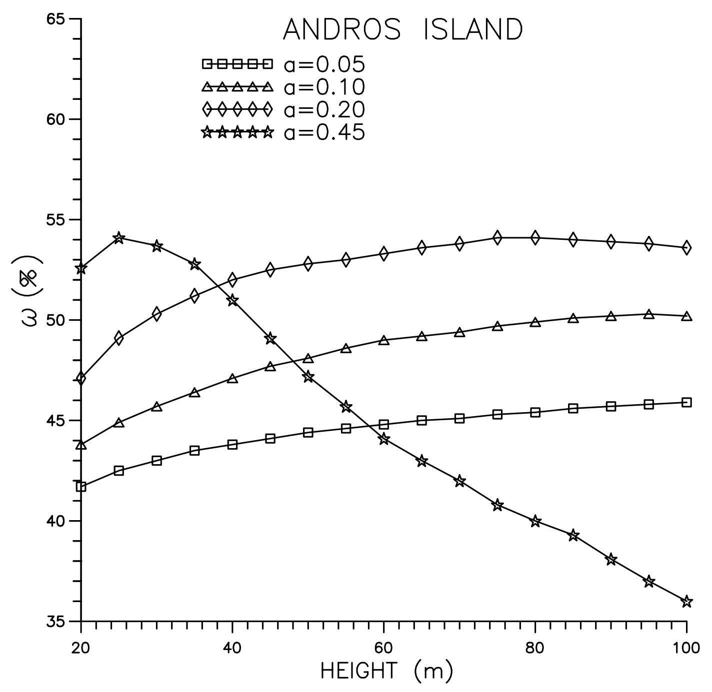

Figure 7: Wind Potential Variation with Hub Height

In figure (6), one may conclude that in fact the "ξ" ratio is between 0.8 and 1.4 and actually between 0.9 and 1.2, while by increasing the rotor diameter the "ξ" value is gradually decreasing. Moreover, the common assumption stating that by increasing the hub height the available wind energy is also increased does not really correspond to all cases[11]. More specifically, given that -for mechanical reasons- a commercial WT operates under a constant wind speed range (e.g. between 3 to 25m/s), then by increasing the tower height of a wind turbine the available wind potential may worsen; see figure (7).

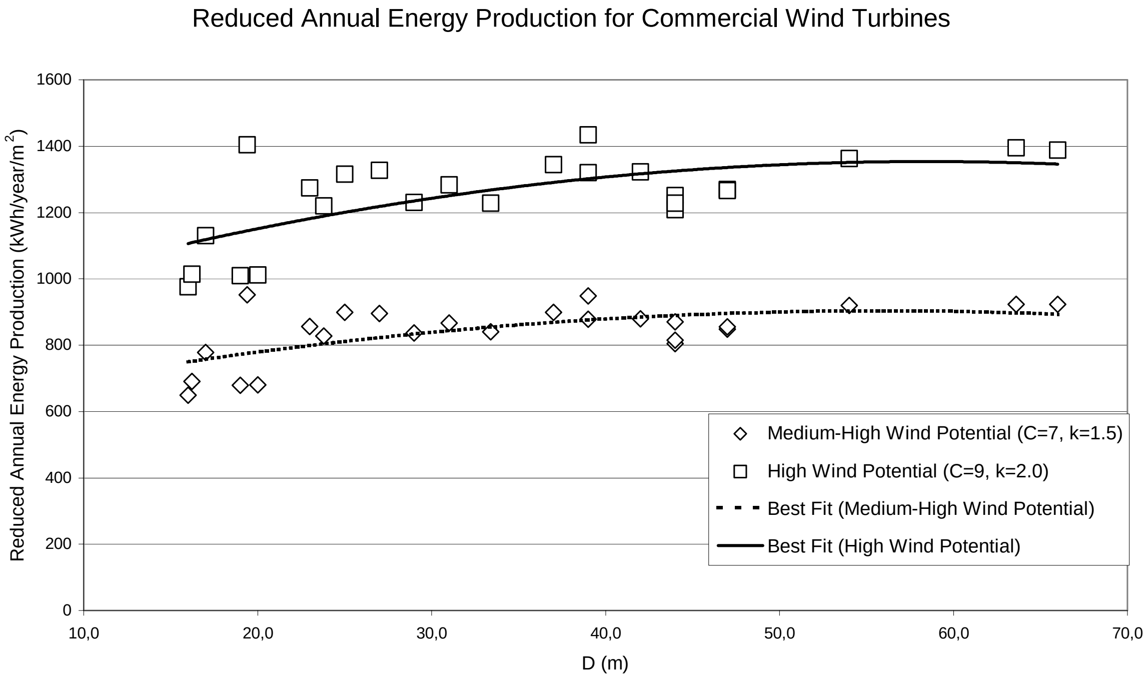

Figure 8: Commercial WTs Reduced Energy Production

Summarizing, the increased noise emissions, the amplified visual impact and the wind potential exploitation limits are particular supplementary factors, limiting the unbounded expansion of wind turbines size. However, in every specific installation the corresponding limits' values are different, hence one cannot propose a single limit valid for all cases.

4. Energy Production Variation

Wind turbines are manmade constructions using the kinetic energy of air to produce mechanical or electrical work. Therefore, their energy productivity is one of the most important criterions for proper operation. More specifically, the most widely used parameter to rank commercial wind turbines is their reduced annual energy yield (divided by the rotor swept area) under given wind potential conditions, i.e. "E_o" defined as:

$$E_o = 4 \cdot E / (\pi \cdot D^2) = 8760 \cdot CF \cdot N_o / \left(\frac{\pi \cdot D^2}{4}\right) \tag{14}$$

where the capacity factor "CF" of the installation is the product[6] of the technical availability "Δ(t)" with the mean power coefficient "ω(t)" of the installation, i.e. CF=Δ.ω.

Using the above presented analysis along with the commercial wind turbines official power curves[4] (at standard day conditions), it is possible to express the "E_o" variation as a function of WT rotor diameter, being generally an explicit function of time, see also figure (2). As it is obvious from figure (8), including the time-series WT production of selected typical manufacturers, the resulting reduced energy production is maximized for wind turbines of a 50m diameter, although the corresponding energy production at a 30m or 60m diameter is also satisfying.

Another way of wind turbine time-evolution assessment may be achievable by investigating the "mean power" coefficient variation[6] with time. In fact, using "ω" one has the opportunity to examine the annual energy production of a WT per kW of the engine rated power, see equation (14).

More precisely, the mean power coefficient introduced by the authors[16] since 1991, can be predicted as:

$$\omega = \int_{V_c}^{V_F} \frac{N(V)}{N_o} \cdot f(V) \cdot dV \tag{15}$$

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.

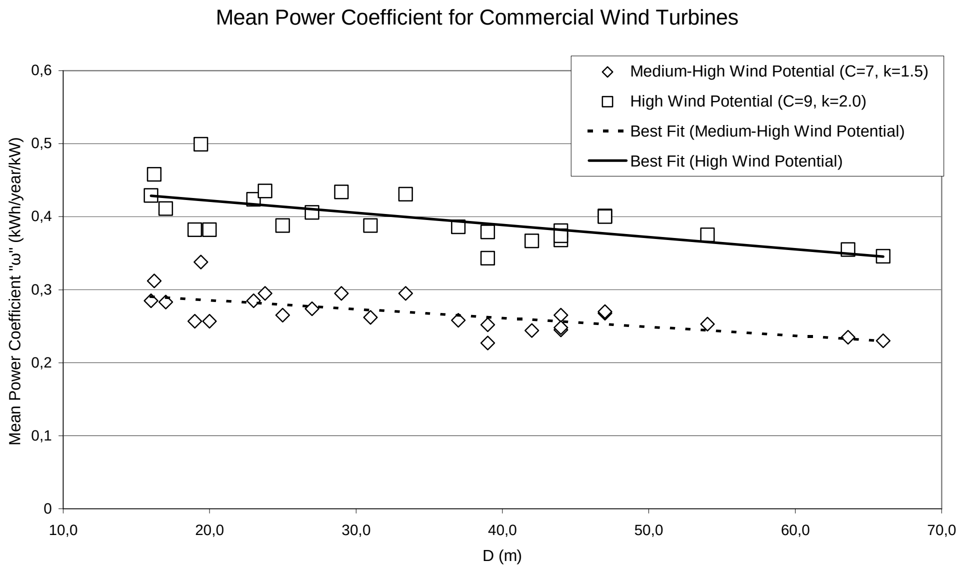

Figure 9: Mean Power Coefficient of Commercial WTs

By analyzing the "ω" time variation for WTs of the same companies (so as to avoid comparing different design philosophies) against the corresponding rotor diameter (figure (9)) it is possible to infer conclusions about the specific energy productivity of commercial WTs in course of time.

5. Cost Time Variation

One of the main advantages of developing larger wind converters is the expected significant cost reduction, mainly due to the scale economies. In this logic, one has analyzed the specific price "P_r" time evolution of commercial wind turbines, expressed as a function either of their rated power (Euro/kW) or their swept area (Euro/m^2). The main results[17] of this analysis (based on official data) are the following:

i) There is a gradually decreasing price evolution of WTs with time, expressed by the following time-lag equation:

$$P_r(t_o) = \left[f_N(\nu) + c_\infty \cdot \left(1 + \varepsilon_1 \cdot e^{-\varepsilon_2 \cdot x}\right)\right] \cdot \sigma_p(z) \tag{16}$$

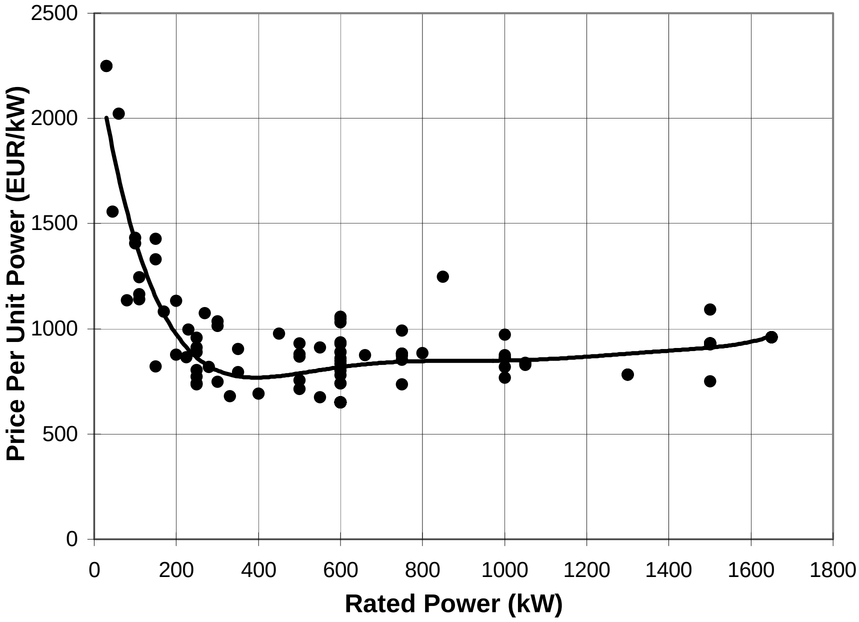

Figure 10: WTs' Ex-Works Specific Price

ii) At the same time the specific price distribution of commercial WTs presents a minimum value at a given WT nominal value, varying every year. This minimum value results according to the mostly established wind power technology annually (see equation (1)), i.e. the most mature technology applied, the resulting volume production etc., see also figure (10), concerning 1999 values. In order to take this information into account the following simplified relation is proposed by the authors:

$$f_N = 566 \cdot e^{-\nu/0.35} - 132.5 + 100 \cdot \nu \tag{17}$$

where the relative size "ν" of a wind turbine is defined in comparison with the optimum (best seller) wind turbine size for each year "$N_o^*(t_o)$", thus:

$$\nu = \frac{N_o}{N_o^*(t_o)} \tag{18}$$

iii) Finally, "$\sigma_p(z)$" describes the impact of WTs number used to create the wind power station.

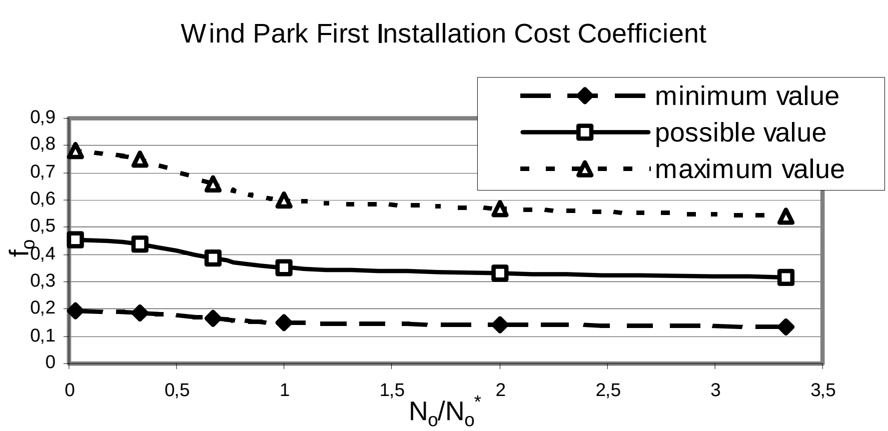

Figure 11: First Installation Cost Coefficient

Similarly, the balance of the plant cost[17] coefficient "f" (including foundation cost, electrical interconnection cost, land purchase, planning cost, approvals, infrastructure, management of the project and grid connection cost) is also a function of "ν" (figure (11)), although the major parameters affecting its value is the area infrastructure situation and the number of wind turbines "z" used.

Recapitulating, the initial investment cost "IC_o" of a wind park consisting of "z" wind converters with rated power "N_o" is the sum of the market price (ex-works) "$P_r.z.N_o$" of the equipment and the corresponding installation cost "$f\cdot(P_r.z.N_o)$" of the wind plant examined[18]. Hence, one may write:

$$IC_o = P_r \cdot z \cdot N_o \cdot (1+f) \qquad (19)$$

Using equation (19), one has the opportunity to express the ratio of annual energy yield of a wind park to the first installation cost of the investment (E/IC_o) as a function of WT used size, for a specific time period "t_o". More precisely, using equation (14) one gets:

$$\frac{E}{IC_o} = \frac{8760 \cdot \omega \cdot \Delta}{P_r \cdot (1+f)} \qquad (20)$$

Generally speaking, the technical availability "Δ" of a new wind park during its first years of operation mainly depends on the technological status[18] during the period of time that the investment is realized ($x=t_o$-1990), thus one may write:

$$\Delta^+(t_o) = 10^{-5} \cdot x^3 - 0.0009 \cdot x^2 + 0.0191 \cdot x + 0.8768 \qquad (21)$$

Disregarding any accessibility difficulties -due to bad weather conditions- of remote islands and any upper limits of wind power penetration in the existing autonomous electrical grids, one may state[18] that:

$$\Delta(t_o) = \Delta^+(t_o) \cdot \frac{1}{\sigma_\Delta(\nu)} \qquad (22)$$

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

$$\sigma_\Delta = 0.9903 + \frac{0.24438}{(1+1.41611 \cdot \nu)^{3.676741}} \qquad (23)$$

The results of application of equation (20) are summarized in figure (12), supporting the existence of WTs optimum size.

Finally, the annual fixed maintenance and operation cost of a wind power station[17] during its first years of operation, is usually expressed as a fraction "m" of the initial capital invested. Subsequently, one may write:

$$m(t_o) = m^+(t_o, z) \cdot \sigma_m(\nu) + \delta \qquad (24)$$

where "$m^+(t_o,z)$ depends on the technological status and the number of the wind turbines used, along with the accessibility of the wind park (distance, weather conditions, infrastructure, island/mainland etc.), hence:

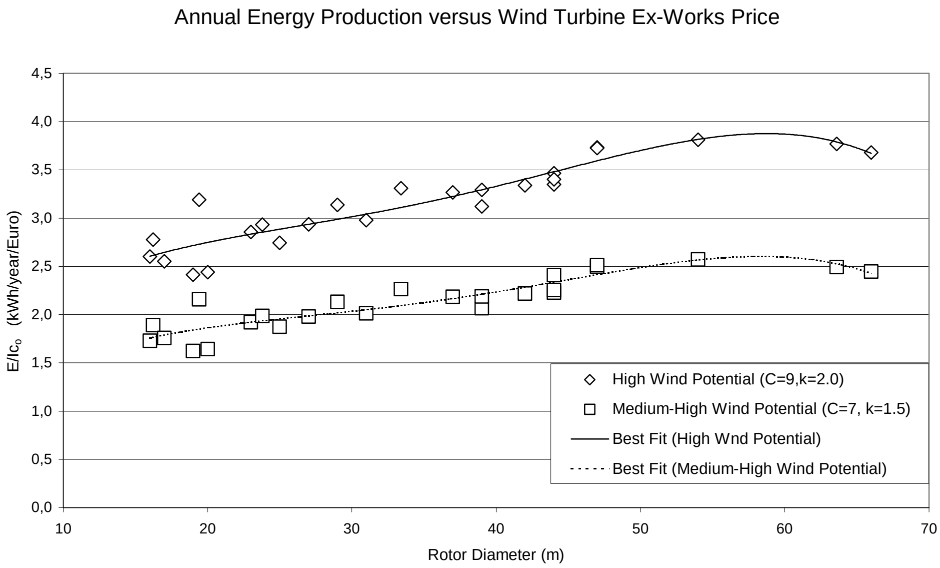

Figure 12: Annual Energy to Ex-Works Price Ratio

$$m^+(t_o, z) = A_m(z) \cdot e^{-B_m(z) \cdot x} \tag{25}$$

with "$A_m(z)$ and "$B_m(z)$" coefficients predicted via figure (13).

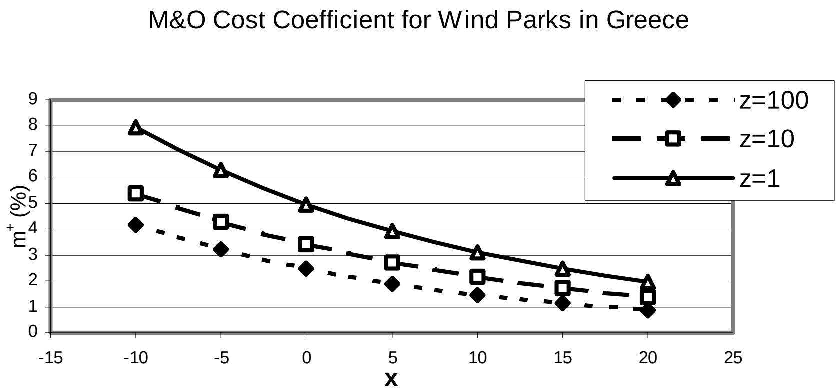

Figure 13: M&O Cost Coefficient Time Variation

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

$$\sigma_m = 0.74185 + \frac{2.71646}{(1 + 55.09515 \cdot \nu)^{0.585302}} \tag{26}$$

Summarizing, by using the analysis of section 5 one has the ability to investigate the cost variation of commercial wind turbines as a function of time, for the period 1980-2005.

6. Conclusions

The present paper is devoted to the time-evolution analysis of the main techno-economic parameters determining the optimum size of wind turbines used to create an economically attractive wind power investment. Hence, an extensive investigation is carried out concerning the numerical values of several wind turbine parameters, expressed as a function of the rotor diameter or the time. More precisely, the vast majority of the widely used parameters is included here. By analyzing the variation of the above-described parameters, it is possible to predict the optimum rotor diameter for the near future, under the precondition that the optimization function is well defined. According to the results obtained, the optimum wind turbine size depends on the optimization function selected. Thus, 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.

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AN INTEGRATED AERODYNAMIC SIMULATION METHOD OF WIND TURBINE ROTORS

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Abstract

Wind turbine aerodynamic analysis is one of the most complex subjects, since the real flow field is governed by the Navier-Stokes equations. However, many simplified aerodynamic models are used in almost all cases of practical rotor design analysis. In the present work, at first, a complete aerodynamic model is developed, based on a coherent combination of the Rankine-Froude actuator disc model and the Glauert annulus momentum vortex-theory. Additionally, an extended free-wake vortex theory is included along with an improved quasi-three dimensional airfoil theory. Accordingly, the complete algorithm is applied to several classical and modern wind turbine rotors, using an inverse procedure in order to revise the main semi-empirical information used. The necessary computational power is minimum, since the calculations can be carried out even by an outmoded Pentium-III machine. Subsequently, using the proposed analysis, the aerodynamic load profile along a rotor blades is estimated for several blade angle positions (variable pitch) and the calculated power curve (versus wind speed) is successfully compared to the experimental data by the manufacturer. Finally, the obtained results, give the opportunity to develop an integrated and revised aerodynamic analysis model, proper to be used with limited computational cost for the design of high performance and minimum loss wind turbine rotors.

Keywords: Three-Dimensional Flow Effects; Actuator Disk Model; Blade Aerodynamics; Navier-Stokes Equations; Wind Turbine Rotors; Aerodynamic Method

1. Introduction

During the last twenty years the number of wind power applications has remarkably increased and more than 50,000 wind turbines (WT's) of any size have been installed all over the world. In order to increase the energy produced by WT's and to ameliorate their economic attractiveness[1], it is necessary to develop more sophisticated numerical tools, proper to be used with limited computational cost for the design of high performance and minimum loss wind turbine rotors.

In real world, when the rotor is working in natural conditions, the actual flow field is inhomogeneous and unsteady. Therefore, the real flow field is governed by the Navier-Stokes equations. However, in almost all cases of practical rotor design analysis (even in cases of supersonic turbomachines), many simplified aerodynamic models are used with remarkable success[2][3].

In the present study, the Rankine-Froude actuator disc model[4] is extended to a multiple streamtube theory, taking also into account the secondary vorticity model developed by the authors[5]. Subsequently, the Glauert annulus momentum vortex theory is revised to include three dimensional airfoil effects. Finally, special attention is put on the coherent combination of the two procedures.

Kavadias K.A., Kaldellis J.K., 2003, *"An Integrated Aerodynamic Simulation Method of Wind Turbine Rotors", Applied Research Review Jr, Vol. VIII, No 1, pp.221-242, Technological Education Institute of Piraeus ed., Greece.*

Nomenclature

c	Blade chord
C_D	Drag coefficient
$C_{d2\text{-}D}$	2-D drag coefficient
$C_{d3\text{-}D}$	3-D drag coefficient
C_L	Lift coefficient
$C_{l2\text{-}D}$	2-D lift coefficient
$C_{l3\text{-}D}$	3-D lift coefficient
C_P	Power coefficient
C_T	Thrust coefficient
D	Drag force
F_θ	Force component in the peripheral direction
L	Lift force
M	Torque
P	Power
p^-	Static pressure just before the rotor
p^+	Static pressure just after the rotor
p_o	Static pressure at the rotor plane
r	Rotor radius
r'	Radial position at the rotor plane
r_1	Radius of the streamline far downstream of the rotor
r_1'	Radial position far downstream of the rotor
r_H	Hub radius
r_o	Radius of the streamline far upstream of the rotor
r_o'	Radial position far upstream of the rotor
T	Thrust
u	Axial component of the wind velocity at the rotor plane
u_1	Axial component of the wind velocity far downstream of the rotor
u_o	Axial component of the wind velocity far upstream of the rotor
v	Peripheral component of the wind speed at the rotor plane
v^-	Peripheral component of the wind speed just before the rotor
v^+	Peripheral component of the wind speed just after the rotor
v_1	Peripheral component of the wind speed far downstream of the rotor
v_o	Peripheral component of the wind speed far upstream of the rotor
w	Radial component of the wind speed at the rotor plane
w^-	Radial component of the wind speed just before the rotor
w^+	Radial component of the wind speed just after the rotor
w_1	Radial component of the wind speed far downstream of the rotor
w_o	Radial component of the wind speed far upstream of the rotor
W_{ref}	Reference wind speed
W_x	x axis component of the wind speed
W_y	y axis component of the wind speed
W_θ	Component of the wind speed in peripheral direction
z	Number of blades
α	Airfoil angle of attack
β	Pitch angle
Γ	Wind turbine axis tilt
ε	Axial interference factor at the rotor plane
ε_1	Axial interference factor far downstream of the rotor
κ	Integration numerical constant
λ	Tip speed ratio
ξ_m	Meridional vorticity component
ρ	Air density
φ	Incoming flow angle
Ψ	Blade coning angle
Ω	Rotational speed

2. The Multiple Streamtube Theory

The multiple streamtube theory is based on the streamline curvature or the meridional flow analysis[6][7] used in turbomachines, while it utilizes the basic idea of the actuator disc theory (figure (1)). Hence, using the mass conservation equation for incompressible flow across each streamtube (figure (2)), it is possible to estimate the streamline geometry from a distance "r_o" upwind to a distance "r_1" downwind the rotor. More precisely we get:

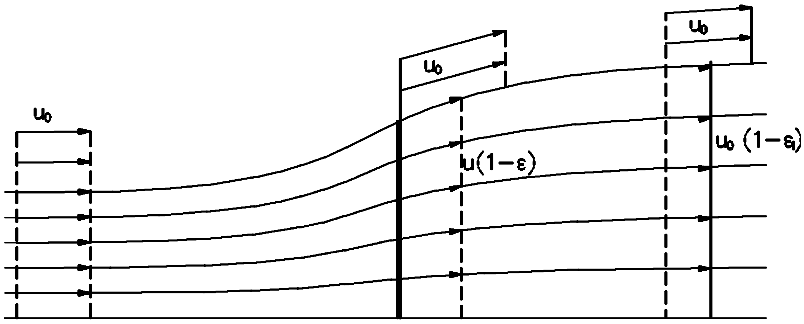

Figure 1: Flow field streamlines through rotor

$$\int_0^{r_0} u_0 \cdot 2\pi \cdot r_0' \cdot dr_0' = \int_{r_H}^{r} u \cdot 2\pi \cdot r' \cdot dr' = \int_0^{r_1} u_1 \cdot 2\pi \cdot r_1' \cdot dr_1' \quad (1)$$

where "u_o" is the axial component of the wind velocity far upstream of the machine.

Using the axial interference factors "ε" and "ε_1" at the rotor plane and far downstream of the rotor we have:

$$u=u_o \cdot (1-\varepsilon) \quad (2)$$

$$u_1=u_o \cdot (1-\varepsilon_1) \quad (3)$$

In the simplified actuator disc theory it is taken $\varepsilon=2\varepsilon_1$, while "ε" and "$\varepsilon_1$" are assumed uniform over the entire rotor surface, which is not necessarily the case.

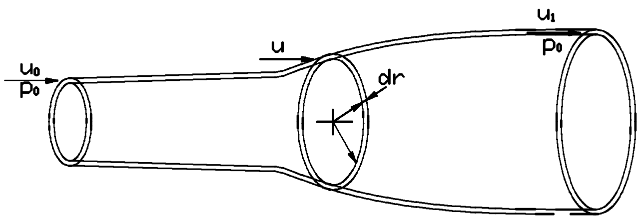

Figure 2: Streamtube geometry near the rotor

For the calculation of the peripheral component of the wind speed "v" throughout the rotor the meridional vorticity "ξ_m" transport equation is used, see for details [2] and [5] where:

$$\xi_m = \frac{1}{r} \cdot \left(\frac{\partial (r \cdot v)}{\partial r} - \frac{\partial w}{\partial \theta} \right) \quad (4)$$

Taking into account that the proposed analysis is based on the streamtube hypothesis and thus the radial component "w" of the wind speed is assumed small, i.e. $w \approx 0$, one gets:

$$v = \frac{1}{r} \int r \cdot \xi_m \cdot dr + \frac{\kappa}{r} \quad (5)$$

In the case that $\xi_m \rightarrow 0$ eqt. (5) reads:

$$r \cdot v = \kappa \quad (6)$$

which is the expression used by almost all previous theoretical approaches[4][8]. In that case one must assume that the wake rotation starts discontinuously at the rotor, while Glauert assumes that the air has acquired half of its final swirl when it reaches the rotor. On the contrary, the complete analysis proposed here, eqts. (4) and (5), takes into account any divergence of the wind velocity from the axis of the machine (yaw angle) since $v_o \neq 0$ and it is based on a parabolized form of the Navier-Stokes equations[6], which is already validated in similar cases, even in presence of flow separation and under strong compressibility effects.

According to Glauert[4], the element of torque "dM" exerted on the rotor at distance "r" is equal to the rate of angular momentum imparted to the corresponding annular element of the slipstream, i.e:

$$dM=(\rho\cdot u\cdot 2\pi\cdot r\cdot dr)\cdot(v_1-v_o)=2\pi\cdot r\cdot\rho\cdot u_o\cdot(1-\varepsilon)\cdot(v_1-v_o)\cdot dr \quad (7)$$

Using the simplified form of the energy conservation equation for very low Mach number cases where incompressible flow may be assumed before "-" and after "+" the WT's rotor, we get for the static pressure "p" field:

$$p_o+0.5\cdot\rho\cdot u_o^2+0.5\cdot\rho\cdot v_o^2+0.5\cdot\rho\cdot w_o^2=(p^-)+0.5\cdot\rho\cdot u^2+0.5\cdot\rho\cdot(v^-)^2+0.5\cdot\rho\cdot(w^-)^2 \quad (8)$$

$$p_o+0.5\cdot\rho\cdot u_1^2+0.5\cdot\rho\cdot v_1^2+0.5\cdot\rho\cdot w_1^2=(p^+)+0.5\cdot\rho\cdot u^2+0.5\cdot\rho\cdot(v^+)^2+0.5\cdot\rho\cdot(w^+)^2 \quad (9)$$

The term "w_o" is included here, although it is generally at least one order of magnitude less than "u_o", in order to give us the possibility to analyze cases where the axis of the machine is inclined in comparison to the horizontal plane ($\Gamma\neq 0$), or to reduce the blade root stresses when wind turbine rotor is preconed ($\psi\neq 0$). Note that "p^-" and "p^+" are the static pressure distribution just before and just after the WT's rotor. Subtracting eqts. (8) and (9) and after some simplifications ($w\approx 0$, $v_o\approx v^-<<v^+$) we derive the following expression:

$$\Delta p=p^- - p^+=0.5\cdot\rho\cdot u_o^2 - 0.5\cdot\rho\cdot u_1^2 + 0.5\cdot\rho\cdot((v^+)^2-v_1^2) \quad (10)$$

or

$$\Delta p= 0.5\cdot\rho\cdot u_o^2 \cdot\varepsilon_1\cdot(2-\varepsilon_1) + 0.5\cdot\rho\cdot((v^+)^2-v_1^2) \quad (11)$$

Therefore, the element of thrust "dT" exerted at the elementary area ring "2πrdr" of the rotor turning circle is given as:

$$dT=\Delta p\cdot 2\pi\cdot r\cdot dr \quad (12)$$

Recapitulating, the flow field around a WT's rotor can be estimated with sufficient accuracy using the fundamental laws, like the mass conservation equation, the vorticity transport equation, the energy conservation equation etc. However, in order to achieve a close form of the above equations, the distribution of the parameters "ε", "ε_1" and "v^+" is needed across the rotor. These three parameters are not independent, since the following equation for the power exchanged "dP" at the "2πrdr" element of the rotor is valid, i.e:

$$dP=dM\cdot\Omega=dT\cdot u=dT\cdot u_o\cdot(1-\varepsilon) \quad (13)$$

Hence, by assuming a distribution for "ε" and "ε_1" (generally is taken $\varepsilon_1\approx 2\varepsilon$), the complete flow field can be estimated according to the multiple streamtube theory.

3. The Quasi 3-D Blade Element Theory

The proposed analysis is based on the Glauert's momentum vortex blade element theory[4] and it has already been applied in various turbine and compressor applications[9][10]. According to this approach, the flow field throughout a WT's rotor is studied in small radial sections of blades, as they result by the multiple streamtube theory. The analysis begins by considering an annular section of the rotor and by examining a small section of radial length "dr" of one blade (figure (3)). The net effect on air flowing

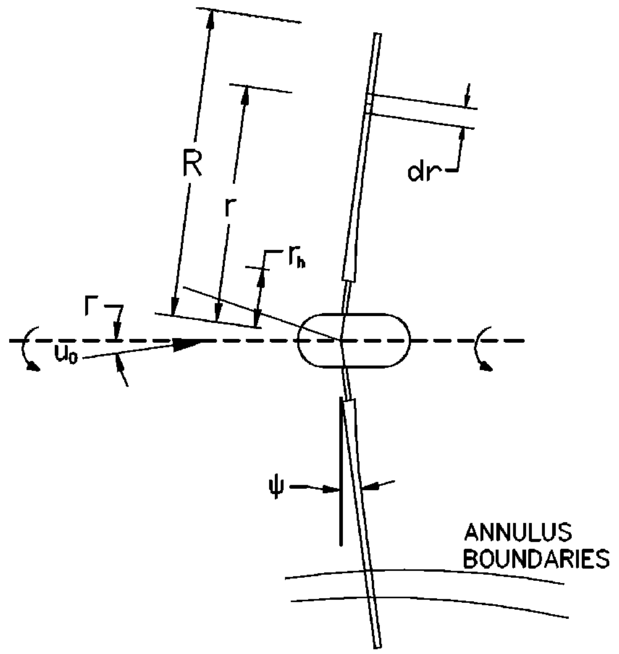

Figure 3: Rotor geometry

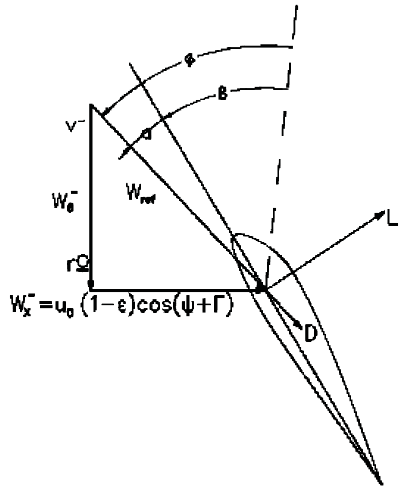

Figure 4: Velocity diagram at the rotor inlet

through this annular section of the rotor results from the forces and moments on all "z" blades of the rotor.

The normal to the blade plane relative to the rotor wind speed at the airfoil's leading edge "$W^-=(W_x,W_\theta)$" varies with blade radius "r" and it is given as:

$$W_x^-=u_o\cdot(1-\varepsilon)\cdot\cos(\psi+\Gamma) \tag{14}$$

and

$$W_\theta^-=r\cdot\Omega+v^- \tag{15}$$

while the corresponding wind speed component "W_y" which is parallel to the blade plane is approximately equal to:

$$W_y^-=u_o\cdot(1-\varepsilon)\cdot\sin(\psi+\Gamma)+w^- \tag{16}$$

More precisely, the value of the velocity that the blade element faces (figure (4)) is given as:

$$W_{ref}=u_o\cdot(1-\varepsilon)\cdot\left(\frac{\cos(\psi+\Gamma)}{\sin\phi}\right) \tag{17}$$

while the incoming flow angle "φ" is predicted as:

$$\tan\phi=\frac{u_o\cdot(1-\varepsilon)\cdot\cos(\psi+\Gamma)}{r\cdot\Omega+v^-} \tag{18}$$

Taking into account that the angle of the blade chord with respect to the plane of rotation is denoted by "β(r)" (blade pitch angle / blade twist angle), it is possible to predict the angle of attack of the airfoil "α" with respect to the local relative wind speed "W_{ref}". Accordingly, the drag force "D" is aligned with the relative velocity "W_{ref}", while the lift force "L" is perpendicular to it. Thus one gets:

$$\alpha=\varphi-\beta \tag{19}$$

$dL=0.5\cdot\rho\cdot C_L\cdot W_{ref}^2\cdot c\cdot dr$ (20)

$dD=0.5\cdot\rho\cdot C_D\cdot W_{ref}^2\cdot c\cdot dr$ (21)

and

$$C_L = C_{l_{2-D}}(\alpha) + \Delta C_{l_{3-D}} \quad (22)$$

$$C_D = C_{d_{2-D}}(\alpha) + \Delta C_{d_{3-D}} \quad (23)$$

where, the lift "C_L" and drag "C_D" coefficients are usually given as functions of the angle of attack "α" for their 2-D part, while various 3-D correlations are used in cases of full blade analysis[9][11]. In the present analysis, it is adopted the quasi 3-D profile loss model[9] recently modified[11]. This model is in accordance with the experimental data of various compressor and turbine airfoil test cases, see for example [12] and [13]. According to the proposed model, the flow deviation angle at the airfoil trailing edge is also estimated, giving the wind speed velocity vector behind the rotor, i.e. (u,v^+). Summarizing, one may write that:

$C_L=C_L(\alpha)=C_L(\varphi)=C_L(\varepsilon)$ (24)

$C_D=C_D(\alpha)=C_D(\varphi)=C_D(\varepsilon)$ (25)

$v^+=v^+(\alpha)=v^+(\varphi)= v^+(\varepsilon)$ (26)

Subsequently, having found the analytical expression of the two main aerodynamic force components (i.e. "dL" and "dD"), the corresponding force components in the axial "dT" and in the peripheral "dF_θ" direction can be predicted and thus:

$dM=r\cdot dF_\theta=0.5\cdot\rho\cdot W_{ref}^2\cdot r\cdot(C_L\cdot\sin\varphi-C_D\cdot\cos\varphi)\cdot z\cdot c\cdot dr$ (27)

$$dT = 0.5\cdot\rho\cdot W_{ref}^2\cdot(C_L\cdot\cos\phi + C_D\cdot\sin\phi)\cdot\frac{z\cdot c}{\cos(\psi+\Gamma)}dr \quad (28)$$

According to eqt. (13), eqt. (27) and (28) are not independent. In order to establish a coherent closed formulation between the multiple streamtube model and the Q3-D blade element theory, the "dM" term from eqt. (7) must be equal to the value obtained using eqt. (27). If this is true, eqts. (12) and (28) give also the same value for "dT". Therefore, comparing the expressions of eqts. (7) and (27), one gets:

$$2\pi\cdot r\cdot\rho\cdot u_o\cdot(1-\varepsilon)\cdot(v_1-v_o)\cdot dr = \rho\cdot\frac{u_o^2\cdot(1-\varepsilon)^2\cdot\cos^2(\psi+\Gamma)}{2\cdot\sin^2\phi}\cdot r\cdot$$
$$\cdot(C_L\cdot\sin\phi - C_D\cdot\cos\phi)\cdot z\cdot c\cdot dr \quad (29)$$

or

$$\frac{v_1-v_o}{u_o}\cdot\frac{1}{1-\varepsilon} = \frac{z\cdot c\cdot\cos^2(\psi+\Gamma)}{4\pi\cdot r}\cdot\frac{C_L\cdot\sin\phi - C_D\cdot\cos\phi}{\sin^2\phi} \quad (30)$$

In order to get an expression similar to that by Glauert[4], using eqt. (18), eqt. (30) reads:

$$\frac{v_1 - v_o}{r \cdot \Omega + v^-} = \frac{z \cdot c \cdot \cos(\psi + \Gamma)}{4\pi \cdot r} \cdot \frac{C_L \cdot \sin\phi - C_D \cdot \cos\phi}{\sin\phi \cdot \cos\phi} \tag{31}$$

Only in the simplified case that $\psi+\Gamma \approx 0$, $v_o \approx 0$, $v_1=2v^+=2v^-$ and the 3-D effects on "C_L" and "C_D" are neglected, eqt. (31) or (30) coincides with the expression given by Glauert[4].

4. Calculation Procedure

Using the above presented models, the flowfield in the vicinity of a WT's rotor can be computed (see also figure (5)) as follows:

Step 1: Assume an initial distribution of the axial interference factor "$\varepsilon(r)$", e.g. $\varepsilon=1/3$.
Step 2: Estimate the streamtube geometry for the upstream to the rotor flow region, using eqt. (1).
Step 3: Using the equation of vorticity transport (meridional component), estimate the corresponding meridional vorticity field upwind of the rotor.
Step 4: Calculate the peripheral velocity component of the wind speed "v^-", eqt. (5).
Step 5: Predict the velocity triangle at the rotor inlet, from eqt. (17),(18) and (19).
Step 6: Estimate the velocity triangle at the rotor outlet, along with the corresponding lift and drag coefficients, eqt. (24) to (26).
Step 7: Using eqt. (4), the meridional vorticity component can be computed at the rotor exit.
Step 8: Assuming a distribution for the "ε_1" parameter (e.g. $\varepsilon_1=2\varepsilon$), estimate the streamtube geometry downstream the rotor from eqt. (1).
Step 9: Predict the meridional vorticity field downwind the rotor, using the transport of vorticity equation.
Step 10: Calculate the peripheral wind speed component "v_1", using eqt. (5).
Step 11: Solving eqt. (13), a new value for "ε_1" is predicted. This value is compared to the corresponding distribution of step 8 and an iterative procedure is established.
Step 12: Calculate a new profile for "ε", using eqt. (30). This value is compared with the corresponding values of step 1 and convergence is achieved using an iterative numerical procedure.
Step 13: Estimate the distribution of the force and torque components along the blades. Then the total thrust and the WT's power is computed by integrating the appropriate force and torque components. Subsequently, the flow field streamtubes are predicted by eqt. (1). Finally, the corresponding power "C_p" and thrust "C_T" coefficients are calculated by the following equations:

$$C_p = \frac{8P}{\rho \cdot u_o^3 \cdot \pi D^2} \tag{32}$$

$$C_T = \frac{8T}{\rho \cdot u_o^2 \cdot \pi D^2} \tag{33}$$

For the realization of the calculation procedure, the geometry of the machine (e.g. rotor diameter "D", hub radius "r_H", blade coning angle "ψ", axis tilt "Γ" etc.) along with its rotational speed "Ω" are needed. Additionally, the wind speed vector (u_o,v_o,w_o) at one or two diameters upstream the rotor is also necessary.

The above described calculation algorithm "AIOLOS-NEW" is usually stable and presents an overlinear convergence rate. The numerical algorithm can be easily executed on a P-III personal computer, and each complete iteration requires 10 to 100 sec CPU time on a 1 GHz machine.

5. Calculation Results

In order to validate the semi-empirical assumptions implicitly used in the proposed analysis, the first version of the new numerical code "AIOLOS-NEW" is used to analyze a typical wind turbine by L. Freris[14]. The wind turbine has three blades and a 4m diameter. The blades are tapered (figure (6)) but untwisted and have a NACA 4415 airfoil section. The rotor is set upwind the tower and is unconed (ψ=0). The blades are set at a constant pitch angle of β=8° to the chord line. The maximum value of "C_p" reached by this WT is 0.41 at a tip speed ratio λ=5.5, while the corresponding Reynolds number is in the area of 100,000 to 1,000,000.

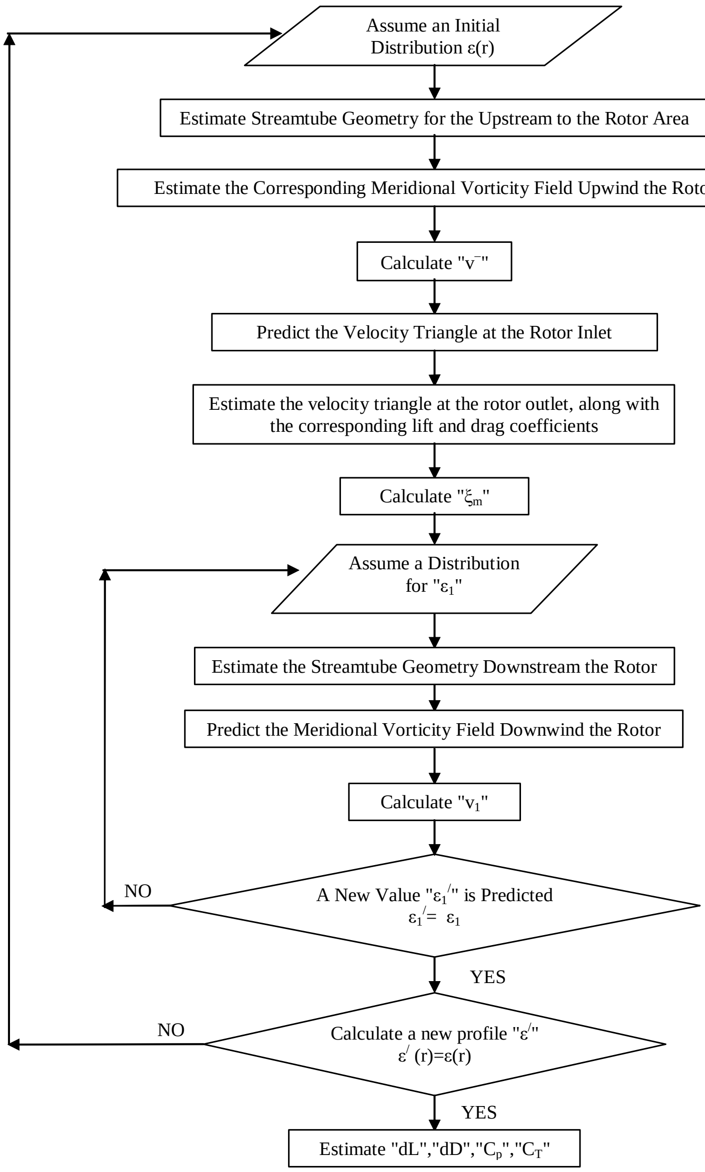

Figure 5: Flow chart of the proposed calculation procedure

Applying the proposed analysis on the above test case, we calculate, after eleven (11) iterations, the distribution of the "ε(r)" for λ=5.0, i.e. near the design point of the machine.

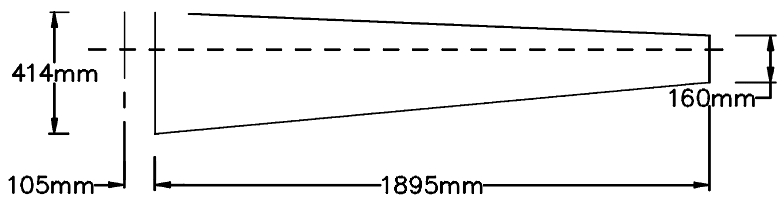

Figure 6: Blade geometry by Freris[14]

The calculations resulting by the present method are well compared with the data by Freris (figure (7)). This is also the case for the distribution of the torque and the thrust along the blade (figure (8), (9)), although the present method gives more flat distribution, especially for the thrust of the rotor.

Similar results are predicted for other operation points of the WT (λ=1,2,...,9,10,11), which cannot be presented here due to lack of space. However, in order to have a complete picture of the behaviour of the machine at various operational conditions, at figure (10) the computational results for the (C_p-λ) performance curve of the rotor are given in comparison with the data by Freris. As it can be seen, the predicted results validate the semi-empirical assumptions made in the proposed analysis.

The second test case to be analyzed is the "Super 5" rotor of the AeroStar Denmark A/S and the data are extracted from the patent No 1480/88 of Denmark[15]. The rotor of the Super-Line S5.0 series has also three blades and a 10.8m diameter. The blade characteristics are given in figure (11), while the blade twist is 19°. The used profile belongs to the NACA-44 group, slightly modified for a stall regulated rotor blade, according to the requirements of the wind turbine industry. The recommended coning angle for the blades is between 0° and 3.5°, while for this test case it is taken ψ=2°. Finally, the maximum value of "C_p" is approximately 0.5 at an optimal tip speed ratio λ=5.7.

After applying the analysis of "AIOLOS-NEW" in the second rotor the calculated power and thrust coefficients are presented in figure (12) and (13), in comparison with the data by the manufacturer. Although the general behaviour of the machine is well described by the present algorithm, the maximum "C_p" value predicted is almost 8% less than that AeroStar's. On the contrary, a more than 5% higher value of the thrust coefficient "C_T" is predicted by the proposed method in comparison with the data given.

Recapitulating, an almost 120min CPU time is required on a 1 GHz P-III machine to compute the (C_p-λ) or (C_T-λ) performance curves given in figure (12) and (13) for the 10.8m diameter rotor "S5.0".

The last case briefly analyzed here is the HSW-30 variable pitch wind turbine with a rotor diameter of 12.5m, set downwind to simplify the passive yaw control of the machine. According to the technical description of the machine[16] the rotor has two blades, the axis tilt "Γ" is Γ=0° and the corresponding cone angle is ψ=4.5° (figure (14)). The rotor blade has a length of 6100mm and the airfoil type is "FX 84-140/218". The maximum power coefficient value realized is 0.4 and the corresponding tip speed ratio takes a value of 7.5.

Applying the proposed method on the HSW-30 WT the performance curve (power versus wind speed) (P-u_o) is predicted. The calculation results are next presented (figure (15)) in comparison with measurements done from 20.12.90 to 9.1.91 according to IEA guidelines, by the WT's manufacturer. The calculation results reproduce fairly well the experimental data, although the maximum power predicted is less than 30kW. On the other side, the predicted performance of the rotor at

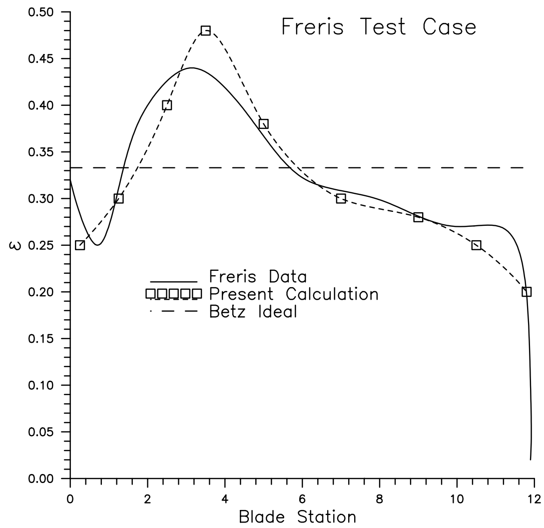

Figure 7: Variation of the axial interference factor along the blade of Freris [14]

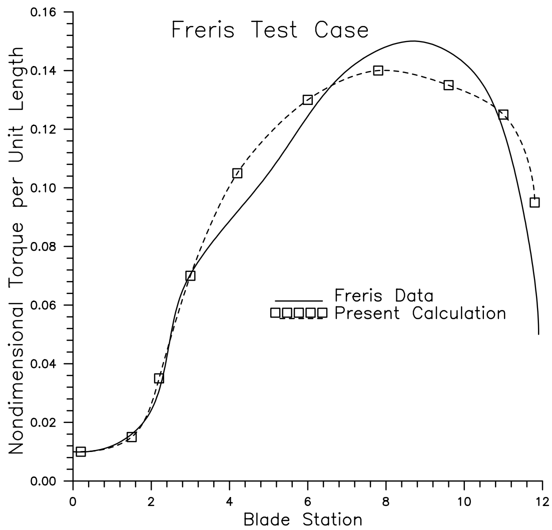

Figure 8: Variation of torque along the blade of Freris[14]

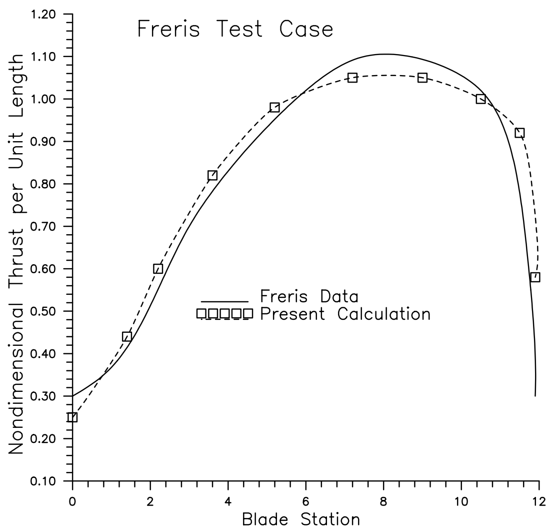

Figure 9: Variation of thrust along the blade of Freris[14]

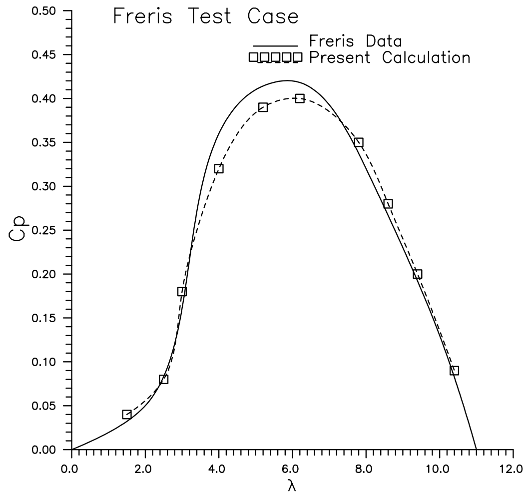

Figure 10: Performance curve for the blade of Freris[14]

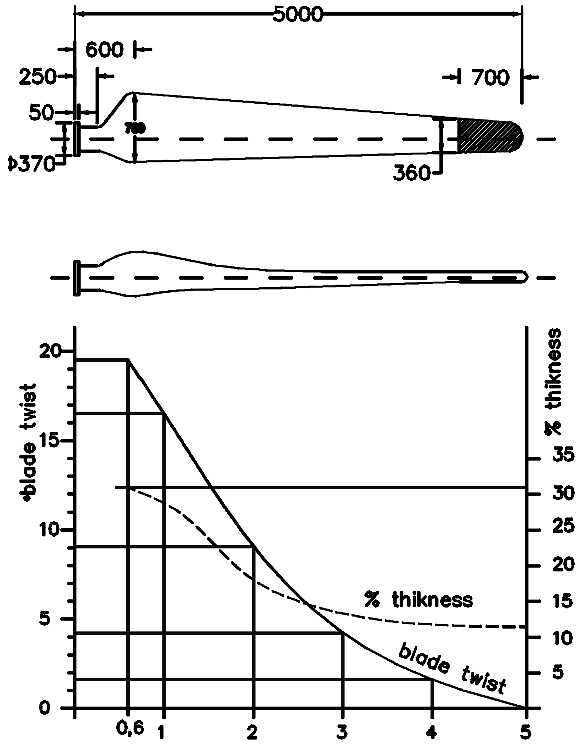

Figure 11: AeroStar's blade geometry[15] (Dimensions are given in mm)

its operation transitional part (i.e. $u_o \leq 13.0$m/s) is quite better than the experimental one, possibly due to the different pitch control algorithm used by the authors. Take also into account that the efficiency of the asynchronous generator (pole-changing) is assumed equal to 0.92 at every operation point, which is of course an oversimplification.

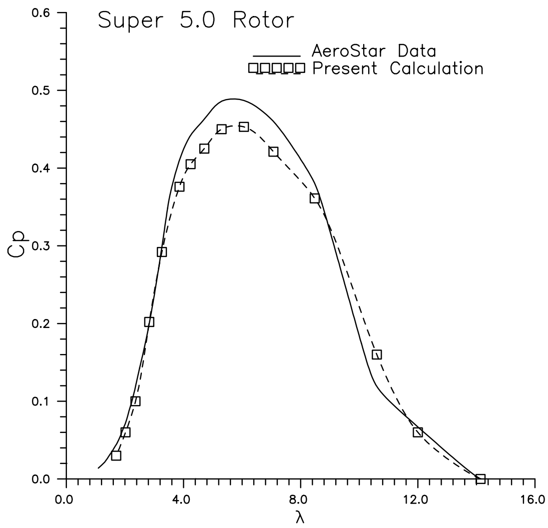

Figure 12: (C_p-λ) Performance curve for the AeroStar's blade[15]

6. Conclusions

An integrated aerodynamic model is developed to improve the understanding of the flow pattern of the wind passing throughout a wind turbine rotor. The proposed model is based on a coherent combination of the multiple streamtube model (vorticity transport equation included) and the quasi 3-D blade element theory, based on a revised profile loss model by the authors.

Additionally, favourable comparisons are obtained between the calculation results and the corresponding experimental data by the manufacturers for several test cases (including stall and pitch control machines), proving the accuracy and the applicability of the proposed method. Hence, the method developed in this paper could be used for any future investigation of the flow field pattern near the blade hub and tip. Of course, additional effort is necessary to improve the accuracy of the method in post-stall cases, where the limits of the multiple streamtube model are strongly tested.

Finally, the results obtained encourage the authors to continue their analysis. Having the present work as a basis, the main target is the development of a complete numerical code able to design high performance and minimum loss wind turbine's rotors, increasing the effectiveness of the wind energy conversion systems.

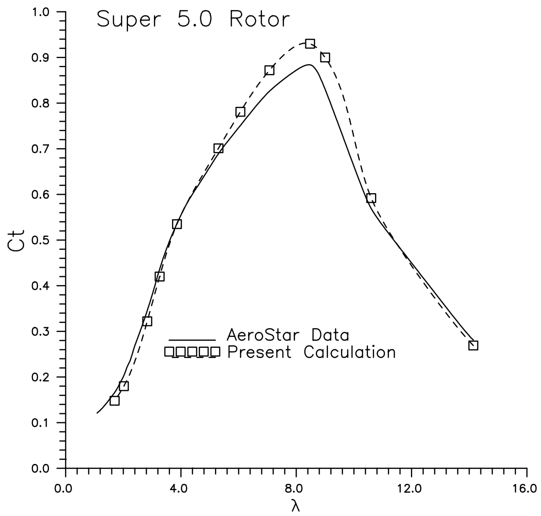

Figure 13: (C_T-λ) Performance curve for the AeroStar's blade[15].

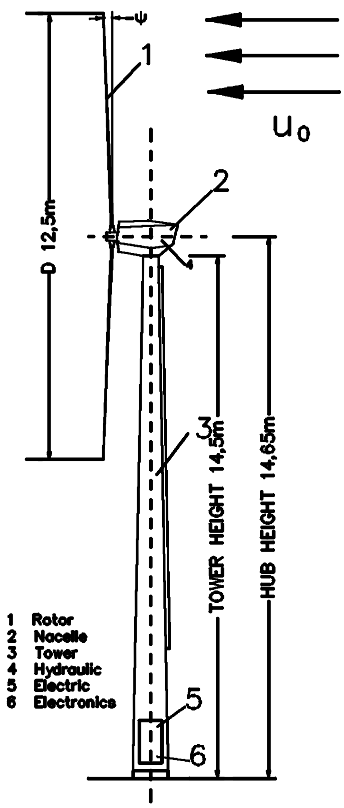

Figure 14: HSW-30 wind turbine[16]

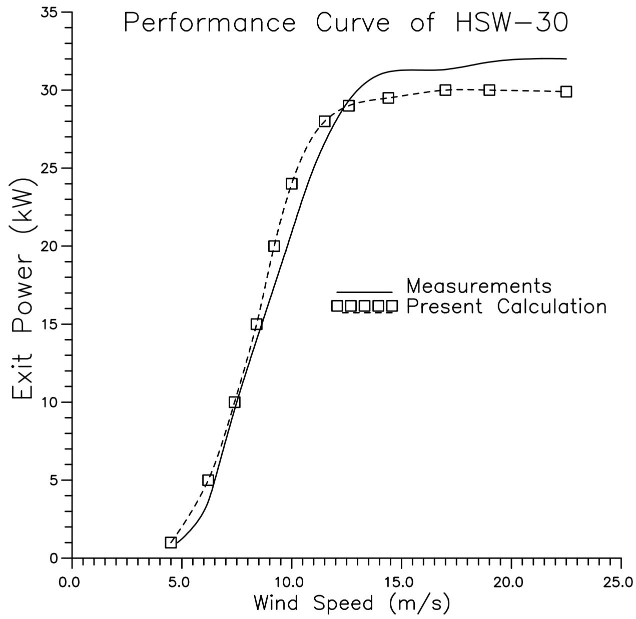

Figure 15: HSW-30, performance curve (P-u_o)

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PART TWO

HYBRID SYSTEMS

- Stand-Alone Systems
- Wind-Hydro

PARAMETRICAL INVESTIGATION OF THE WIND-HYDRO ELECTRICITY PRODUCTION SOLUTION FOR AEGEAN ARCHIPELAGO ISLANDS

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Abstract

The development of a combined wind-hydro electricity production system is found to be the supreme method of handling energy shortage and excessive electricity production cost problems for the remote Aegean Sea islands, taking also advantage of the existing high quality local wind potential. In the present study, a parametrical investigation concerning the applicability of the recommended solution for several different cases is carried out. Among the most important parameters affecting the energy behaviour of the proposed configuration are the wind turbines used number, the selected water reservoirs size, the corresponding water pumps rated power and the local wind potential quality, along with the system electricity consumption characteristics. Throughout the parametrical analysis, the impact of all above-mentioned parameters on the system energy autonomy and electrical efficiency is examined. On top of that, detailed energy balance profiles on an hourly basis are also included. Finally, the simulation results obtained strongly support the suggested solution, especially when the conclusions of the present work are taken into consideration.

Keywords: Wind-Hydro Energy System; Renewable Energy Sources Penetration; Electrical Efficiency; Energy Autonomy; Energy Balance

1. Introduction

Electricity consumption and power demand have significantly increased in Greece during the last decades, approaching the 48TWh in 2000. In this context, the corresponding electricity consumption increase, in most Aegean Sea Islands, has approximated 6% per annum for 1990-2000 period, Table I. At the same time, the maximum (peak) load increase in the same areas is more abrupt, approaching annual values in the order of 8% Table I.

Table I: Electricity Consumption Characteristics of Several Aegean Sea Remote Islands

	Kithnos		Karpathos		Ikaria	
Year	**Annual Electricity Consumption (MWh)**	**Peak Load Demand (kW)**	**Annual Electricity Consumption (MWh)**	**Peak Load Demand (kW)**	**Annual Electricity Consumption (MWh)**	**Peak Load Demand (kW)**
1990	2654	1180	11467	3060	8974	2760
1991	2719	1280	12961	3550	9927	3300
1992	2975	1480	14376	4000	10880	3280
1993	3004	1830	14939	4000	11526	3260
1994	3191	1800	16576	4550	11827	3600
1995	3672	1840	18995	4850	12590	4020
1996	4022	1840	19333	5050	14093	4220
1997	4340	1760	20419	5700	14593	4660
1998	4820	1880	21890	6150	16150	5100
1999	5216	1960	24369	6500	18570	5400

Up to now, the electricity requirement has been hardly fulfilled by the existing outdated autonomous power stations (APS) of PPC, at very high fuel consumption values. For the near future, the

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establishment of new electricity production plants is characterized as an extremely urgent engagement, in order to protect the local electrical grids from certain disoperation.

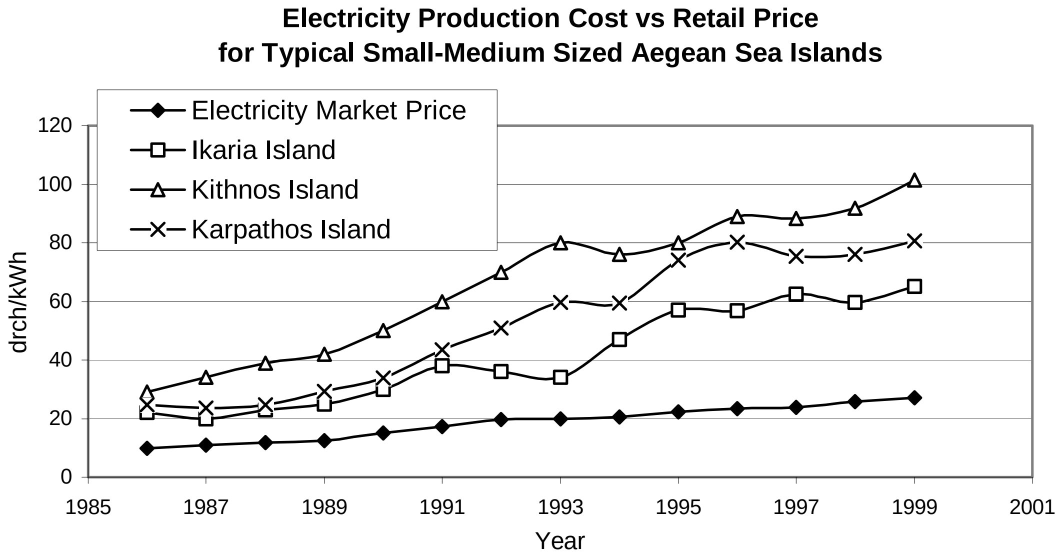

Figure 1: Time Evolution of Electricity Production Cost for Various Remote Islands.

Another important issue is the extremely high electricity production cost by the small existing thermal power plants spread over Aegean Sea, in comparison with the corresponding market price of electricity, figure (1). The problem of inadequate electricity production cost-market price balance becomes more obvious after the electricity market liberalization[1] in Greece (law 2773/99) becomes effective on 19.02.2001, ending the State controlled PPC monopoly in the local market. From now on, the minimum electricity production cost in these islands should be a matter of concern[2].

The erection of several wind parks in these islands should be an ideal solution in terms of minimum energy cost production, as in the majority of them the local wind potential is excellent. However, the strong disharmony between the highly varying (on daily and seasonal basis) electricity demand[3] and the stochastic behaviour of wind speed, poses strict limitation on the maximum wind power penetration in the local networks, in order to maintain the grid stability.

For all these reasons, in an attempt to rationalize the electricity production cost and increase the renewable energy sources (RES) penetration in the local electricity market, a quite interesting wind-hydro solution has been elaborated[4] since mid-90, and recently presented[5] in an integrated form[6]. Hence, taking into account the positive preliminary techno-economic evaluation results and Greek State amplified concern for this solution[7], a parametrical investigation has been carried out, in order to examine the applicability of the proposed plan for several Aegean Sea islands, underlining at the same time the "pro and con" of this application in different cases.

2. Wind-Hydro Solution for Aegean Sea Area

Using as a basis the information included in recent works by authors[4][5][6], the proposed wind-hydro integrated solution (figure (2)) consists of:

a. A number "z" of wind turbines (WTs) spread over the area examined; rated power "N^*_{WP}", with:

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

where "N^*_j" is the nominal power of each wind turbine used (usually $N^*_j=N^*_o$). Keep in mind[5][6] that:

$$z_{\mathbf{min}} \le z \le z_{\mathbf{max}} \tag{2}$$

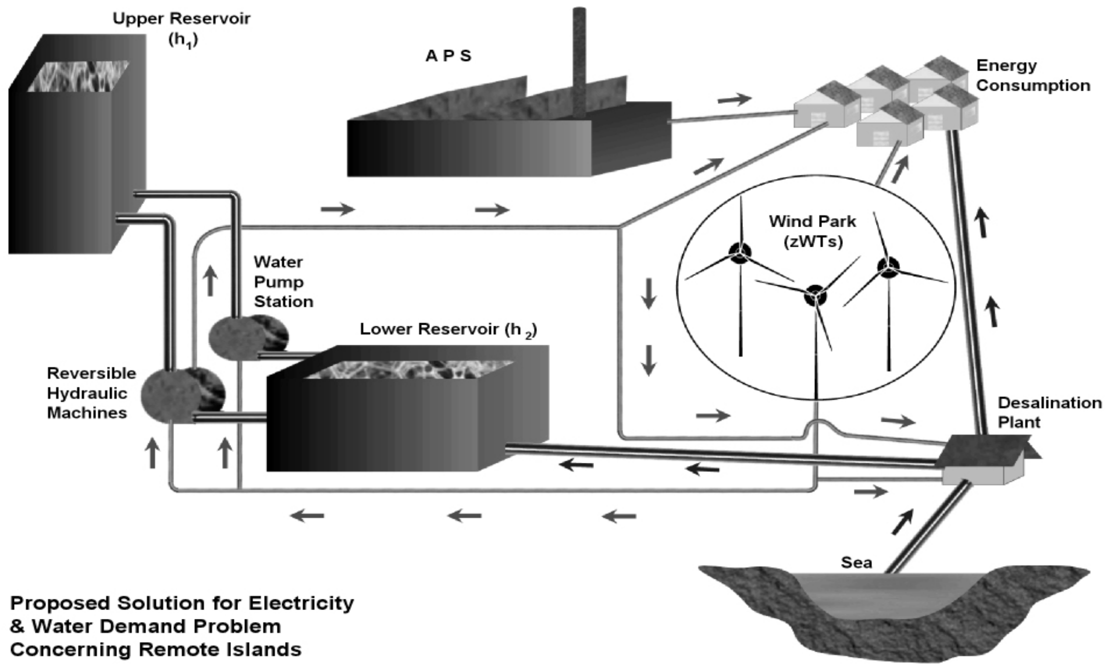

Figure 2: Schematic Presentation of the Proposed Wind-Hydro Solution for Remote Islands.

b. A small hydroelectric power plant[8][9] of at least two reversible water turbines able to meet the local grid maximum demand "N_{peak}", including an optional (Table I) future increase "δN"; rated power "$N^{*/}_H$"

c. A water pump station[10], which in collaboration with the reversible[11] water turbines (operating as water pumps) should have the capability to absorb the maximum power surplus of the system, i.e. maximum wind power-minimum load demand; rated power "N^*_p"

d. Two water reservoir[12] groups (an upper and a lower one) working in closed circuit along with the corresponding pipelines. The water reservoir capacity is described via the desired energy autonomy days (or hours) of the system "d_o", expressing the number of typical days for which the electricity consumption of the local society can be fulfilled, if the water stored in the upper reservoir is forwarded to the existing hydro turbines

e. The existing thermal power station of PPC, so far used exclusively to cover the electricity needs of the system; rated power "N_{APS}"
f. A properly sized[13] desalination plant, able to produce clean water from seawater, by absorbing the system energy surplus. Furthermore, low priority electricity loads may also be used in cases of excessive energy surplus.

The main target of the wind-hydro system under consideration is to cover the electricity demand "N_D" of the local market during the whole year (100% reliability) under the following constraints:

- Maximum hours of energy autonomy (APS mode off)
- Minimum energy contribution (minimum oil consumption) of the local APS
- Remarkable contribution on local clean (potable) water reserves

- Given (per capita) maximum first installation cost

Finally, during a long-term energy balance analysis of the proposed solution the following operational situations may appear:

i. The wind power produced is greater than the energy demand of the system, thus the energy surplus is stored, by the water pumping system, in the upper reservoir.
ii. The wind power produced is greater than the energy demand of the system, however the upper reservoir is full. Thus, the energy surplus is forwarded to other alternative usages, like the water desalination plant.
iii. The electrical power demand is higher than the wind park output; hence the hydro-turbines cover the power deficit.
iv. The electrical power demand is higher than the wind park output, but the upper reservoir is almost empty. In this case the internal combustion engines of the "APS" take over the power deficit, under a scheduled[14] operational plan.

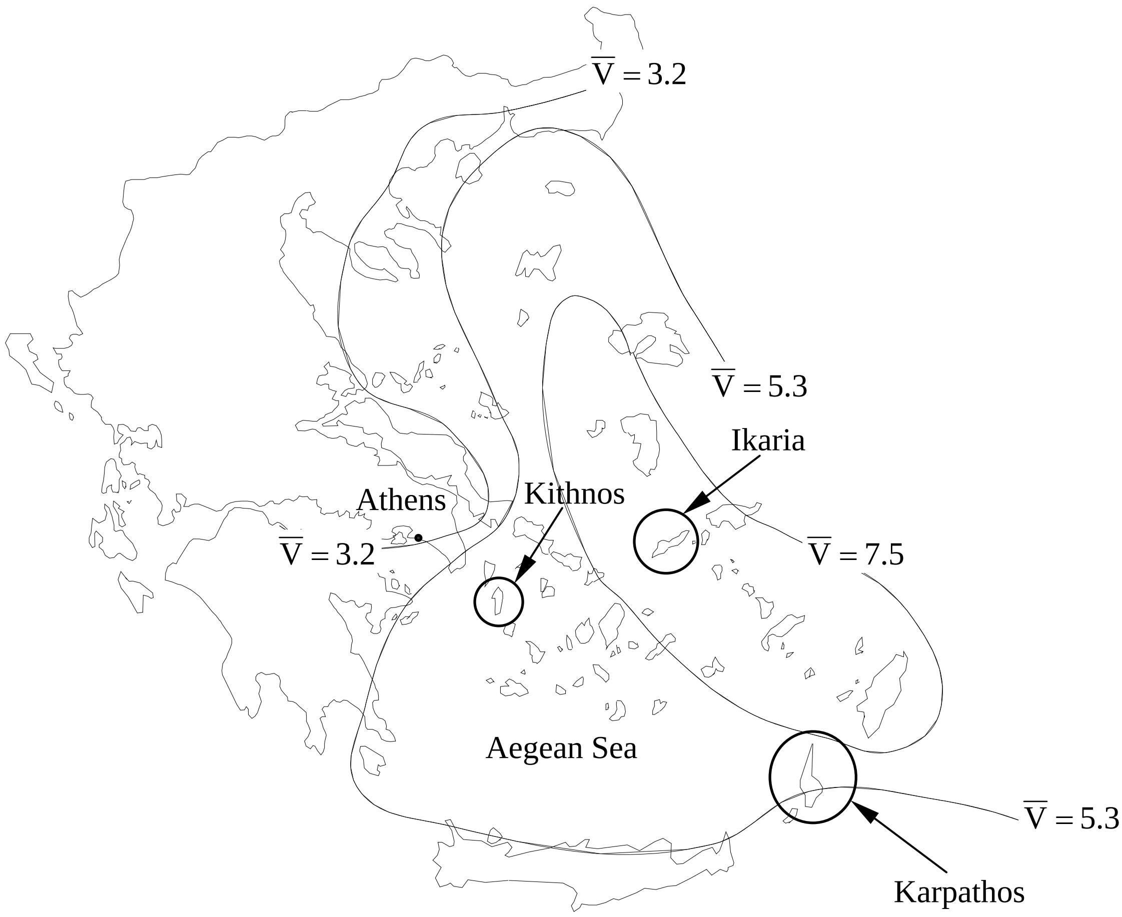

Figure 3: Wind Potential Estimates for Selected Aegean Sea Islands at 30m Height.

3. Wind Potential and Island Size Impact on Wind-Hydro Solution

Greece, and more precisely the Aegean Archipelago, has an excellent wind potential, as in many regions the annual mean wind speed at hub height (30÷50m) is up to 11m/s, see also figure (3). In order to obtain a clear-cut picture of the wind potential impact on a generalized application of the proposed wind-hydro solution in Aegean area, three typical islands are selected representing:

- A small island-medium quality wind potential case (Kithnos)
- A high wind potential-medium sized island case (Karpathos)
- A high wind potential-small sized island case (Ikaria)

An effort to take into account the island size (i.e. annual energy consumption-island area) is also attempted, in the proposed parametrical analysis, by including islands of different size.

Table II. Main Characteristics of Island Cases Analyzed

	Kithnos	**Karpathos**	**Ikaria**
Area (km^2)	94	301	255
Population	1700	7100	6200
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
z_{min}	5	13	13
z_{max}	20	27	27
Water Reservoir Volume per Energy Autonomy Day (m^3)	60,000	250,000	150,000

More precisely, Kithnos is a small island (figure (3)-Table II) located southeast of Athens. The topography of the island includes gentle slopes, absence of flat fields, low mountains and spare vegetation. The peak load demand was approximately 2MW for 1999 and the corresponding capacity factor of the local APS hardly exceeded the 28.5%. On the other hand Karpathos is a medium sized island (Table II), belonging to Dodekanesa complex (the second biggest after Rhodes). The local terrain is very intense, including rocky mountains with sharp slopes. The peak load demand (slightly above 6.5MW) appears during summer, while the corresponding capacity factor of the local thermal station was 43.3%. In the island there exists a remarkable natural water reservoir (≈2,000,000m^3). Finally, Ikaria is a small medium-sized island of East Aegean Sea, located 240km from Athens. The local topography is similar to Karpathos one. The corresponding peak load demand exceeds 5MW, while the local APS capacity factor is 38.2%. In Ikaria, there also exists a remarkable water reservoir (≈800,000m^3) at almost 700 meters elevation.

For comparison purposes, the corresponding annual wind speed probability density[15] profiles are presented in figures (4a), (4b) and (4c), while the resulting annual specific (kWh/(kW.year)) energy production values[16] of the 300kW wind turbines used[6] are given also in Table II.

Applying the proposed solution[17] to these three islands, for z=13 (13 wind turbines, N^*_{WP}=13x300=3.9MW) and for several water reservoir sizes ($1 \le d_o \le 3$), one may predict the values of RES penetration "R", of electrical efficiency "η_{el}" and total efficiency "η_{tot}" of the system analyzed. More precisely, the definition of the above-mentioned parameters is expressed as:

$$R = 1 - \frac{\text{APS Annual Operation Hours}}{8760} \tag{3}$$

$$\eta_{el} = \frac{\text{Wind Energy Finally Transfered to Consumption}}{\text{Total Energy Production of Wind Park}} \tag{4}$$

$$\eta_{tot} = 1 - \frac{\text{System Energy Loss}}{\text{Total Energy Production of Wind Park}} \quad (5)$$

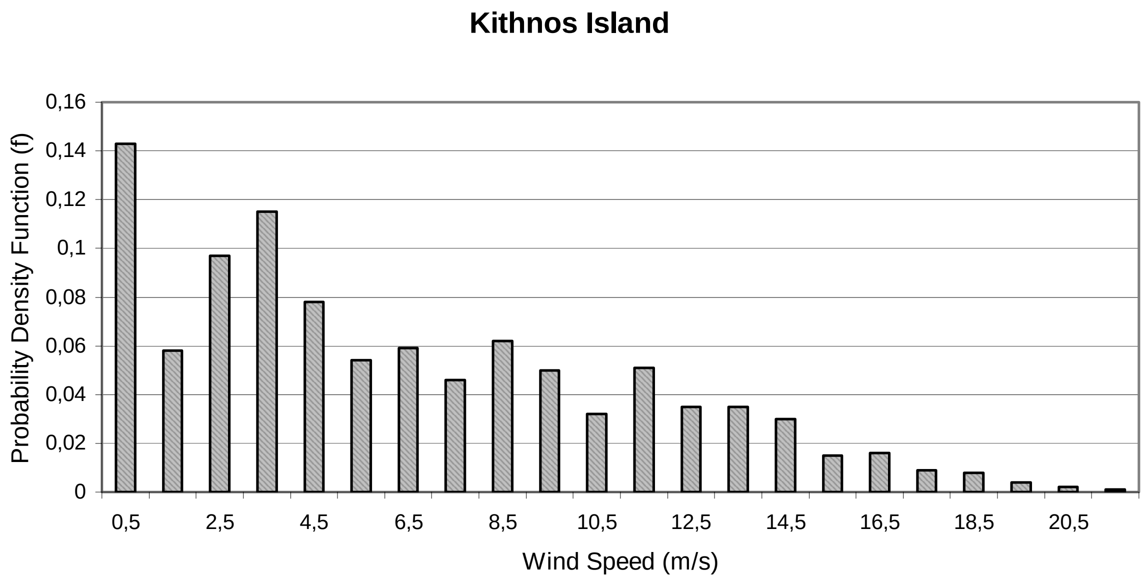

Figure 4a: Wind Potential Characteristics for Kithnos Island

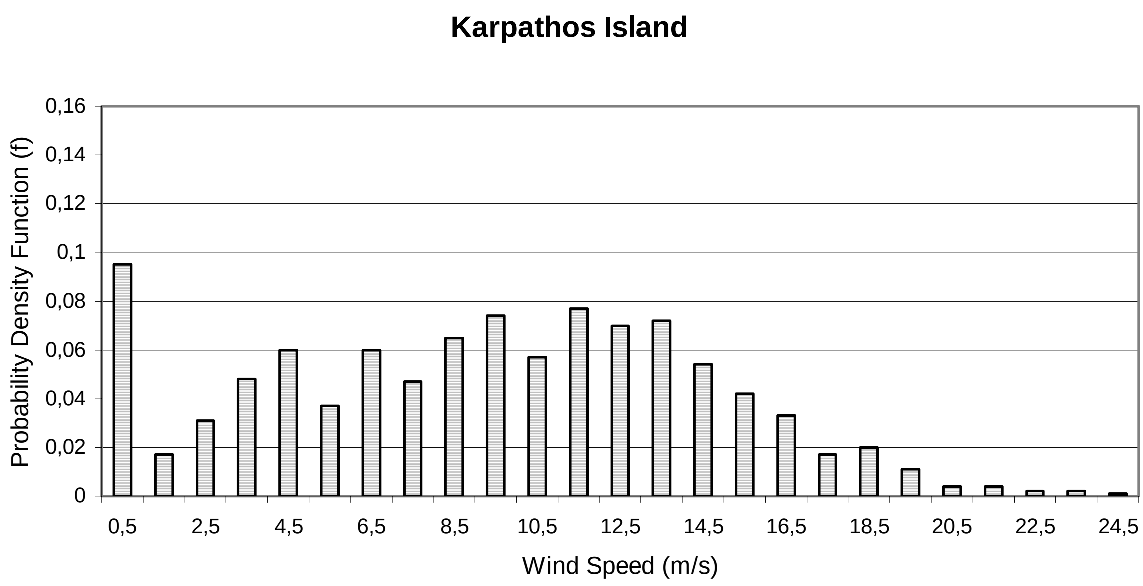

Figure 4b: Wind Potential Characteristics for Karpathos Island

According to the results of figures (5a),(5b) and (5c) the RES penetration is quite high for all cases analyzed, being slightly depending on the water reservoir size (mainly for Kithnos island). At the same time, the corresponding electrical efficiency is very low for Kithnos Island (≤40%), although the total efficiency of the system (including energy used for desalination) is in the order of 90%.

Combining the simulation results of all three cases in figure (6) and comparing the solutions realized for a high and a medium wind potential island, under the same RES penetration "R" values, it is obvious that the electrical efficiency of Ikaria is by far higher than the one of Kithnos. A similar picture appears (figure (7)) if a larger wind turbine number (z=20) is tested. According to figure (7), for similar 'R" values the efficiency of a high wind speed area is more than threefold the corresponding value of a medium wind potential island.

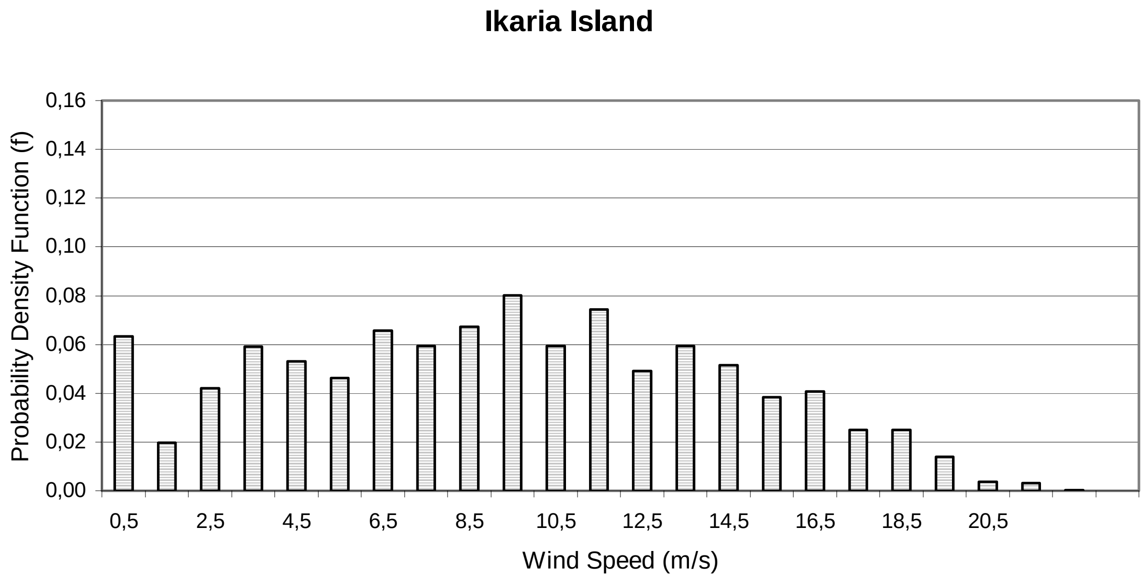

Figure 4c: Wind Potential Characteristics for Ikaria Island

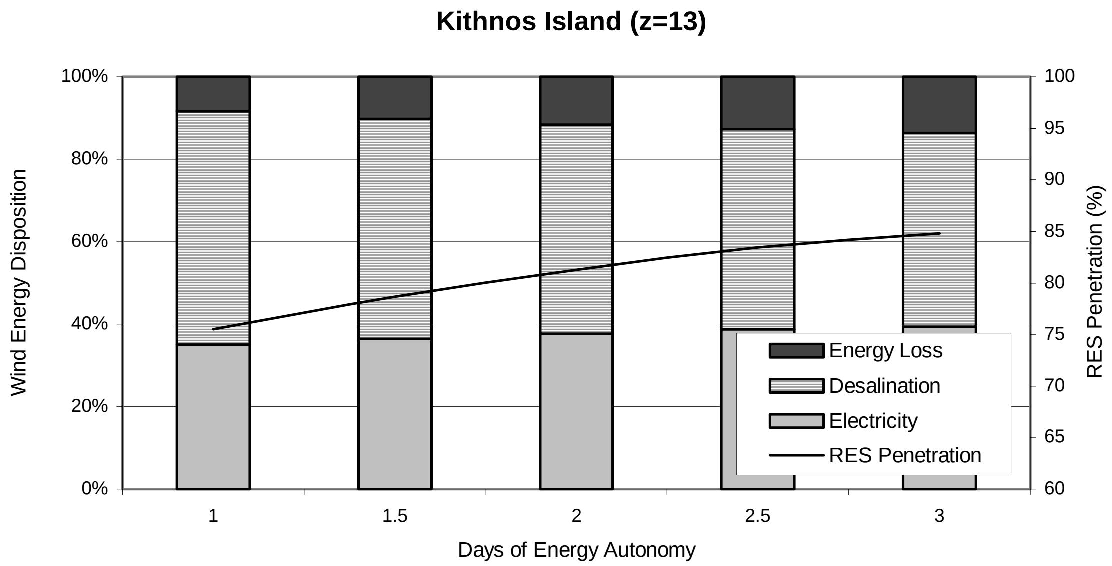

Figure 5a: Wind Energy Disposition for Kithnos Island, Wind-Hydro Solution

Subsequently, for similar wind potential quality cases (Ikaria, Karpathos) the increase of "R" is realized at electrical efficiency loss.

Finally, comparing the results of Karpathos and Ikaria cases one may conclude that for similar wind potential cases, the bigger island presents an efficiency advantage, while higher RES penetration values are realized for the smaller island.

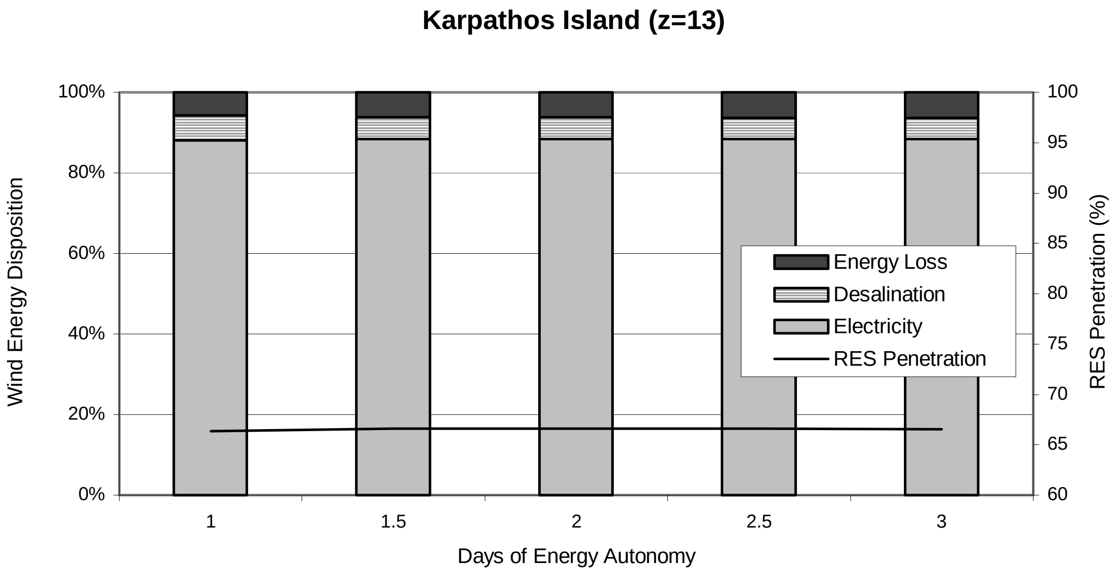

Figure 5b: Wind Energy Disposition for Karpathos Island, Wind-Hydro Solution

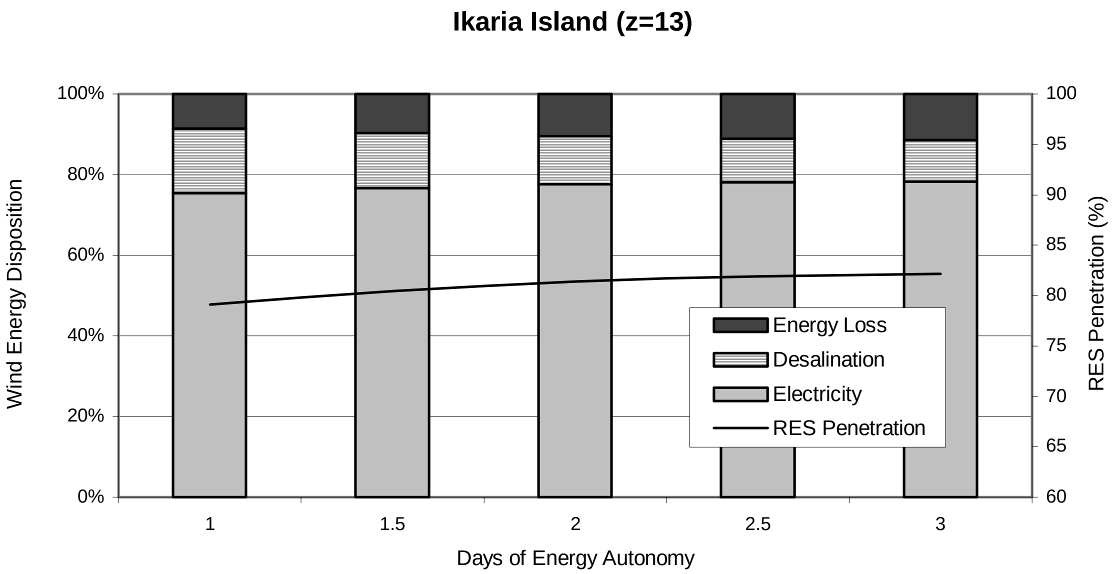

Figure 5c: Wind Energy Disposition for Ikaria Island, Wind-Hydro Solution

4. The Influence of Wind Park Size on Wind-Hydro Solution Parameters

According to previously presented research[6][17], the number of wind turbines used (rated power of each turbine "N^*_o") varies between a minimum "z_{min}" and a maximum "z_{max}" value. The minimum theoretical wind turbine number is defined in order the wind park to cover directly the annual electricity consumption "E_{annual}" of the island, including an optional (Table I) future increase ("δE"). On the other hand, the "z_{max}" value is based on the theoretical hypothesis that a complete (100%) disharmony between electricity demand and wind energy production occurs. Thus, the wind energy is exclusively market forwarded via the existing storage system, with transformation efficiency "η^*". Recapitulating, one may assume that:

$$z_{\mathbf{min}} = \frac{E_{annual} + \delta E}{8760 \cdot CF \cdot N_o^*} \leq z \leq \frac{E_{annual} + \delta E}{8760 \cdot CF \cdot N_o^* \cdot \eta^*} = z_{\mathbf{max}} \tag{6}$$

where the wind turbine capacity factor "CF" depends[18] on the local wind potential "f(V)" and the specific turbine used power curve "N(V) -both functions of wind speed "V"- as well as on the installation mean annual technical availability, thus:

$$CF = \Delta \cdot \int_0^{\infty} f(V) \cdot \frac{N(V)}{N_o} \cdot dV \tag{7}$$

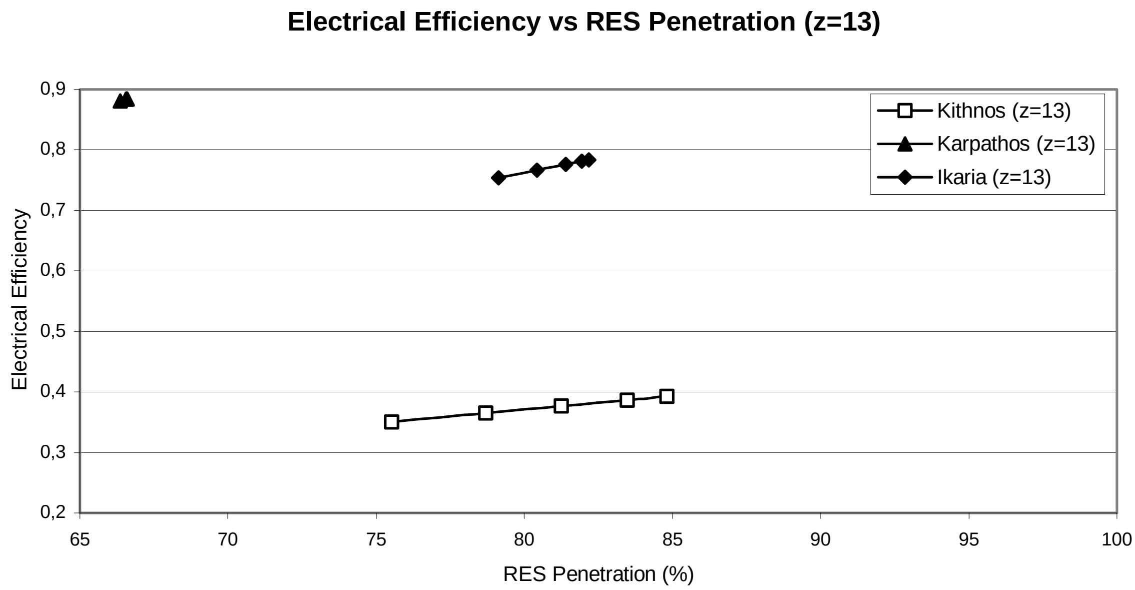

Figure 6: Electrical Efficiency and RES Penetration Evolution, Wind-Hydro Solution (z=13)

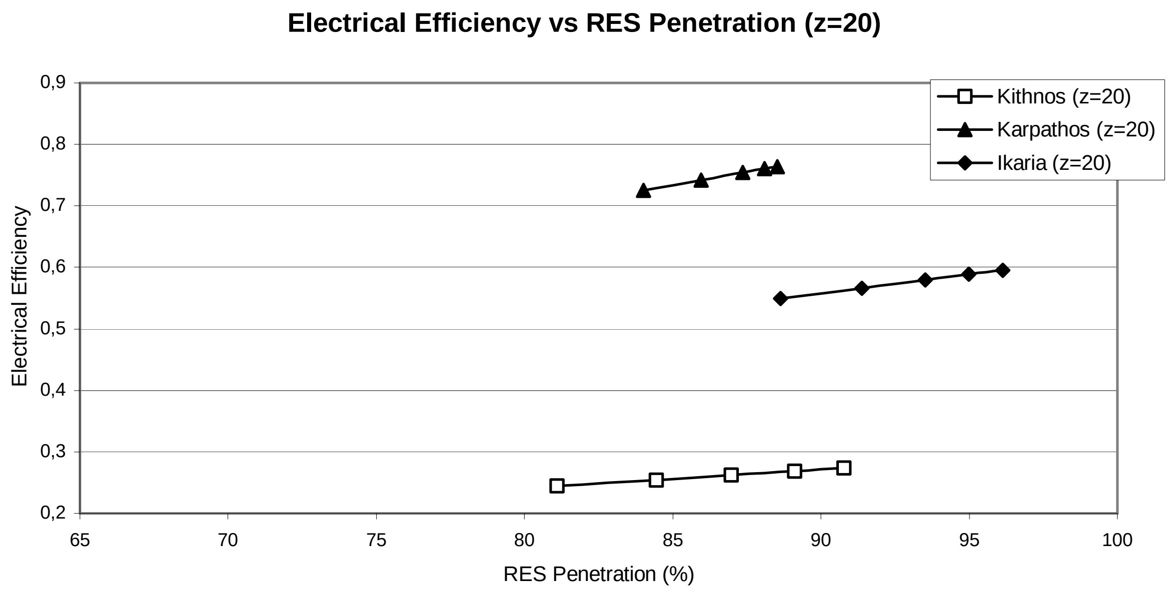

Figure 7: Electrical Efficiency and RES Penetration Evolution, Wind-Hydro Solution (z=20)

Using equations (6) and (7), the "z" variation field ($\Delta z = z_{max} - z_{min}$) is given in Table II, for all cases examined. Thus, according to calculation results of figures (8a),(8b) and (8c) one may state that a remarkable RES penetration increase takes place by increasing the wind park size (i.e. by increasing "z"). More precisely, the increase is much more pronounced when z takes values between "z_{min}" and "$z_{min}+\Delta z/2$", while for higher "z" values an almost asymptotic behaviour of "R" is encountered.

The above conclusions are also supported by figures (9a),(9b) and (9c), where the evolution of the system electrical efficiency is presented as a function of "R" values realized, for all three island cases examined. According to the results obtained the electrical efficiency is strongly decreased by increasing the wind turbine number from "z_{min}" to "$z_{min}+0.5\Delta z$". The decrease rate of "η_{el}" is milder when z varies between "$z_{min}+0.5\Delta z$" and "z_{max}".

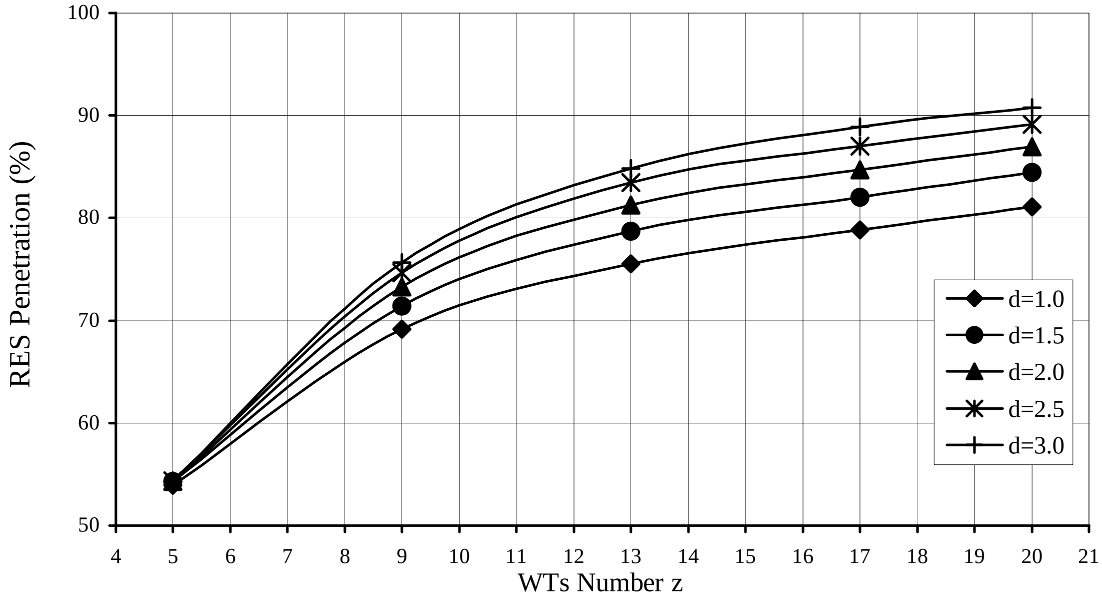

Figure 8a: RES Penetration in the Local Electrical System of Kithnos, Wind-Hydro Solution

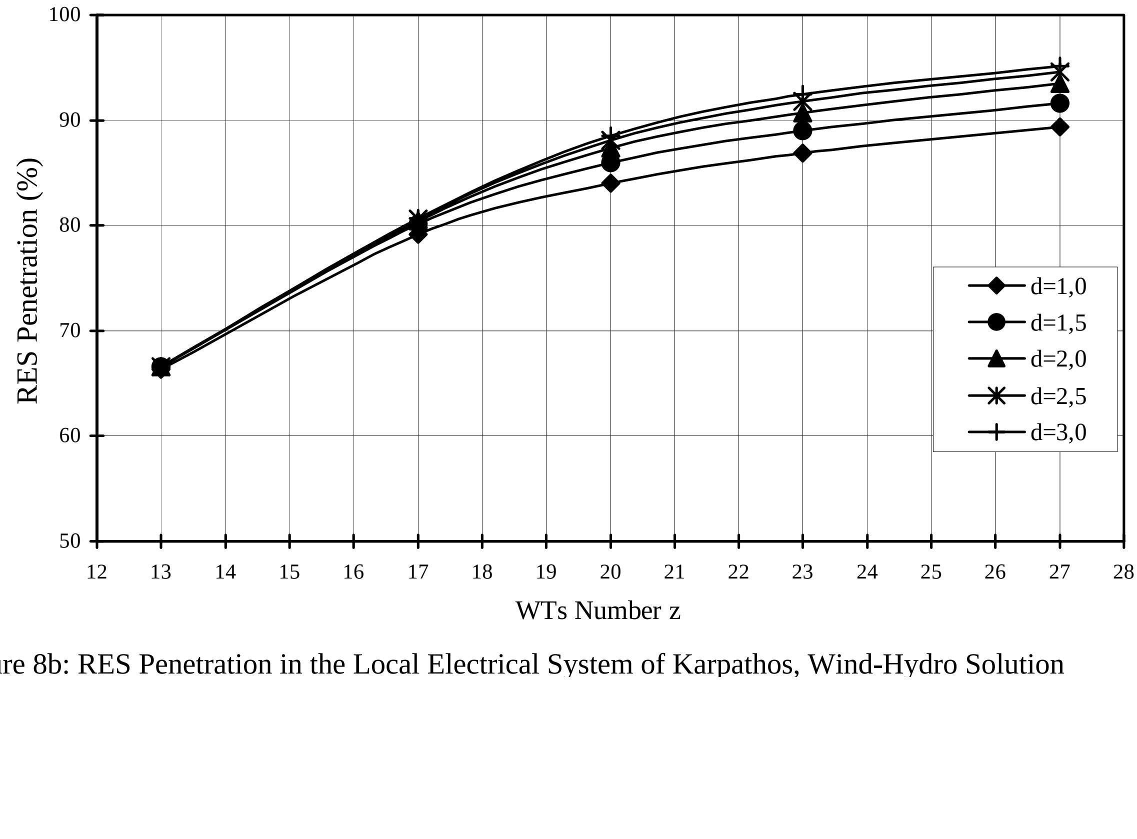

Figure 8b: RES Penetration in the Local Electrical System of Karpathos, Wind-Hydro Solution

Finally, for a typical case (d_o=2) concerning Karpathos Island, there is the opportunity to examine in details (at least on an hourly basis) the local system energy balance for a typical ten-days period and for several "z" values, figures (10a) and (10b). According to these figures, the energy deficit (negative –y axis profile) is slightly influenced by the wind turbines number, as during calm spells the energy output of any wind turbine combination is practically zero. On the other side, the contribution of local APS on the system energy deficit coverage is drastically reduced when the quantity of wind turbines used rises. Thus, although the local APS operates for 19≤t≤49h and 105≤t≤192h for z=13 (figure (10a)), the corresponding operation period is limited between 135 and 190 hours (135≤t≤190), if z=20. In the maximum wind penetration case (z=27) the internal combustion engines of the system are used for only one hour (t=164) during the whole ten-days period of analysis.

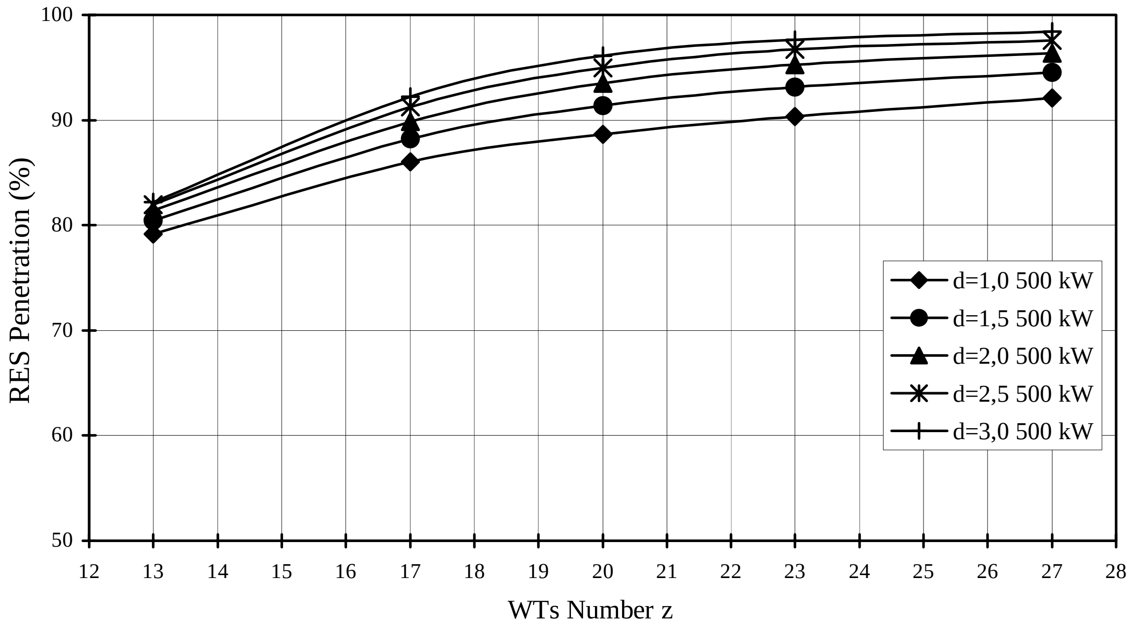

Figure 8c: RES Penetration in the Local Electrical System of Ikaria, Wind-Hydro Solution

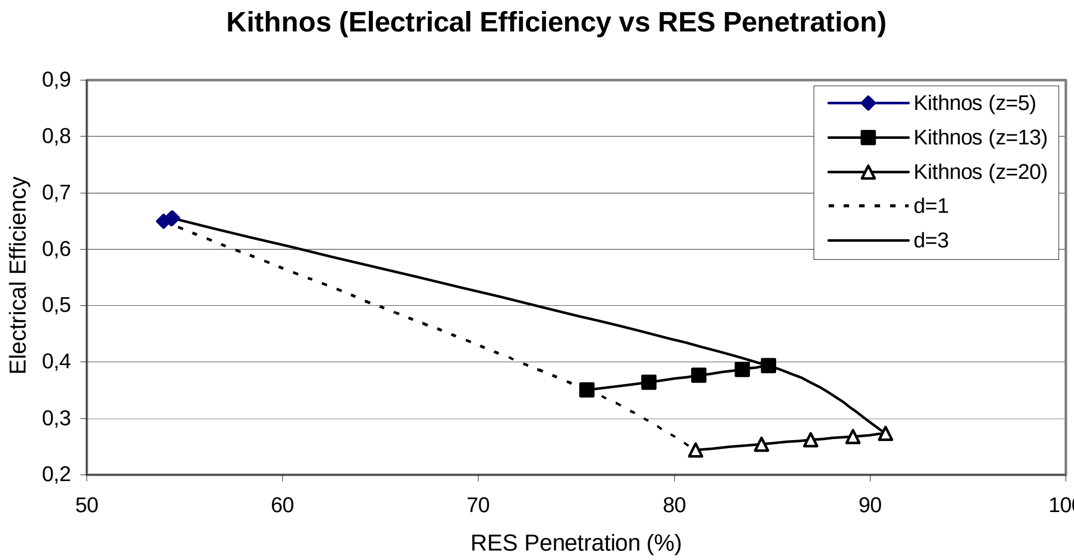

Figure 9a: Electrical Efficiency Variation as a Function of RES Penetration & Wind Turbines Number, Kithnos Island

5. The Influence of Water Reservoir Size of Wind-Hydro Solution Parameters

The water reservoir size "V_o" depends[6][12] on the annual electricity consumption of the local society, the desired days of the system energy autonomy and the upper to lower reservoir elevations difference "Δh", thus:

$$V_o \approx f\left(E_{annual}, d_o, \frac{1}{\Delta h}\right) \tag{8}$$

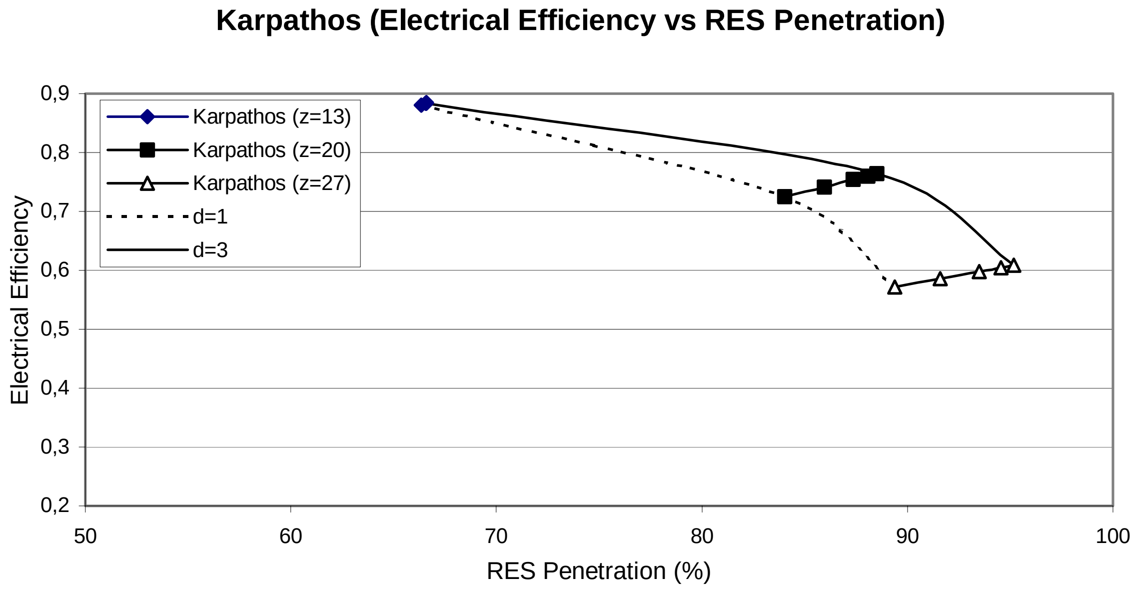

Figure 9b: Electrical Efficiency Variation as a Function of RES Penetration & Wind Turbines Number, Karpathos Island

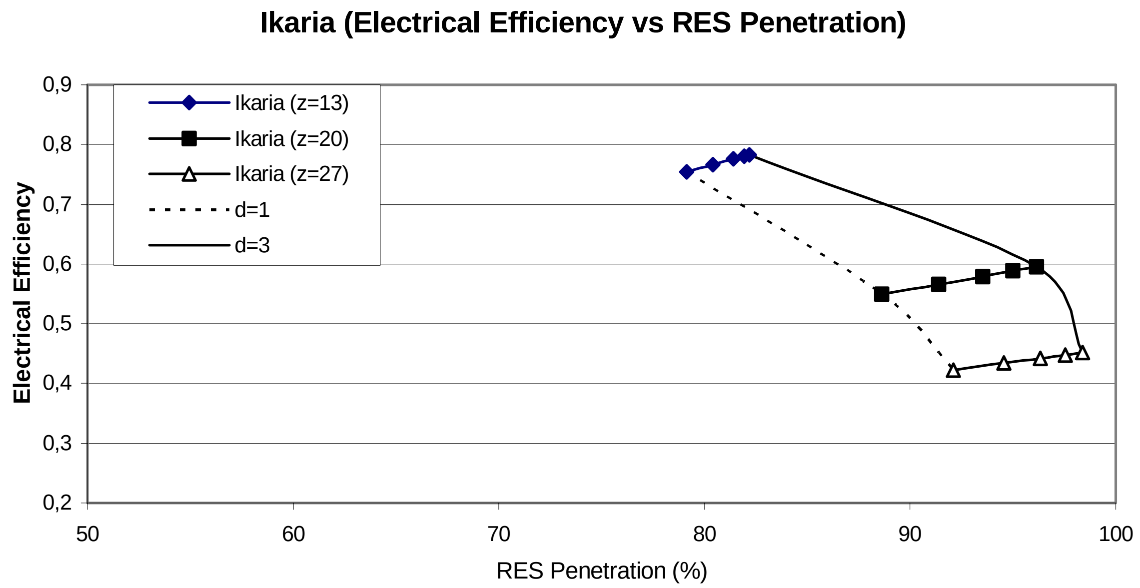

Figure 9c: Electrical Efficiency Variation as a Function of RES Penetration & Wind Turbines Number, Ikaria Island

According to figures (8a),(8b) and (8c) the influence of "d_o" on RES penetration is negligible for low "z" values, being much more important as "z" grows. On top of that, the "R" increase is even more intense when "d_o" varies from one to two than when it varies from two to three. In addition, keep in mind that the above remarks are also validated from figures (9a),(9b) and (9c). More precisely, the "R" and "η_{el}" values are completely unaffected from "d_o" variation, for $z=z_{min}$ and for Kithnos and Karpathos islands, figures (9a) and (9b). This is not the case for Ikaria Island, figure (9c).

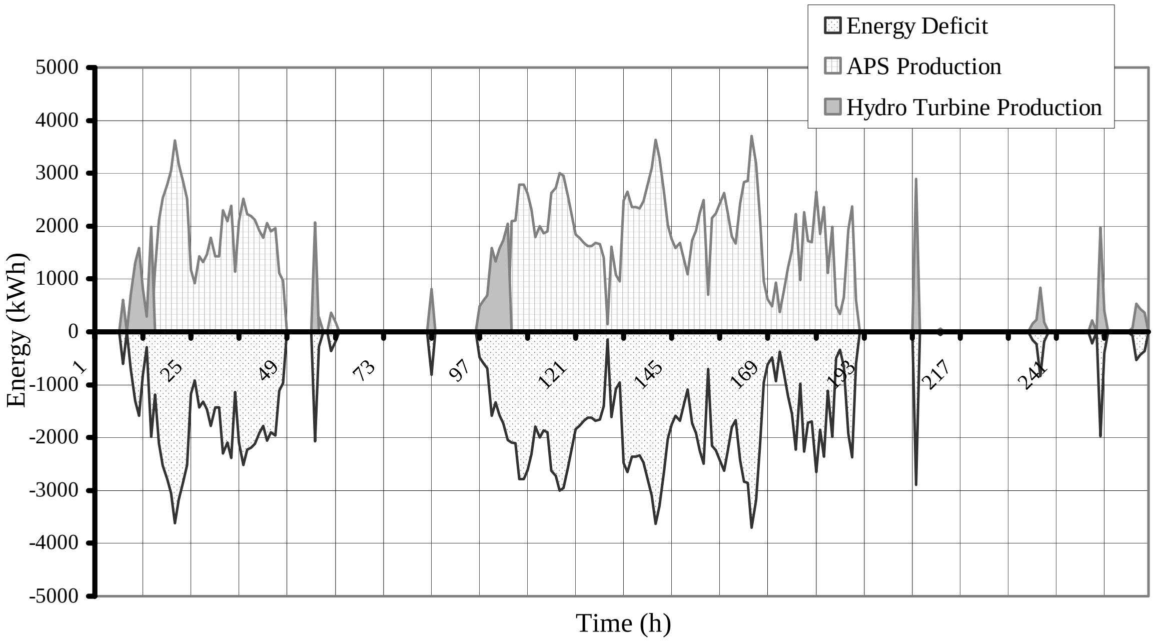

Figure 10a: Energy Balance for the Wind-Hydro System, Karpathos Island (z=13, d_o=2.0)

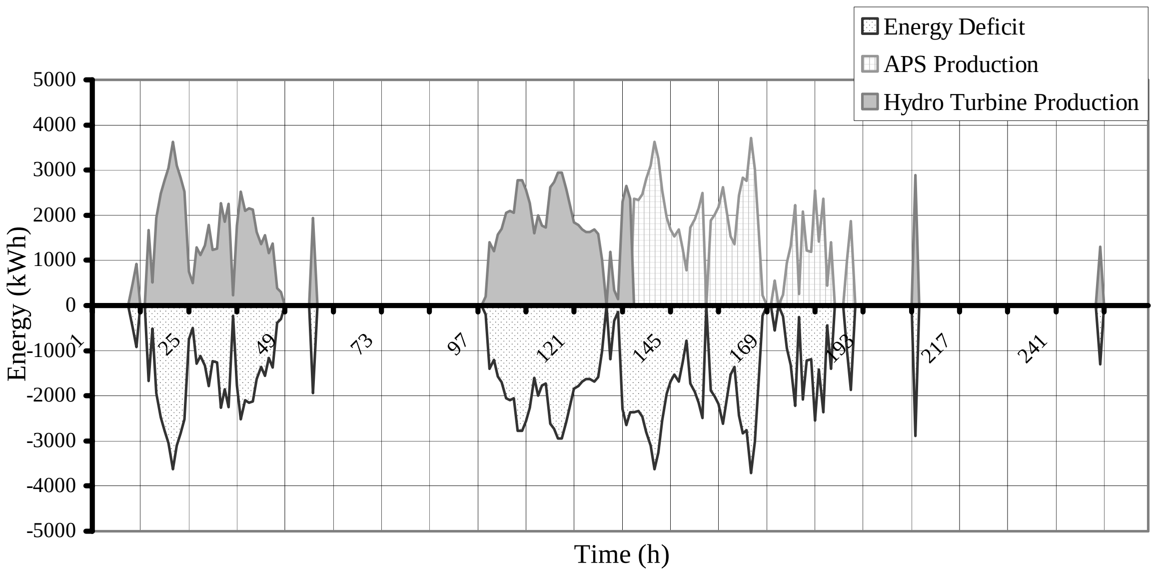

Figure 10b: Energy Balance for the Wind-Hydro System, Karpathos Island (z=20, d_o=2.0)

Another important conclusion drawn from the present analysis states that by increasing the days of the system energy autonomy, the electrical efficiency is increased, especially for remarkable wind park size cases. Finally, it is almost obvious that the contribution of "d_o" is significantly substantial for large "z" values.

For a further detailed investigation of the water reservoir size influence on the energy balance of Karpathos (proposed) electricity system, the corresponding energy distributions are summarized in figures (11a) and (11b). As it is expected, the energy deficit profile is completely independent from "d_o" variation. However, by increasing "d_o" the APS contribution is decreased, especially after a high wind speed values period (33h≤t≤49h).

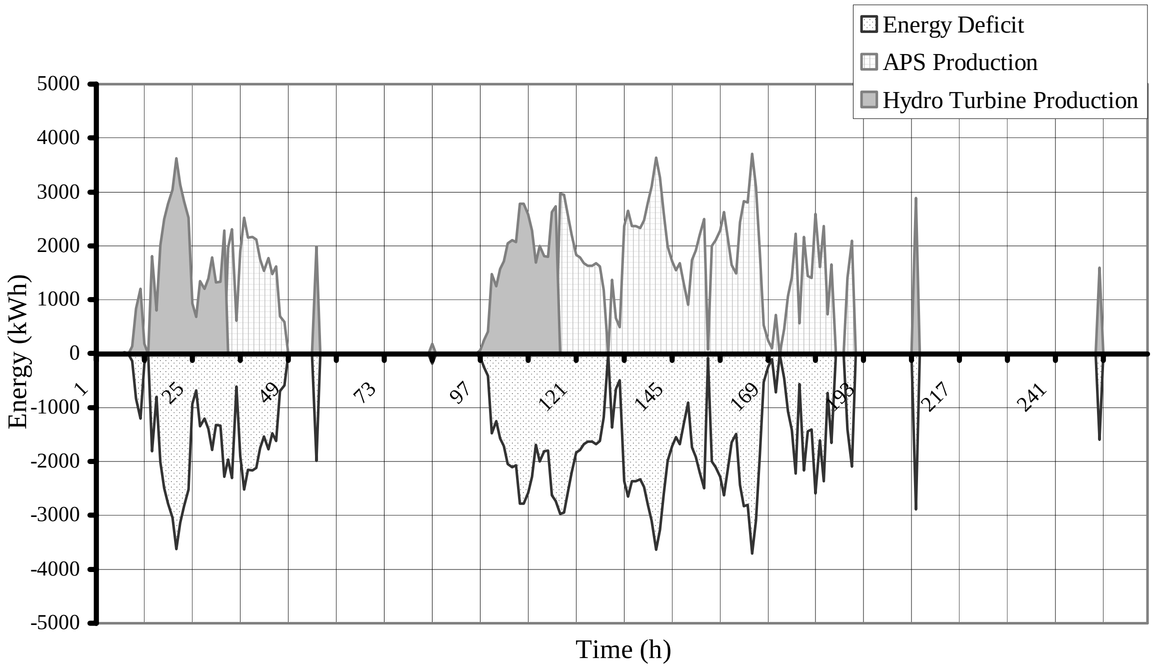

Figure 11a: Energy Balance for the Wind-Hydro System, Karpathos Island (z=17, d_o=1.0)

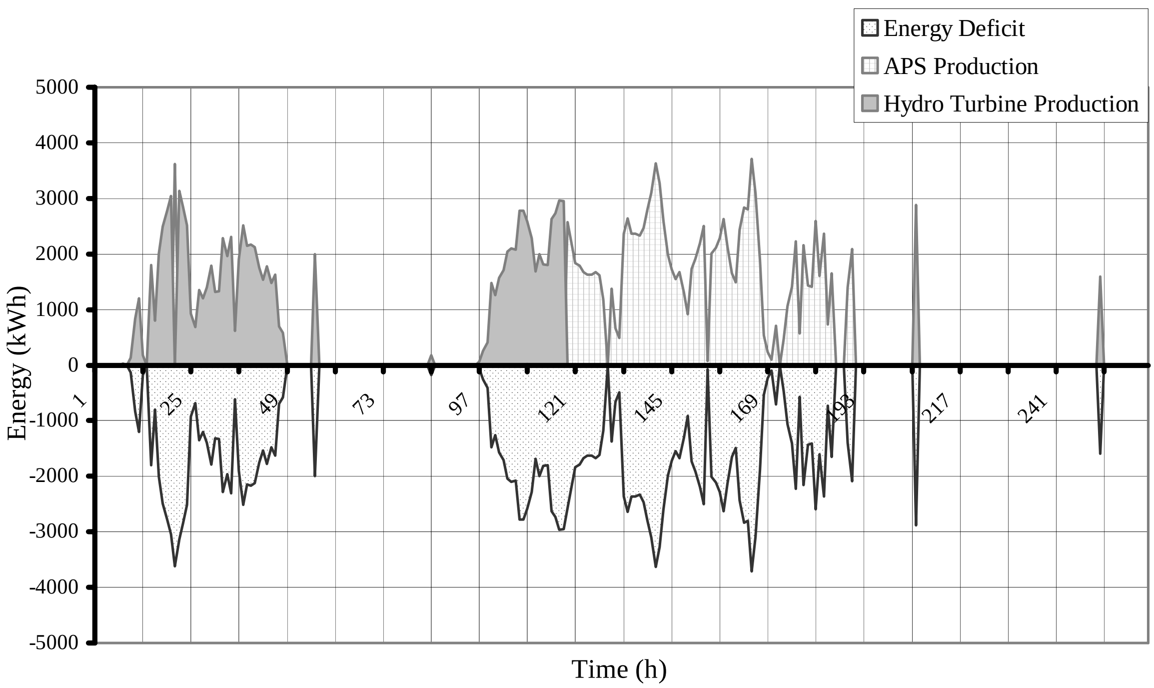

Figure 11b: Energy Balance for the Wind-Hydro System, Karpathos Island (z=17, d_o=3.0)

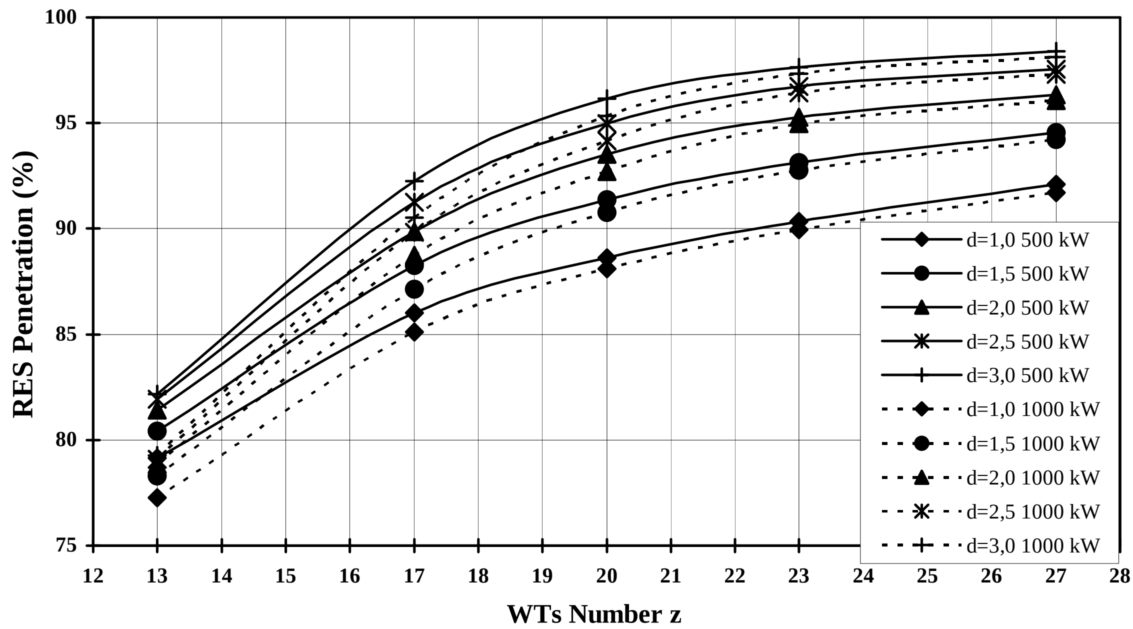

Figure 12: Comparisons on the Basis of Water Pumps Size, Ikaria Island

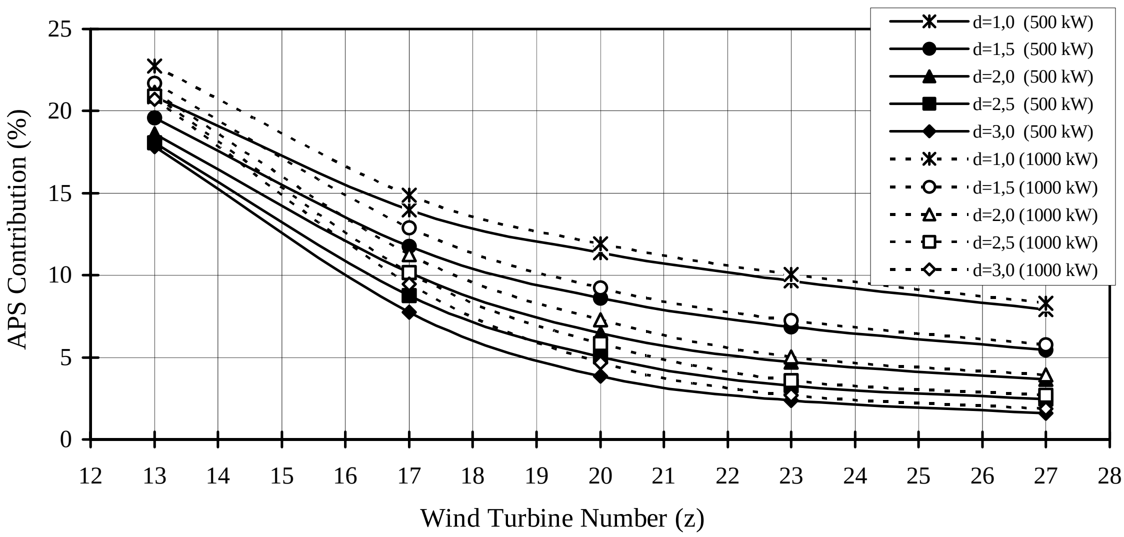

Figure 13: APS Energy Contribution on the Basis of Water Pumps Size, Ikaria Island

6. The Influence of Water Pump Size on the Wind-Hydro Station Energy Behaviour

The water pump system is used -in collaboration with the reversible water turbines- to transfer water from the lower to the higher reservoir, absorbing the wind energy surplus of the installation. In order to forward the appropriate water volume, the selected water pumps are operating in parallel connection[10][11]. Thus, the minimum flow rate transferred depends on the corresponding minimum operation flow rate of one of the water pumps used, in order to avoid instability and cavitation problems.

During the present analysis, two simulation scenarios are examined, concerning the nominal power of the water pumps used. Hence, by using 500kW water pumps instead of 1000kW ones (e.g. Ikaria case) the energy autonomy of the system is remarkably increased, figure (12), for small reservoir size and low wind turbine cases. These results are also validated by the energy contribution of the existing APS in the local system electricity production values, figure (13). According to the results obtained, one may state that by selecting smaller water pumps the energy autonomy of the system is increased while the energy contribution of the APS is reduced, especially for low RES penetration cases. On the contrary, for high "z" values the influence of the water pump size is limited.

7. Conclusions

An extended parametrical investigation, concerning the application results of the wind-hydro electricity production solution, is carried out for several small-medium sized Aegean Sea remote islands. During the present analysis the influence of the local wind potential, the local annual electricity consumption along with the impact of wind park, water reservoir and water pumps size on the basic energy balance parameters of the hybrid system is examined in details.

Among the most important conclusions is the strong system energy autonomy and electrical efficiency dependence on the wind turbine number. Additionally, one may underline the dominant effect of the local wind potential on the solution quality obtained, the increasing influence of water reservoir size (in high wind penetration case) and the electrical efficiency-energy autonomy advantage offered by the utilization of relatively small water pumps.

The simulation results obtained strongly support the proposed solution, especially when the conclusions of this study are taken into consideration. In almost all cases analyzed up to now, the best energy balance behaviour is accomplished for two days of energy autonomy water reservoirs, 500kW water pumps and approximately "$(z_{min}+z_{max})/2$" wind turbines configuration. Subsequently, the electrical efficiency of the wind-hydro system is quite lower for medium wind potential quality cases compared to high wind speed areas, under the target of maximum renewable energy sources penetration. Finally, the bigger islands present an energy efficiency advantage over smaller ones, while the small islands reach higher RES penetration values.

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ELECTRICITY LOAD MANAGEMENT OF APS USING WIND-HYDRO SOLUTION

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Abstract

In most Greek islands the electricity consumption increase imposes the establishment of new electricity production plants. The fluctuations, however, of daily and seasonal electricity demand leads to a low capacity factor of existing power stations. As a result, the mean production cost of the Greek APS is more than double the corresponding marginal cost of the PPC. In an attempt to limit the excessive additional power of new scheduled thermal power plants, taking also advantage of the excellent wind potential of the area, the possibility to use combined wind-hydro stations in order to manage short and medium term load variations is hereby examined.

Keywords: Electricity Cost; Thermal Power Stations; Capacity Factor; Wind-Hydro Power Station; APS; Load Variation

1. Introduction

In most Greek islands the electricity consumption increase has exceeded 5% per annum, while the corresponding maximum (peak) load intensification is much more abrupt (8%). For this purpose, the establishment of new electricity production plants is considered by the authorities as the only solution to protect the local electrical grid from several problems, like voltage and frequency instability or even total power failure[1].

However, the fluctuation of daily and seasonal electricity demand in almost all island grids leads to a low capacity factor of existing power stations, being usually over-sized in order to face the extremely sharp summer peaks. Despite this continuous effort, in several cases during summer the maximum available power of local grids is often beneath the demanded load, leading thus to electrical black outs[2]. As a result, the mean production cost of the Greek APS (autonomous thermal-power stations) is more than double the corresponding marginal cost of the PPC. On top of that, the low quality or even the shortage of energy is the principal factor delaying the local societies' economic development and worsening the habitants' living standard.

On the other side, all these islands have an excellent wind potential enabling them to produce plenty of "cheap" electricity based on wind power plants[3]. However, serious limitation to wind power penetration is imposed under the restriction that the local grid stability should be protected from production fluctuations[4]. Additional barriers against the wind energy penetration in these autonomous grids also result, due to the stochastic availability of the wind speed, leading to important disharmony between the wind energy production and the electricity demand[2][4].

In an attempt to limit the excessive additional power of new scheduled thermal power plants, taking also advantage of the various lake-tanks found in most Aegean Sea islands, the possibility to use combined wind-hydro stations in order to manage the short and medium term load variations is hereby examined[5]. During the proposed analysis, emphasis is laid on predicting the optimum size of similar installations, considering a large variety of techno-economic parameters.

***Kaldellis J.K., Kavadias K.A., Vlachou D.S., 2002**, "Electricity Load Management of APS Using Wind-Hydro Solution", International Conference Med Power 2002, Paper MED02_126a, Athens, Greece.*

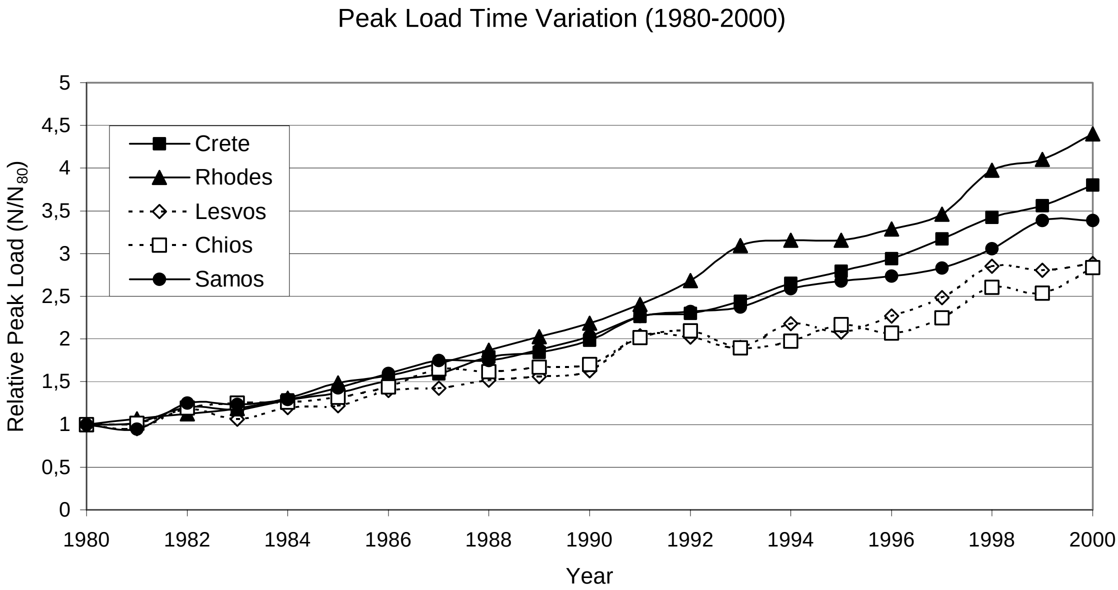

Figure 1: Peak Load Evolution in Large Greek Islands

2. Present Situation

The Greek electrical system includes the central electrical network of mainland along with a number of remote electrical grids covering the electrification need of most Greek islands. In this context, almost fifty autonomous power stations -scattered on Aegean Sea- are based mainly on outmoded diesel generators and partly in high cost gas turbines. Their annual energy production varies between 200MWh and 200000MWh, apart from the islands of Crete and Rhodes, where the corresponding energy productions are 2500000MWh and 600000MWh respectively.

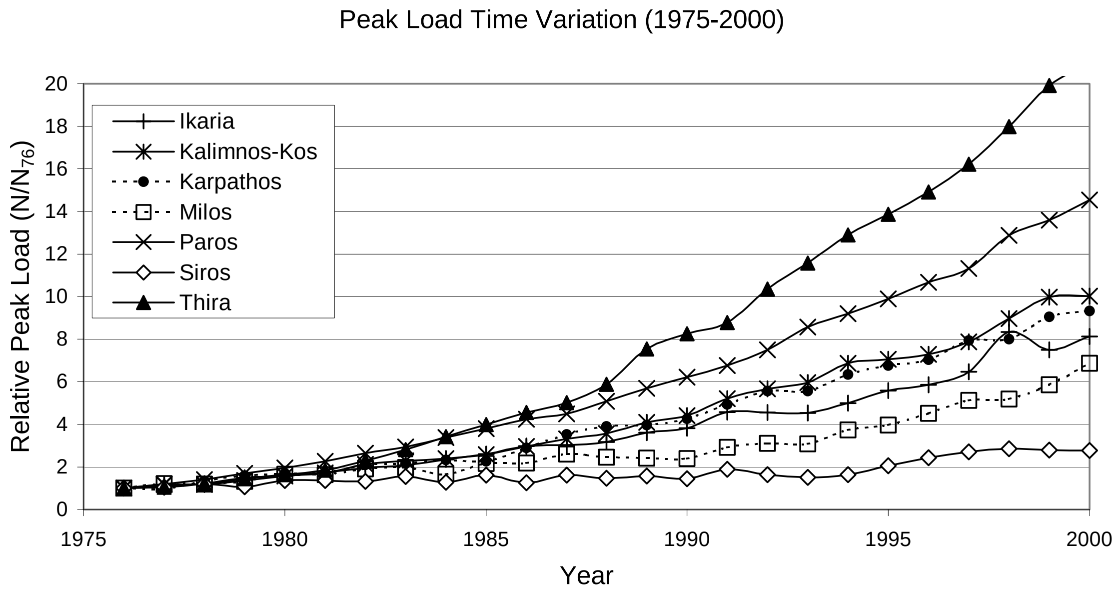

Figure 2: Peak Load Evolution in Medium Sized Greek Islands

According to the data analyzed the peak load of all these autonomous electrical grids presents an overlinear increasing rate, figure (1) and (2). More precisely, during the last twenty-years, the peak load has increased by a factor of 3 to 4.5 for large islands, growing to be approximately 10 for medium-sized cases[6].

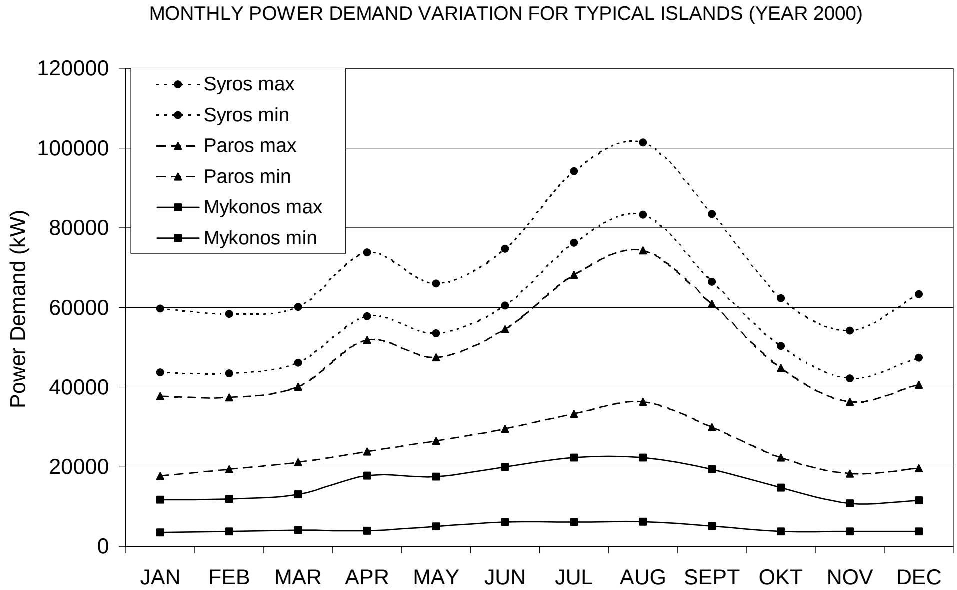

Figure 3: Seasonal Minimum and Maximum Electrical Load Demand

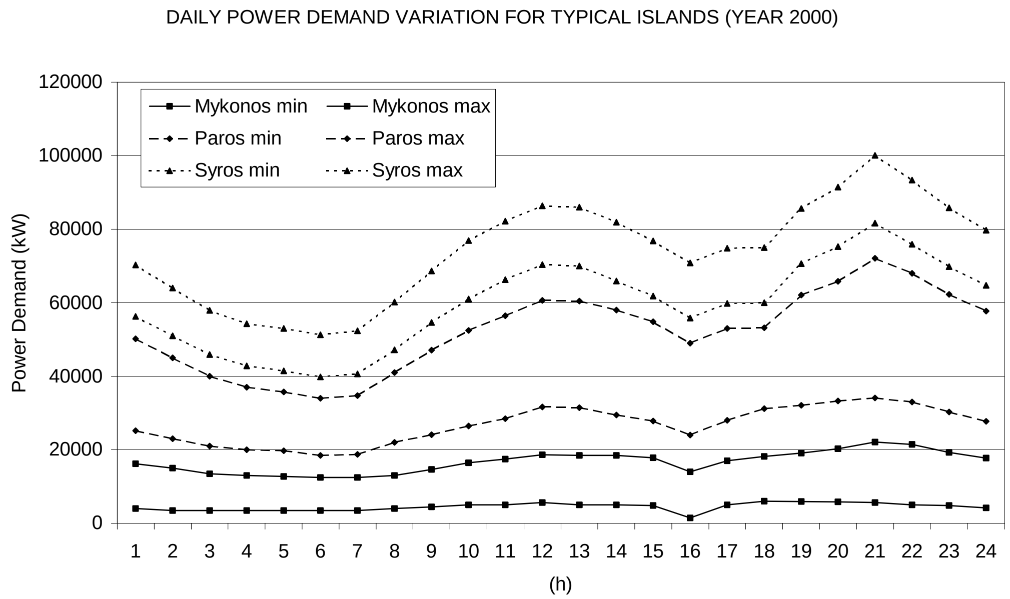

Figure 4: Daily Minimum and Maximum Electrical Load Demand

To face this remarkable power demand, new wind diesel generators are purchased, being however used only during the summer season. In fact, a considerable seasonal (e.g. figure (3)) and daily fluctuation (e.g. figure (4)) is common in all these islands. More specifically, in several cases the monthly maximum to minimum load demand ratio exceeds the 4:1, while the ratio is even higher on a daily base. Bear in mind, that this irrational usage of the invested capitals leads to low capacity factor of the thermal stations, figure (5) and finally to extremely high operational cost for the vast majority of the existing autonomous power stations[7].

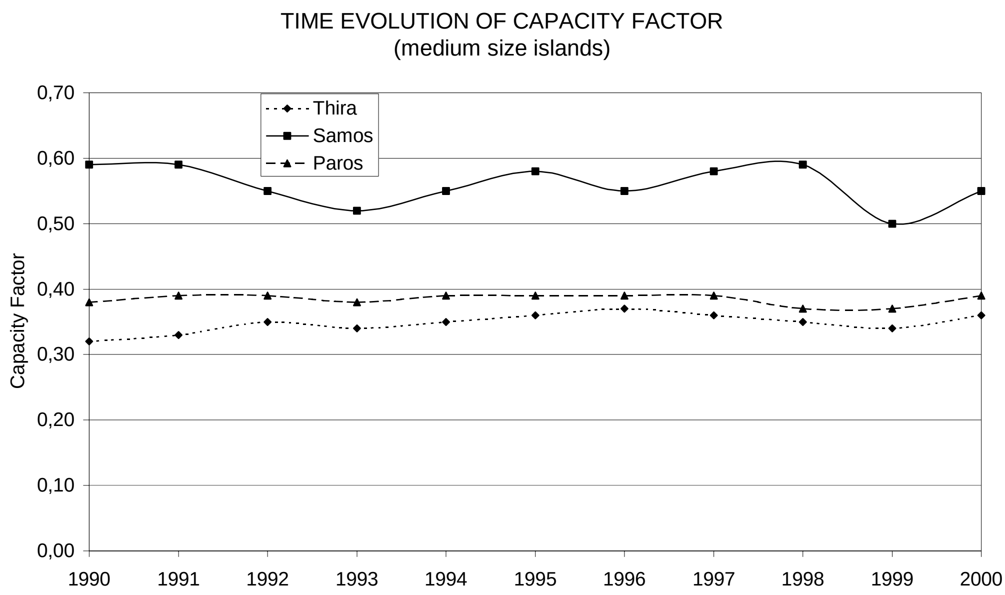

Figure 5: Time-Evolution of Local APS Capacity Factor

Using, the results of a recent analysis by the authors[8], one may clearly state that during the last twenty years the marginal production cost of the APS entirety has increased (using historical data) by a factor of 10 to 50, see also figure (6), hence the marginal cost of the of Greek APS totality is more than double the corresponding production cost of Greek PPC; figure (7). Finally, one should also consider that the imported fuel cost constitutes the 40% to 50% of the above mentioned electricity production cost; figure (8).

In view of this situation and due to the attempted electrical market liberalization, this excess of electricity production cost should no further get covered by PPC, surcharging thus directly the Greek society[9]. On the other hand, it is well established that Aegean Archipelago possesses an excellent wind potential, as in several areas the annual mean wind speed approaches the 10m/s at hub height[3].

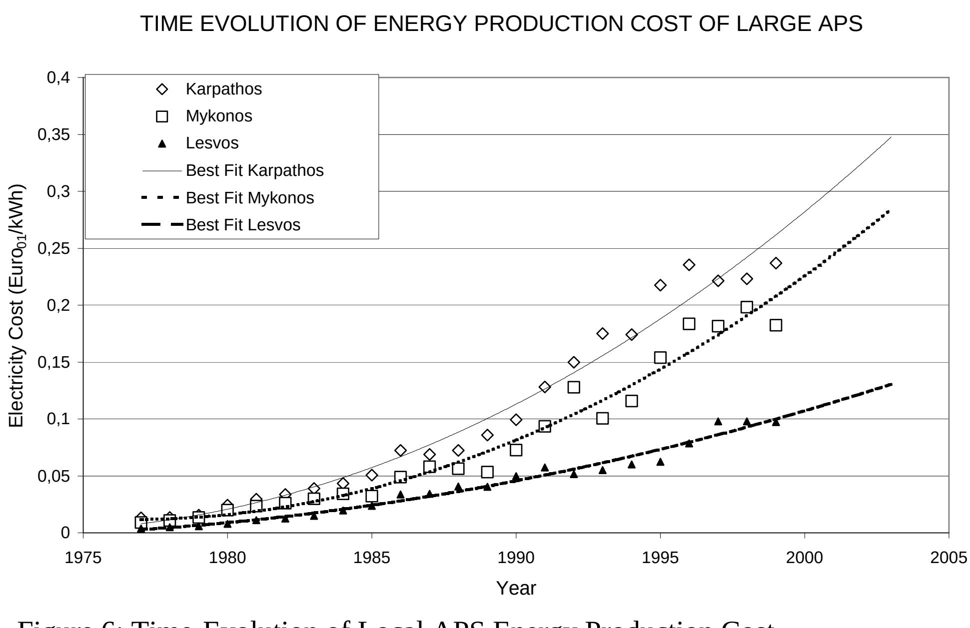

Figure 6: Time-Evolution of Local APS Energy Production Cost

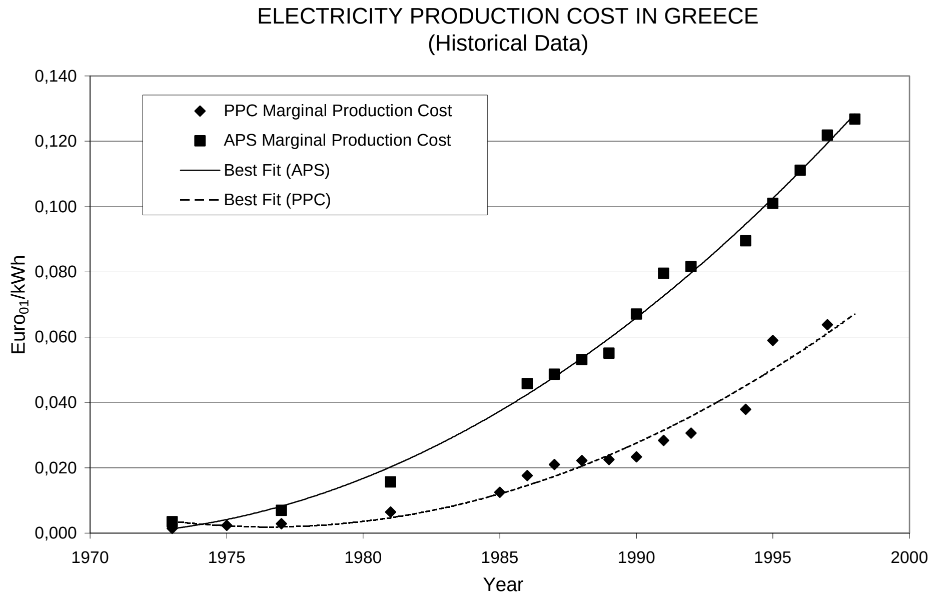

Figure 7: Time-Evolution of Electricity Production Cost in Greece

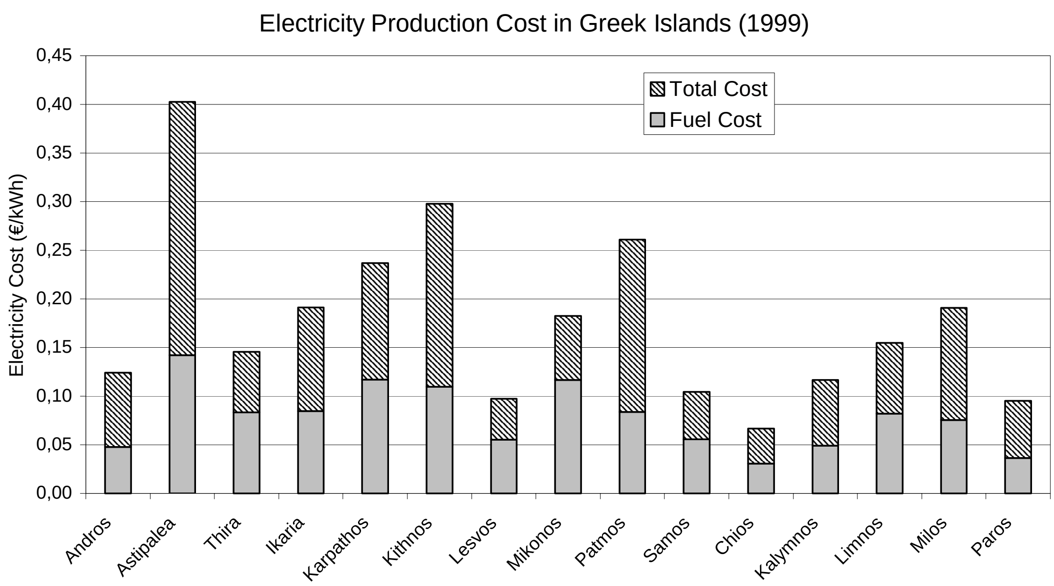

Figure 8: Imported Oil Contribution in the Total Production Cost

Unfortunately, in all these island grids the maximum wind power capacity is restricted by a variety of technical parameters, established to protect the local system from undesirable operational situations. For this purpose, there is a remarkable wind energy production absorption decrease as the wind power penetration increases, figure (9). This decreasing wind energy absorption by the local grid is one of the most serious constrains reducing the economic attractiveness of a wind power investment[10], as additional wind turbines are installed in an autonomous electrical system, figure (10). Besides, by creating new wind parks, one may expect not only lower economic efficiency of invested capital, but also financial deterioration of all the already operating installations[4], due to the grid absorption percentage reduction, figure (9).

3. Proposed Solution

In an attempt to handle this serious economic obstacle, limiting the wind energy penetration, the idea of storing the wind energy surplus is investigated in parallel studies[11][12]. Besides, it is possible to dispose this energy amount in peak demand periods, under prearranged framework. Up to now, during these high electricity consumption periods the load demand is covered by either low efficiency outmoded diesel engines or high operational cost gas turbines. For example, the energy production cost of gas turbines in Crete and Rhodes approaches the 0.3€/kWh in comparison with the

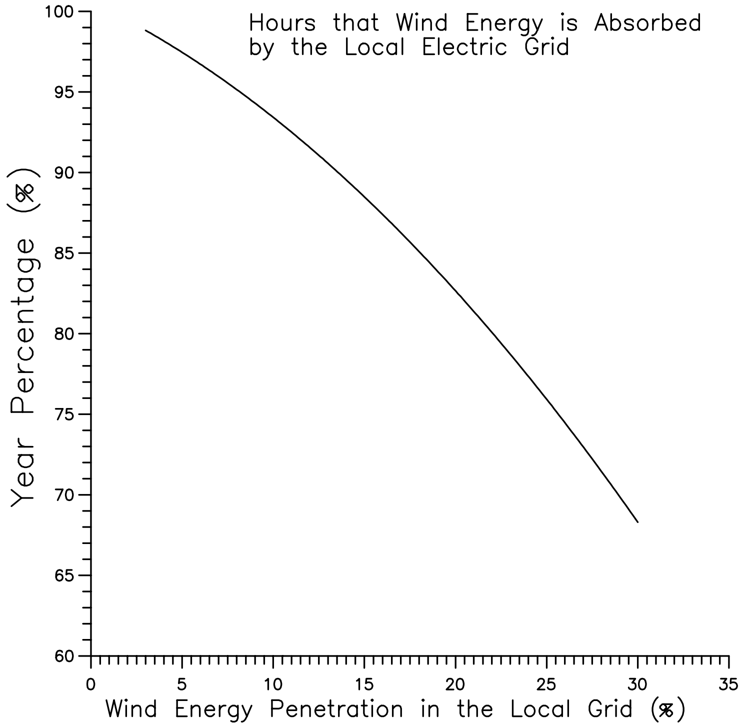

Figure 9: Min Annual Wind Energy Absorption by Autonomous Electrical Grids

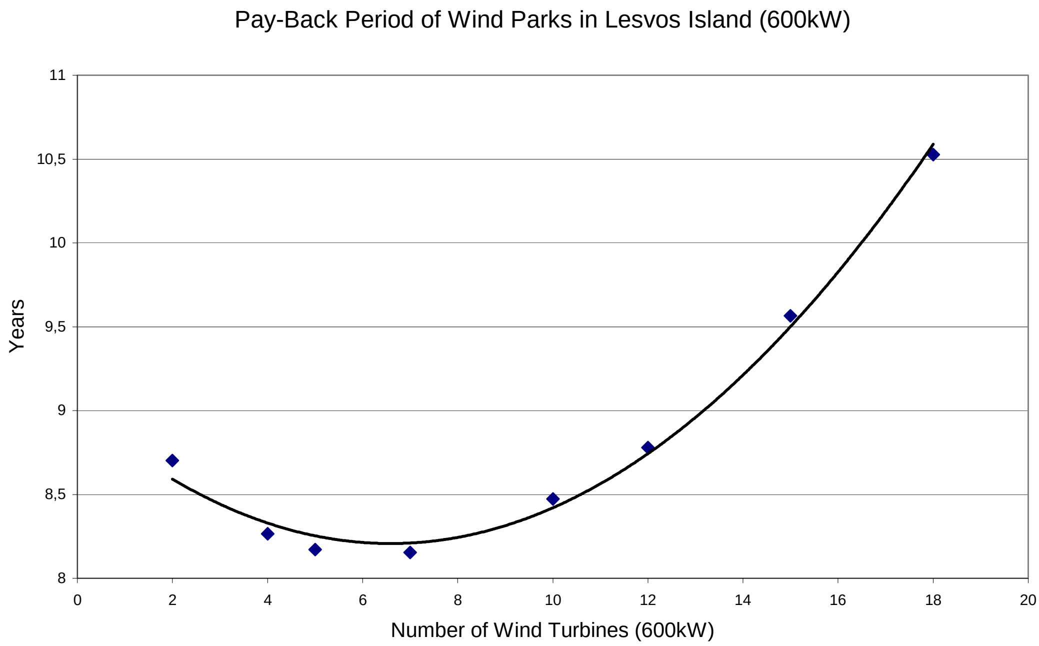

Figure 10: Pay-back Period of Wind Parks in Lesvos

corresponding electricity market price of 0.075€/kWh.

Using the results of previous work[13], the most efficiency way of energy storage for medium sized islands is the utilization of the wind-hydro solution elaborated by the authors since 1995, see also figure (11), under different operational conditions and restrictions[14]. More precisely, the proposed solution is based on:

i. a wind park (WP) of "z" wind turbines and rated power "N_{wp}",
ii. a micro hydroelectric power plant (HPP) of two (or more) small hydraulic machines,
iii. a water pump station (WPS) of "k" water pumps,
iv. two water reservoirs at elevations "h_1" and "h_2" ($h_1>h_2$) working in closed circuit and the corresponding pipelines,
v. an autonomous power station (APS) based on several existing internal combustion engines,
vi. a small desalination plant, utilizing the energy surplus of the local system (optional).

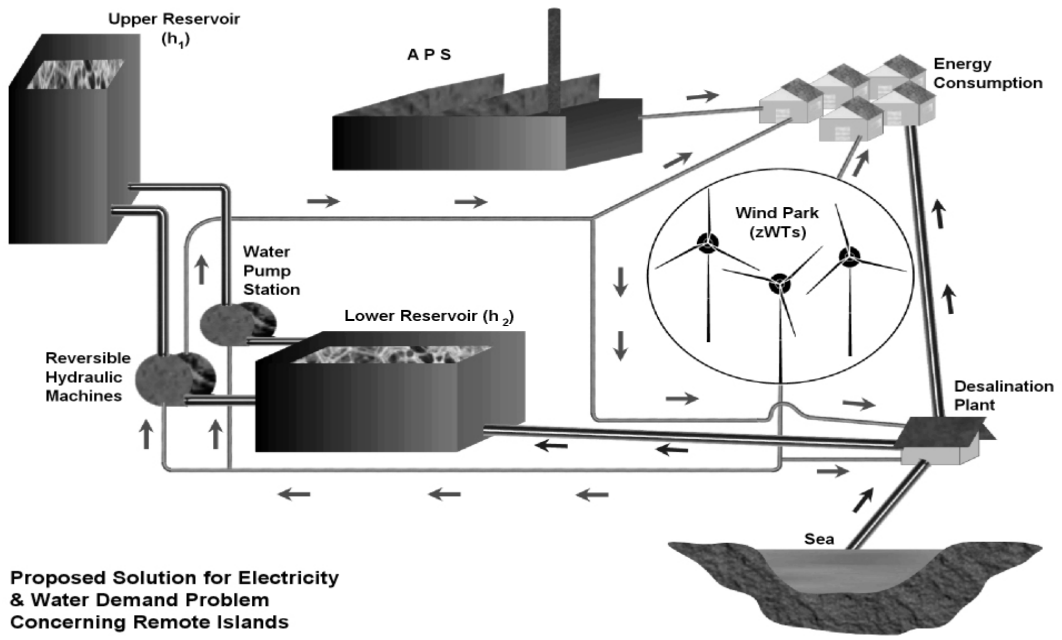

Figure 11: Schematic Presentation of the Proposed Wind-Hydro Solution

In this specific situation, the main purpose of the proposed solution is to store the -not absorbed by the local grid- energy surplus at a high elevation water reservoir by using the water pumps -with minimum transportation loss- and to give it back during the peak load demand by using the hydro-turbines.

In the above-described configuration the following parameters determine the economic viability and attractiveness of the entire project, i.e.:

A. The energy transformation efficiency "η^*" of the complete water cycle or equivalently the wind energy surplus, which is finally forwarded to the consumption via the storage system. The energy transformation coefficient depends on several parameters, while its numerical value varies between 0.7 for large systems to 0.5 for small installations[5][14].
B. The wind-hydro station first installation cost. In the present case the wind parks already exist, therefore the additional cost includes basically the hydro turbines purchase and installation cost, the water reservoir construction cost and secondarily the water pump station and water pipes network cost along with the necessary electronic equipment needed to ensure the unimpeded co-operation with the local electrical network.
C. The wind-hydro energy market price, which is provided on a scheduled base (guaranteed power) during specific time period of a day. The price offered by the local network manager should

represent the corresponding marginal cost of using expensively operating and low efficiency thermal power stations, under the precondition that the wind park owner is responsible to cover -in any case- this energy amount for the time period agreed.

In this context, the annual energy amount provided to the local grid by the proposed wind-hydro station "ΔE" can be expressed as:

$$\Delta E = \left[(1 - \Delta_G) \cdot \omega \cdot \frac{\Delta}{\Delta_G} \cdot N_t \cdot 8760 \right] \cdot \eta^* \tag{1}$$

where:
N_t is the total power of the wind park
Δ is the technical availability of the installation
Δ_G is the grid absorption coefficient, figure (9)
ω is the mean power coefficient of the installation, being function of the available wind potential and the power curve of the wind turbine used[15].

Recapitulating, during the long-term operation of he proposed installation the following situations are possible:

a. The wind power production is lower than the upper penetration limit; hence the grid absorbs all the wind power.
b. There is significant wind power excess that cannot be forwarded directly to the consumption. In this case the energy surplus is stored via the wind pumps to the upper reservoir. If the upper reservoir is full, then either the energy is used in low priority loads or some wind turbines may shut down.
c. During the scheduled time-period, there is a remarkable grid energy deficit. The water turbines cover the arranged power, using the water supply of the wind-hydro station.
d. In case the upper reservoir is empty or a technical problem appears in the hydro power station, the energy deficit is covered by the back up thermal power stations in expense of the wind-hydro station owner (guaranteed power).

4. Application Results

In order to investigate the economic viability of such an investment, one may use the cost-benefit analysis by the authors[10][14][15]. Thus the present value "c_o" of the energy provided by the wind-hydro station to the grid during the high consumption period for a n-year operation period is given as a function of the pump-hydro station first installation cost "IC_o" as:

$$\frac{c_o^{(n)}}{IC_o} = \frac{(1-\gamma) \cdot g_1 + m \cdot g_2}{\Delta E} \tag{2}$$

where:
γ is any State subsidization percentage, e.g. γ=40%
m is the fixed maintenance and operation cost coefficient, expressing the annual fixed M&O cost as a portion of initial capital invested, and:

$$g_1 = \frac{1}{\frac{1+e}{e-i} \cdot \left[\left(\frac{1+e}{1+i} \right)^n - 1 \right]} \tag{3}$$

$$g_2 = \frac{\frac{1+g^m}{g^m - i} \cdot \left[\left(\frac{1+g^m}{1+i} \right)^n - 1 \right]}{\frac{1+e}{e-i} \cdot \left[\left(\frac{1+e}{1+i} \right)^n - 1 \right]} \tag{4}$$

with:
i the local market capital cost
e the energy provided by the wind-hydro station annual escalation rare, and
g^m the M&O cost annual inflation rate

Keep in mind that according to previous analysis the pump-hydro station first installation cost consists of the hydro-power station turnkey cost "$Pr_1 x N_{WH}$", the two reservoirs creation cost "$Pr_2 x V_{st}$", plus the additional cost of the installation, including the water pumps cost, the water piping cost etc. This last term is usually expressed as a fraction "f" of the main station components cost, thus:

$$IC_o = (\mathbf{Pr}_1 \cdot N_{WH} + 2\,\mathbf{Pr}_2 \cdot V_{st}) \cdot (1+f) \tag{5}$$

Taking into account that each water reservoir total storage capacity should fulfill the following equation:

$$V_{st} \geq \frac{N_{WH} \cdot h_g}{\eta \cdot \rho \cdot \overline{H}} \tag{6}$$

where:
h_g is the number of hours per day that the hydro station provides specific power N_{WH} to the consumption
$\overline{H}$ is the average water turbines head
η is the corresponding water turbines efficiency
ρ is the water density

equation (5) reads:

$$IC_o = \xi \cdot N_{WH} \tag{7}$$

where:

$$\xi = \left(\mathbf{Pr}_1 + 2\,\mathbf{Pr}_2 \cdot \frac{h_g}{\eta \cdot \rho \cdot \overline{H}} \cdot \lambda \right) \cdot (1+f) \tag{8}$$

while "λ" is an empirical safety coefficient ($\lambda \geq 1$). Substituting equation (7) in equation (2), in view of equation (1), one finally gets:

$$\frac{c_o^{(n)}}{\xi} = \frac{(1-\gamma) \cdot g_1 + m \cdot g_2}{8760 \cdot \eta^* \cdot \frac{\omega \cdot \Delta}{\Delta_G} \cdot (1-\Delta_G)} \cdot \frac{N_{WH}}{N_t} \tag{9}$$

According to equation (9) "$c_o^{(n)}$" depends on several parameters like the specific cost of the entire pump-hydro station "ξ", the wind park -grid absorption free- capacity factor ($CF=\Delta.\omega$), the energy transformation coefficient "η^*", the wind power penetration in the local electrical grid "Δ_G", the local market economic parameters (i,e,g^m), the State subsidization percentage "γ", the M&O cost coefficient "m" and the ratio of the hydro station rated power to the corresponding wind park nominal power "N_{WH}/N_t".

In the following, the energy production cost present value is predicted for three representative wind power penetration scenarios and for a ten-years time horizon of the investment. For the present analysis a set of realistic numerical values is selected, representing the local economy situation, thus i=8%, g^m=3% and e=0%-6%. Besides, m is taken equal to 0.02, while the grid-free wind park capacity factor is assumed equal to 30%. Finally, the "ξ" value is taken equal to 3000€/kW, which is the upper limit of a similar pump-hydro station.

According to the calculation results, figure (12), the maximum wind-hydro production cost increases with the hydro power station size, under given wind park rated power. On top of that "c_o" is decreasing as the wind power penetration is amplified, underlining the necessity of creating such an energy storage system, if high wind penetration values are to be expected. At this point it is important to mention that the relative to wind park rated power size of the hydropower station is not arbitrarily selected, but it is the result of a parallel study not presented here due to lack of space.

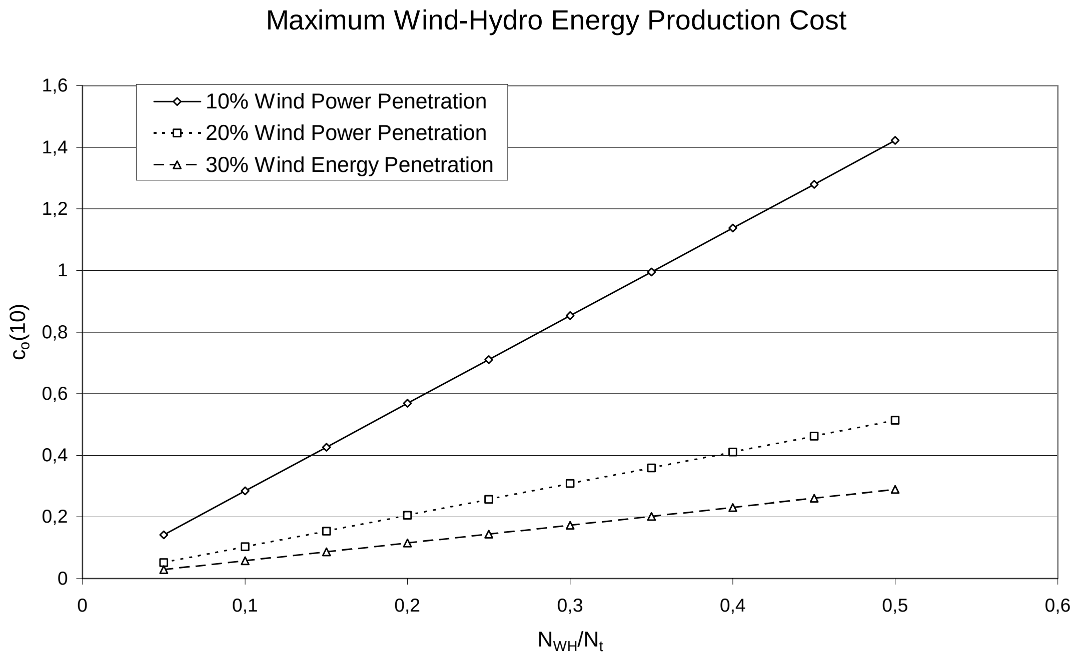

Figure 12: Wind Power Penetration Impact on Energy Production Cost

Accordingly, the wind-hydro energy production cost is also affected by the energy transformation coefficient "η^*", hence higher "c_o" values are realized as "η^*" decreases, figure (13). Additionally, the "c_o" decrease is more intense when "η^*" increases from 50% to 60% than when "η^*" increases from 60% to 70%.

Lastly, the impact of energy annual escalation rate on the energy production cost is predicted, figure (14), for "e" values varying between 0% and 6%. Thus, for a hydro power station being almost 20% of the corresponding wind park size, the present energy value decreases from 0.24€/kWh to 0.17€/kWh as "e" increases from 0% to 6%.

Summarizing, according to the preliminary results obtained, the maximum wind-hydro energy production cost is in the order of 0.1€/kWh to 0.3€/kWh, for a ten-years service period of the station only. Even this quite pessimistic value presents a competitive advantage versus the local APS annual mean marginal production cost. Of course it is evident that this numerical values can certainly be diminished -by 30% at least- via an optimization study. However, in any case, the proposed solution is an economically attractive opportunity in order to face the strongly varying electrical loads of Aegean Sea islands using primarily renewable energy sources.

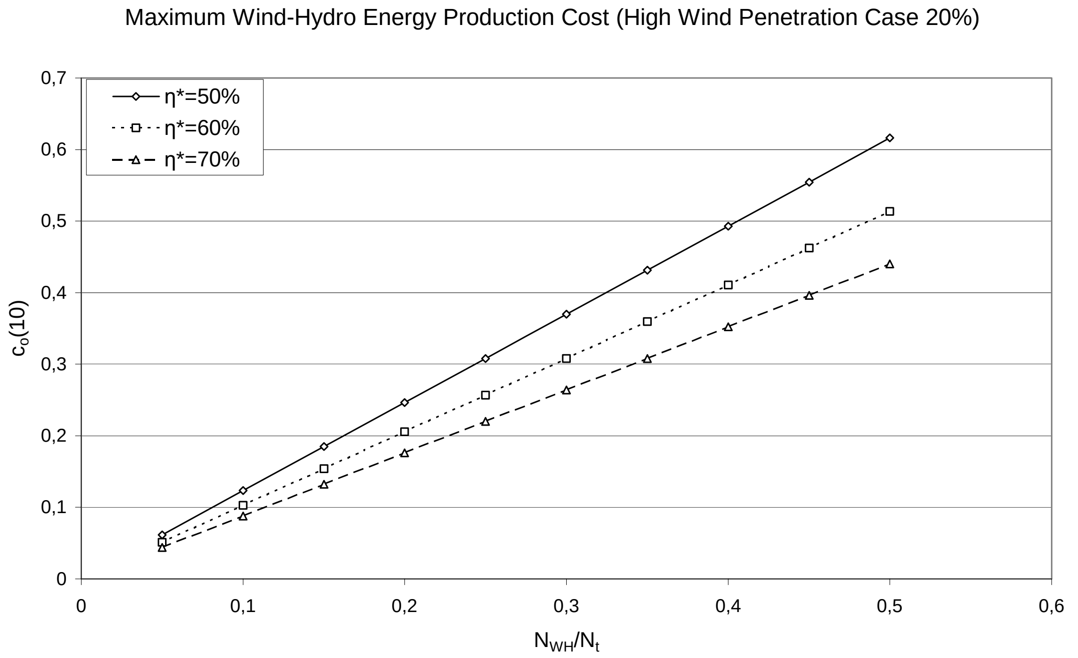

Figure 13: Energy Transformation Coefficient Impact on Production Cost

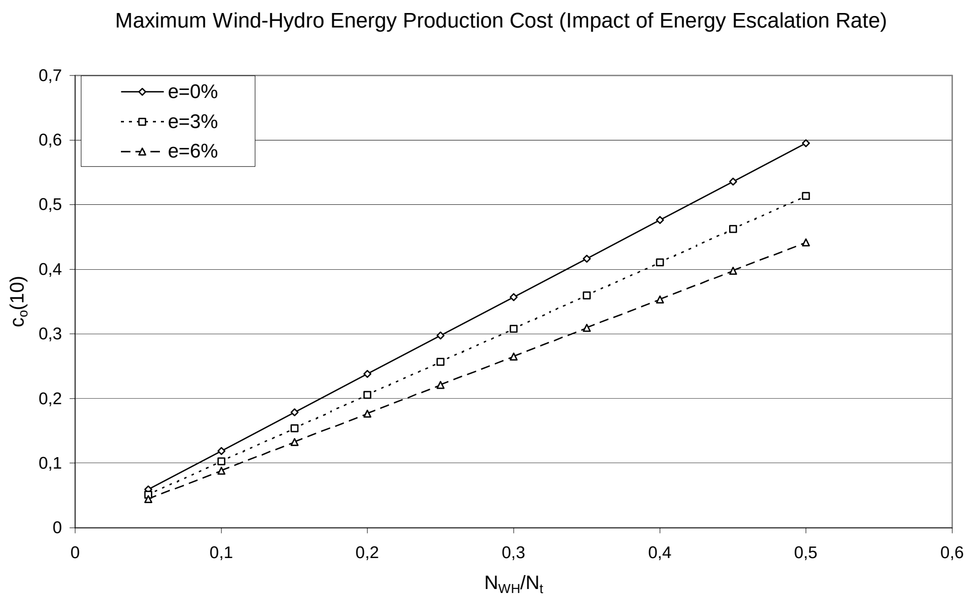

Figure 14: Energy Escalation Rate Impact on Energy Production Cost

5. Conclusions

The possibility to limit the excessive additional power of new scheduled thermal power plants, taking advantage of the excellent wind potential and the various lake-tanks found in most Aegean Sea islands is investigated, by proposing the creation and operation of a properly sized wind-hydro power station.

According to the elaborated solution there is a strong opportunity to manage the short and medium term load variations of almost the entirety of Greek islands, without excessive cost. On top of that, such an investment is almost mandatory for the wind parks owners, as the wind power penetration in the local grid is increasing and, consequently, there appears a remarkable energy percentage not absorbed by the grid manager during low consumption periods.

Summarizing, during the preceding analysis, emphasis is laid on predicting the optimum size of similar installations, considering a large variety of techno-economic parameters. The developed methodology is also applied to selected island cases with motivating results. Thus, according to the results obtained, it is almost certain that similar solutions present financial interest being fully competitive to the operational cost of existing APS. Additional work is needed first to define -in details- the appropriate size of all the components of the system and secondly to check the efficiency operation of the installation using analytical real time data.

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AN INTEGRATED FEASIBILITY ANALYSIS OF A STAND-ALONE WIND POWER SYSTEM, INCLUDING NO-ENERGY FULFILLMENT COST

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Abstract

Autonomous wind power systems are among the most interesting and environmental friendly technological solutions for the electrification of remote consumers. However, the expected system operational cost is quite high, especially if the no-load rejection restriction is applied. The proposed work describes an integrated feasibility analysis of a stand-alone wind power system, considering, beyond the total long-term operational cost of the system, the no-energy fulfillment or the alternative energy coverage cost of the installation. Therefore, the impact of desired system reliability on the stand-alone system configuration is included. Accordingly, a detailed parametrical investigation is carried out concerning the influence of the hourly no-energy fulfillment cost on the system dimensions and operational cost. Thus, by using the proposed method, one has the capability -in all practical cases- to determine the optimum wind-power system configuration that minimizes the long-term total cost of the installation, considering also the influence of the local economy basic parameters.

Keywords: Wind Power; Stand-Alone System; Reliability; Cost-Benefit Analysis

1. Introduction

An autonomous wind power system is one of the most interesting and environmental friendly technological solutions for the electrification of remote consumers[1][2] or entire rural areas[3]. For this purpose, a properly sized small wind turbine is necessary to exploit the available medium-high wind potential producing useful electrical energy.

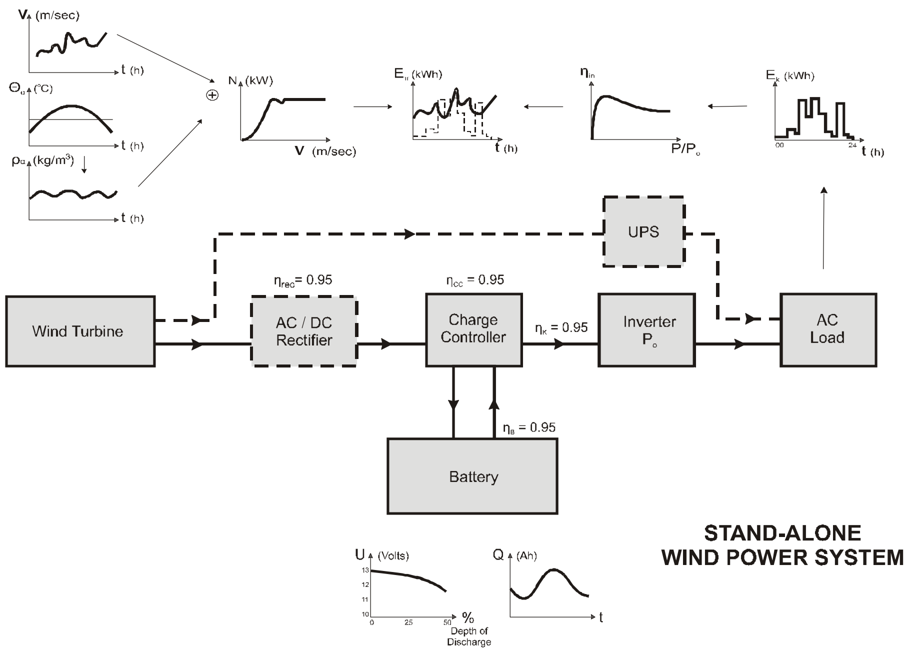

Figure 1: Proposed Stand-Alone Wind Power System

***Kaldellis J.K., 2003**, "An Integrated Feasibility Analysis of a Stand-Alone Wind Power System, Including No-Energy Fulfillment Cost", Wind Energy Jr, Vol. 6/4, pp. 355–364.*

Due to the stochastic behaviour of the wind, the existence of an energy storage system-usually a lead-acid battery bank, able to match the electricity demand of the consumer and the energy output of the wind turbine- is absolutely necessary. The complete system also includes (see figure (1)) several electronic devices[1][4], used either to control the battery operation (AC/DC rectifier, battery charge controller) or to guarantee high quality electricity for the consumers. Besides, a UPS (Uninterruptible Power Supply) and a DC/AC inverter should be used at the outlet of the system, in case that alternative current (AC) of 50/60Hz and 220/110Volt is required.

One of the most expensive components of such a stand-alone system is the battery bank necessary to guarantee the desired system reliability *at any cost*. Thus, in cases of increased system autonomy, the battery contribution to the initial or the total operational cost is found to be dominant[5] (up to 85%), determining the complete system economical viability. In addition the system batteries should be replaced every 6 to 8 years[6], increasing thus the system operational cost. The battery dimensions may be remarkably reduced if the no-load rejection criterion (theoretical reliability 100%) is substituted by a more realistic[7][8] number of load rejections or a moderated reliability coefficient.

In the present analysis, the annual number of load rejections is used to define the reliability parameter, being also equal to the total hours that the system cannot annually fulfill the energy demand of the consumption. The desired system reliability is directly depended on the type of applications supported by the stand-alone wind power system. More specifically, 99% (or even less) reliability is assumed acceptable for house applications, like lighting, clothes washing, cooking etc. On the other hand, for high reliability applications, such as telecommunication systems, the minimum reliability is set equal to 99.9%, being equivalent to less than ten load rejections yearly or 8.76 hours lacking electricity per annum.

In an attempt to include the required system reliability in the proposed analysis, the no-energy (electricity) fulfillment cost "A" parameter should be introduced on the generalized total operational cost function of the system. More precisely, the parameter "A" describes (in Euro/h) the cost of not covering the electricity demand of the system per hour. In order to obtain the no-load rejection case, one simply assign to "A" an arbitrary high value (i.e. $A\rightarrow\infty$). Of course, since the value of "A" is not easily defined, a parametrical analysis should be carried out embracing several numerical values of "A".

2. Cost-Benefit Analysis of the Proposed Configuration

The initial cost of a stand-alone wind power system "IC_o" includes the ex-works price of the wind turbine "IC_{WT}", the battery system purchase cost "IC_{bat}", the electronic equipment cost "IC_{elec}" and the corresponding balance of the plant cost, expressed as a percentage "f" of the wind turbine price. Thus, one may write:

$$IC_o = IC_{WT} + IC_{bat} + IC_{elec} + f \cdot IC_{WT} \quad (1)$$

Using the analysis of previous works[5][7] the following expression is assumed valid:

$$IC_o = \left(\frac{a}{b + N_o^x} + c \right) \cdot N_o \cdot (1 + f) + \xi \cdot Q_{max}^{1-\omega} + \lambda \cdot N_p^{1-\tau} + B \cdot N_o \quad (2)$$

where "N_o" is the wind turbine rated power, "N_p" is the consumption peak load demand (including an appropriate safety factor, e.g. 1.3) and "Q_{max}" is the battery capacity. Besides "a, b, x and c" are numerical constants used to simulate[4] the ex-works price of small wind converters (up to 100kW) in the local market. Their numerical values are equal to $8.7\text{x}10^5$Euro/kW, 621, 2.05 and 700Euro/kW respectively. Similarly, parameters "ξ and ω" are selected[7] to describe the battery bank initial cost, thus ξ=5.04Euro/Ah and ω=0.078. Finally, parameters "λ, τ and B" are respectively equal to 483Euro/kW, 0.083 and 380Euro/kW, used also to estimate[7] the electronic devices initial cost.

Accordingly, the future value of the total investment cost over a -n year period "C_n" of the stand-alone system under investigation, including the corresponding fixed (expressed as a fraction "m" of the initial capital "IC_o" invested) and variable maintenance and operation cost[5][9], is given as:

$$C_n = IC_o \cdot (1+i)^n \cdot \{(1-\gamma) + m \cdot \frac{1+g}{g-i} \cdot \left[\left(\frac{1+g}{1+i}\right)^n - 1\right] + \Psi\} \quad (3)$$

where "Ψ" takes into consideration the battery replacement cost "$r_b.IC_o$" every "n_b" years (n_b=6-8 years) and is expressed as:

$$\begin{aligned} &\Psi = 0 \quad \text{for } n \le n_b = 7 \\ &\Psi = r_{bat} \cdot \left[\frac{1+g_b}{1+i}\right]^{n_b} \quad \text{for } n_b + 1 \le n \le 2n_b \\ &\Psi = r_{bat} \cdot \left[\frac{1+g_b}{1+i}\right]^{n_b} + r_{bat} \cdot \left[\frac{1+g_b}{1+i}\right]^{2n_b} \quad \text{for } 2n_b + 1 \le n \end{aligned} \quad (4)$$

with

$$r_{bat} = \frac{\xi \cdot Q_{max}^{1-\omega}}{IC_o} \quad (5)$$

Keep in mind that "i" describes the time-mean capital cost index, while "g" is the corresponding local market inflation rate, see also[10]. The above analysis implicitly assumes that both M&O and battery replacement cost increase every year according to the local market inflation "g". Finally, "γ" is the subsidy percentage (e.g. 30%-40%) by the Greek State, according to the current development law (e.g. 2601/98) or the corresponding National Operational Competitiveness Program.

3. Cost Reduction by Accepting a Specific Number of Load Rejections

In the following, the above-described total cost analysis (equation (3)) applies to two separate cases, for which detailed wind potential data are given. More precisely, the first case concerns an island of excellent wind potential (mean annual wind speed between 9m/s and 9.8m/s), i.e. the Andros Island. The second case examined corresponds to a stand-alone system created in the island of Kithnos. The island possesses a medium-high quality wind potential, since the annual mean wind speed varies between 6.3m.s and 7.1m/s. Several medium-sized wind turbines[11] already exist in both islands, mainly belonging to Greek PPC (Public Power Corporation). In both cases the analysis is carried out by using a year's wind speed measurements, see References [1] and [12].

Thus, in figure (2), six distinct numerical curves are drawn representing the zero load rejection solution (R=100%, h=0) and the R=99.9%, 99.5%, 99%, 98%, 95% cases for Andros Island. More specifically, each point belonging to these curves represents a stand-alone wind power system minimum configuration (i.e. minimum wind turbine rated power and minimum battery capacity) that guarantees a given reliability value for Andros island and for a year-long period. In the same figure the corresponding 10-years total cost constant-value curves are also drawn, in order to estimate the minimum total cost solution for every reliability level. All the minimum cost points are represented by the "best points" curve given also in the figure.

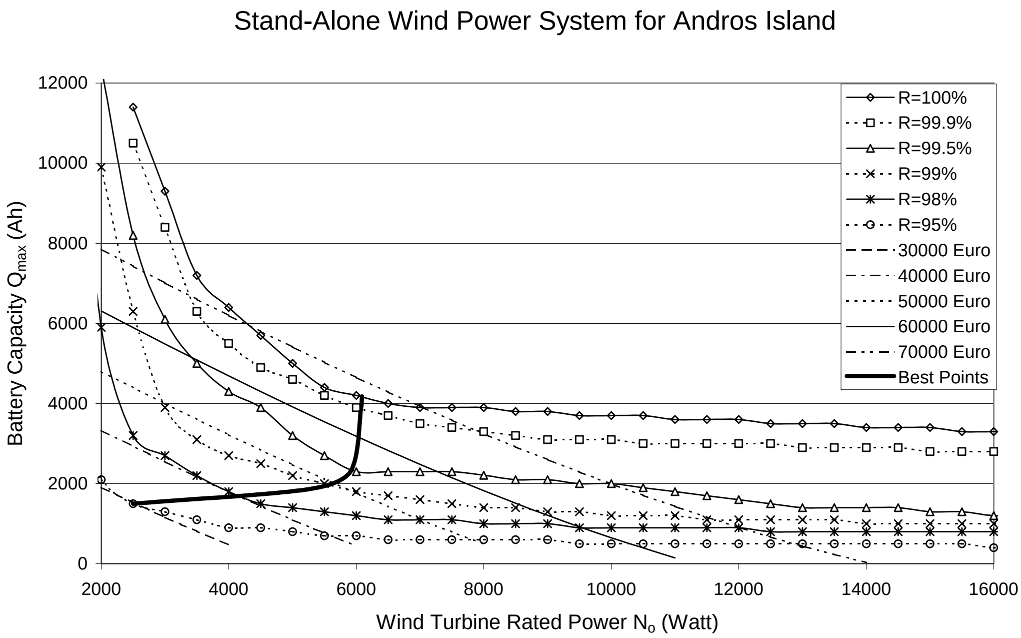

Figure 2: The Relation between the Configuration of a Stand-Alone Wind Power System and the 10-Years Total Cost, for variable Reliability Values; Andros Island

In fact, there is a remarkable total cost diminution as the required theoretical reliability is decreased from 100% to 95%. This 10-years total cost reduction may be in the order of 55% as the desired system reliability drops from the theoretical value of 100% to 95%. Even for high reliability values (e.g. 99%) the 10-years total cost diminution is significant (almost 20000€), while the corresponding lacking-electricity hours are less than 100 per year. It is, however, worth mentioning that for moderated reliability -between 100% and 99%- there appears a considerable battery capacity diminution (approximately 50%), while the corresponding wind turbine size remains unaffected. For lower reliability values, though, the battery capacity remains almost constant as the wind turbine rated power decreases from 6kW to 2.5kW.

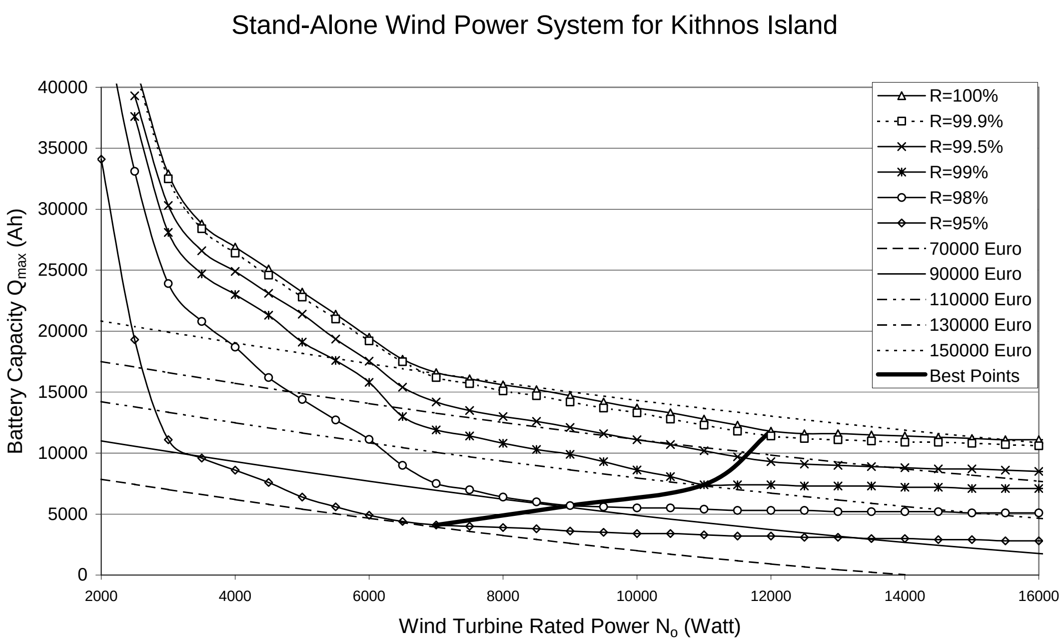

Figure 3: The Relation between the Configuration of a Stand-Alone Wind Power System and the 10-Years Total Cost, for variable Reliability Values; Kithnos Island

Similar conclusions apply to the Kithnos Island case, figure (3), as well. According to the calculation results obtained, there is a considerable system optimum size change as the desired reliability varies between 95% and 100%. More specifically, the optimum battery capacity declines from 11900Ah (R=100%) to only 4300Ah (R=95%), while at the same time the wind turbine rated power required is also decreased from 12kW to 7kW. Finally, the corresponding initial cost reduction is more than 50%. As in the Andros case, the reliability decrease -between 100% and 99%- is mainly realized by reducing the optimum battery capacity (from 11900Ah to 7500Ah), while the corresponding wind turbine nominal power decreases by less than 1kW. For inferior reliability, on the other hand, the battery capacity is fairly decreased, while the wind turbine rated power detracts from 11kW to 7kW.

Summarizing, one may clearly state that the dimensions and the initial investment cost of a stand alone wind power system is substantially limited as the required system reliability by the consumer decreases from the theoretical value of 100% to a fair value, like 99% or in less crucial applications to 95%. To be more precise, the parameter that usually determines the reliability lower boundary of a stand-alone system is the no-energy fulfillment cost per hour (or the alternative energy coverage cost) of the remote installation.

4. Optimum System Configuration by Incorporating the No-Energy Fulfillment Cost

As already mentioned in the introduction and proved in the previous section of this study, a remarkable total cost decrease is encountered by reducing the system reliability, while -on the other hand- isolated consumers may face various problems in no energy fulfillment cases. In order to take this incident into consideration, a more generalized approach is adopted, including the no-energy (electricity) fulfillment cost variable "A". For this purpose, the new function "F" to be minimized is defined as:

$$\tilde{F}_n = \tilde{C}_n + \tilde{N}_n \tag{6}$$

where "$\tilde{C}_n$" represents the total cost of the system in constant (e.g. 2002) values, see equation (3), and "$\tilde{N}_n$" describes the corresponding no-energy fulfillment (or alternative energy coverage) cost function for a n-year time period, also in constant values. Keep in mind that the symbol "$\tilde{x}$" of a quantity in constant values can be expressed as:

$$\tilde{x} = \frac{x}{(1+g)^n} \tag{7}$$

which is equal to the current value of "x" divided by the total inflation of the economy during the n-year period.

Similarly, the no-energy fulfillment cost function can be approximated as:

$$N_n = h \cdot A \cdot \left[(1+\alpha)\cdot(1+i)^{n-1} + (1+\alpha)^2 \cdot (1+i)^{n-2} + \ldots + (1+\alpha)^{n-1}\cdot(1+i) + (1+\alpha)^n\right] \tag{8}$$

or equivalently:

$$\tilde{N}_n = h \cdot A \cdot \left(\frac{1+i}{1+g}\right)^n \cdot \frac{1+\alpha}{1+i} \cdot \frac{\left(\frac{1+\alpha}{1+i}\right)^n - 1}{\frac{1+\alpha}{1+i} - 1} \tag{9}$$

where "α" is the time-mean annual change of "A" value[10] and "h" represents the hours per annum that the consumption is not covered by the existing wind power system. More precisely one may write:

$$h = (1 - R) \cdot 8760 \tag{10}$$

At this point it is important to mention that in equation (9) it is indirectly assumed that "A" remains constant and independent of "h" during a year. Substituting equations (3), (9) and (10) into equation (6), taking also into account equation (7) one gets:

$$\tilde{F}_n = IC_o \cdot y^n \cdot \left\{ (1-\gamma) + m \cdot \frac{1+g}{g-i} \cdot \left[\left(\frac{1}{y} \right)^n - 1 \right] + \Psi + 8760 \cdot (1-R) \cdot \frac{A}{IC_o} \cdot \frac{1+\alpha}{\alpha - i} \cdot \left[\left(\frac{1}{z} \right)^n - 1 \right] \right\} \tag{11}$$

with:

$$y = \frac{1+i}{1+g} \tag{12}$$

and

$$z = \frac{1+i}{1+\alpha} \tag{13}$$

Thus, for any reliability level "R" chosen by the consumer, the minimum cost value "C_n" is predicted and, therefore, the minimum total cost can be computed based on the "A" value defined. Recapitulating, for every case analyzed "F_n" is a function of "R", since both "Q_{max}" and "N_o" are in fact functions of "R", hence a minimum "F" value can be estimated according to the desired "R" level and the assumed numerical value of "A".

5. Application Results

In this context, the proposed methodology is applied to an autonomous wind-power system functioning in Kithnos Island. This present analysis considers the no-energy fulfillment cost parameter, while the results obtained are expressed as a function of system reliability. Thus, in figure (4) the ten-years system total cost (see equations (6) and (11)) is given as a function of the desired system reliability, using the hourly no-energy fulfillment cost "A" as the fundamental parameter of the problem.

According to the results of figure (4), for 0<A≤25€/h there is an optimum reliability value that minimizes the 10-years system total cost. For higher "A" values, the analysis "dictates" the maximum technically realized system reliability. On the other hand, for low "A" values (A→0) the system reliability cannot get estimated by a similar model, thus other factors may determine the installation characteristics, e.g. in this approach "R_{min}" is set equal to 95%.

The same configuration may also apply to the Andros Island, figure (5). Due to the superior wind potential of the area, the total cost values turn naturally to be quite lower. Hence, as in Kithnos case, for 0<A≤25€/h there is an optimum reliability value that minimizes the 10-years system cost, no-energy fulfillment cost included. However, for "A" values greater than 25€/h maximum reliability value is required, while for A→0 system dimensions should be defined using additional criteria, like the maximum capital to be invested.

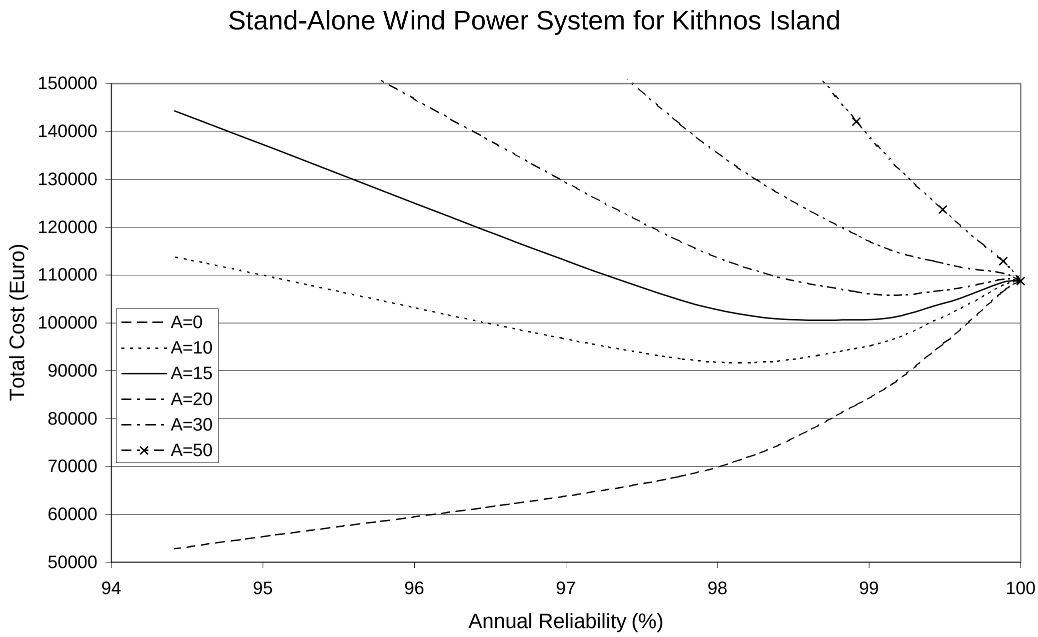

Figure 4: The Impact of System Reliability on a Stand-Alone Wind Power Installation 10-Years Operational Cost for Kithnos Island

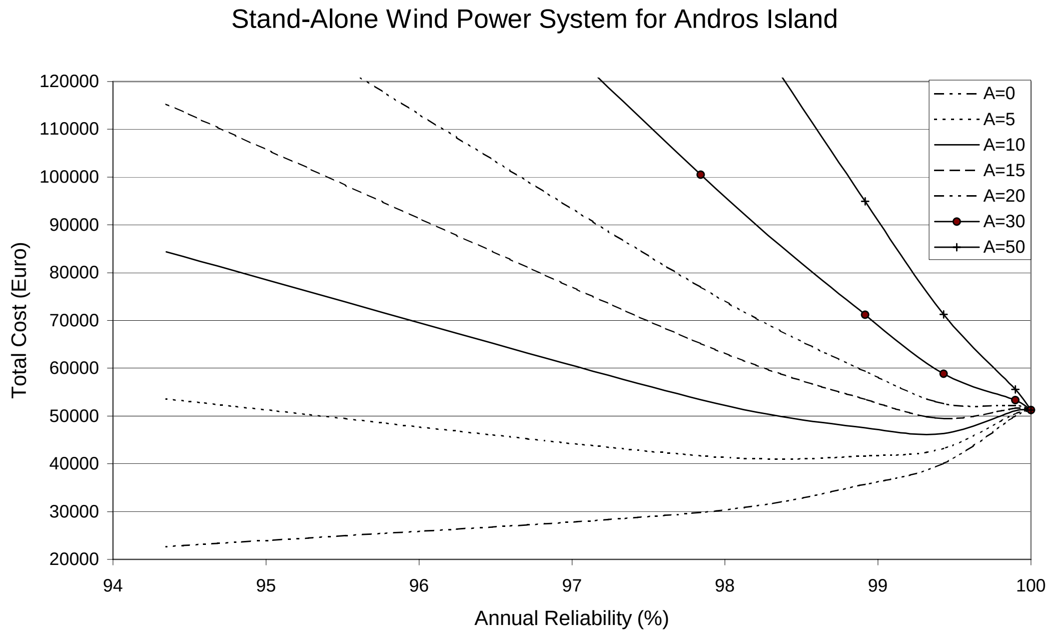

Figure 5: The Impact of System Reliability on a Stand-Alone Wind Power Installation 10-Years Operational Cost for Andros Island

As a general conclusion from the two representative cases analyzed, one may state the following:

i. When the "A" value is approximately identified, there is an optimum system reliability value (R≈98%-99.5%) minimizing the system total cost.

ii. When the desired (or minimum acceptable) reliability limit is defined by the applications supported by the stand-alone installation, system configuration and total cost is a function of the numerical value of parameter "A".

iii. In cases that both "R" and "A" are given, the optimum system size and total operational cost may be computed, depending mainly on the available wind potential of the installation site.

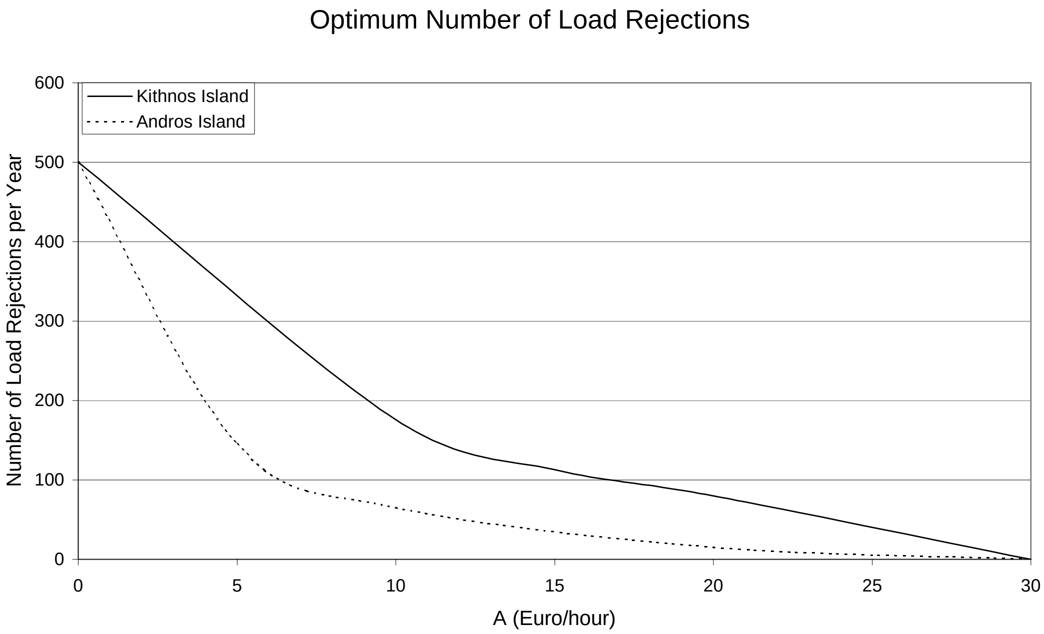

Figure 6: The Impact of No-energy Fulfillment Cost on the Annual Number of Load Rejection for Typical Stand-Alone Wind Power Systems

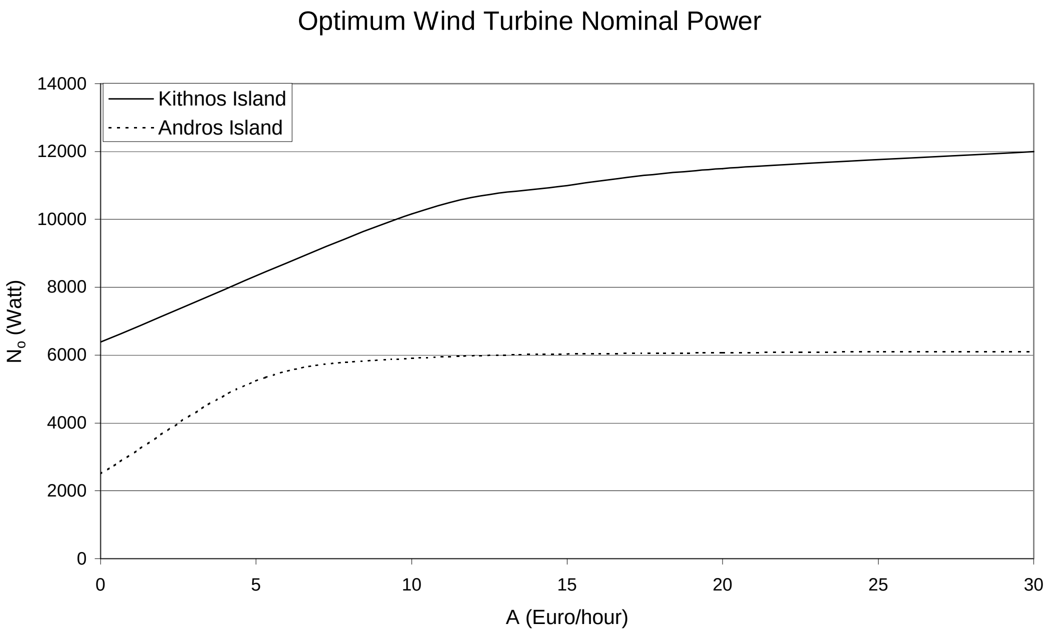

Figure 7: The Impact of No-energy Fulfillment Cost on the Optimum Wind Turbine Size for Typical Stand-Alone Wind Power Systems

In the following, an attempt is made to estimate the optimum wind-power stand-alone system main parameters as a function of "A". Hence in figure (6), the number of hourly load rejections "h" per annum is given as a function of "A" for both islands. According to the results obtained, there is a distinct bend on both curves of figure (6). This bend is located at A≈7€/h for Andros and at A≈13€/h for Kithnos island respectively. Despite the different wind potentials of those two regions, differences and similarities between the two curves should be attributed to the fact that -up to the bend point- the number of load rejections depends on both wind turbine rated power and battery capacity, see also figure (7). Subsequently, the h(A) curve slope is considerably diminished, although continuously negative up to 30€/h, where the rejection number practically zeros. One sound explanation for this slope change results from the fact that after the bend point the calculations indicate that only the battery size practically influences the reliability of the system.

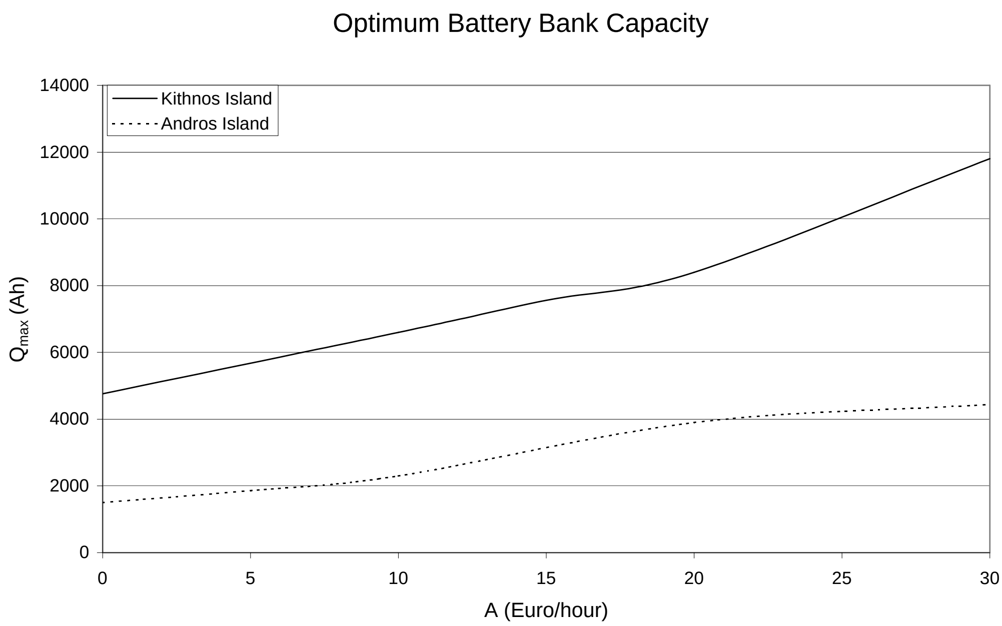

Figure 8: The Impact of No-energy Fulfillment Cost on the Optimum Battery Bank Capacity for Typical Stand-Alone Wind Power Systems

The next parameter examined is the rated power "N_o" of the wind turbine used by the autonomous wind-power system; figure (7). The results of the present study demonstrate that the optimum "N_o" value, that minimizes the 10-years stand-alone system operational cost, increases with "A", especially as "A" varies between 0-20€/h for Kithnos and 0-10€/h for Andros island. For higher "A" values the "N_o" value increase is quite lower, leading to asymptotic behaviour, which is more evident for high wind potential areas. This means that in order to increase system reliability there is no need for further wind power but for spare battery capacity to face large calm spells. This fact is almost obvious if one takes into consideration the corresponding "best points" curves of figures (2) and (3).

On the other hand, the system optimum battery capacity "Q_{max}" is continuously increasing (almost linearly) as "A" increases; figure (8). To be more precise, analyzing more carefully the Q(A) curve for Andros island, one may distinguish three separate regions, two of them also appearing in Kithnos island curve. Thus, at A≈8€/h (A≈17€/h for Kithnos) a slope increase is encountered. This fact is quite rational, considering that -after this point- the contribution of wind turbine size to the stand-alone system energy autonomy is inferior, see also figure (7). In this case, it is realistic to acquire higher battery capacity, so as to achieve the desired reliability level; see also "best points" curves in figures (2) and (3). After A≈21€/h (there is no corresponding point in figure (8) for Kithnos island due to lower wind potential) the Q(A) curve slope decreases, presenting an almost asymptotic behaviour. This means that, for Andros case if A≥21€/h the maximum system reliability value (R→100%) is achieved; hence there is no need for additional battery capacity (i.e. battery capacity of 4200Ah guarantees 40h of energy autonomy[12]). On the contrary, this is not the case for Kithnos island, where batteries are considered necessary to face calm spells[12] approaching 200h. Considering also that for A≥15€/h the contribution of wind turbine size is not fundamental to Kithnos system reliability improvement, see figure (7), higher battery capacity is the only way to obtain the desired stand-alone system reliability level.

Finally, in figure (9) the first installation cost "IC_o" of the optimum stand-alone wind power system is given for both applications as a function of "A", State subsidization excluded. As it results from equation (2), the "IC_o" value is determined by "N_o" and "Q_{max}". Taking into account the results of figures (7) and 8 and the cost functions of equation (2), the "IC_o" value should be continuously increasing with "A", especially for Kithnos Island. For Andros Island case, the "IC_o" increase is gradually decelerated, since the optimum system dimensions does not dramatically change for "A" values higher than 30€/h.

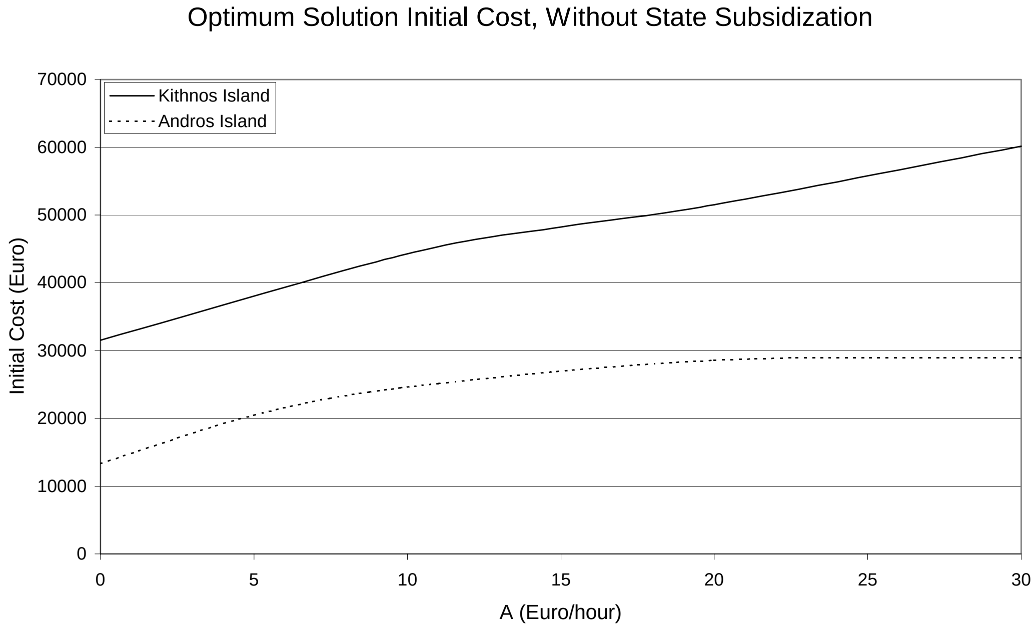

Figure 9: The Impact of No-energy Fulfillment Cost on the Optimum Initial Cost for Typical Stand-Alone Wind Power Systems

6. Conclusions and Proposals

An integrated feasibility analysis method of a stand-alone wind power system is developed. The new model takes into consideration, beyond the total long-term operational cost of the system, the no-energy fulfillment (or the alternative energy coverage) cost of the installation. In this way, the impact of desired system reliability on the stand-alone system configuration is included. Accordingly, a detailed parametrical investigation is carried out concerning the influence of the hourly no-energy fulfillment cost on the system dimensions and operational cost. The proposed methodology was successfully applied in two representative wind potential islands of Aegean Archipelago.

By using the up to now gained experience, one may suggest that for every realistic no-energy fulfillment cost value there is an optimum system configuration, imposing also a minimum system reliability limit. On the other hand, once the desired system reliability is specified, the optimum system configuration is a function of the region wind potential and the estimated no-energy fulfillment cost value, attributed by every consumer at the above-mentioned specific reliability level. Hence, the proposed analysis provides the capability to determine -in all practical cases- the optimum wind-power system configuration that minimizes the long-term total cost of the installation, also considering the influence of the local economy basic parameters.

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OPTIMUM AUTONOMOUS WIND POWER SYSTEM SIZING FOR REMOTE CONSUMERS, USING LONG-TERM WIND SPEED DATA

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Abstract

The usage of autonomous power systems is one of the most successful ways to treat the electrification requirements of numerous isolated consumers not only in Greece but also worldwide. Such an autonomous system comprises a micro-wind converter and a battery storage device, along with the corresponding electronic equipment. Considering the high wind potential of several regions in our country, an integrated study is carried out, based on long-term wind potential experimental measurements, in order to determine the optimum configuration of a stand-alone wind power system. The proposed solution "guarantees" zero load rejections for all the four-year period examined. For this purpose two separate calculation approximations are developed, presenting almost similar results. Of course, the application of the "WINDREMOTE II" numerical code based on detailed measurements, gives greatly analytical results concerning the energy autonomy and the operational status of the autonomous system components. Finally, by introducing preliminary financial aspects, it is possible to determine the optimum system dimensions on a minimum first installation cost.

Keywords: Autonomous Wind Power System; Optimum System Sizing; Remote Consumers

1. Introduction

In the beginning of the 21st century, almost every one of the European Union habitants has access to a continuous electricity supply, although this is not the case for the complete planet population. However, in spite of this technological achievement lasting for the three former decades, there still is a small part (≈500,000) of the E.U. residents who have not a direct access to a local utility network[1]. In Greece, mainly due to the existing peculiar topography and the large number of small islands, there are[2] more than 50,000 remote consumers, conceivably doubled once the existing country houses, shelters, telecommunication stations, lighthouses and remote military stations are taken into consideration.

The decision of not being grid-connected is commonly compulsory, either due to local electrical network scarcity in the area (e.g. tinny islands, mountainous areas) or due to the prohibitively high connection cost (e.g. 8,000 to 11,000 Euro/km)[3].

On the other hand, in many of these isolated regions a high quality wind potential subsists all over the year, mainly characterized by remarkable annual mean wind speeds and relatively limited calm spells. On top of that, during the last twenty years, wind power technology obtains an outstanding maturity status, while an astonishing improvement takes place in the battery construction and electronic equipment sectors.

Taking into account all the above-mentioned information, it is a common belief[4] that by using autonomous wind power systems, there is an excellent opportunity to face the electricity demand requirements of remote consumers, contributing thus to a significant amelioration of their life quality-level.

Nomenclature

C_{bat}	battery purchase cost
C_{elec}	electronic equipment buy-cost
CF	wind turbine capacity factor
C_{WT}	wind turbine ex-works price
DOD_L	maximum battery depth of discharge
E_{tot}	electricity consumption for a given time period
E^*_{tot}	total annual electricity demand
f	first installation cost coefficient
f(V)	wind speed probability density function
h	calm spell duration
h_o	selected hours of autonomy
IC_o	autonomous system initial cost
N(V)	wind turbine power curve versus wind speed
N_o	wind turbine nominal (rated) power
N_{min}	minimum wind power required
N_{max}	maximum wind power required
N_p	consumption peak load demand
n_c	battery maximum operation cycles
Q_{max}	maximum battery capacity
Q_{min}	minimum battery capacity
U	battery operation voltage
V	wind speed value
V_c	wind turbine cut-in speed
V_F	wind turbine cut-out speed
y	annual number of calm spells
Δ	technical availability
Δt	time-period in hours
η^*	energy transformation coefficient
η_s	storage system efficiency
ω	wind turbine mean power coefficient

2. Position of the Problem

The problem to be solved in the present essay concerns the electricity demand fulfillment of a typically remote consumer (four to six member family), under the precondition of a rational investment cost. The proposed solution takes advantage of the existing wind potential of the area investigated, thus a small (micro) wind converter may be used. Additionally, three representative weekly electricity consumption profiles are selected -after an extensive local market survey- on an hourly basis[5], being also depended on the year period analyzed (winter, summer, other). The data used are based on information provided by the Greek National Statistical Agency, concerning the electricity demand profile of selected representative households. In figure (1) the most viable electricity load demand profile is presented, for the typical family adopted, during a representative winter and summer week. According to the consumption profile approved, the annual peak load "N_p" is set at 3.5kW, while the weekly electricity consumption varies between 80kWh and 100kWh. Summarizing, the total electricity consumption for every month of a year is sited in Table I. The electricity consumption in association with the available wind potential values remain the main inputs defining the appropriate size of the system wind turbine.

Consequently, due to the stochastic behavior of the wind, the existence of an energy storage system[6] (in the present case a lead-acid battery row) able to match the electricity demand of the consumer and the energy output of the wind turbine is absolutely necessary. More precisely, the battery capacity is one of the parameters strongly affecting the energy autonomy of the stand-alone system, influencing also the operational cost of the installation.

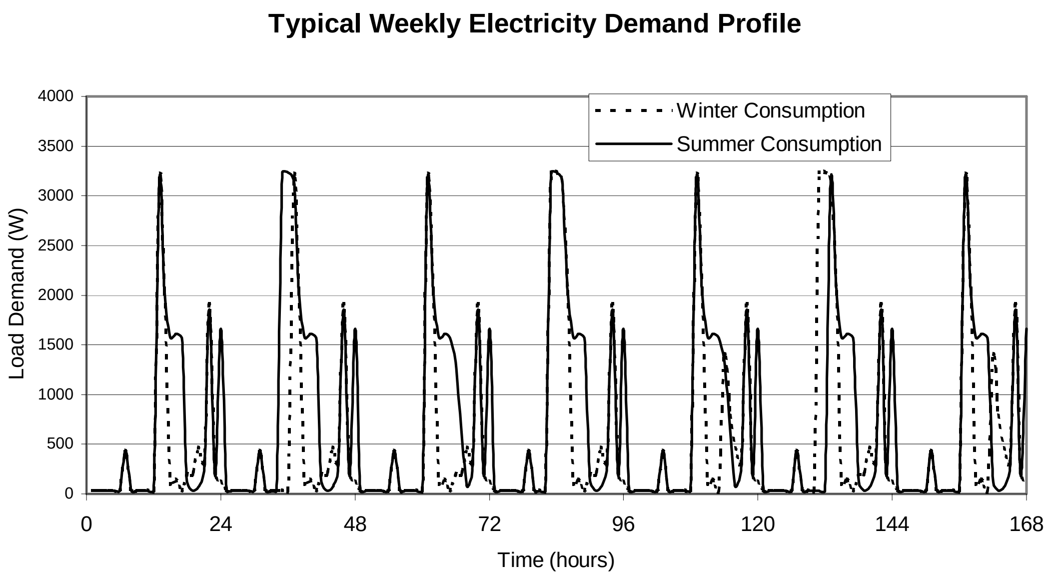


Figure 1: Typical Electricity Demand Profile of the Remote Consumer Analyzed

3. Proposed Configuration-System Sizing

In order to meet the electricity demand of remote consumers, an integrated autonomous wind power system is devised[7], similar to one of figure (2). Hence, the proposed system comprises:

i. A small wind converter
ii. A lead acid battery storage system
iii. An AC/DC rectifier
iv. A DC/DC converter
v. A UPS (Uninterruptible Power Supply)
vi. A DC/AC inverter

More specifically, the micro wind converter (rated power "N_o") is connected either to the AC load via a UPS or to a battery row via a rectifier and a battery charge controller. The case that the wind turbine generates direct current (although similar to the one analyzed) is not examined here. The rated power of the selected wind turbine depends on the system electricity demand, the available wind potential and the operational characteristics of the machine[8]. Keep also in mind that the wind turbine output curves are given at standard-day conditions, without air humidity. Thus, in real day conditions, the ambient temperature and pressure along with the relative humidity are used to obtain the real air density and the corresponding wind turbine output[9].

More precisely, using also the data of Table I, the nominal power "N_o" of the machine is confined as:

$$N_{\mathbf{min}} = E_{tot}(\Delta t) / (\Delta t \cdot CF) \le N_o \le E_{tot}(\Delta t) / (\Delta t \cdot CF \cdot \eta^*) = N_{\mathbf{max}} \qquad (1)$$

where "$E_{tot}(\Delta t)$" is the system electricity consumption (increased by 20% to take into account future changes) for the examined period "Δt" -in hours- (e.g. one month or one year), "CF" the capacity factor of the installation for the same time period and "η^*" the energy transformation coefficient, expressing the portion of the wind energy produced and stored via the battery system, which is finally given to consumption[6][10]. Note also that the power output of the proposed wind turbine should be big enough to face the maximum (peak) load demand "N_p" of the system, without the usage of the inverter.

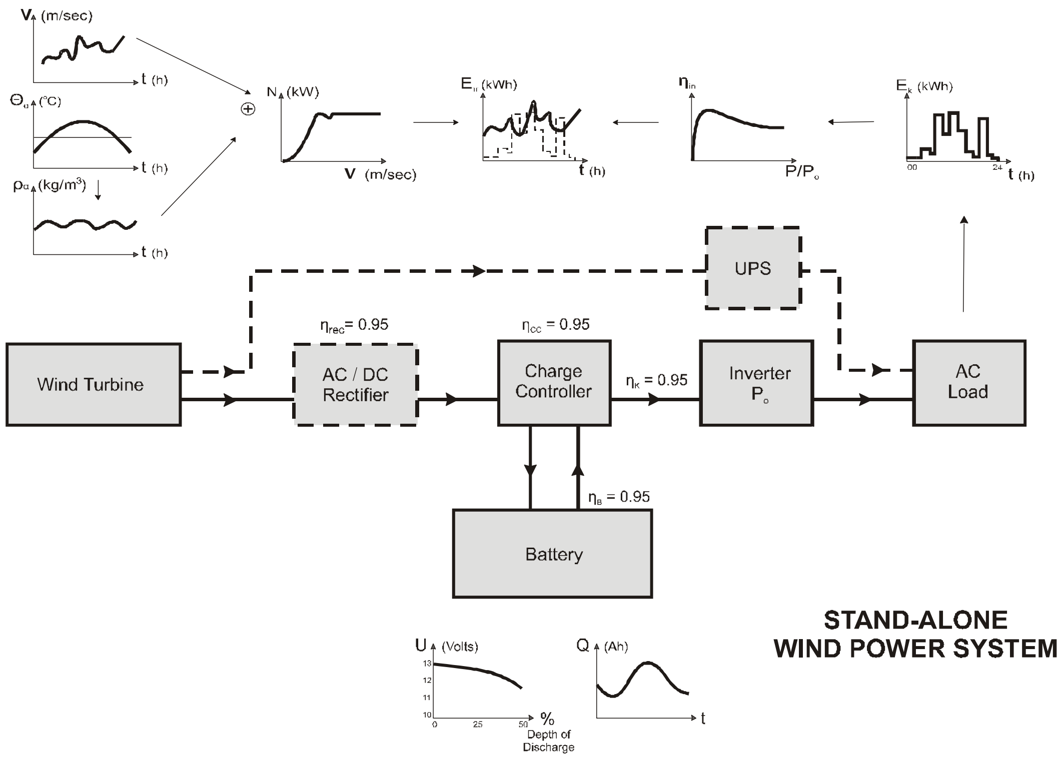


Figure 2: Proposed Autonomous Wind Power System

Table I: Four-Year Analysis Results for Kithnos Island

Kithnos			1st Year			2nd Year			3rd Year			4th Year		
Month	**E_{tot} (kWh)**	**Temp(°C)**	**$\overline{V}$ (m/s)**	**ω**	**≤N_o (kW)**	**$\overline{V}$ (m/s)**	**ω**	**≤N_o (kW)**	**$\overline{V}$ (m/s)**	**ω**	**≤N_o (kW)**	**$\overline{V}$ (m/s)**	**ω**	**≤N_o (kW)**
January	335	11.5	7.69	.39	2.89	8.98	.47	2.40	8.65	.45	2.50	8.28	.43	2.62
February	303	11.9	9.48	.50	2.25	8.40	.44	2.56	8.62	.45	2.50	7.87	.40	2.81
March	325	12.8	7.30	.38	2.87	6.44	.32	3.41	7.30	.38	2.87	7.04	.36	3.03
April	315	16.0	5.51	.27	4.04	5.56	.27	4.04	4.78	.23	4.75	3.68	.15	7.28
May	325	19.6	5.63	.27	4.04	6.21	.31	3.52	5.02	.25	4.37	4.40	.20	5.46
June	410	24.2	4.21	.19	7.50	3.64	.15	9.50	3.71	.15	9.50	5.63	.27	5.28
July	424	26.5	4.52	.21	6.78	6.06	.30	4.75	5.05	.26	5.48	4.84	.24	5.94
August	424	26.2	8.07	.42	3.39	6.86	.35	4.07	6.23	.31	4.60	6.28	.31	4.60
September	315	23.5	7.20	.37	2.95	5.11	.25	4.37	7.22	.37	2.95	6.26	.31	3.52
October	325	20.0	5.08	.25	4.37	5.38	.26	4.20	6.76	.34	3.21	7.24	.37	2.95
November	324	16.4	6.32	.32	3.52	6.27	.31	3.63	9.37	.49	2.30	8.24	.42	2.68
December	335	13.2	9.02	.48	2.35	7.52	.38	2.96	7.93	.41	2.75	6.36	.32	3.52

E_{tot} (Electricity Consumption per Month), Temp (Monthly Mean Temperature), $\overline{V}$ (Monthly Average Wind Speed), ω (Mean Power Coefficient value for each month), N_o (Wind Turbine Rated Power)

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.:

$$CF = \Delta \cdot \omega \tag{2}$$

More precisely, "ω" can be computed[11] as:

$$\omega = \int_{V_c}^{V_F} \frac{N(V)}{N_o} \cdot f(V) \cdot dV \tag{3}$$

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 (figure (3)) versus wind speed "V" and "f(V)" is the wind speed probability density function at hub height describing the local wind potential for the time period "Δt". In cases that no detailed wind speed data exists for the area under investigation, the well-known Weibull distribution "f(V)" is used[12]. However, this is not the case in the proposed analysis, since the calculations are based on available experimental data of the wind potential for various regions of Greece[13].

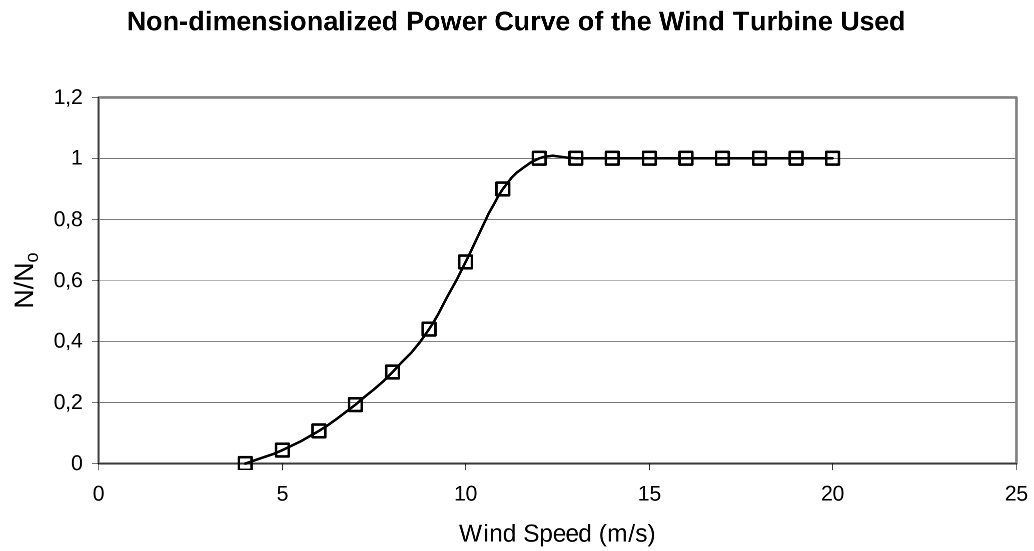


Figure 3: Non-dimensionalized Power Curve of the Wind Turbine Used

Additionally, the system includes a battery row, of "Q_{max}" capacity, selected to be sufficient to store the energy produced during the windy days, for usage during the calm spells. The battery size is defined by the autonomy hours "h_o" of the system, the total annual energy demand "E_{tot}^*", the efficiency of the storage system "η_s" and the maximum permitted depth of the batteries discharge "DOD_L"[14]. Selecting a U=24V or 48V battery operation voltage, the maximum battery capacity (in Ah) is given as:

$$Q_{\mathbf{max}} = \left((h_o \cdot E_{tot}^*) \big/ (8760 \cdot \eta_s \cdot DOD_L \cdot U) \right) \tag{4}$$

At any case the battery capacity "Q" varies between Q_{min} and Q_{max}, where:

$$Q_{min} = (1 - DOD_L) \cdot Q_{max} \tag{5}$$

while the "DOD_L" value is strongly related to the life duration (operational cycles -"n_C") of the batteries, e.g.:

$$DOD_L \cdot n_c \approx 1500 \text{ to } 1800 \quad (6)$$

The AC/DC rectifier and the battery charge controller size-definitions are based on the wind turbine and the battery operational characteristics (e.g. "N_o" kW, U=24 or 48Volt, charge rate "R_{ch}" in A, where the charge current numerical value must not exceed 20% of the storage capacity value). Similarly, the UPS characteristics depend on the maximum load demand "N_p" and the service time (e.g. 2min), along with the operational voltage (e.g. 220 to 240Volt).

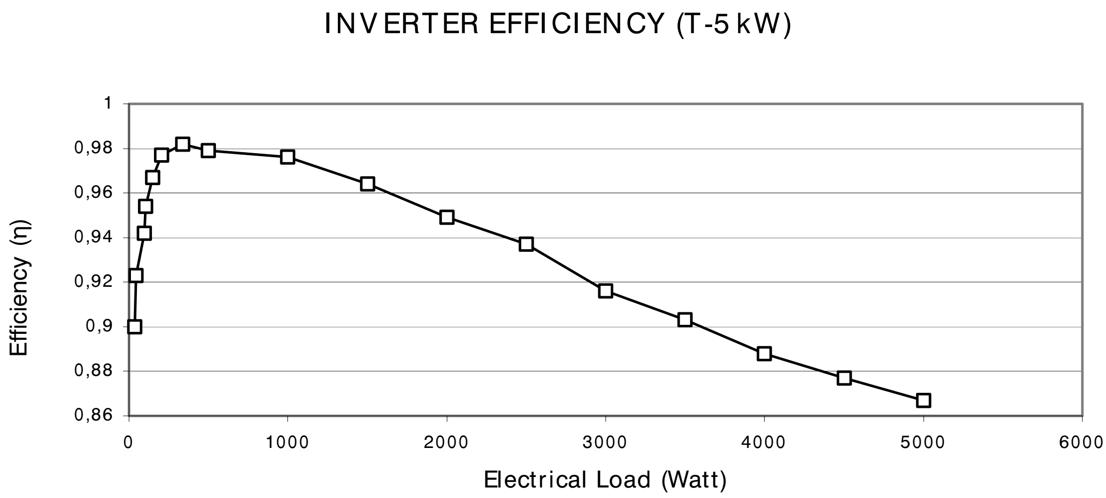


Figure 4: Typical 5kW Inverter Efficiency Evolution

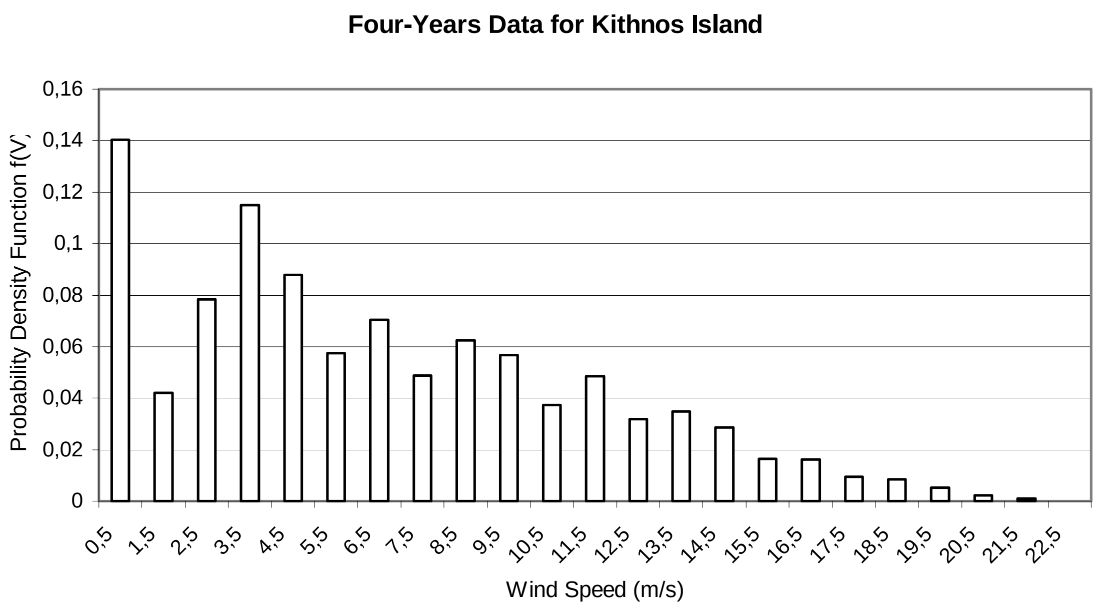


Figure 5a: Four-Year Wind Potential Characteristics

Finally, the size of the inverter is selected[7] to fulfill the maximum load demand of the consumption "N_p", including a safety coefficient. In figure (4) a typical inverter efficiency profile is presented, as a function of the relative electrical load covered by the device.

Recapitulating, during the long-lasting operation of the proposed stand-alone system, the following situations may appear:

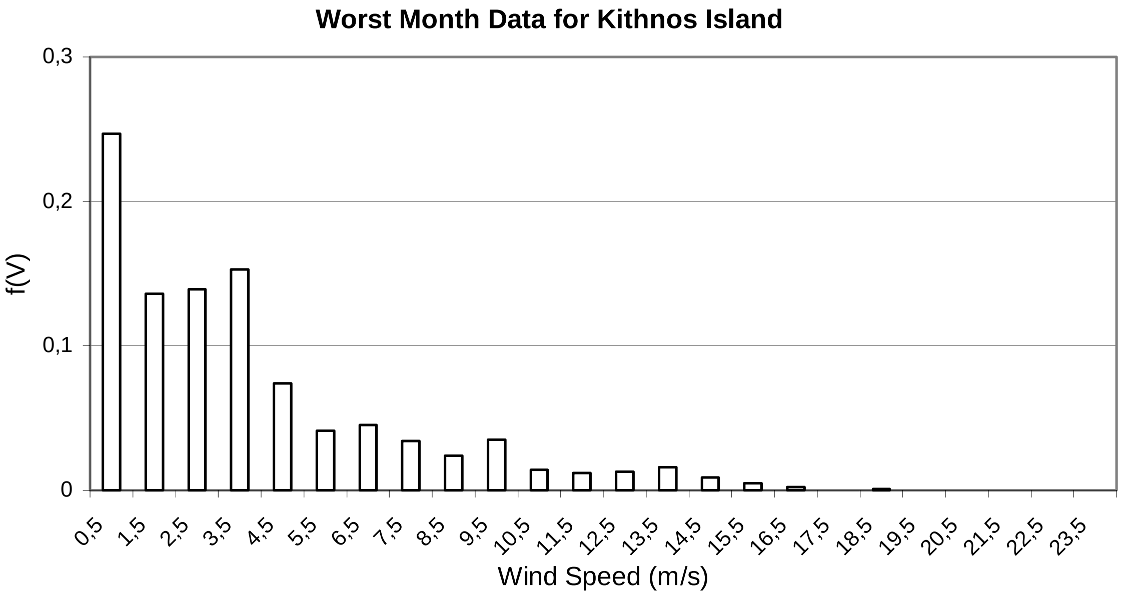


Figure 5b: Worst Month Wind Potential Characteristics

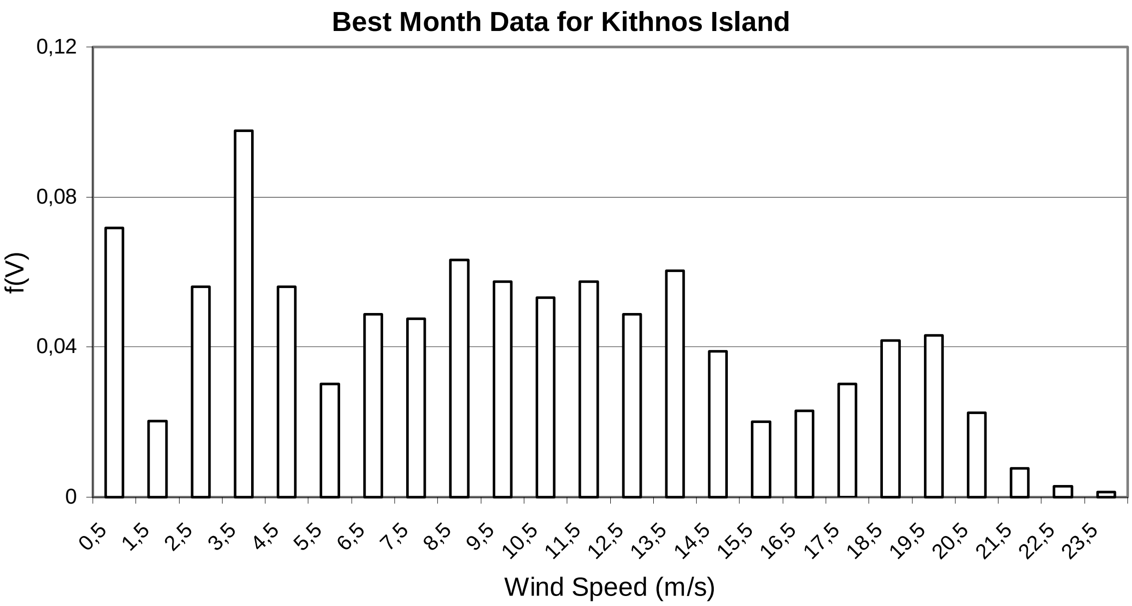


Figure 5c: Best Month Wind Potential Characteristics

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 power output of the wind turbine, (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 DC/DC converter 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 (Δ=80%)), i.e. $N_w=0$. In this case, all the energy demand is fulfilled by the battery-DC/DC controller-DC/AC inverter subsystem, under the condition that $Q>Q_{min.}$ In cases (b) and (c), when the battery capacity is near the bottom limit, an electricity demand management plan should be applied; otherwise the load would be rejected.

4. Wind Potential Analysis

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. Due to the insufficient infrastructure (e.g. road network), there are many isolated consumers with 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.

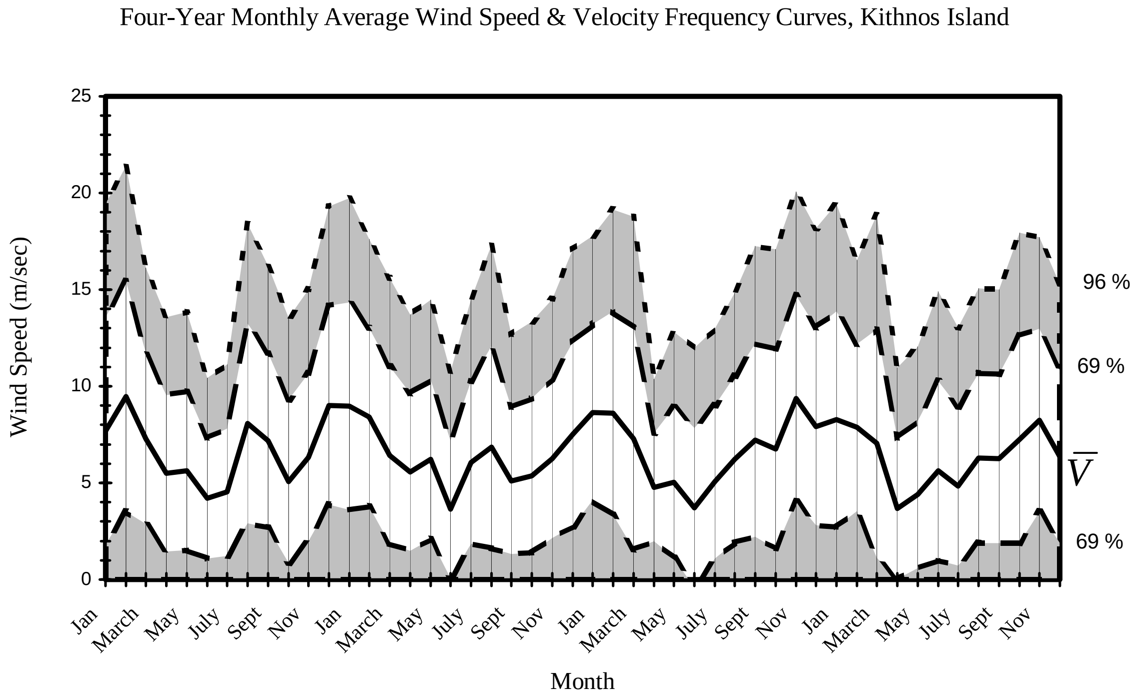


Figure 6: Long-Term Monthly Mean Values of Kithnos Wind Speed

Using the available wind speed data[13] for a relatively long (four years) period, it is possible to create the experimental 4-year wind speed probability density function distribution "f(V)", see figure (5a). In figures (5b) and (5c), we present the corresponding "f(V)" distribution for the worst (April-4) and the best (February-1) month of the period examined (see also Table I), concerning the available wind potential.

In the next figure (6) the monthly average wind speed is cited along with the corresponding velocity frequency curves for the 4-year period analyzed. The numerical monthly average wind speed values for each year analyzed are also given in Table I. As it is obvious from these results, the minimum wind speed values appear in Kithnos mainly during the end-of-spring, beginning-of-summer period (i.e. April, May and June); therefore the selected wind turbine size should strongly depend on the wind potential characteristics of this period.

Finally, in stand-alone systems further detailed data are necessary to guaranty the energy autonomy of the installation. In similar applications, the annual duration of calm spells without a break is very important, as it indicates the period to be covered by storage systems. Hence, after a thorough analysis of the available detailed wind speed values[15], it is possible to estimate the calm spell phases ($V \leq 5$m/s) for Kithnos island for the complete period investigated, figure (7). Accordingly, an analytical function is also used to simulate the relation between the annual number of calm spells "y" and the calm spell duration "h", thus:

$$y = \frac{\alpha}{h^{\beta}} \tag{7}$$

where α=60.2 and β=0.948.

5. System Sizing-1st Order Approximation

Small wind turbines used for electricity production start operating (cut in speed) at a wind speed approximately 3 to 5m/s, figure (3). In order to obtain an unambiguous picture, the monthly mean wind speeds are also calculated for the complete time period analyzed (Table I), along with the monthly frequency curves; see for example figure (6). Subsequently, using the available experimental probability density function distributions for every month (e.g. figure (5)) of the 4-year period under investigation, the minimum acceptable nominal power of the wind turbine selected is predicted using equations (1) to (3), according to the following relation:

$$N_o = \mathbf{max}\left\lfloor \mathbf{\underset{i}{max}}\, N_{\mathbf{max}_i}, N_p \right\rfloor \tag{8}$$

Hence, the resulting nominal power for the Kithnos Island is set equal to 9.5kW.

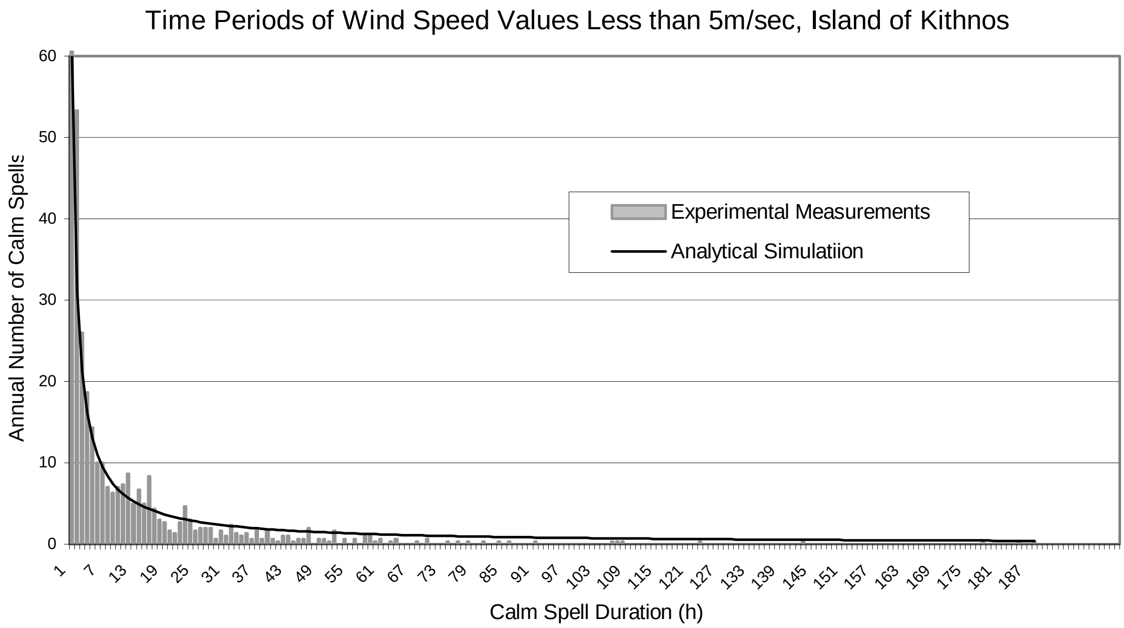


Figure 7: Long-Term Calm Spell Periods for Kithnos Island

Consequently, taking into account the above-presented investigation, it is concluded that an 180h calm spell appears at least once per year in the area of Kithnos, while there is a 95% possibility that the calm spell does not exceed the 140h per year. Summarizing, the maximum acceptable calm spell (180h) may be used to define the **minimum** battery size, in order to avoid the load rejections of the stand-alone system. Thus, from equation (4) one gets (η_s=0.8, DOD_L=75%, U=24V) Q_{max}=7200Ah.

Recapitulating, according to the 1st order approximation analysis, based on a monthly wind speed data, the proposed stand-alone system consists of a small wind converter of 10kW, an AC/DC rectifier of 10kW, a UPS of 5kW/240V/2min, a DC/AC inverter of 5kW/240V/50Hz and a battery storage system of 7200Ah/24V. The exact battery size is selected according to the expected maximum calm spell duration, resulting from the long-term analysis of the local wind potential.

6. System Sizing-2nd Order Approximation

As mentioned above, the main prospect of the present study is to estimate the appropriate dimensions of a stand-alone wind power system for every remote consumer sited in Kithnos Island; under the condition that detailed wind speed (along with ambient pressure-temperature-humidity) data exists. The two governing parameters used during the optimization procedure are the rated power "N_o" of the wind turbine and the battery maximum size "Q_{max}". To confront similar problems, a computational algorithm "WINDREMOTE-II" is devised[16]. The developed numerical code is used to carry out the necessary parametrical analysis on an hourly energy production-demand base.

More precisely, for each pair of "N_o" and "Q_{max}" the "WINDREMOTE-II" algorithm is executed for the specific time-period selected (e.g. one month, six-months, one year or even four years), while emphasis is laid on obtaining zero-load rejection operation.

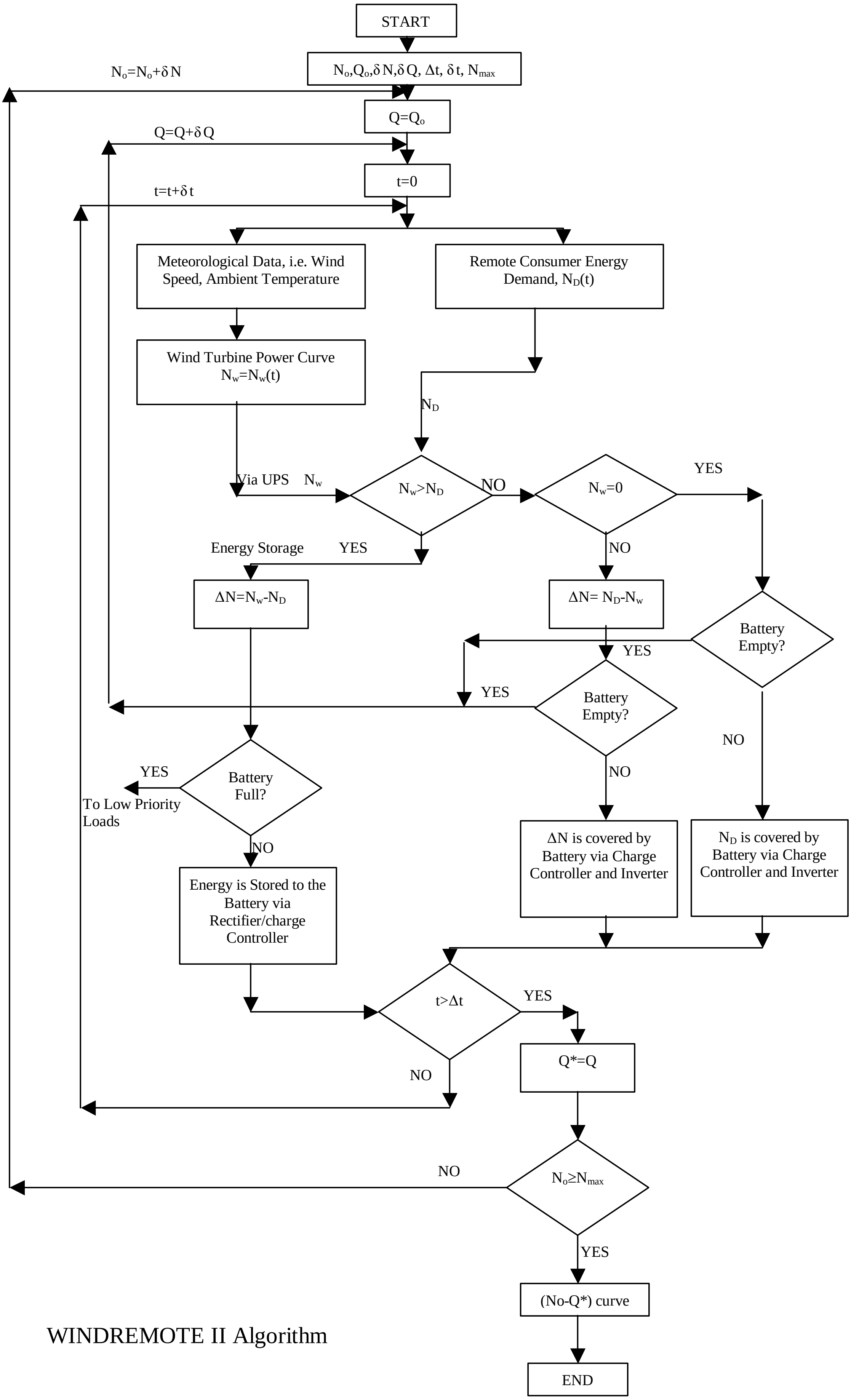
If this is not achievable, the battery size is increased and the calculation is performed again, up to the case that the no-load rejection condition is fulfilled, i.e. $Q^*=\min\{Q_{max}\}$. Next, another wind turbine size is selected and the calculations are repeated. Thus, after the integration of the analysis a (N_o-Q^*) curve is predicted under the no-load rejection restriction, figure (8). To get a clear-cut picture, keep in mind that for every pair of (N_o-Q^*) the stand-alone wind power system is energy autonomous for the period investigated.

More precisely, in figures (9), (10), (11) and (12) the computational results of "WINDREMOTE-II" algorithm are presented for four successive years for Kithnos island. In the same figures the "100 annual permitted load rejection curves" are also given for comparison purposes. As it is expected, according to the numerical results obtained, the battery size is significantly increased as the rated power of the selected wind turbine is decreased. This increase is much more abrupt for relatively small wind turbines ($N_o \leq 5$kW), while the battery size shows an asymptotic behaviour for wind turbines of the order of 10kW.

Additionally, the no-rejection (N_o-Q^*) curves for every year analyzed do not present similar distributions, since for small wind turbines the 4th year examined imposes the largest battery storage capacity. On the contrary, for bigger wind converters the 3rd year results seem to dominate the battery capacity values. Finally, the windiest year seems to be the 2nd one, taking into consideration the quite small battery capacity needed to guarantee whole year energy autonomy.

Another interesting conclusion drawn from these four figures (9) to (12) is the substantial decrease in storage requirement, provided that a reasonable number of annual load rejections is acceptable. This "Q^*" value decrease is relatively limited for small wind converters adopted ($N_o \leq 5$kW), approaching significant values (up to 35% decrease) in cases that "N_o" exceeds the 10kW.

In order to obtain a complete picture of the problem analyzed, the four "annual no-load rejection (N_o-Q^*) curves" are grouped in figure (13), along with the corresponding solution 4-year distribution. According to the numerical results obtained, the 4-year autonomy curve encloses the corresponding annual profiles, thus the 4-year autonomy curve is defined on the basis of the worst annual case, or for every "N_o" value the battery size "Q_{opt}" is given as "$\max\{Q^*_i(N_o)\}$", where "i" refers to the year analyzed, taking integer values between one and four.



WINDREMOTE II Algorithm

Figure 8: WINDREMOTE-II Algorithm

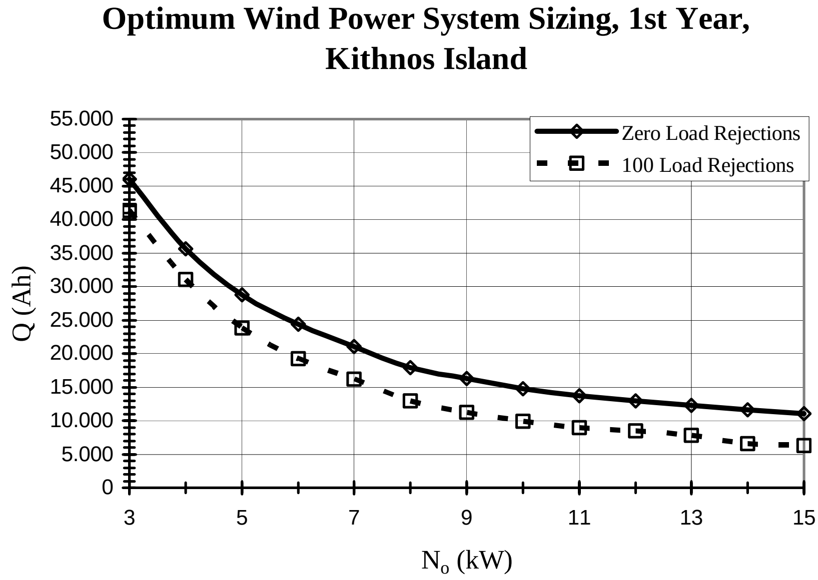


Figure 9: Battery Storage Capacity Requirement versus Wind Turbine Rated Power (1st Year Calculation Results)

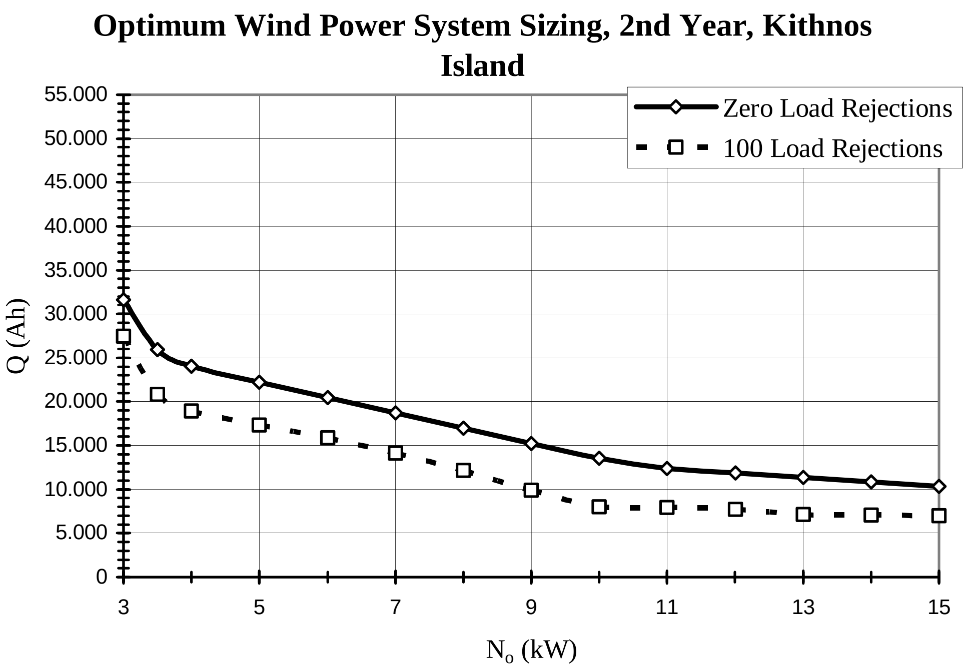


Figure 10: Battery Storage Capacity Requirement versus Wind Turbine Rated Power (2nd Year Calculation Results)

Similarly, for comparison purposes, the 1st order approximation solution is placed in the same figure. As it is clear, the 1st order approximation solution is not validated by the analytical results, since the corresponding battery size is almost the 40% of the optimum value given by the "WINDREMOTE-II" numerical code. This remarkable discrepancy may be attributed to the fact, that a load rejection will most likely be realized during two or more successive calm spells, even though the battery is sized enough to face the electricity demand of the major calm spell of a whole year. More precisely, in cases that there is not enough time between successive calm spells to recharge the energy storage system, the real duration of the worst calm spell may be almost equal to the sum of the above mentioned successive time periods. On the other side, the 1st approximation solution gives a reasonable estimation of the optimum size of the proposed stand-alone wind power system (especially for "N_o"), although it is not possible to ensure a completely autonomous operation of the installation.

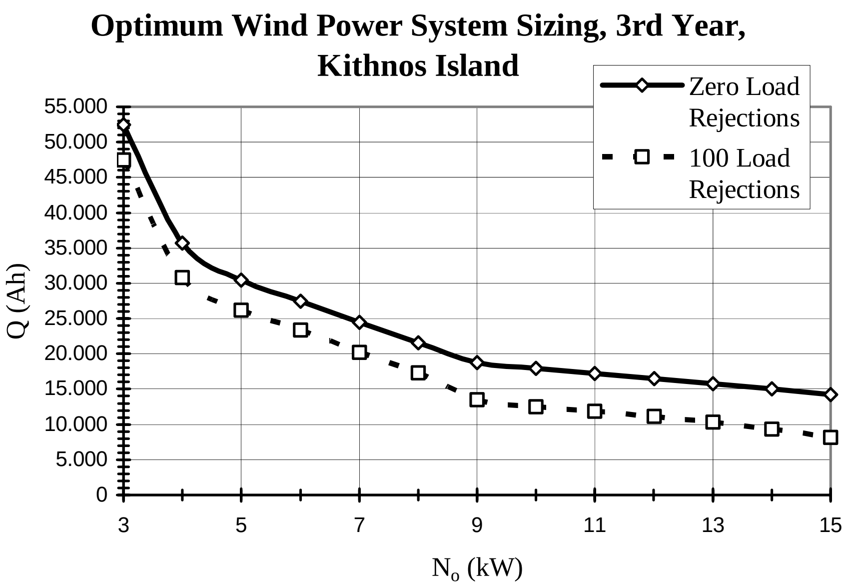


Figure 11: Battery Storage Capacity Requirement versus Wind Turbine Rated Power (3rd Year Calculation Results)

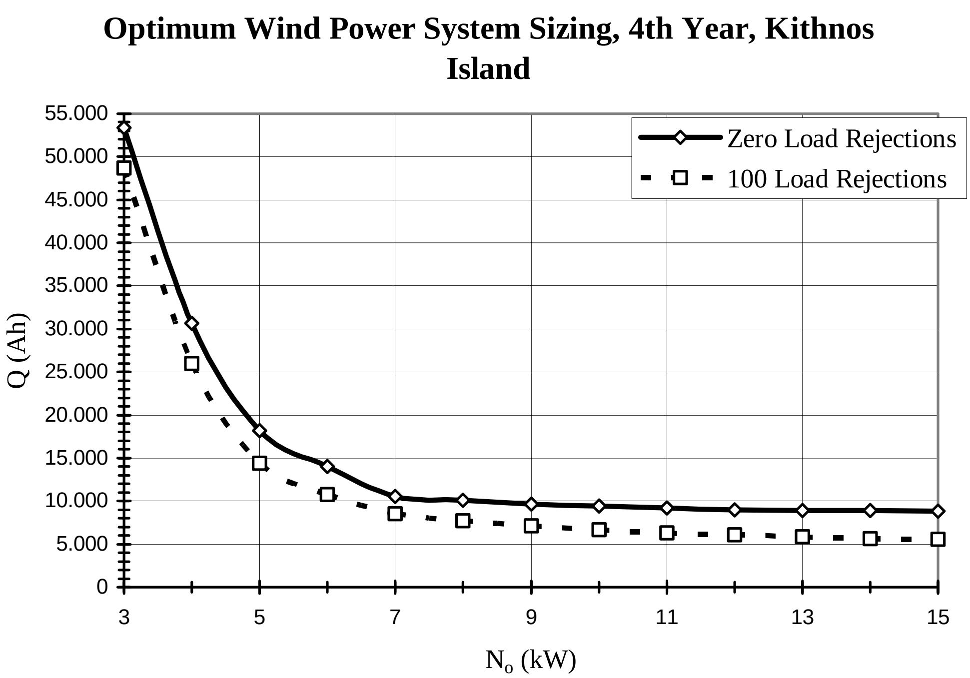


Figure 12: Battery Storage Capacity Requirement versus Wind Turbine Rated Power (4th Year Calculation Results)

Integrating the present analysis, it is interesting to introduce (not in details) the influence of the first installation cost on the optimum configuration selected. More precisely, according to previous analysis by the authors[17], the initial cost "IC_o" of the investment under investigation can be approximated as:

$$IC_o = C_{WT} + C_{Bat} + C_{elec} + f * C_{WT} \tag{9}$$

where the wind turbine (ex-works) cost for small wind converters ($N_o \leq 100kW$) is given[18] as:

$$C_{WT} = \left(\frac{a}{b + N_o^x} + c\right) \cdot N_o \qquad \text{(in Euro, for } N_o \leq 100kW) \tag{10}$$

($a=8.7x10^5$; b=621; x=2.05; c=700, [18])

and

$$C_{Bat} = c_b * Q_{\mathbf{max}} \qquad \text{(in Euro)} \tag{11}$$

Note that "c_b" is slightly depended[7] on battery capacity, while for the local market -after a market survey concerning lead-acid batteries- essential values may be approximated by the following semi-empirical relation:

$$c_b = 5.0377 / Q_{\mathbf{max}}^{0.0784} \tag{12}$$

Additionally, the first installation cost coefficient "f" (excluding the cost of electronic equipment) is relatively small for micro wind turbines, e.g. f=0.15[19]. On top of that, the cost of the remaining electronic equipment is a function of the peak load demand (UPS, Inverter, i.e. $A=A(N_p)$), while it also depends on the wind turbine size (rectifier, charge controller). Thus, since the maximum electricity demand of the remote consumer is prescribed, the following simplified relation is valid[16] for the Greek market:

$$C_{elec} = A + B * N_o \qquad (N_o \geq 1kW) \qquad \text{(in Euro)} \tag{13}$$

with A=2200Euro and B=380Euro/kW.

Recapitulating and substituting equations (10), (11), (12) and (13) into equation (9) one gets:

$$IC_o = \left(\frac{a}{b + N_o^x} + c\right) \cdot N_o * (1 + f) + c_b(Q_{\mathbf{max}}) * Q_{\mathbf{max}} + A + B * N_o \tag{14}$$

Consequently, according to equation (14), the installation initial cost is a function of "N_o" and "Q_{max}", i.e.:

$$IC_o = IC_o(N_o, Q_{\mathbf{max}}) \tag{15}$$

By drawing the corresponding initial cost constant-value curves on figure (13), it is possible to estimate the optimum (minimum initial cost) solution, which guarantees energy autonomy of the remote consumer for the four-year period examined. Of course, since the optimum solution is strongly depended on the slope of the initial cost (IC_o=const.) curves, a more detailed investigation is necessary, taking into consideration the current values and opportunities of the European market. In any case, the resulting optimum autonomous solution for Kithnos Island is based on a 9.5 (or 10) kW wind converter and on an 18,000Ah-24V battery row. Accordingly, the first installation cost is approximately 42,000Euro, if the 40% Greek State subsidy is taken into account[18][19].

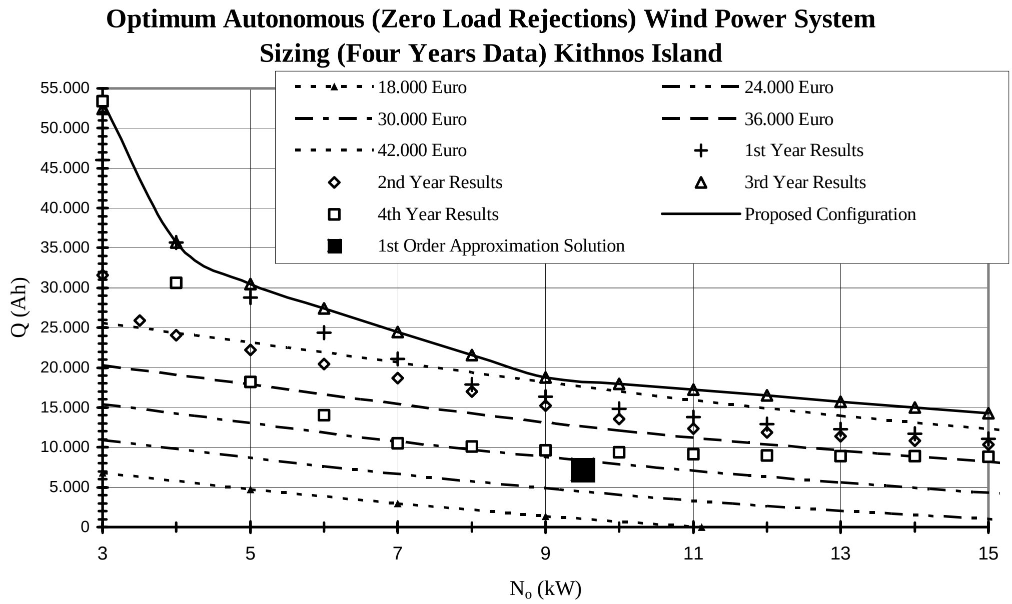


Figure 13: Calculation Results Comparison for the Entire Period Analyzed, Kithnos Island

For comparison purposes, it is interesting to repeat that the grid connection cost is almost 10,000Euro/km, while the proposed wind based autonomous system is offering enough electricity for at least twenty years, with minimum maintenance and operation cost (excluding the battery replacement every 5 to 7 years), independent of oil prices and with fundamental environmental and social benefits.

Conclusions

The optimum dimensions of an autonomous wind power system are defined for a representative island in the Aegean Sea, using extensive wind speed data. The results obtained are based on experimental measurements and operational characteristics by the autonomous system components manufacturers. For this purpose two separate computational approximations are developed. The first one, based on monthly mean velocity values, calm spells and velocity frequency curves, estimates with reasonable accuracy the necessary parameters of the proposed configuration, but it does not guaranty the no-load rejection constraint for all the period examined.

Subsequently, the second method, based on detailed wind-speed and ambient temperature-pressure time series, predicts -via the "WINDREMOTE II" numerical code- the corresponding wind turbine size and battery capacity that ensures the remote system energy autonomy. Additionally, according to the results obtained, the one year data based analysis is not enough to provide long-term energy autonomy of the system, thus at least three to five years extensive data are needed.

Finally, although the economic behaviour investigation is not the prospect of the present analysis, it is demonstrated that the proposed wind powered energy autonomous system is the best solution to meet the electricity demand of the remote consumers' vast majority, especially in high wind potential locations. On top of that, subsidization possibilities either by local authorities or via European funds should greatly increase the economic attractiveness of similar wind energy applications.

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PART THREE

PHOTOVOLTAICS

- Stand-Alone Systems
- Hybrid-Photovoltaic Systems

OPTIMUM TECHNO-ECONOMIC ENERGY-AUTONOMOUS PHOTOVOLTAIC SOLUTION FOR REMOTE CONSUMERS THROUGHOUT GREECE

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Abstract

Autonomous photovoltaic systems have turned into one of the most promising ways to handle the electrification requirements of numerous isolated consumers worldwide. Such an autonomous system comprises a number of photovoltaic panels properly connected and a battery storage device, along with the corresponding electronic equipment. Considering the high solar potential of most Greek territories, an integrated study is carried out, based on long-term solar potential experimental measurements, in order to determine the optimum configuration of a stand-alone photovoltaic system at representative locations all over Greece. The proposed solution "guarantees" zero load rejections for all the areas and time period examined. For this purpose a fast and reliable numerical code "PHOTOV-III" is developed. The algorithm provides analytical results concerning the energy autonomy and the operational status of the autonomous system components. Besides, the optimum panel tilt angle -minimizing the first installation cost of a small photovoltaic system- is predicted. Finally, by introducing available financial aspects, it is possible to determine the optimum system dimensions on a minimum first installation cost basis. According to the results obtained, an autonomous photovoltaic system can definitely contribute to the urgent electrification problem of remote consumers spread throughout Greece, also improving their life quality level.

Keywords: Autonomous Photovoltaic System; Optimum System Sizing; Remote Consumers

1. Introduction

Photovoltaic systems (PVS) significantly contribute to environmental protection and potentially reduce the dependency of Europe on oil imports. However, their main disadvantage remains the relatively high cost compared with their annual yield. On the other hand, the PVS laboratory efficiency recently approaches its theoretical upper limit, while the cost of PVS electricity production is remarkably decreased and is still shrinking (figure (1)) at a rate faster than any other energy production technology[1]. This considerable cost reduction turns PVS into a viable electrification solution, especially for remote stand-alone applications and high solar intensity areas[2][3].

In Greece -and especially in the Aegean and Ionian Archipelago areas- several isolated consumers (such as private farms, tiny villages, shelters, lighthouses, telecommunication stations, etc.) have no access to an electrical grid[4]. So far, in an attempt to cover their urgent electrification needs, they consider small oil-fired electrical generators to be their only alternative. Besides, most Greek territories possess -due to the geographical position of Greece- an abundant and reliable solar supply all year round; figure (2).

Hence, to face the urgent electrification problem of remote consumers spread throughout Greece, the present study is devoted to investigate the possibility of creating an integrated photovoltaic station, based on a small photovoltaic generator and an energy (battery) storage device, along with the corresponding electronic equipment. This analysis is mainly planning to estimate the optimum dimensions of a stand-alone PVS under the restriction of minimum installation cost, for several representative Greek areas, figure (2).

***Kaldellis J.K., 2003**, "Optimum Techno-Economic Energy-Autonomous Photovoltaic Solution for Remote Consumers Throughout Greece", Energy Conversion & Management Jr, ECM-2083, on-line available in www.ScienceDirect.*

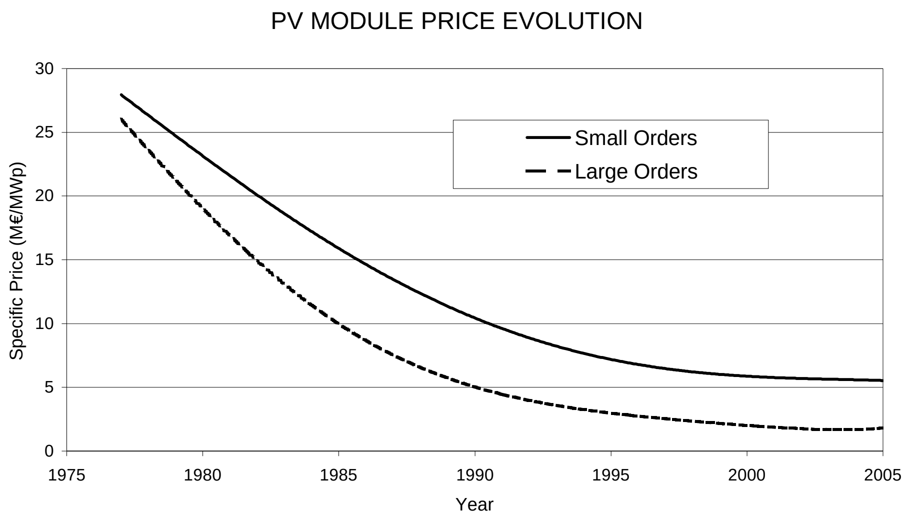

Figure 1: Photovoltaic Modules Price Evolution (estimation after 2002)

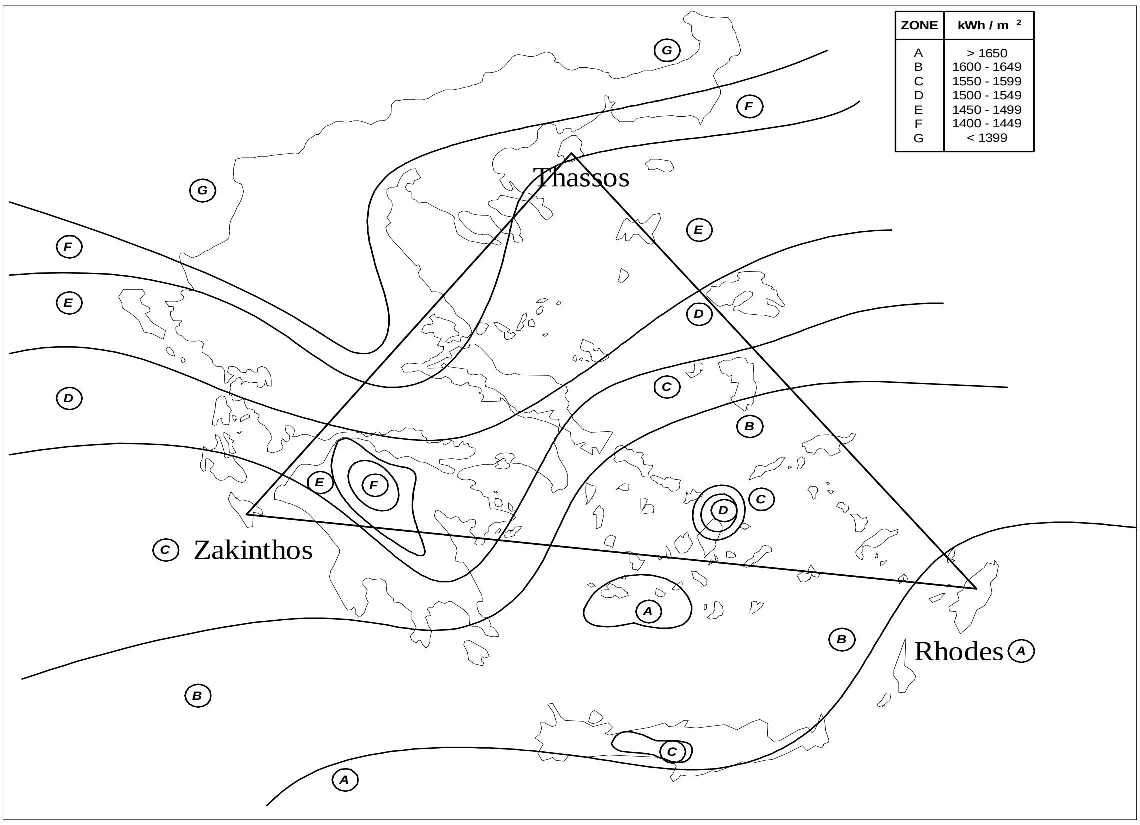

Figure 2: Solar Potential of Greece[22]

2. Proposed Configuration-System Sizing

In an attempt to facilitate the electricity demand problem of remote consumers, taking also advantage of the excellent solar potential of Greece, the following autonomous PVS is proposed; see also figure (3). In particular, the stand-alone PVS comprises an array of PV modules connected to a battery via a battery charge controller or to a DC/AC inverter. Keep in mind that the battery charge controller switches the PV array off when the battery is fully charged and switches (rejects) the load off before the battery gets completely discharged, e.g. $DOD \geq DOD_L$. The usage of a maximum power point tracker (MPPT) is not suggested for small scale applications[5]. The energy storage system (a lead acid battery is found to be the most appropriate solution, given the present technological status[6]) should be adequate to store the energy production during sunlight hours for use at night or bad weather conditions. Finally, since most applications are based on alternative current[7], a DC/AC inverter is also required.

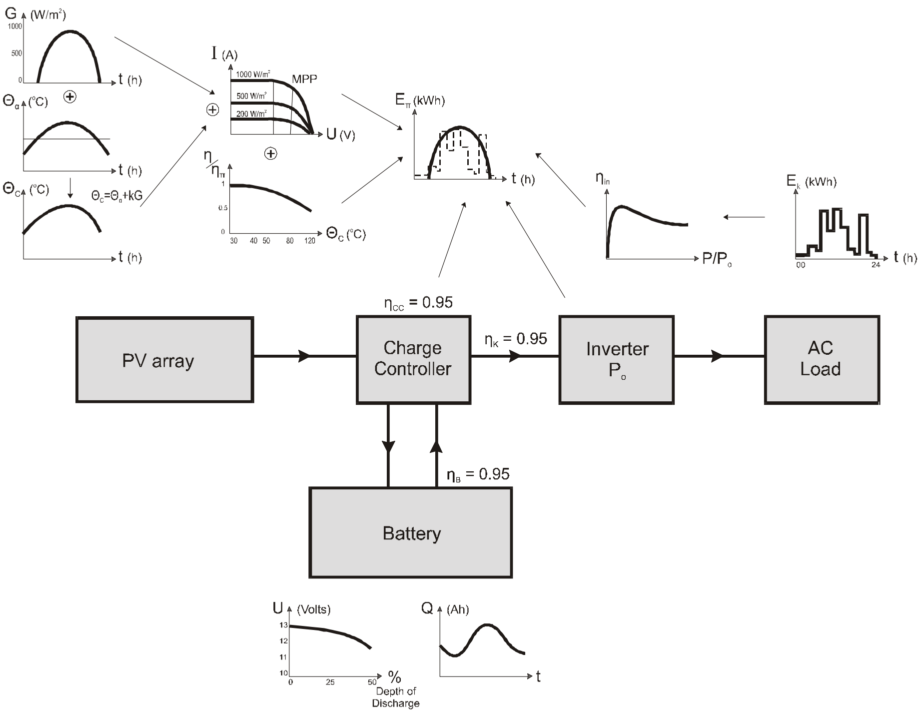

Figure 3: Proposed Autonomous PVS Configuration for Remote Consumers

Recapitulating, the proposed PVS is based[8] on:

i. A photovoltaic system of "z" panels ("N_o" maximum power of every panel) properly connected (z_1 in parallel and z_2 in series) to feed the charge controller to the voltage required. The peak power of the photovoltaic array "N_{PV}" is given as:

$$N_{PV} = z \cdot N_o \tag{1}$$

and

$$z = z_1 \cdot z_2 \tag{2}$$

ii. A DC/AC charge controller[9] of "N_c" rated power, charge rate "R_{ch}" and charging voltage "U_{CC}"

iii. A lead acid battery storage system[10] with total capacity of "Q_{max}", operation voltage "U_b" and maximum depth of discharge "DOD_L", thus:

$$Q_{\mathbf{min}} = (1 - DOD_L) \cdot Q_{\mathbf{max}} \tag{3}$$

iv. A DC/AC inverter[11] of maximum power "N_p" able to meet the consumption peak load demand, increased by an appropriate safety factor (e.g. 1.3).

v. The no-active part of installation, including supporting structures, power conditioning devices and wiring.

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

a. The power demand "N_D" is less than the power output of the PV array at the outlet of the inverter, i.e.:

$$\Delta N = \eta_{INV} \cdot N_{PV} - N_D \succ 0 \tag{4}$$

In this case the energy surplus "ΔN" is stored via the battery charge controller. If the battery is full ($Q=Q_{max}$), the residual energy "E_{res}" is forwarded to low priority loads.

b. The power demand is greater than the power output of the PV, which is not zero, i.e. $\Delta N<0$ and $N_{PV}\neq 0$. In similar situations, the energy deficit "ΔN" is covered by the batteries via the charge controller and the DC/AC inverter.

c. There is no solar energy production (e.g. zero solar radiation, system not available etc.), i.e. $N_{PV}=0$. In this occasion all the energy demand is fulfilled by the battery-charge controller-DC/AC inverter subsystem, provided that $Q>Q_{min}$. In cases (b) and (c), when the battery capacity is near the bottom limit, an electricity demand management plan should be applied; otherwise the load would be rejected.

Summarizing, the main parameters -defining the size and subsequently the first installation cost of a similar system- include the photovoltaic module number "z" and peak power "N_o", the batteries maximum capacity "Q_{max}" selected to guarantee the system energy autonomy for the desired time-period along with the rest electronic equipment (inverter, charge controller) peak load capacity "N_p".

3. Proposed Analytical Solution

As already mentioned, the main prospect of this analysis is to estimate the appropriate dimensions of a stand-alone PVS for remote consumers sited all around Greece. The main inputs of the problem are:

- Detailed solar radiation "G" measurements for a given time period (e.g. one year) usually at horizontal plane
- Ambient temperature "θ" data for the entire period analysed
- Operational characteristics (current, voltage) of photovoltaic modules selected, i.e. I=I(U,G) and "N_o"
- Operational characteristics of all the other electronic devices of the installation, i.e. inverter efficiency, battery cell (Q-U;θ) curve etc.
- The electricity consumption profile, based on information provided by the Hellenic National Statistical Agency[12], on an hourly basis (see figure (4)), being also depended[13][14][15] on the year period analysed (winter, summer, other).

Using the above-described information, one should define the numerical values of photovoltaic panels number "z" and the battery maximum size "Q_{max}". For this purpose a computational algorithm "PHOTOV-III" is developed, in order to carry out the necessary parametrical analysis on an hourly energy production-demand base.

Thus, for each pair of "z" and "Q_{max}" the "PHOTOV-III" algorithm (figure (5)) is executed for a specific time period (e.g. one month, six-months, one year etc) and for an hour-long time step, while emphasis is laid on obtaining zero-load rejection operation. If this is not achievable, the battery size is increased and the calculation is repeated until the no-load rejection condition is fulfilled, i.e.:

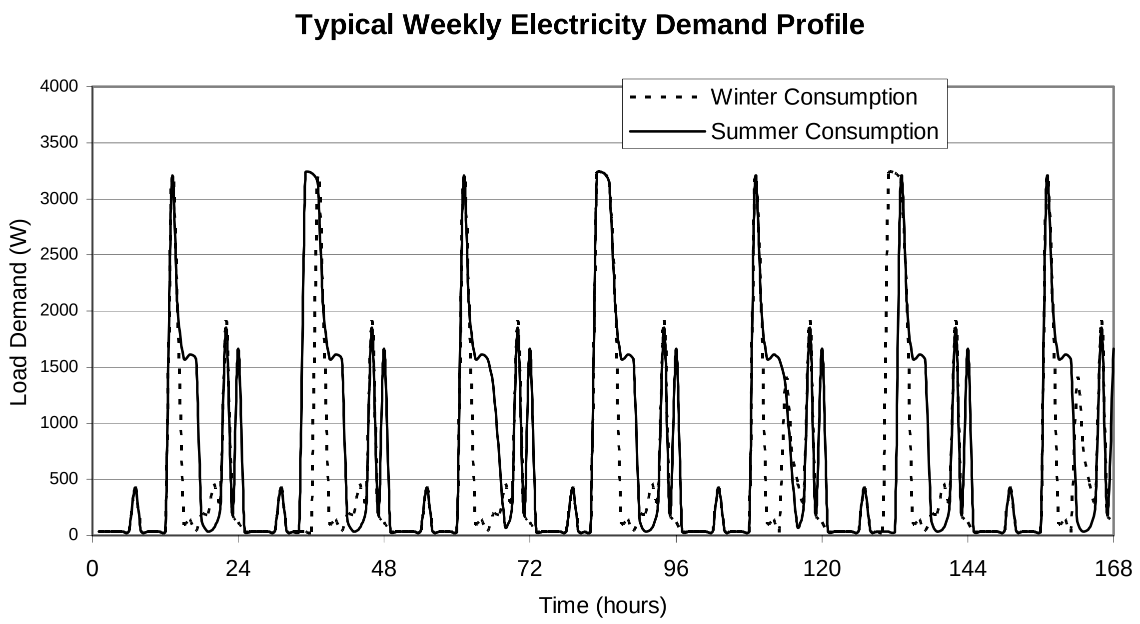

Figure 4: Typical Electricity Demand Profile of the Remote Consumer Analyzed

$$Q^* = \mathbf{min}\{Q_{\mathbf{max}}\} \tag{5}$$

Then the number of photovoltaic panels is increased and the calculation is performed from the very beginning. After the integration of the analysis, a (z-Q^*) curve is predicted under the no-load rejection restriction. To get a clear-cut picture, keep in mind that for every pair of (z-Q^*) the stand-alone photovoltaic system is energy autonomous for the period investigated. Finally, the optimum pair may be selected from the (z-Q^*) no-load rejection curve, if an optimisation criterion is set.

4. Optimum Solution Estimation on the Basis of Minimum First Installation Cost

Integrating the present analysis, it is interesting to introduce the estimation of the first installation cost function, which is used in order to calculate the optimum configuration selected. More specifically the initial cost "IC_o" of a photovoltaic stand-alone system can be approximated as:

$$IC_o = C_{PV} + C_{bat} + C_{elec} + f \cdot C_{PV} \tag{6}$$

where "C_{PV}" is the photovoltaic modules ex-works cost. For small size systems this cost varies[16][17] between 5000€/kWp-7000€/kWp. Similarly "C_{bat}" is the battery bank buy-cost expressed[17][18] as:

$$C_{bat} = c_b \cdot Q_{\mathbf{max}} \tag{7}$$

while "c_b" slightly depends on battery capacity. Thus for the local market –furthering a market survey concerning lead-acid batteries– the following semi-empirical relation may be used:

$$c_b = \frac{5.0377}{Q_{\mathbf{max}}^{0.0784}} \tag{8}$$

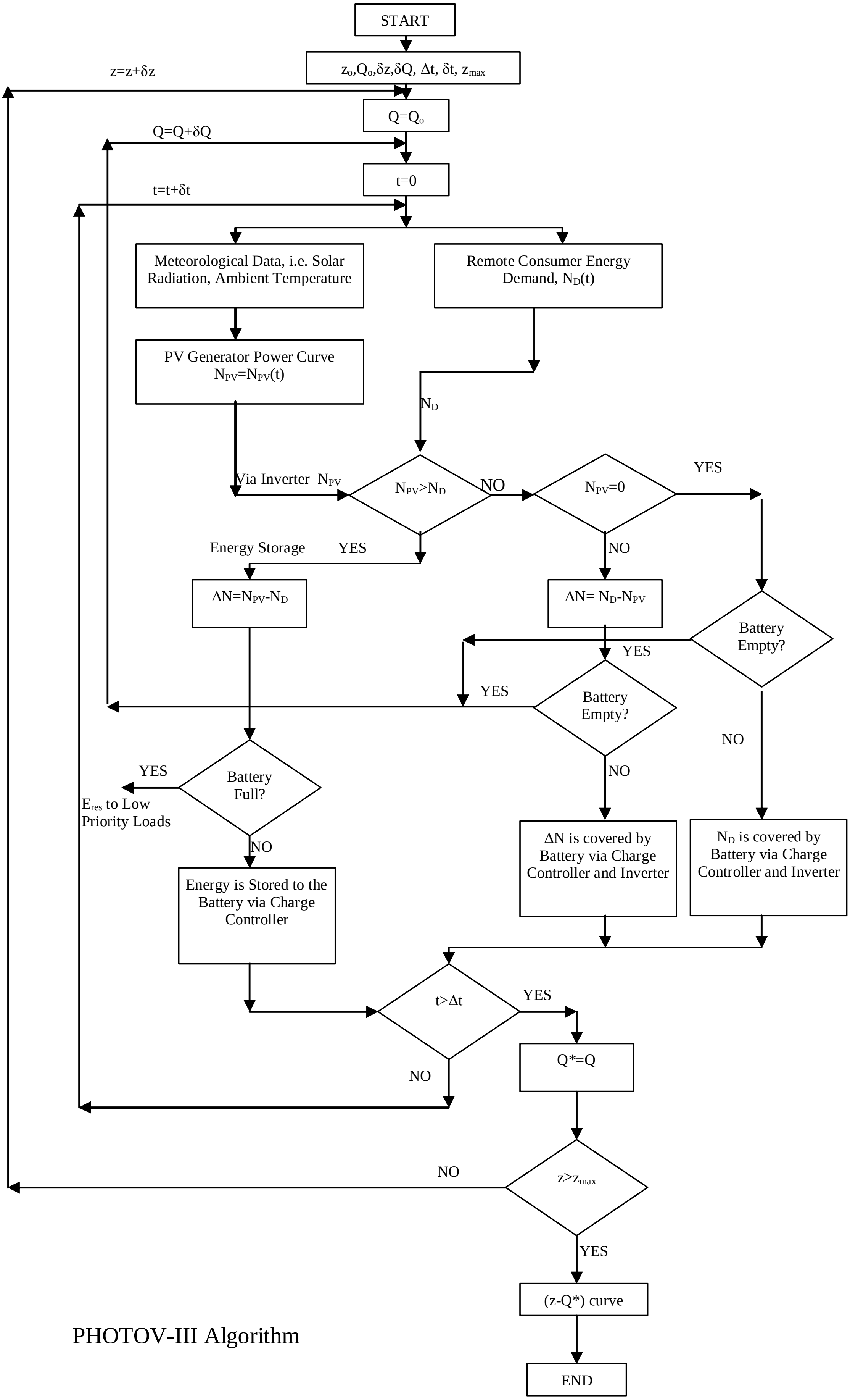

Figure 5: PHOTOV-III Algorithm

Additionally, the cost of the major electronic devices is a function of the peak load demand (e.g. inverter) and the photovoltaic modules rated power (e.g. charge controller). Thus, since the maximum electricity demand of the remote consumer under investigation is prescribed, one may use the following simplified relation valid for the local market:

$$C_{elec} = a + b \cdot (z \cdot N_o) \quad (z \cdot N_o \geq 1kW) \tag{9}$$

with a=1000Euro and b=250Euro/kW.

Finally, the BOS (balance of system) cost is expressed via the first installation cost coefficient "f" (excluding cost of electronic equipment). According to available information[5][8], regarding remote photovoltaic installations, f=5%-15%. Recapitulating and substituting equations (7) to (9) into equation (6) one gets:

$$IC_o = \zeta \cdot z \cdot \mathbf{Pr} \cdot N_o \cdot (1 + f) + c_b \cdot Q_{\mathbf{max}} + a + b \cdot z \cdot N_o \tag{10}$$

where "ζ" is a function of "z" (i.e. $\zeta=\zeta(z)$), expressing the scale economies for increased number of photovoltaic panels utilized, see also figure (1). Subsequently "P_r" is the specific buy-cost of a photovoltaic panel (generally $P_r=P_r(N_o)$) expressed in Euro/kW_p.

Consequently, according to equation (10) the initial installation cost is a function of "z" and "Q_{max}", if "N_o" is defined, thus one may write:

$$IC_o = IC_o(z, Q_{\mathbf{max}}) \tag{11}$$

By drawing the corresponding initial cost constant-price curves, it is possible to estimate the optimum (minimum initial cost) solution, which guarantees energy autonomy of the remote consumer for the time-period examined. In fact, since the optimum solution is strongly depended on the slope of the initial cost (IC_o=const) curves, a more detailed investigation is required, considering the present status and future potentiality of the international market[1][19].

On top of that, it is important to note that Greek State and European Union strongly subsidy small PVS, while the subsidization percentage varies between 40% and 70%. For comparison purposes, it is interesting to remind that the grid connection cost[16][19] exceeds 10000Euro/km, in regions with local electrical network.

5. Application Results

Rhodes is a medium-sized sunny island (98500 habitants, area of 1398km^2) in the SE Aegean Sea, located approximately 600km from Athens. The island is a very famous tourist resort, possessing extremely attractive coaches and abundant sunlight. Several small islands are scattered near Rhodes, which is the capital of the Dodekanessa complex. In those islands, a remarkable number of isolated families reside, having no access to a reliable electrical grid, hence they cover their needs using small oil-fired diesel generators[20].

For all the above-mentioned reasons, Rhodes area is one of the most promising Greek territories to build and operate autonomous photovoltaic systems with significant social, environmental and financial benefits. Figure (6) presents the measured[21] monthly averaged solar energy values (kWh/m^2.mo) for the specific year analysed, in comparison with long-term (1970-82) monthly averaged experimental values[22]. Obviously, the year investigated may be characterized as typically solar-potential, presenting a monthly average distribution similar to the long-term data. Accordingly, in figure (7), the measured solar radiation (on an hourly basis) at horizontal plane is demonstrated for the worst winter (December) and summer (June) solar potential weeks. Parallel measurements of ambient temperature are also utilized. According to the data provided, the proposed installation may possibly face two or three continuous days lacking noteworthy solar radiation.

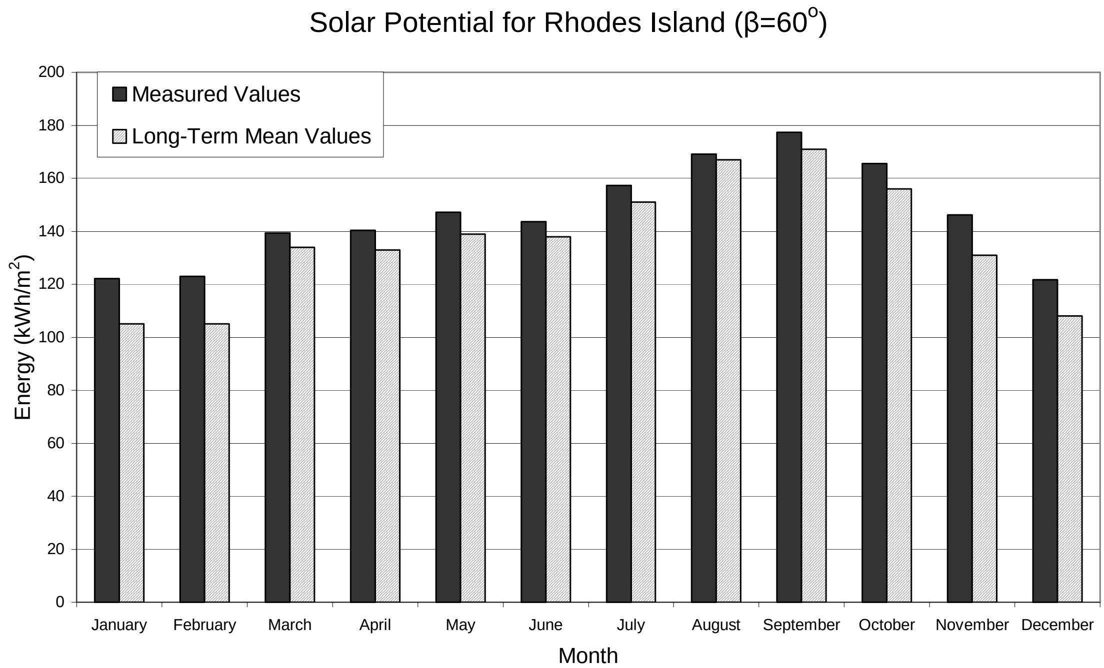

Figure 6: Measured Solar Energy Potential for Rhodes Island

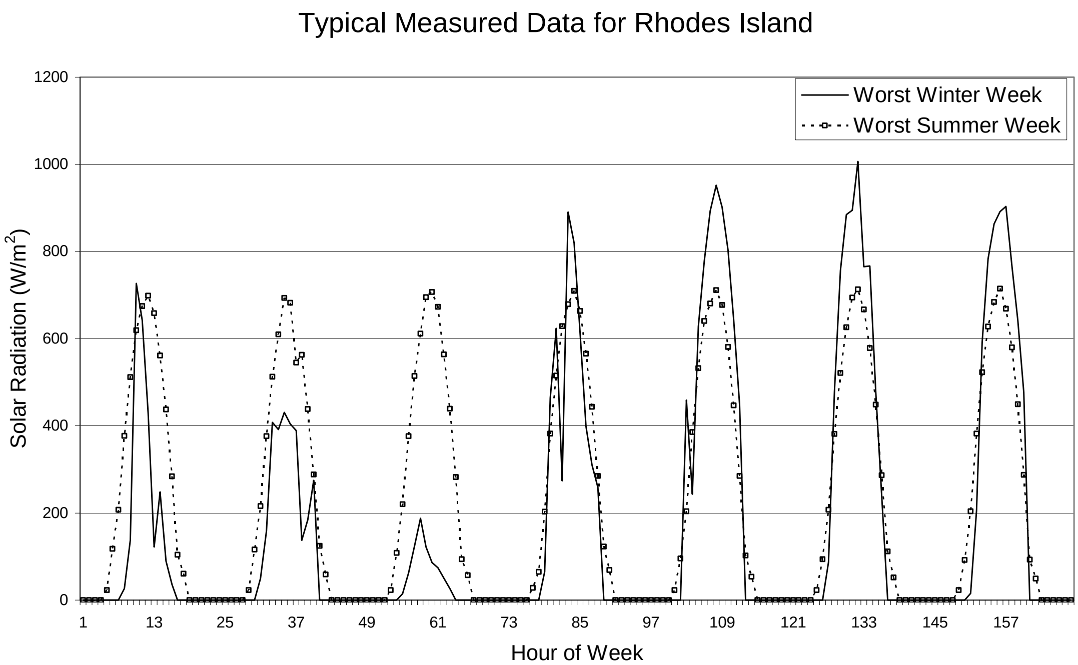

Figure 7: Measured Data on Hourly Basis for Rhodes Island

Using the available experimental data for Rhodes island and applying the "PHOTOV-III" numerical algorithm, the calculation results concerning autonomous photovoltaic panel and battery capacity combinations are summarized in figure (8) for several panel tilt angles (β). More specifically, in figure

(8) one presents all the energy autonomy (Q_{max}-z) pairs of a PVS, for panel tilt angles varying from zero to ninety degrees (0°≤β≤90°). For almost all constant "β" energy autonomy curves, two distinct parts can be defined. In the first part the battery capacity is significantly reduced as the photovoltaic number is slightly increased. This rapid change is more evident for "β" angles greater than 50 degrees. In the second part the battery capacity remains almost constant, not depending on the photovoltaic panels number, achieving an asymptotic value of Q_{max}=1000Ah, for all "β" values examined.

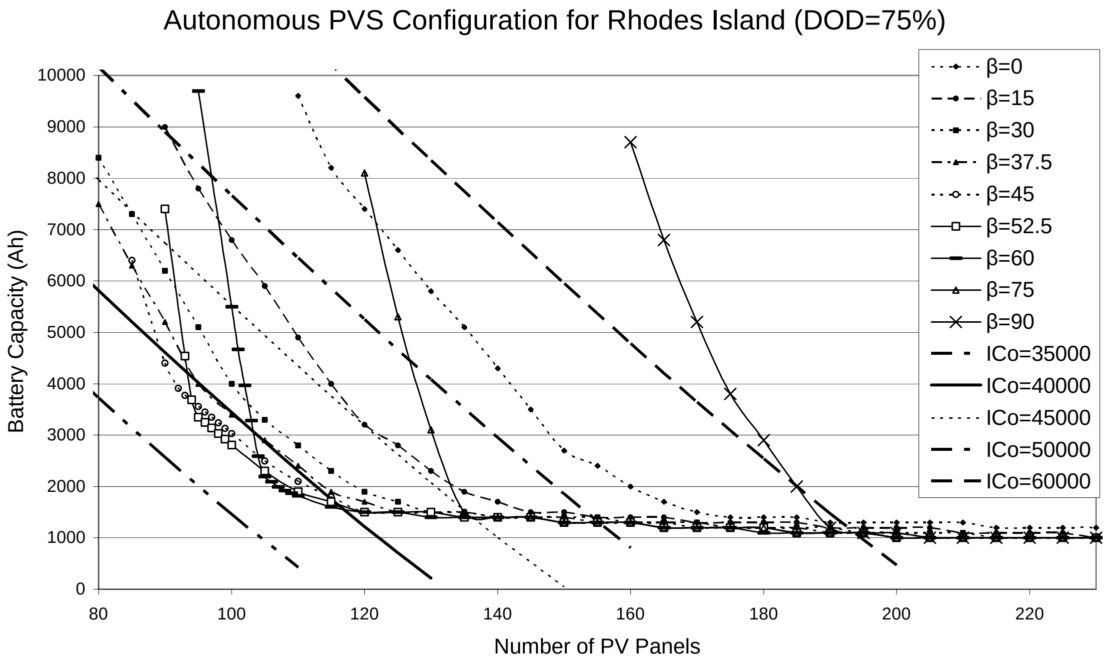

Figure 8: Optimum Autonomous PVS Configuration for Rhodes Island

On the other hand, the influence of "β" angle on the PVS configuration is significant. More specifically, there is a considerable "z" diminution as "β" increases from zero to thirty degrees, while the "z" number is significantly increased as "β" takes values from sixty to ninety degrees, under the restriction of constant battery capacity. Finally, for "β" values in the region of thirty-five to sixty degrees there are several rational (Q_{max}-z) combinations that guarantee zero-load rejection for the time-period analysed.

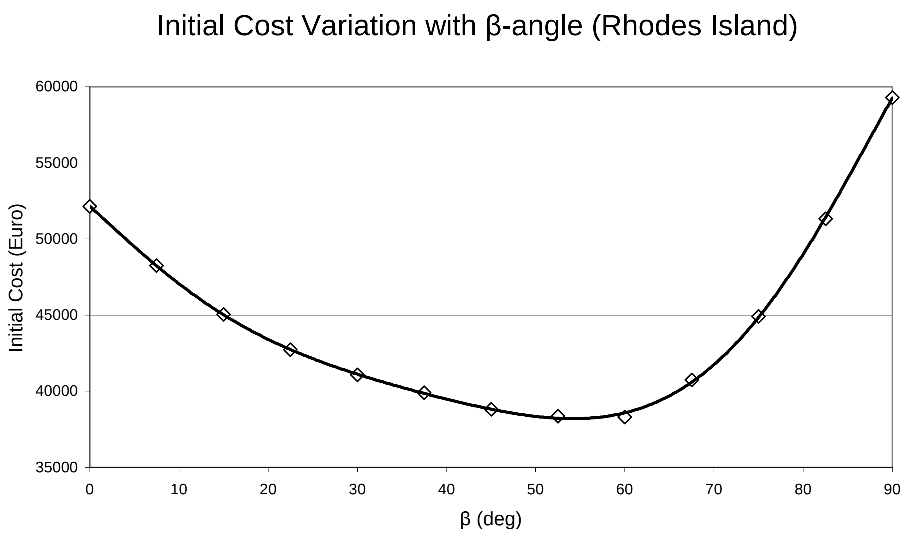

Figure 9: Influence of Panel Tilt Angle on First Installation Cost of an Autonomous PVS

This last comment is more obvious, if the constant initial cost curves (without any subsidization) are taken into consideration. In this context, one has the ability to select the minimum initial cost solution that guarantees the system energy autonomy for the year examined. Hence, the optimum configuration may be achieved using either ninety-five photovoltaic panels (z=95, N_o=51W) at panel tilt angle of 52.5° and battery capacity of 3350Ah (DOD=75%, 24Volt) or one hundred-five panels (z=105, N_o=51W) at panel tilt angle of 60° and battery capacity of 2190Ah. Keep in mind that the "IC_o=ct" curves are based on current local market information, valid during 2002. Concluding, the minimum initial cost autonomous PVS configuration at Rhodes region turns to be the second one (figure (9)), with a minimum capital to be invested equal to 19000Euro, since there is a 50% State subsidization option for small photovoltaic systems (under 20kW) in the current frame of National Competitiveness Programme.

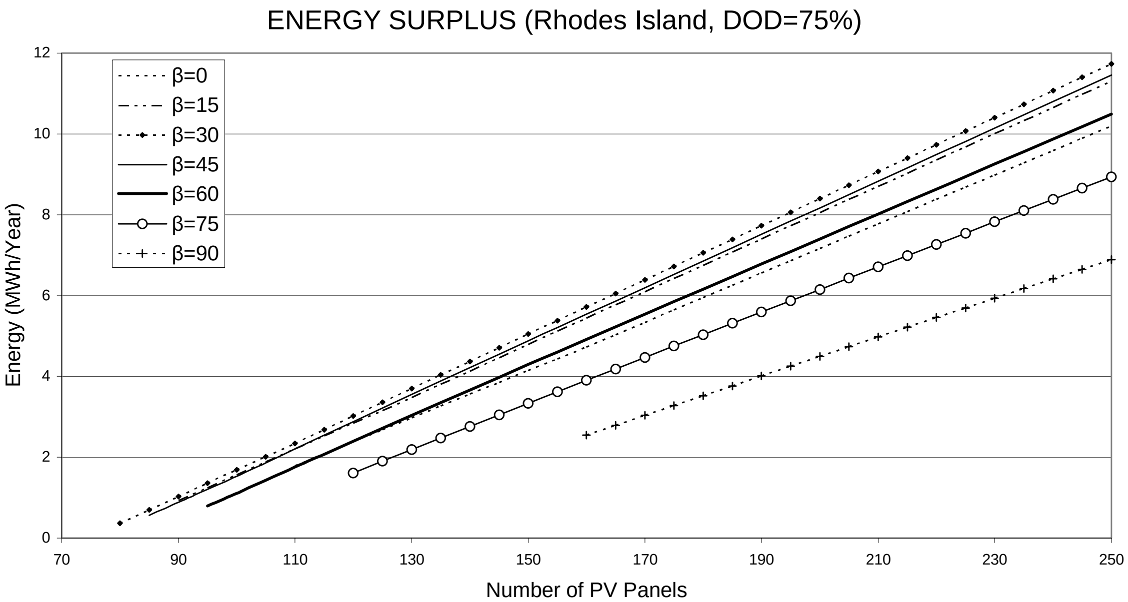

Figure 10: Energy Surplus of an Autonomous PVS in Rhodes Island

Another interesting information resulting from the application of the "PHOTOV-III" numerical code is the annual energy surplus "E_{res}" of the stand-alone system, figure (10). As expected, the energy surplus is a linear function of photovoltaic panels' number, while for "z" greater than ninety the energy surplus represents a significant part of the PVS energy consumption (i.e. approximately 5MWh per year). At this point it is important to mention that the minimum initial cost solution (i.e. β=60°, z=105, Q_{max}=2190Ah) represents a low energy surplus case.

Subsequently, analysing on a monthly basis the energy surplus profile for the optimum system configuration, figure (11), one may easily observe that there is a considerable solar energy over-production during the hot months (summer); a fact that may encourage the optional usage of energy surplus by a small desalination plant[23], in order to cover the increased clean water demand during summer.

The second case to be analysed concerns Zakinthos (39000 habitants, area of 434km^2), an island located at the South Ionian Sea next to NW Peloponessos. Zakinthos island also possesses a very high solar potential, figure (2), while the local wind speeds are limited, hence the exploitation of photovoltaic energy is the most promising electrification solution for remote consumers. Generally speaking, the solution obtained for Zakinthos island, figure (12), concerning the optimal PVS configuration for various panel tilt angles is quite similar to the Rhodes island one, considering that they are almost 1000km apart. Thus, as in the previous case for constant battery bank capacity, there is a considerable "z" reduction when "β" increases from zero to thirty degrees, while the opposite change is encountered when "β" exceeds sixty degrees. Another interesting conclusion drawn from figure (12) is the asymptotic behaviour of battery capacity needed (1450Ah) to guarantee energy autonomy of the system, being almost independent from the photovoltaic power used.

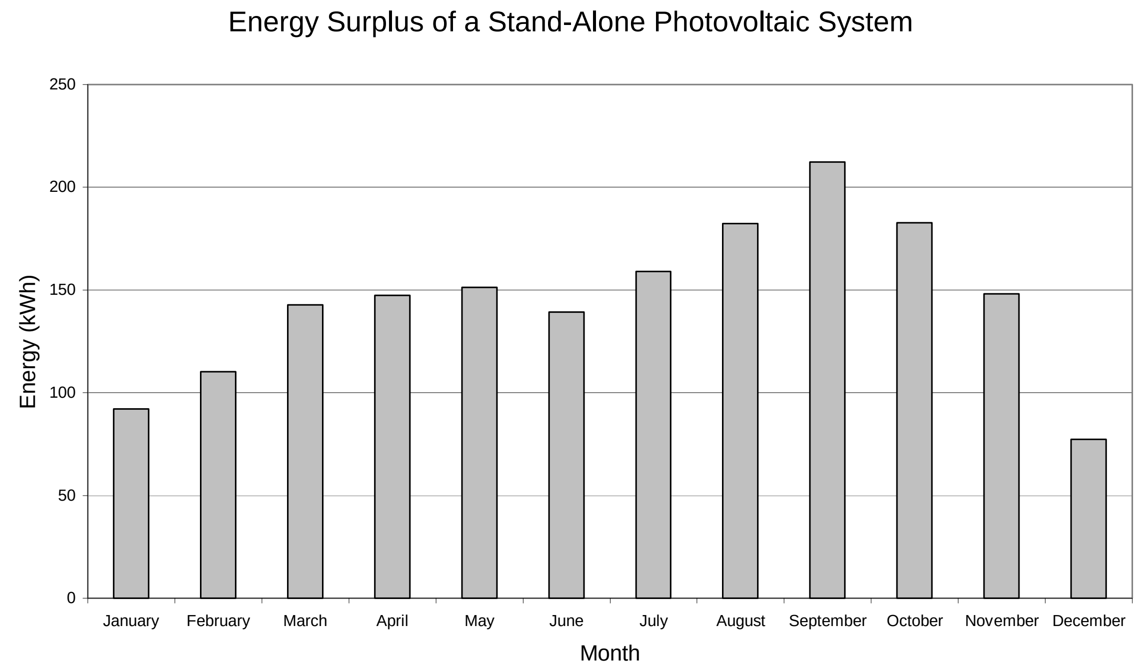

Figure 11: Energy Surplus Profile for the Optimum Autonomous PVS Configuration, Rhodes Isl.

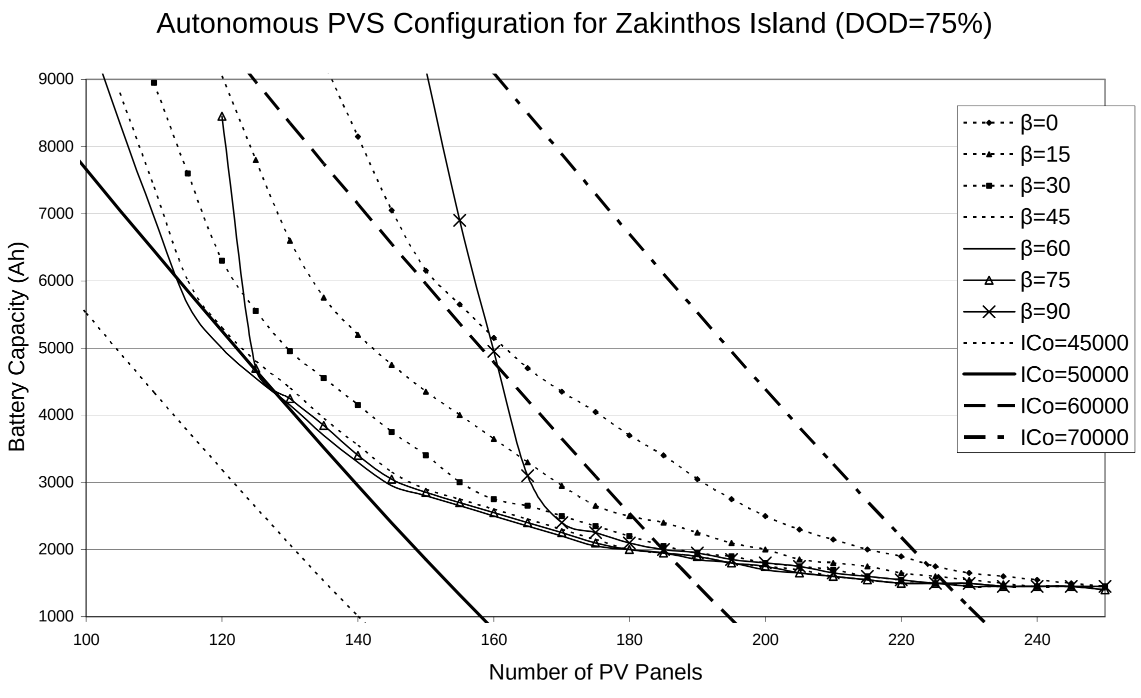

Figure 12: Optimum Autonomous PVS Configuration for Zakinthos Island

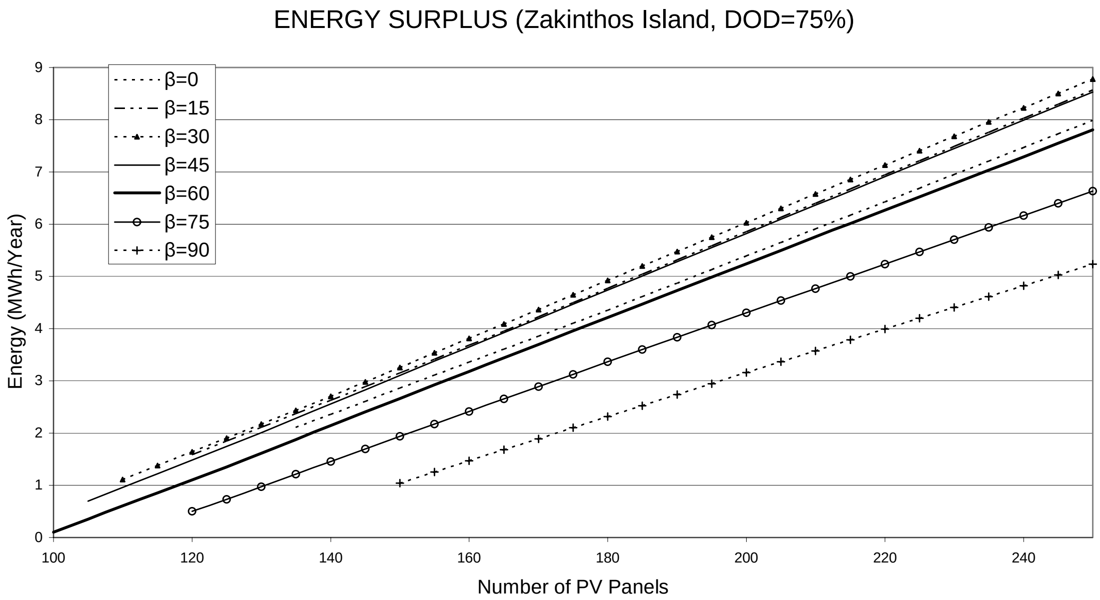

Figure 13: Energy Surplus of an Autonomous PVS in Zakinthos Island

The minimum initial cost solution can be estimated using the "IC_o=constant" curves, see also equation (10). Hence, the minimum initial cost configuration is based on 120 photovoltaic panels of 51W each (i.e. N_{PV}=6120W), a 24Volt battery of 5000Ah (90kWh, DOD=75%), while the corresponding first installation cost is approximately 49400Euro, being normally half subsidized by the Greek State.

Evidently, by using an increased number of photovoltaic panels there is remarkable energy excess, which is a linear function of the photovoltaic panel number "z", figure (13). As expected, the energy surplus for high "β" values is less than the corresponding one for medium and low "β" values (i.e. β≤45°), while the optimum PVS configuration for panel tilt angle equal to 60 degrees achieves quite limited energy surplus values, figure (13).

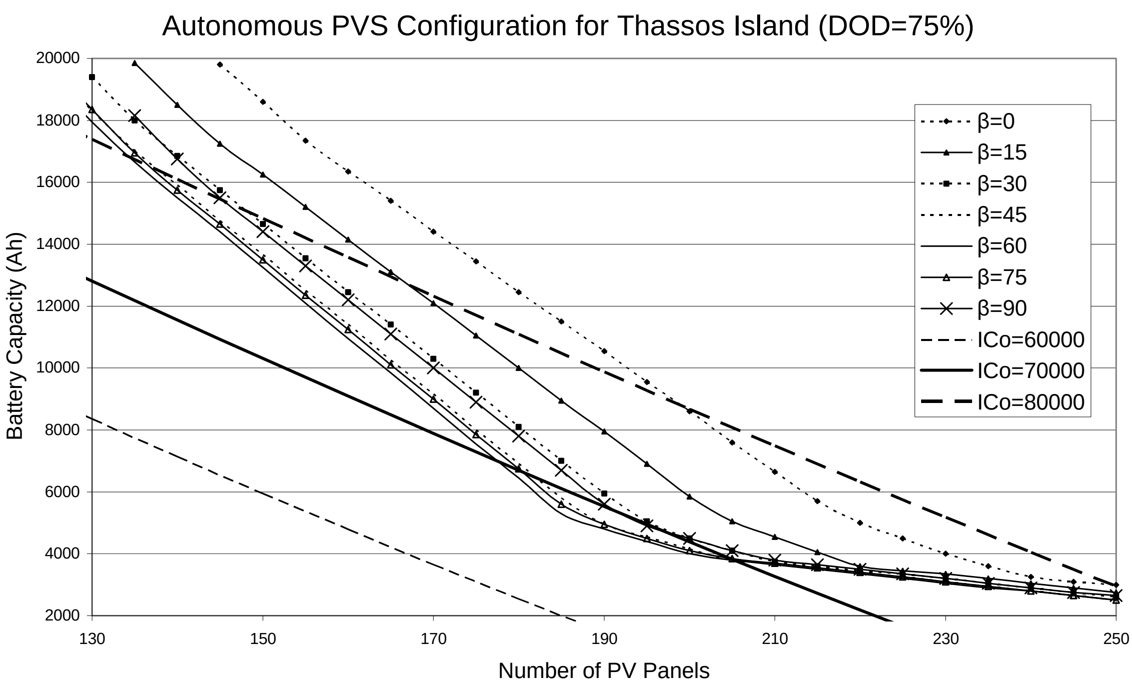

Figure 14: Optimum Autonomous PVS Configuration for Thassos Island

The last case investigated is Thassos, a small North Greece island (13500 habitants, area of 395km^2), located in north Aegean Sea, near Kavala city. In this area, the solar radiation is below Rhodes or Zakinthos, being however greater than 1400kWh/(m^2 and year). Using the "PHOTOV-III" numerical code to define the size of an energy-autonomy PVS in this North Greece area, the calculation results are summarized in figure (14), along with the constant initial cost curves. For this last case, the (Q_{max}-z) curves are similar to the ones of figures (8) and (12), although the slope of the constant "β" curves is less abrupt than the Rhodes and Zakithnos island cases. On top of that, the size of the proposed PVS configuration is almost double (i.e. 185 photovoltaic panels of 51W and 5300Ah of nominal battery capacity), leading the first installation cost close to the 68000Euro, without any external subsidization. Finally, as in the previous two cases examined, the optimum panel tilt angle for a PVS in Thassos island is also sixty degrees.

Another interesting output of the proposed analysis is the annual energy surplus distribution given in figure (15) for all the system combinations analysed. As derived from figures (10), (13) and (15), the energy surplus in Thassos area presents a distribution similar to the Rhodes and Zakinthos cases, being however lower than the other regions for the same "z" number. On the other hand, the optimum configuration solution leads to higher energy surplus values due to the increased photovoltaic panel number used.

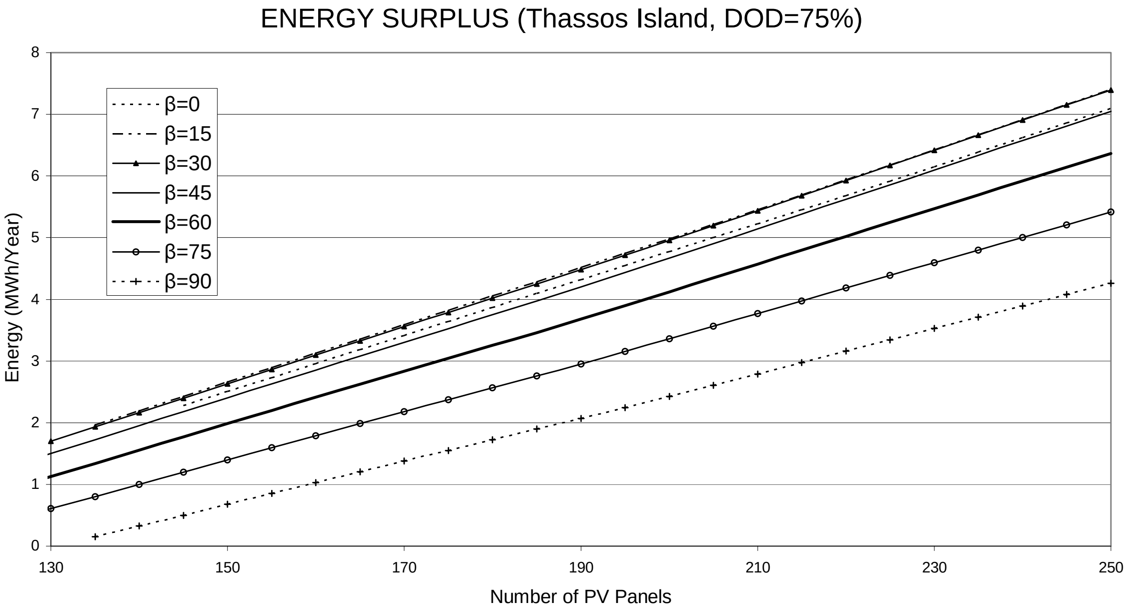

Figure 15: Energy Surplus of an Autonomous PVS in Thassos Island

Recapitulating, Table I presents the calculation results concerning the main characteristics of an autonomous photovoltaic system situated in three representative island territories of Greece, figure (2). For comparison purposes, figure (16) portrays the initial cost variation for all three regions analysed and for the same time period as a function of the panel tilt angle. According to the information presented, the optimum angle tilt is around sixty degrees for all cases analysed, while the dimensions and the initial cost of an autonomous photovoltaic system are strongly depended on the exact location or more accurately the solar potential of the installation. Thus, it is quite amazing to remark that between south and north Aegean Sea one needs more than double battery bank capacity and almost 80% greater photovoltaic power to meet the electricity requirements of the same consumer. However, the first installation cost is not prohibitive, even for the worst case, considering the significant financial support provided by the Greek State (≈50%) and the required amount of almost 10000-12000Euro per kilometre of electrical grid extension.

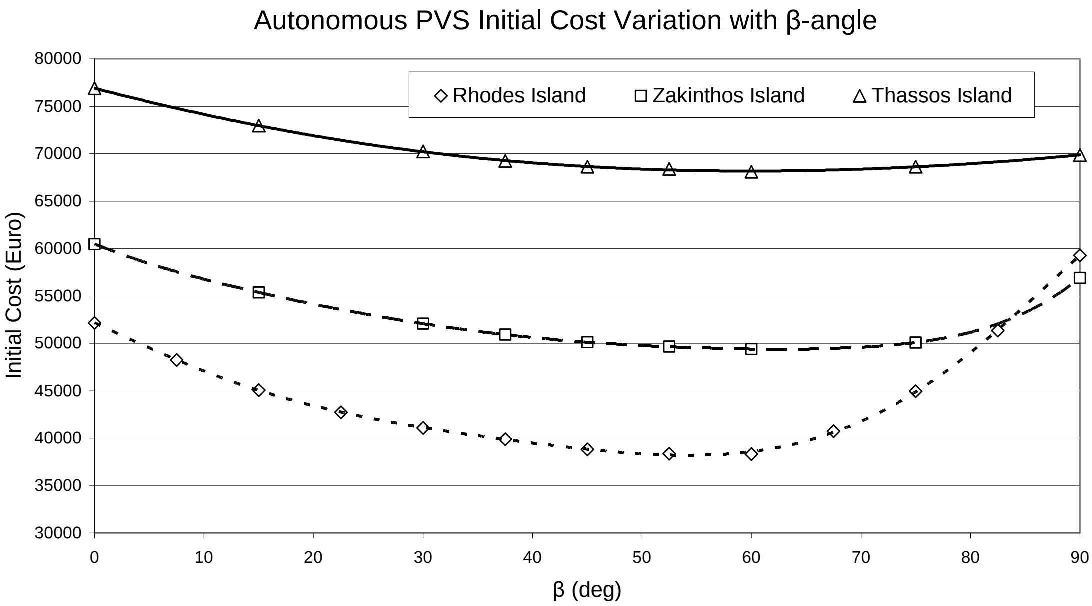

Figure 16: Initial Cost Variation with Panel Tilt Angle for Typical Greek Island PVSs

Table I: Photovoltaic Stand-Alone System Characteristics for Representative Greek Islands

Location	**(z) PV Panel Number**	**Q_{max} (Ah)**	**ICo (Euro)**
Rhodes Island	105	2190	38300
Zakinthos Island	120	5000	49400
Thassos Island	185	5300	68100

6. Conclusions

The optimum dimensions of an autonomous photovoltaic system are defined for typical regions of island Greece, using representative solar potential data. The results obtained are based on experimental measurements and operational characteristics by the autonomous system components manufacturers. For the system simulation a reliable and fast numerical code "PHOTOV-III" has been developed, in order to estimate the energy-autonomy photovoltaic panel number and battery bank capacity combinations, for every region and time period analysed. Besides, the algorithm finds the optimum panel tilt angle that minimizes the first installation cost of the proposed PVS.

Among the most interesting findings of the present research it is the energy-autonomous curve (Q_{max}-z) shape and the impact of panel tilt angle on it. Accordingly, one may underline the remarkable autonomous PVS size difference between South and North Greece locations, leading to a more than 75% higher initial cost in North than in South Greece. However, in all cases analysed the capital to be invested -considering the 50% State subsidization- varies between 19000 and 39000Euro, being equivalent to 1.5 to 3km of electrical grid extension, if obtainable.

Recapitulating, the proposed photovoltaic energy autonomous system turns to be one of the most excellent solutions for the electricity demand of numerous remote consumers' even in North Greece areas. On top of that, for high solar radiation areas small PVS are characterized as economically attractive investments, especially if the subsidization opportunities by local authorities are taken into consideration. Thus, according to the results obtained the authors believe than an autonomous photovoltaic system can definitely contribute on solving the urgent electrification problem of remote consumers spread throughout Greece, also improving their life quality level.

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OPTIMUM SIZING BASIC PRINCIPLES OF A COMBINED PHOTOVOLTAIC-WIND-DIESEL HYBRID SYSTEM FOR ISOLATED CONSUMERS

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Abstract

Aegean Archipelago is a remote Hellenic area, where a considerable number of isolated consumers - having no access to a constant and reliable electricity resource- exist. However, all the area possesses an abundant and reliable solar energy supply for the entire year, along with a remarkable wind potential. In an attempt to minimize the oil dependency and improve the life-quality of isolated consumers, the idea of creating a combined photovoltaic-wind-diesel hybrid system with the existence of an additional energy storage device is investigated. In this context, the main parameters of the proposed hybrid system dimensions are defined, according to the electricity consumption requirements, along with the characteristics of the local solar and wind potential. Finally, the present study takes into account the existing information concerning the initial and the maintenance and operation cost of similar small size power stations, in view of the remarkable Greek State subsidization for similar renewable energy applications.

Keywords: Wind; Solar; Hybrid System; Diesel; Isolated Consumer

1. Introduction

Aegean Archipelago is a remote Hellenic area, at the east side of the mainland, including several hundreds of scattered islands. In these regions there is a considerable number of isolated consumers having no access to a constant and reliable electricity resource and being, therefore, forced to meet their needs using small diesel-electrical generators consuming expensive imported oil[1].

On the other hand, all these islands are located in regions with an abundant and reliable solar energy supply for the entire year, while their majority also possesses remarkable wind potential[2], figure (1). In an attempt to minimize the oil dependency and improve the life-quality of isolated consumers, the idea of creating a combined photovoltaic-wind-diesel hybrid system[3,4] with or without the existence of an additional energy storage device[5] is investigated.

In this context, the main parameters of the proposed hybrid system dimensions are defined, according to the electricity consumption requirements, along with the characteristics of the local solar and wind potential. More specifically, the supplementary availability (see for example figure (2)) of solar and wind energy significantly reduces the inevitable diesel engine operation and the energy storage requirements.

Finally, the present study takes into account the existing information concerning the initial and the maintenance and operation cost of similar small size power stations[4], in view of the remarkable Greek State subsidization for similar renewable energy applications.

2. Position of the Problem

The problem to be solved in the present study concerns the electricity demand fulfillment of an isolated consumer, on the basis of renewable energy resources and under the precondition of a rational investment cost. The proposed solution takes advantage of the existing wind and solar potential of the area investigated, thus a micro wind converter and a small photovoltaic station may be used, in collaboration with an internal combustion engine and a properly sized energy storage device.

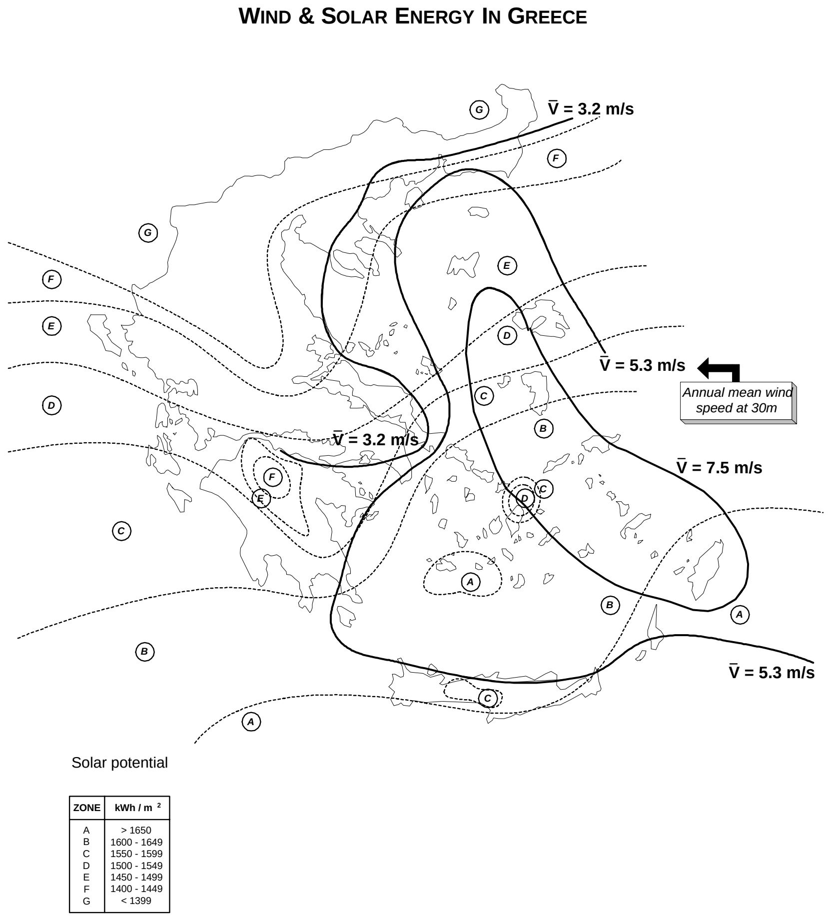

Figure 1: Wind-Solar Potential in Greece

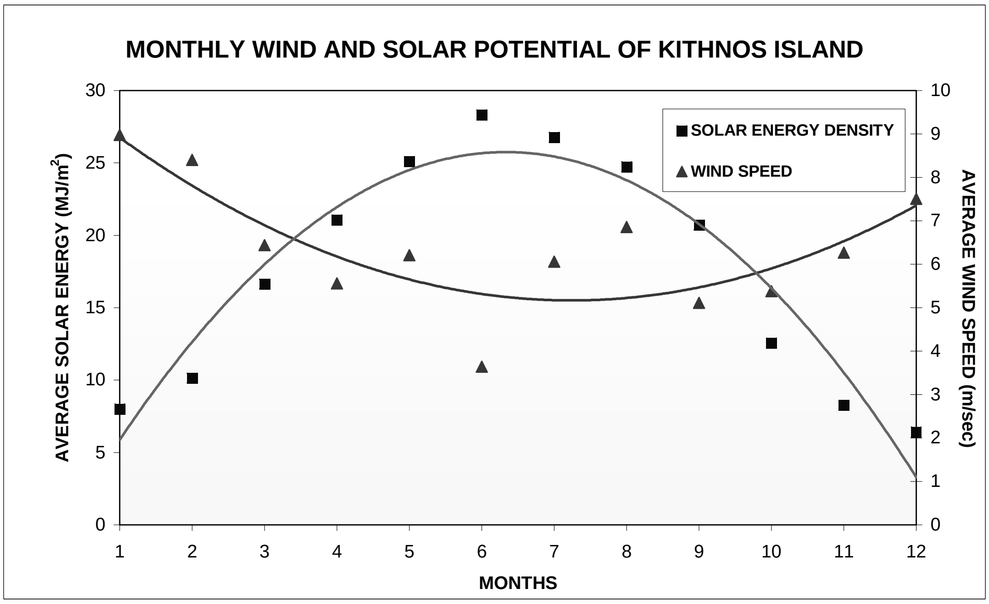

Figure 2: Wind-Solar Potential of a Typical Remote Island

Among the necessary data, in excess of wind and solar potential characteristics, there are the electricity consumption profile of the isolated consumer and the corresponding ambient conditions for at least one year. The main purpose of the new solution is to fulfill the electricity demand "N_D" of the system in any case, with minimum production cost, limiting the contribution of the diesel generator. According to the present analysis, the following cases are possible:

(I) The energy production by the combined wind-solar station is higher than the power demand. In this case, the energy surplus is forwarded to the energy storage device. If this system is full, the energy excess is used by low priority loads.

(II) The power demand is higher than the power output of the wind-solar station. Hence, the power deficit is covered by the energy storage system, assuming that the batteries are not near the low discharge limit.

(III) The power demand cannot be covered by the wind-solar station and the batteries are near the maximum permitted depth of discharge. In similar cases, the internal combustion engine starts working under a scheduled procedure[6]. For this last case, in order to minimize the diesel start ups and protect the batteries from deep discharge versus increased fuel consumption, one has to choose whether the diesel generator should be used only on emergency cases or on a regular basis, so as to charge the battery system.

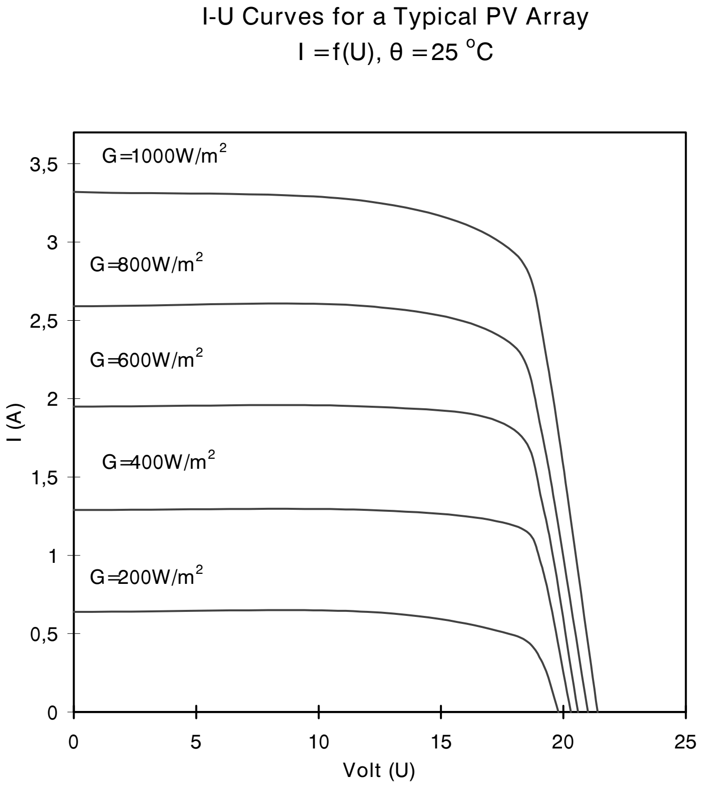

Figure 3: Operational Curves for a Typical Crystalline Silicon PV Array

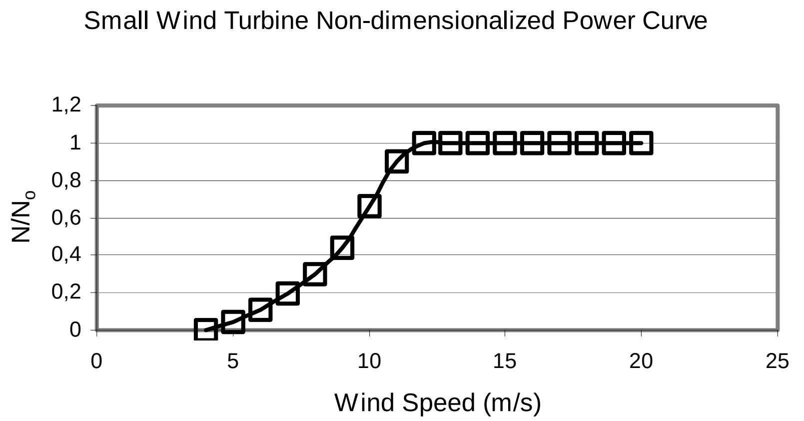

Figure 4: Non-dimensionalized Power Curve for a Typical Wind

3. Theoretical Model

The power produced at a time point "t" by the proposed hybrid station "N(t)" is mainly dependent[2] on the local wind speed "V(t)" and the available solar radiation "G(t)", along with the existing ambient conditions (i.e. temperature, pressure, humidity etc.) and the operational characteristics of the equipment used (i.e. micro wind turbine and photovoltaic panels). Thus one may write:

$$N(t) = N_{PV}(t) + N_{WT}(t) + N_d(t) \quad (1)$$

where:

$$N_{PV}(t) = z \cdot N_{PV}(G, U, \theta) \quad (2)$$

$$N_{WT}(t) = N_{WT}(V, p, \theta) \quad (3)$$

$$N_d(t) = \eta_d \cdot \dot{m}_f \cdot H_u \quad (4)$$

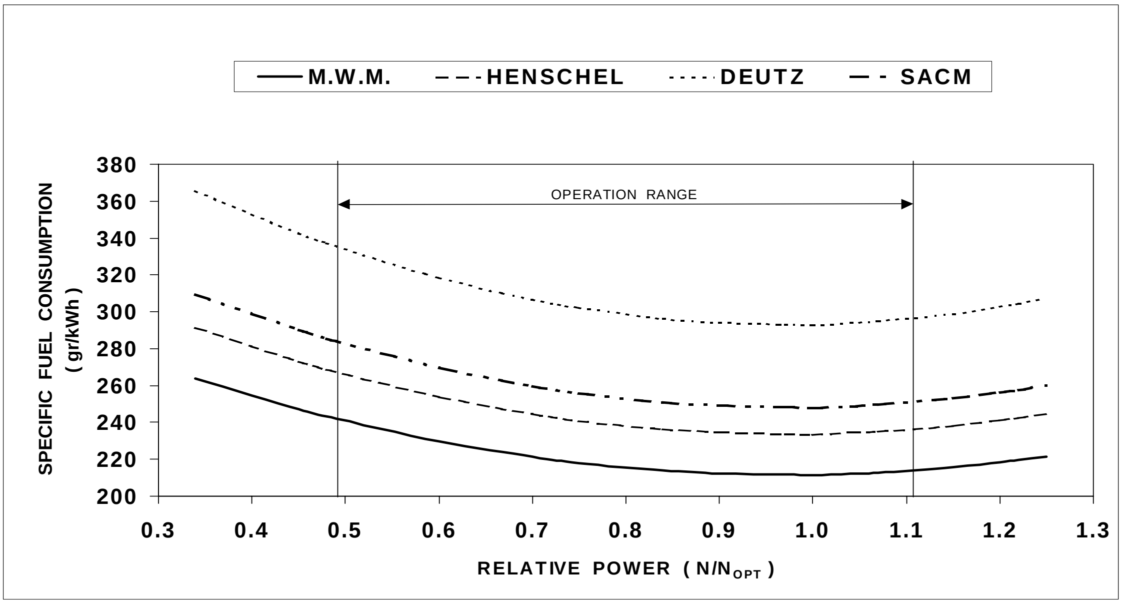

Figure 5: Diesel generators' SFC

More specifically the photovoltaic system consists of "z" similar panels properly connected (z_1 in parallel x z_2 in series), while the power curve (N_{PV}) of each panel used depends on the available solar intensity "G" and the corresponding air temperature "θ". In figure (3), the "N=N(U)" curve is presented as a function of the system voltage for variable solar intensity and given panel temperature.

Similarly, the exit power of the selected micro-wind converter is a function of the available wind speed "V", the ambient conditions (mainly air density) and the operational characteristics of the machine, figure (4).

Finally, the internal combustion engine outlet power is strongly related to the specific fuel consumption (SFC) and the demanded load from the engine, figure (5). Note that the engine efficiency "η_d" and the fuel specific calorific value "H_u" define the "SFC", while "$\dot{m}_f$" is the corresponding mass fuel consumption of the engine.

On top of that, in case that an energy storage device is included, a lead-acid heavy-duty industrial battery system is assumed as the most appropriate solution[5]. In this context, the selected battery system is characterized by the maximum storage capacity "Q_{max}", the operational voltage "U", the maximum permitted depth of discharge "DOD_L" and the corresponding Q=Q(U,θ) operational curve under given temperature conditions.

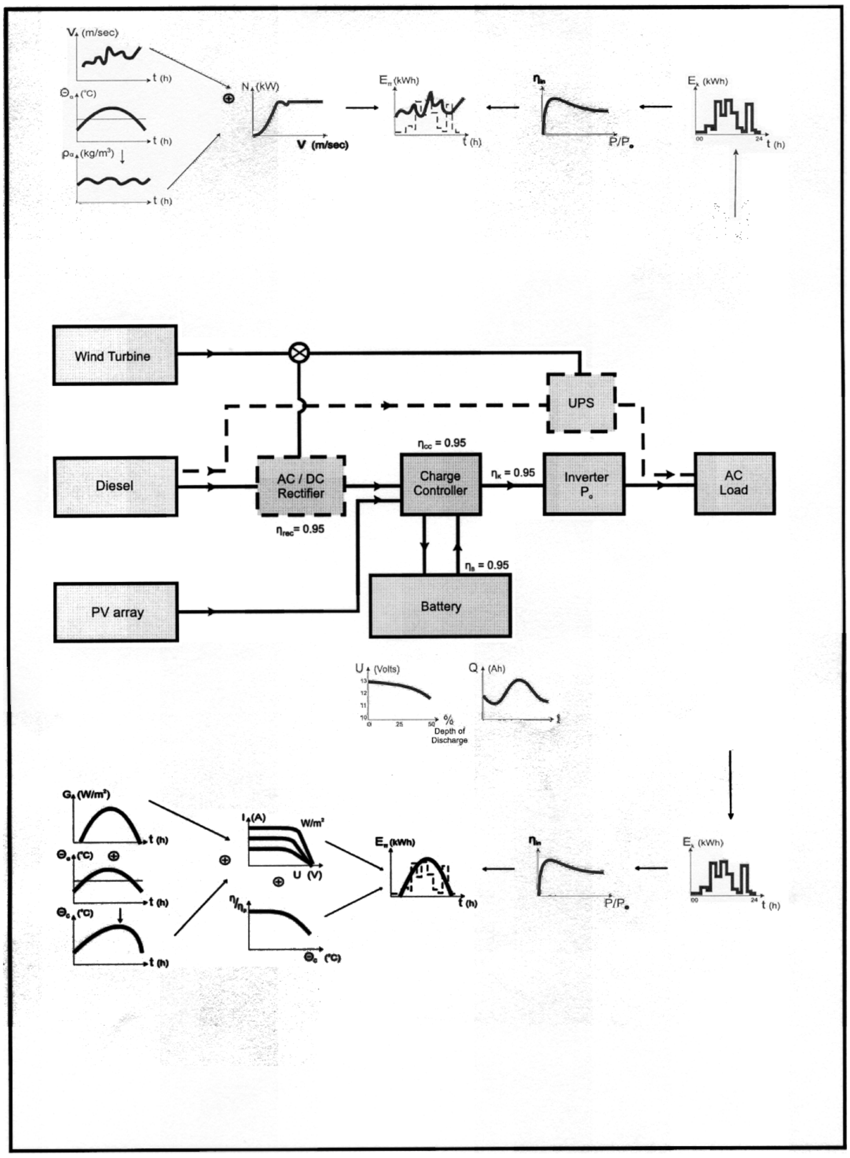

Figure 6: Proposed Autonomous Hybrid System

Accordingly, the first installation cost "IC_o" of the proposed configuration includes[3,4] the wind turbine price (ex-works) "C_{WT}", the photovoltaic system purchase cost "C_{PV}", the batteries buy-cost "C_{bat}", the internal combustion engine initial cost "C_d", the additional cost of the electronic equipment "C_{elec}" and the cost of creating the stand-alone system, expressed as a fraction "f" of the ex-works price of the equipment mentioned[7], i.e.:

$$IC_o = (1 + f) \cdot (C_{WT} + C_{PV} + C_d + C_{elec} + C_{bat}) \tag{5}$$

Accordingly, the maintenance and operation (M&O) cost can be split[7] into the fixed maintenance cost "FC_n" and the variable one "VC_n". The variable M&O cost is defined by the replacement of some major parts of the installation (e.g. batteries, diesel engine, rotor blades or gear box, electronics) with shorter lifetime than the complete installation. On the other hand, the annual fixed M&O cost of the energy production system can be expressed as a fraction "m" of the corresponding initial capital invested (using also an annual increase of the cost equal to "g^{Σ}") plus the fuel consumption -by the diesel generator- cost. Summarizing, the future value of the total investment cost can be expresses as:

$$C_n = (1 - \gamma) \cdot IC_o \cdot (1 + i)^n + FC_n + VC_n \tag{6}$$

where "γ" is the subsidy percentage by the Greek State. For example, according to the existing 2601/98-development law, a 40 percent subsidy is provided to private investors in the area of renewable energy applications, for all over the country, and "i" is the corresponding capital cost.

4. Proposed Solution

In order to meet the electricity demand of isolated consumers, an integrated energy production system is devised[8], similar to the one of figure (6). Hence, the proposed system comprises:

a. A micro wind converter of rated power "N_o"
b. A photovoltaic station based on "z" panels with peak power "N_p"
c. A small internal combustion engine of "N^*" kW
d. A lead acid battery storage system of "Q_{max}" Ah
e. An AC/DC rectifier
f. A DC/DC converter
g. A UPS (uninterruptible power supply)
h. A DC/AC inverter

During the operation of the system the following energy production scenarios exist:

- ✓ Energy (AC current) is produced by the micro wind converter and sent directly to the consumption via the UPS
- ✓ Energy is produced (AC current) by the small diesel generator and is forwarded to the consumption via the UPS
- ✓ Energy is produced (DC current) by the photovoltaic station and it is forwarded to the consumption via the (DC/AC) inverter
- ✓ The energy output of the wind turbine is transformed to DC current (via AC/DC rectifier) and subsequently is stored at the batteries via the charge controller
- ✓ The diesel generator is used to charge the batteries via the AC/DC rectifier and the charge controller
- ✓ The battery is used to cover the energy deficit via the charge controller and the DC/AC inverter

Recapitulating, using the above-described piece of information it is possible to determine the proposed system dimensions in order to fulfill the maximum load demand of the consumption, including a safety coefficient.

5. System Sizing

5.1 Wind Turbine

Small wind turbines used for electricity production start operation (cut-in speed) at a wind speed approximately 3-5m/s, while they stop their operating at almost 20m/s. Thus, for the estimation of the nominal power "N_o" of a wind turbine the following relation may be used:

$$\frac{E_{tot}}{8760 \cdot CF} \le N_o \le \frac{E_{tot}}{8760 \cdot CF \cdot \eta^*} \qquad (7)$$

where "E_{tot}" is the system annual electricity consumption (increased by 15% to take into account future changes) and "CF" is the capacity factor of the installation. 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:

$$\mathrm{CF} = \Delta \cdot \omega \tag{8}$$

More precisely, "ω" can be computed[9] as:

$$\omega = \int_0^\infty \frac{N(V)}{N_o} \cdot f(V) \cdot dV \tag{9}$$

with "V_c" and "V_F" the corresponding[2] 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.

Eventually, "η^*" is the energy transformation coefficient of the system, expressing the portion of the wind energy produced, stored via the battery system and finally contributed to consumption.

5.2 Photovoltaic Generator

Photovoltaic systems comprise an array of PV modules that produce electricity, taking advantage of the existing solar radiation. Due to the limited size of the installation, the usage of a Maximum Power Point Tracker (MPPT) is not suggested[10]. As it is obvious from figure (4), the magnitude of the direct current output from a PV array varies directly with the level of solar radiation. On the other hand, the voltage of a PV cell is mainly depending on the cell temperature. Thus, the number "z" of PV panels is defined as:

$$\frac{E_{tot}}{8760 \cdot CF'} \le z \cdot N_p \le \frac{E_{tot}}{8760 \cdot CF' \cdot \eta'} \tag{10}$$

where:

$$z = z_1 \cdot z_2 \tag{11}$$

and

$$z_2 = \frac{U_{cc}}{U_{pv}} \tag{12}$$

Note that "CF'" is the photovoltaic installation capacity factor, "U_{pv}" is the PV cells operation voltage, "U_{cc}" is the charge controller voltage and "η'" is the corresponding energy transformation coefficient, similar to "η^*", taking into account that the PV production is not rectified.

5.3 Diesel Generator

The most widely applied solution for fulfilling the remote consumers' electrification needs is the installation of a small internal combustion engine in combination with a small electrical generator. Although the efficiency of such a system is quite low (~20%) the corresponding buy cost is restricted (~150€/kW) in comparison with the initial cost of the collaborating renewable energy devices. On the other hand, the corresponding maintenance & operation cost (mainly due to fuel cost) is quite high, if one takes into consideration the continuously escalating diesel oil price in Greece, especially in remote areas[11]. In this context the diesel generator nominal power is assumed equal to peak load demand "N_{max}" increased by "δN" for safety reasons, thus:

$$N_d = N_{\mathbf{max}} + \delta N \tag{13}$$

In case that the diesel is used exclusively to charge (efficiency "η_{ch}") the system batteries in a specific time period "τ" under voltage "U_{cc}'" and charge current "R_{ch}", one may write:

$$N_d = \frac{\int_{Q'_{min}}^{Q_{max}} Q(U) \cdot dU}{\eta_{ch} \cdot \tau} \tag{14}$$

5.4 System Batteries

The battery size is defined by the autonomy hours "h_o" of the system without the diesel engine usage, the total annual energy demand "E_{tot}", the efficiency of the storage system and the maximum permitted depth of discharge "DOD_L". Selecting "U_{bat}" as the battery operation voltage ($U_{bat} \leq U_{cc}^{/}$), the maximum battery capacity (in Ah) is given as:

$$Q_{max} = \frac{h_o \cdot E_{tot}}{8760} \cdot \frac{1}{\eta_s \cdot DOD_L \cdot U_{bat}} \tag{15}$$

At any case the battery capacity "Q" varies between:

$$(1 - DOD_L) \cdot Q_{max} = Q_{min} \leq Q \leq Q_{max} \tag{16}$$

However, since "DOD_L" value is strongly related to the life duration (operation cycles "n_c") of the batteries, i.e.:

$$DOD_L \cdot n_c \approx 1200 - 1500 \tag{17}$$

one may select a higher minimum permitted battery discharge limit "$Q_{min}^{/}$", taking advantage of the diesel generator existence. In such a case, when "Q" becomes less than "$Q_{min}^{/}$", the diesel generator charges the batteries, in order to avoid deep discharge at expense of oil consumption.

5.5 System Electronic Devices

The AC/DC rectifier size is defined by the wind turbine and diesel generator rated power, along with the corresponding voltage value. Accordingly, the battery charge controller size definition is dictated by the AC/DC rectifier outlet characteristics, the PV generator exit data and the battery operational characteristics, like "U_{bat}" and charge ratio "R_{ch}" in A.

Similarly, the UPS characteristics depend on the maximum load demand "N_{max}" and the service time (e.g. 2-5min) along with he operational voltage and frequency values. Finally, the size of the inverter is selected to fulfill the maximum load demand of the consumption, including a safety coefficient under given frequency and voltage.

Considering the proposed configuration and the above described size definition basic principles, one has the opportunity to define an autonomous hybrid system size able to fulfill the electricity demand of any isolated consumer.

6. Application Results

The main target of the present work is to set the basic principles for the design of a combined photovoltaic-wind-diesel hybrid system for isolated consumers. However, a typical applications example for a stand-alone system in a small island of Aegean Archipelago (Kithnos Island) is also included. Kithnos is a small island (1700 habitants, area of $94m^2$), located approximately 60km southeast of Athens. Due to insufficient infrastructure, there are many isolated consumers with no access to the local electrical grid. The island has high solar radiation and outstanding wind potential. More specifically the proposed methodology is first applied to determine the appropriate size of a photovoltaic generator, able to "guarantee" the energy autonomy (i.e. no load rejection) of a selected remote consumer (5000kWh/year, 3.5kW peak load demand) during the whole year, considering the installation cost values. The load demand data are based on information provided by the Greek National Statistical Agency; see figure (7).

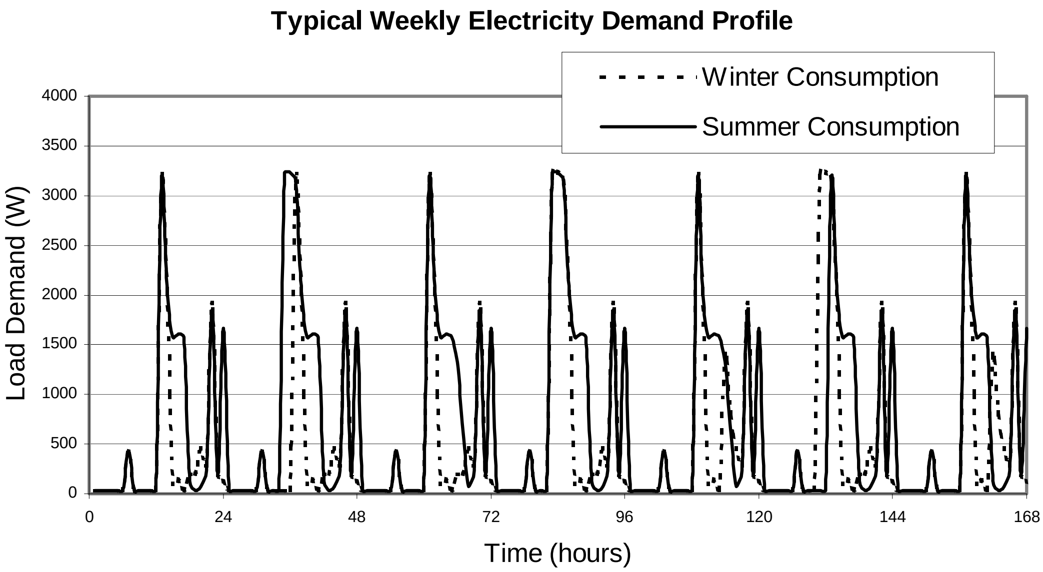

Figure 7: Typical Electricity Demand Profile

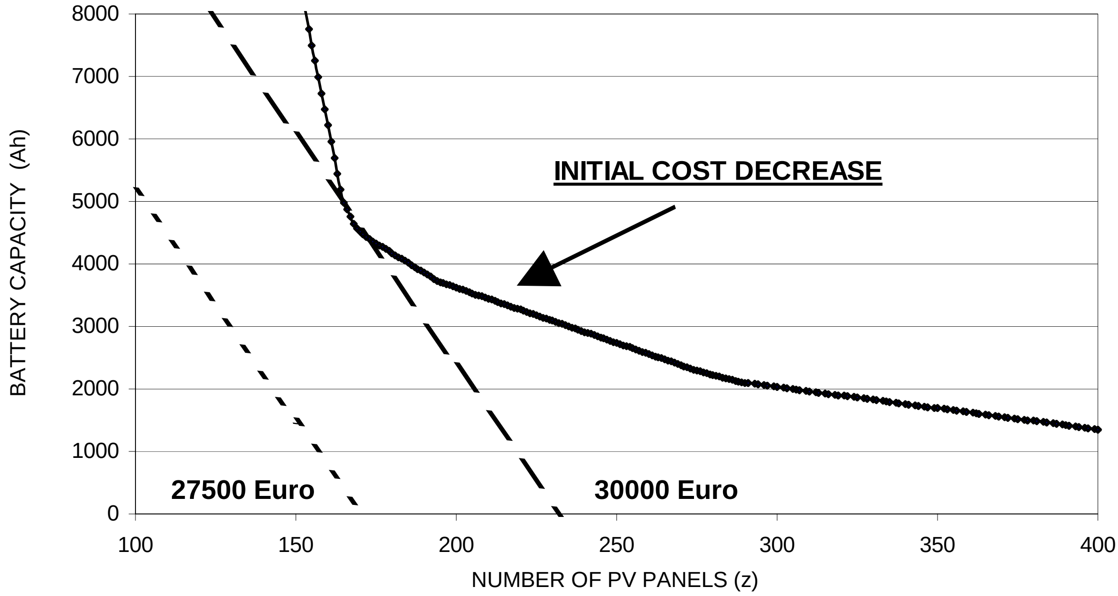

Figure 8: No-Load Rejection Configurations of a Stand-Alone PV-based Hybrid System

According to the calculation results obtained, the no-load rejection curve is given in figure (8), without the diesel generator usage. The minimum initial cost point is based on an 8.5kW photovoltaic generator and battery capacity of 4500Ah. The estimated minimum initial cost is of the order of 30000Euro, taking into consideration the Greek State subsidization of the system by at least 50%. The diesel generator utilization, although does not remarkably increase the first installation cost (by less than 1000€), it strongly contributes to the system batteries capacity decrease. On the other hand, for a long-term economic evaluation, the total cost of the system is amplified mainly due to the fuel (oil) consumption. For this reason, the evaluation of similar application should be based on the entire operational life of the system energy cost values[2].

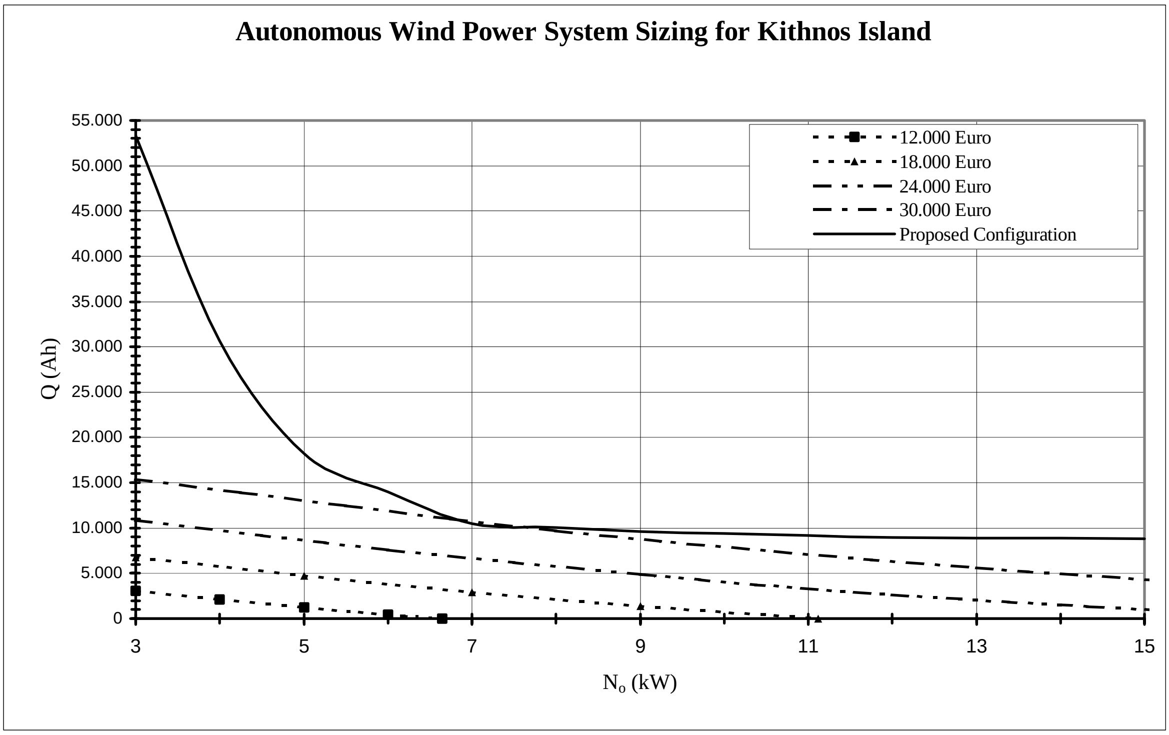

Figure 9: No-Load Rejection Configurations for the Entire Period Analyzed, Kithnos Island

Subsequently, the same load profile is analyzed by adopting a wind-based hybrid system, under the condition of whole year energy autonomy without the usage of diesel generator. Using the calculation results of the proposed analysis, the one-year autonomy curve is given in figure (9). As in the previous case, keep in mind that for every pair of wind turbine rated power and battery capacity (N_o-Q_{max}) the stand-alone wind power system is energy autonomous for the entire year, without the diesel generator utilization. Correspondingly to the photovoltaic system results, the utilization of the diesel generator limits the battery capacity needed, without significant increase of the first installation cost. On the contrary, the mid-term evaluation should be based on the total energy production cost; hence the diesel generator inclusion does not really induce any significant cost reduction.

More precisely, the minimum first installation cost solution for one year energy autonomy of the remote consumer is based on a 7kW wind turbine and on 11000Ah battery capacity, while the corresponding first installation cost is almost 29000€, if the 40% State subsidization is included. By comparing the two extreme cases examined, one may state that both systems are quite expensive, presenting also comparative first installation cost. The incorporation of a small diesel electrical generator reduces the corresponding buy-cost by more that 25%. However, the long-term energy production cost is finally increased in constant terms. In this context, parallel research is carried out to find the optimum combination of photovoltaic panels and wind converter size, under predefined contribution of diesel generator in the existing fuel mix.

7. Conclusions

The idea of creating a combined wind-solar hybrid station, using also a small diesel generator and a battery storage system is analyzed for the Aegean Archipelago region. The proposed solution takes into consideration not only the abundant solar and wind potential of the area but also their supplementary availability to reduce the energy storage requirements. According to the preliminary results obtained, the initial and the maintenance and operation cost of similar size power stations for remote consumers is not prohibitive, in view of the remarkable Greek State subsidization for similar renewable energy applications.

Of course, additional research is needed to optimize the entire system dimensions and check the applicability of the proposed solution in several locations. However, it is the authors' belief that considering the continuous price reduction of photovoltaic systems and the remarkable reliability improvement of contemporary commercial wind turbines, the proposed option is actually a prosperous alternative to improve the life-quality of isolated consumers and minimize their oil dependency.

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PART FOUR

ENVIRONMENT

- Air Pollution
- Solid Wastes
- Environmental Impacts

INTERRELATIONS OF UV-GLOBAL/GLOBAL/DIFFUSE SOLAR IRRADIANCE COMPONENTS AND UV-GLOBAL ATTENUATION ON AIR POLLUTION EPISODE DAYS IN ATHENS, GREECE

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Abstract

An investigation of global ultraviolet (G_{UV}), global (G) and diffuse (G_d) solar intensities, continuously recorded over a period of five years at a station in Athens, Greece, and stored on the basis of hourly time intervals since 1996, has revealed the following: (a) UV-global irradiation, associated with the 290 to 395 nm wavelength region, constitutes 4.1% of global solar. (b) UV-global irradiance ranges from an average minimum of 2.4 W m^{-2} and 3.1% of global solar in January to an average maximum of 45 W m^{-2} and 7.8% respectively in June, both considered at 13:00 hours, solar time. (c) There exists a good correlation among the two dimensionless irradiance ratios G_{UV}/G_d and G_d/G in the form of an exponential relationship. (d) UV-global monthly irradiation data show evidence of temporal variability in Athens, from 1996, to 2000. (e) Anthropogenic and photochemical atmospheric pollutant agents (O_3, CO, SO_2, NO_x, smoke) causing air pollution episodes seem to affect differently solar irradiance components. The main results of analysis (measurements within ±2 hours from solar noon) indicate that a buildup of O_3 and NO_x inside the urban Athens plume during cloudless and windless warm days could cause: (i) UV-global irradiance depletion between 5.4 and 14.4%. (ii) Diffuse solar irradiance enhancement up to 38.1%. (iii) Global solar irradiance attenuation ranging up to 6.3%.

Keywords: UV-Global Irradiance; Depletion; Global and Diffuse Solar Irradiance; Air Pollution; Correlation

1. Introduction

The contradicting evidences for either increase or decrease of terrestrial UV radiation has raised great concern since solar UV plays a very important role on human health, plant growth, animal welfare and material degradation. The significant solar irradiance values reaching ground level in urban Athens area, particularly around midday during warm period, render necessary an assessment of the temporal variation of UV-global, the ultraviolet solar (UV-A plus UV-B) component. In addition, long-term monitoring of the UV irradiance reaching ground in an urban environment leads to establishing the action and bilateral influence of UV in the generation of tropospheric ozone and other photochemical pollutants.

Ultraviolet is radiation in the wavelength region of the electromagnetic spectrum between x-rays at 10 nm all the way through the inner edge of visible light approximately at 400 nm. Solar UV radiation, which comprises 8.73%[1] of the exoatmospheric solar spectrum, consists of three wavelength band-regions, the UV-A (315 to 400 nm), the UV-B (280 to 315 nm) and the UV-C (<290 nm), accounting for 5.9%, 1.33%[2] and 1.5%, respectively. Earth's atmosphere significantly modifies the incoming solar rays due to the absorption and scattering action of oxygen, water vapor, carbon dioxide, ozone, water droplets, dust particles and other biospheric constituents of human and volcanic activities, on different regions of the solar spectrum. In particular, it is the stratospheric ozone's absorption that forms a lower boundary of the solar spectrum reaching the surface, at approximately 290 nm in the UV region. Ozone absorption is significant up to wavelength of 310 nm, decreasing fast afterwards, being zero practically at 345 nm.

Since the UV-C band-region falls beyond the portion of solar spectrum reaching Earth's surface, only UV-A and UV-B band-regions are relevant to ecosystems and the various activities of our life[3][4][5][6][7]. As it comes out, UV-A band accounts for 90% or more of the UV-global irradiance shorter than 400 nm, while the remainder is in the UV-B region, at wavelengths shorter than 320 nm. Nevertheless, although UV-B radiation is three to four orders of magnitude more energetic than UV-A[8], the harmful actinic effect of UV-A[9] is not to be under-estimated because of the high UV irradiance level impinging Athens and all the Aegean area. Sutherland et al.[10] found that UV-A exposure could cause DNA damage and skin-cell mutation to humans and other living organisms. In fact, UV-A is responsible for tanning[11][12] and premature skin aging as well as other biological effects due to its absorption by proteins and DNA. Based on laboratory experiments, Antonelli et al.[13] found that bean plants exposed to UV-A treatment showed a stimulant response regarding their growth.

UV-B, besides being notably destructive to polymers and other plastics[14], is easily absorbed by nucleic and aromatic acids thus having positive as well as deleterious effects on plants, marine ecosystems and humans[15], depending upon the action spectra and the threshold dose received. Chronic exposure of humans to UV-B irradiance poses great risks for the development of erythema[11][8], accelerated aging of skin, malignant skin tumors, keratitis[11], eye-lens cataract[16], retinal degradation, DNA damage, immune deficiencies. On the other hand, exposure of humans to UV-B irradiance is needed for the production of vitamin D, the enhancement of one's physical well-being, and the cure of skin diseases such as psoriasis[17]. Also, UV-B due to its bactericide effects at sufficient doses is used for the sterilization of surgical instruments and the killing of germs, bacteria and viruses in drinking water and food products.

Analysis of solar irradiance measurements taken at low altitude stations all over the world has revealed that monthly mean UV-global radiation constitutes a fraction that, in most cases, represents a value less than 5.5% of global solar. Results of monthly mean UV fractions of the global total are found in the literature, for different places. When a range is indicated, then the higher value is usually referred to rainy or cloudy conditions, and the lower is attributed to days with heavy scattering and UV absorption by dust or other atmospheric pollutants. So, Picha[18] indicates percentages ranging from 4.5% for cloudless days to 5.2% for all days together. A value of 5.0% for the summer months to 5.7% for the winter ones is indicated by Nagaraja et al.[19]. Percentage-wise values ranging from 4.2% in December to 5.2% in August are reported for Kuwait[20][21]. Elhadidy et al.[22] reports percentages ranging from 2.1% for a dusty day to 4.5% for a rainy one, in Dhahran. Using an Eppley radiometer, Feister and Grasnick[23] report UV percentage values ranging from 3.0-4.0% up to 6% for overcast skies. For the city of Makkah (Saudi Arabia), Khogali and Al-Bar[24] have found percentage values ranging from a low 2.8% in July to a maximum 4.3% in February.

UV irradiance reaching Earth's surface is affected, in addition to the solar zenith angle, by altitude, the albedo of the surroundings, as well as atmospheric and other environmental forcing factors as cloud cover, stratospheric and tropospheric ozone, SO_2 and aerosols. Surface ozone concentrations have been going up, since the second half of the 19th century[25]. Nevertheless, it is after the 1950s when studies started to appear showing the significant influence imposed upon UV radiation by ozone and the other atmospheric pollutants present in the plume of an urban environment. As was suggested by Bruhl and Crutzen[26] regarding tropospheric ozone in general and by Cartalis et al.[27] for Athens in particular, ozone, photochemical and other atmospheric pollutants exhibit a strong absorption preference towards UV (UV-B in particular) radiation. The filtering action of these agents has been found and reported by others[28][29][30][31][32]. Thus, the EER (Erythemal Effective Radiation, a notation adopted by Forster[33]) dose during summers, at the pollution-free environment of the Aegean island of Kos, is measured 15% greater than in urban Athens[34]. On the average, the EER irradiance measured in urban Athens is found at least 20% lower than the value estimated for clear sky conditions[35]. UV-B radiation reduction is shown to be close to 39% for urban Athens, during a day with high atmospheric pollution basically characterized by high smoke concentrations[36]. The polluted atmosphere in downtown Mexico City, at an altitude of 2500 m a.s.l, shows a 20% UV-B annual average (years 1994-1995) attenuation compared to a suburban site in the same Metropolitan area, but differences are found to be greater than 40% on polluted days[37].

The National Observatory of Athens, the oldest meteorological establishment of Greece, operates a meteorological station recording a number of atmospheric parameters including UV-B (since 1999), global and diffuse solar irradiance. Solar UV measurements have intensified in the 1990s in this part of the world, with new monitoring stations being added. A number of units operate, either in the National UV-B Observational Network of Greece[34][34][39], or otherwise, as in this current case. A number of studies have been reported based on solar irradiance data from these stations. Their scope was to provide scientific information on the very important issue of UV radiation based on site measurements. Reports can be found on UV radiation at ground level, regarding some Eastern Mediterranean sites. A number of these provide evaluation on the erythemal active UV[38][35][36][39][40]. Others show results indicative of the tropospheric surface ozone and aerosols action on UV-B depletion during air pollution episodes[36][41][40].

In this contribution, we study the temporal variability of UV-global radiation in urban Athens during normal days, as well as on days characterized by air pollution episodes. Results are presented based on measurements of UV-global, global, and diffuse solar irradiance components that were continuously monitored and logged at a ground station in urban Athens, for a five-year period (March 1996 through December 2000). To improve modeling quality on availability and temporal variability of the UV-global, we shall show results of investigations on possible correlation events between the different solar components, including a number of empirical functional relations including absolute and normalized quantities.

2. Instrumentation Description and Measurements

Starting in 1991 (1996 for UV), solar irradiance measurements are taken using an automatic station located on the rooftop of a building at the TEI of Piraeus campus (37.97^0 North Latitude, 23.67^0 East Longitude). The TEI campus, part of the *Ancient Olive Orchard* of Athens, is situated in the midst of the greater Athens Metropolitan area.

The station is continuously monitoring the following solar irradiance components:

- Global solar using a PSP Eppley pyranometer.
- Diffuse solar using a PSP Eppley pyranometer with a shadow ring.
- Total solar on a vertical plane facing south, west, north and east using four Kipp & Zonen pyranometers, type CM 11. The CM 11 pyranometer is well suited for the measurement of incoming global solar radiation and fully compliant with all ISO 9060 Secondary Standard Instrument performance criteria.
- Global ultraviolet using a CUV3 Kipp & Zonen broadband radiometer. The CUV 3 is responsive across the natural UV spectrum, covering both the UV-B and UV-A spectral ranges, responding at 290-390 nm. The CUV3 radiometer has a response time less than 1.0 sec, a good cosine response and non-linearity less than 1% over the full-scale range.

All pyranometers are serviced regularly and checked every two years against a PSP Eppley standard pyranometer. The CUV3 radiometer calibrated and used for the first time in 1996, it has been functioning continuously ever since, with regular services in between.

The Data Acquisition System (DAS) is programmed to scan the output of each one of these seven instruments every 60 seconds, average it over an hour period and store the result in the data logger's memory next to the channel number, solar hour, and corresponding (Julian) day of the year. At midnight, on a daily basis, all data stored in the data logger is dumped into a PC via a RS232, for future processing.

3. Data Analysis and Discussion of Results

In this work the measured monthly values of UV-global irradiation in urban Athens area are presented in figure (1) as a time series variation from March 1996 to December 2000. Looking at the literature, a considerable number of contradicting reports regarding UV variability at different places throughout the world can be found. Further focusing to the eastern Mediterranean region, investigations of the influence of photochemical air pollution on UV reaching the ground in urban Athens area presented by many[32][34][41] all point to the same conclusion. They support the hypothesis of the filtering action air pollution has on UV (UVB). Furthermore, in figure (1)[35], provide a scatter diagram of time series for 1993-97 daily observations of erythemal irradiance in urban Athens area that shows a rather decreasing trend over the years

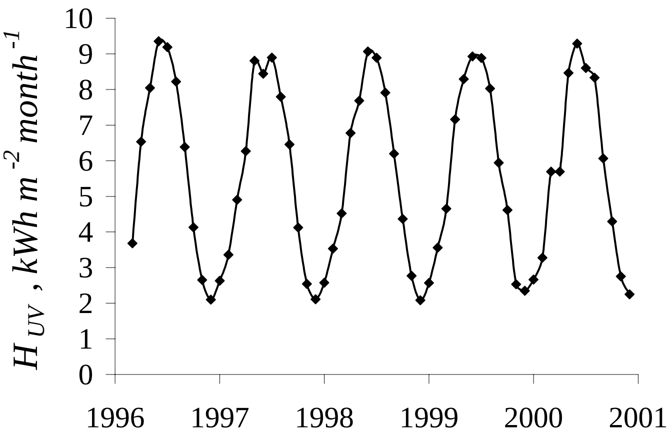

Figure 1: Yearly time series of the monthly UV-global irradiation in urban Athens for the period 1996-2000, in urban Athens area.

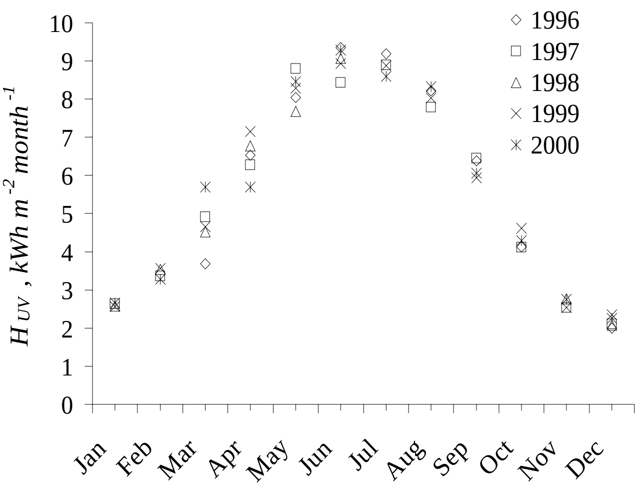

Figure 2: Annual course of monthly UV-global irradiation time series, in urban Athens area, for the period 1996-2000.

The variable weather conditions, often occurring during spring and appearing less frequently in summer and autumn, in Athens, may be the reason for the observed scattering of the monthly UV-global irradiation values shown in figure (2). Thus in March, monthly UV irradiation values may differ by as much as 61%. The absolute monthly UV-global varying from a minimum of 1.99 kWh m^{-2} $month^{-1}$ in December 1996 to a maximum 9.36 kWh m^{-2} $month^{-1}$ for the month of June, same year.

Figure (2) illustrates the yearly course of H_{UVM}, the monthly UV-global irradiation in urban Athens area (in kWh m^{-2} $month^{-1}$), for the period 1996-2000.

Figure (3) presents the plot of UV-global (H_{UVD}) against global solar (H_D), both expressed as monthly-mean daily irradiation data obtained over the five year period, as well as the best line of fit given by equation (1), following a linear least-square regression analysis. The good linear correlation between H_{UVD} and H_D, observed mainly at below average H_D values, is an indication of the weaker filtering action of Athens plume on UV-global reaching the ground at moderate to low sun conditions. This could be attributed to the fact that surface ozone modulation on UV-global becomes important at higher solar irradiance levels which, in conjunction with warm weather and wind absence, might constitute the appropriate conditions for the production of O_3 and other pollutants. Thus O_3, a strong absorbing agent of UV up to wavelength 310 nm, would only affect UV-B and UV-C which both constitute, approximately, 25% of the UV-global.

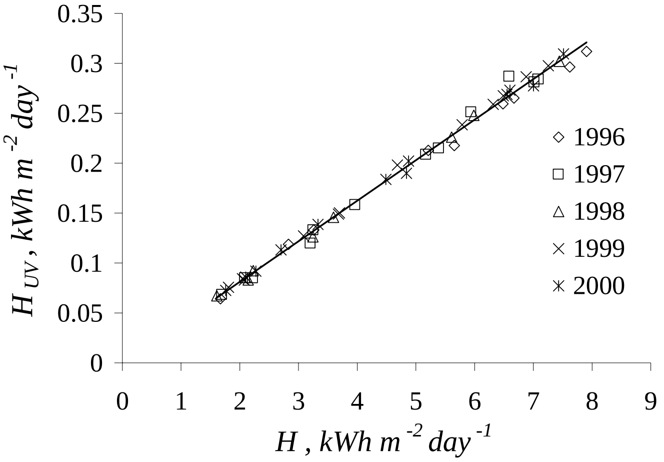

Figure 3: Scatter diagram of the monthly daily-mean irradiation values of UV-global (H_{UVD}) against Global solar (H_D), over the five-year period. Solid line is the best-fit line expressed by the equation H_{UVD}=0.0406H_D-

$$H_{UVD}=0.0406H_D-0.0001 \quad (1)$$

where R^2=0.9955, H_{UVD} and H_D are expressed in kWh m^{-2} day^{-1}

It has been indicated that Rayleigh and particle scattering agents greatly diffuse global solar radiation, thus increasing its total path before it strikes Earth's surface and therefore enhancing its absorption[26]. This action is particularly affecting the shorter wave length regions of solar spectrum. So, in an urban environment, one should expect the relatively large diffuse component of the UV solar radiation to be depleted, being absorbed by ozone, aerosols and the rest absorbing agents, while traveling through the considerable thickness of boundary layer, before reaching the ground. This holds true for the greater Athens Metropolitan area where measurements[41] have indicated an aerosol extinction profile value twice as big over the city (at an altitude of 1500-1700 m) as it is outside the polluted urban zone. Under these circumstances, ground measurements of solar irradiance should simultaneously show depletion of UV, enhancement of diffuse solar, and attenuation of global solar by an amount equal to the part that has turned to diffuse due to scattering effect.

In order to reduce the effects of solar zenith angle, turbidity and albedo, hourly UV-global and diffuse solar were expressed in ratios relative to solar diffuse (G_{UV}/G_d), and solar global (G_d/G), respectively. An attempt to form ratios of hourly UV-global relative to solar global resulted in extended point scattering, when plotted accordingly. Figures (4a) and (4b) are the scatter diagrams showing the variation of G_{UV}/G_d with G_d/G, at 13:00 and 09:00 solar time, respectively, for each hour of the five-year period 1996-2000. The white line curve passing through the 13:00 solar time data points in figure (4a) is the best fit exponential-type line having an expression given by equation (2). This line form is associated with 97.89% of the variance (R^2=0.9789) of G_{UV}/G_d ratio and variations of G_d/G. Similarly, in figure (4b), the 09:00 solar time data is best fitted by a similar exponential line expressed by equation (3) and 89.95% variance, (R^2=0.8995).

$$G_{UV}/G_d=0.0463(G_d/G)^{-0.9283} \qquad (2)$$

Where, $R^2=0.9789$

And,

$$G_{UV}/G_d=0.0426(G_d/G)^{-0.9348} \qquad (3)$$

Where, $R^2=0.8995$

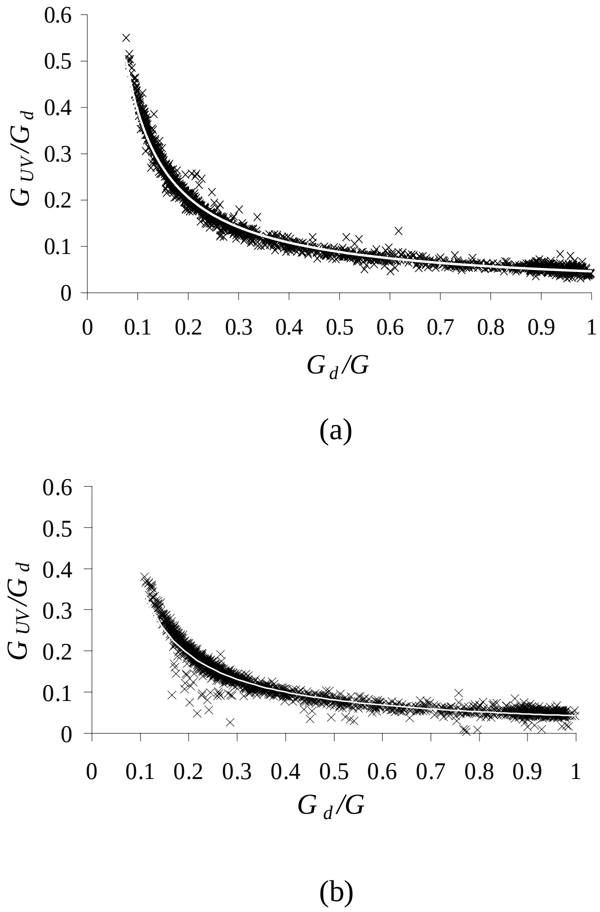

Figure 4: Scatter diagrams of the hourly-mean irradiances expressed in dimensionless ratios G_{UV}/G_d and G_d/G, for the five year-period 1996-2000. Plotted values refer to solar irradiances at 13:00 solar time for (a), and 09:00 for (b), respectively.

In order to investigate the effect of a polluted urban atmosphere upon UV-global when the problem is more acute, three summer cloudless pollution episode days were found, the exact dates are 04/07/1996, 08/07/1996, 18/06/1997. These three days were picked up from the list of days with atmospheric pollution episodes given for each year in the Yearly Report Tables on Atmospheric

Pollution of Athens, edited and published by the Greek Ministry of Environment, Land-Use and Public Works, Air Pollution network of Athens (PERPA). The measured solar irradiance components on these three days are compared to the corresponding irradiances measured during three other, but of same calendar, normal cloudless days. Specifically, conditions of episode day 08/07/1996 are compared to the respective conditions of the 08/07/1999, a normal and cloud-free day. Similarly, episode day 18/06/1997 is matched to the 18/06/1998. Finally, conditions of episode day 04/07/1996 are matched to the conditions of a fictitious day formed and expressed by the average of the irradiances measured on the 24/06/1996 and 12/07/1996, two normal and cloud-free days.

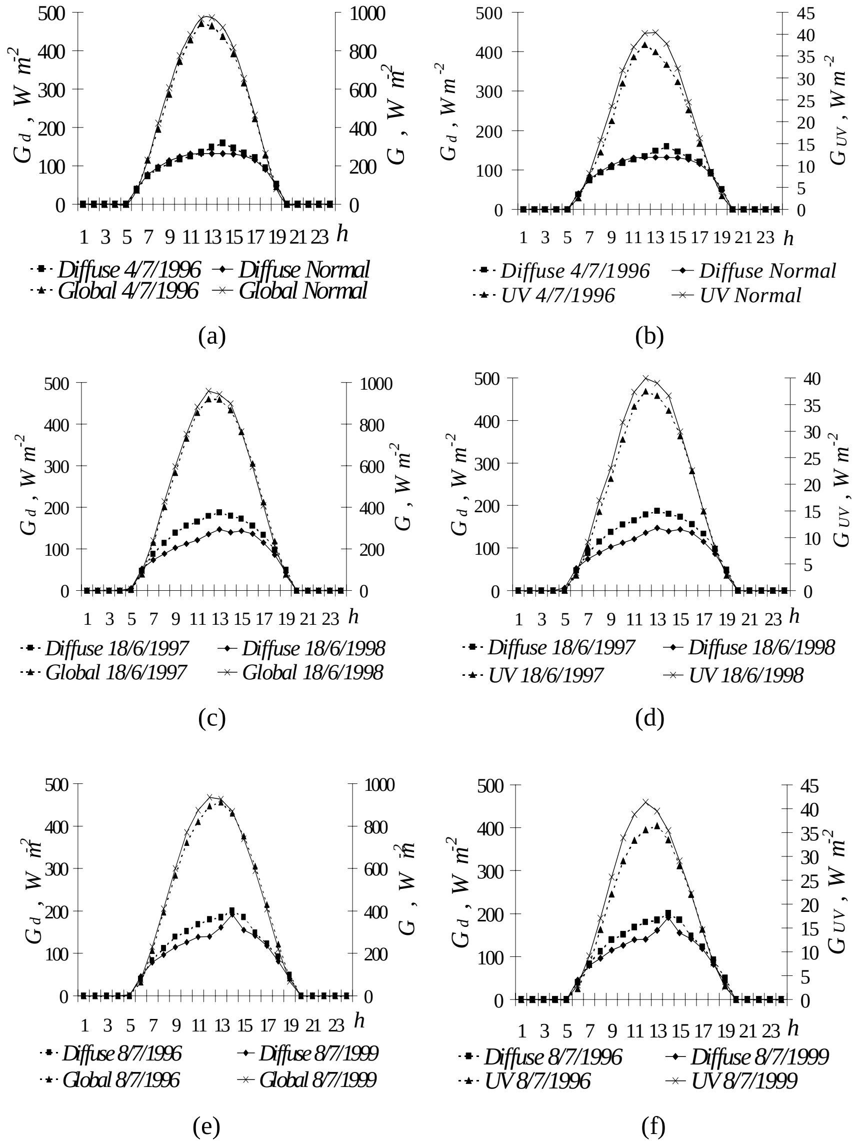

Figure 5: Diurnal variation of diffuse solar (G_d), global solar (G) and UV-global (G_{UV}) irradiances, all expressed in W m^{-2}, for the episode cloudless day and its matching normal day, also cloudless. (a) Time series of G_d and G during pollution episode day 04/07/1996 and the corresponding averages of G_d and G between the two clear days 24/06/1996 and 12/07/1996. (b) Time series of G_d and G_{UV} during pollution episode day 04/07/1996, and the corresponding averages of G_d and G_{UV} between the two clear days 24/06/1996 and 12/07/1996.(c) The same as in (a) but pollution episode day is 18/06/1997 and normal day is 18/06/1998.(d) The same as in (b) but pollution episode day is 18/06/1997 and normal day is 18/06/1998.(e) The same as in (a) but pollution episode day is 08/07/1996 and normal day is 08/07/1999. (f) The same as in (b) but pollution episode day is 08/07/1996 and normal day is 08/07/1999.

Next, the time series of UV-global (G_{UV}), diffuse solar (G_d) and global (G), the diurnal variation of the hourly-mean solar irradiances in urban Athens during the three pollution episode days are compared to the specified matched normal-day solar irradiances. Figure (5) includes three pairs of diagrams, each pair referring to a different episode day. So, diagrams (a) and (b) illustrate irradiance variations on the 04/07/96, (c) and (d) on 18/06/97, and (e) and (f) on 08/07/96. As it could be seen, it is right after 10.00 (during a clear and windless day) when global solar increases most rapidly. The effect of this increase, combined with the high concentrations of pollutants emitted by cars during rush hour and still present in the atmosphere, seems to be the proper recipe for the photochemical production of ozone and NO_2. Concentrations (in $\mu g/m^3$) of NO_2 and O_3 the two major atmospheric pollutants (SO_2 presents no problem during the warm months) for these three highly polluted episode days are as follows:

On the 04/07/96	NO_2	472	O_3	323
On the 18/06/97	NO_2	294	O_3	383
On the 08/07/96	NO_2	243	O_3	309

Figure (5) confirms attenuation of UV-global and global solar, as well as enhancement of diffuse solar on each episode day. It is interesting to note that the greater drop or rise of irradiance occurred in between 10.00 and 14.00, solar time, except on the 04/07/96, an episode day marked with the highest NO_2 concentration (472 $\mu g/m^3$). On the same day, the greater irradiance differences were observed between 12:00 and 14:00, showing a shifting towards the early afternoon hours. Specifically, the sign (- for depletion, + for increase) and the maximum observed percentage fractional deviations of UV-global, global solar and diffuse solar intensities recorded on an episode day and on a clear normal day are as follows:

Episode day 04/07/96 Time of occurrence: 14:00

-12.6% UV-global
-5.0% Global solar
+20.7% Diffuse solar

Episode day 18/06/97 Time of occurrence: 10:00-12:00

-10.2% UV-global
-4.1% Global solar
+38.1% Diffuse solar

Episode day 08/07/96 Time of occurrence: 10:00-12:00

-14.4% UV-global
-6.3% Global solar
+28.2% Diffuse solar

A systematic increase of the daily solar diffuse irradiation was logged on each consecutive episode day, during the five day period associated with photochemical air pollution, in July 1996, from 04/07 through 08/07, that is not explained by normal day solar irradiance fluctuations. Shown below is the daily solar diffuse irradiation recorded on each consecutive day:

Date	04/07	05/07	06/07	07/07	08/07
Diffuse irradiation (kWh $m^{-2}day^{-1}$)	1.72	1.71	1.83	1.85	1.87

Whereas, the corresponding daily solar diffuse measured one day before and two days after the 5-day string, namely on July 3rd, 9th and 10th, is only 1.39, 1.52 and 1.31, respectively, all values in kWh $m^{-2}day^{-1}$.

Parayiannis et al.[41], comparing UV-B irradiance levels between clear and high aerosol day (episode day is 14/09/1994, solar zenith angle=50^0) in urban Athens area, report 10% disagreement between modeled (clear day) and measured UV irradiances in the 305-340 nm spectral region. This difference increases to about 20% for UV with wavelengths lower than 300 nm. A depletion of more than 35% in EER dose is reported for the same September day by Mantis et al.[40]. Acosta and Evans[37] from measurements in the polluted downtown and a suburban site in the high altitude Mexico City, report UV-B differences observed between 11:00 and 16:00 greater than 40% on polluted days.

Our results illustrate that comparing cloudless warm days of low and high air pollution levels in urban Athens, a reduction of 10 to 14.5% in the UV-global is detected within ±2 hours from solar noon. The lower UV depletion values obtained in this work are probably due to the fact that monitored UV-global constitutes mostly of UV-A, a radiation much less affected by atmospheric pollutants compared to UV-B.

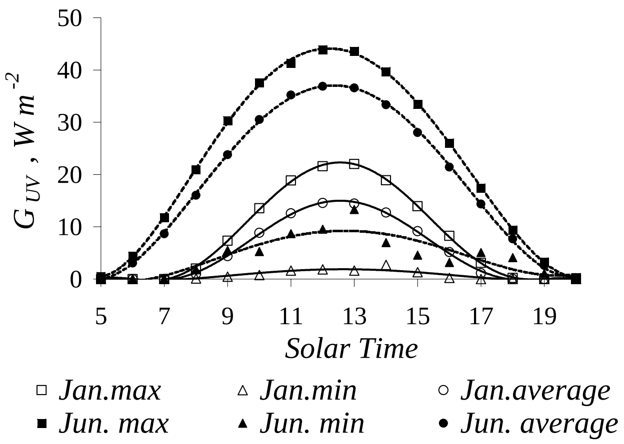

Figure 6: Average-maximum, average-average and average minimum diurnal UV-global irradiance variation curves, in W m^{-2}, for the months of January and June, based on measurements recorded at a ground station in urban Athens area, over the five-year period 1996-2000.

The principal boundaries of the UV-global diurnal variation could be specified in terms of the average-maximum, average-average and average-minimum daily distribution curves. These curves shown for the months of January and June form the lower and upper limit of the minimum and maximum UV-global daily intensity variations recorded at a ground station in Athens, over the annual course. Figure (6) gives an example of these diurnal solar irradiance variation profiles. As it can be seen, solar noon UV-global intensity in Athens takes a minimum value 2.4 W m^{-2} in January, and a maximum one 45 W m^{-2} in June.

4. Concluding Remarks

Measurements of UV-global irradiance along with solar diffuse and global irradiance data measured at the same site in urban Athens area, during the years 1996-2000, processed accordingly, lead to the following conclusions:

a) Because of the limited length of the analyzed time period (5 years), UV-global change in Athens, (figure (1)), does not constitute a statistical significant trend but represents the change observed during these years of measurements, thus, it should not be considered as an indicator of UV-global long-term change.
b) Comparison of the monthly UV-global radiation values (figure (2)) indicates large departures from the mean tending to occur from March through October, dropping to minimum during the cold period months of November through February.
c) The plot of H_{UV} versus H (figure (3)) and the derived linear regression, equation (1), indicate a clear linear correlation between UV-global and solar global, particularly in the region of moderate to low H values. Greater point scattering is observed towards higher solar radiation values, where

UV-global may be influenced at a greater extend by the presence, or not, of suspended lower tropospheric aerosols, O_3 and other absorbing gases.

d) The preference of plotting solar irradiances in dimensionless form, where UV-global forms a ratio with the corresponding diffuse solar and diffuse solar with solar global, produced results shown in figures (4a) and (4b) (13:00 and 09:00 hours, respectively). These results clearly indicate: i) To first order, the removal of influence of solar zenith angle, turbidity, albedo of the surroundings. ii) A good agreement of the distribution of dimensionless data with an exponential fit, based on the model equation $G_{UV}/G_d = a(G_d/G)^{-b}$, where a and b are constants. It should be noted that normalization of UV-global by solar global leads to extended point scattering and a poor correlation scheme. The resulting high values of correlation coefficients indicate that, in the absence of measured data, equation (2) and (3) could be invoked to predict an estimate of G_{UV}, given G_d and G, at low and high solar zenith angles, respectively.

e) The observed UV-global depletion during days with increased air pollution levels points to the conclusion that atmospheric pollutants are capable of reducing UV-global in urban Athens by as much as 14.4%, during warm cloudless and windless days, between 10:00 and 14:00 hours. Another interesting observation is the continuous solar diffuse built-up noted on consecutive clear days with extreme air-pollution anomalies, a phenomenon that could be attributed to the thickening of urban plume formed by the presence of a residual aerosol layer and a gradual upward lifting of polluted air masses.

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ANALYZING THE AIR POLLUTANTS PRODUCTION OF GREEK ELECTRICITY SECTOR FOR 1995–2010 PERIOD

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Abstract

The dominant role of electricity in everyday life quality is well recognized in contemporary human societies. However, the electricity production process is assumed responsible for important air pollution, beyond the monetary and macroeconomic cost. According to previous studies, Greek electricity production is almost exclusively based on fossil fuel, i.e. locally extracted low-quality lignite and imported oil, while only recently a remarkable natural gas penetration is encountered in the local market. On top of that, the electricity consumption increase has approximated 5% per annum, while the corresponding peak load increase exceeds 6%. In this context, an extensive and thorough analysis is carried out concerning the air pollutants quantities resulting from the electricity production sector during 1990-2002 period. Thus, by taking into consideration the historical data analysis and using the proposed analysis, one may estimate on a medium-term time horizon the evolution of the electricity sector air pollutants production, according to selected typical scenarios. Finally, the analytically developed frame provides all necessary information -scientifically documented- in order to display the air pollution impact during the forthcoming electricity market choices.

Keywords: Electricity; Air Pollutants; Carbon Dioxide; Sulphur Dioxide; Nitrogen Oxides

1. Introduction

The dominant role of electricity in everyday life quality is well recognized in contemporary human societies. However, the electricity production process is assumed responsible for important air pollution, beyond the monetary and macroeconomic cost. According to previous studies[1] Greek electricity generation is based –since its foundation in the early 60's– in the usage of local lignite and imported heavy oil. Only recently a remarkable natural gas penetration is encountered in the local energy market, hence significant changes in the electricity sector fuel mix are expected. On the other hand, the contribution of numerous existing hydro power stations is limited, due to their low utilization (capacity) factor. Finally, only recently a modest number of wind parks started their operation mainly in Euboea and Crete.

The figure (1) presents the contribution of lignite, heavy oil, natural gas, hydro power stations and wind parks to the net electricity production of the year 2002. According to official data[2][3], the major role of lignite and heavy oil stations is obvious, as these fuels cover the 84% of the total net annual production. It is interesting to note that the recently operated natural gas stations have already a remarkable portion of Greek electricity production, while one may expect that their importance is going to be amplified in the near future.

In this context, an extensive and thorough analysis is carried out concerning the air pollutants quantities resulting from the electricity production sector during 1990-2002 period[4]. Accordingly, an integrated numerical method is utilized to forecast the expected air pollutants production during the current decade[5]. The model developed not only takes into account the available official historical data but also for several electricity market-related scenarios, accompanied by the corresponding possibility value. On top of that, special attention is paid to include any technological or policy related changes[6] of the local electricity sector, in view of European electricity market "liberalization".

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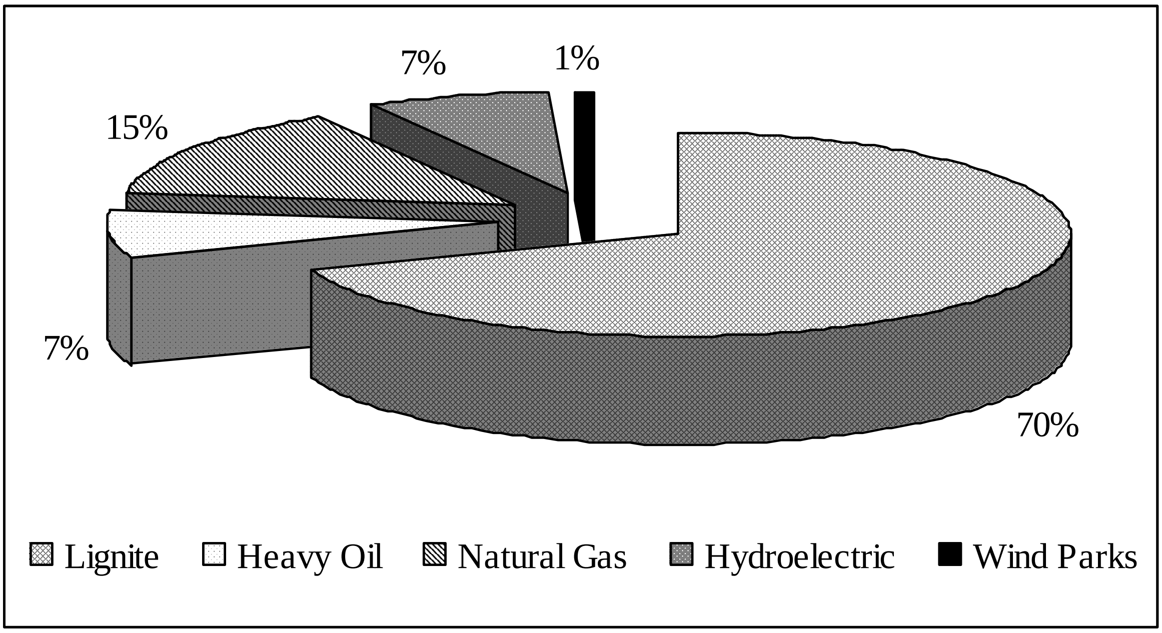

Figure 1: Analysis of electricity production in Greece, 2002

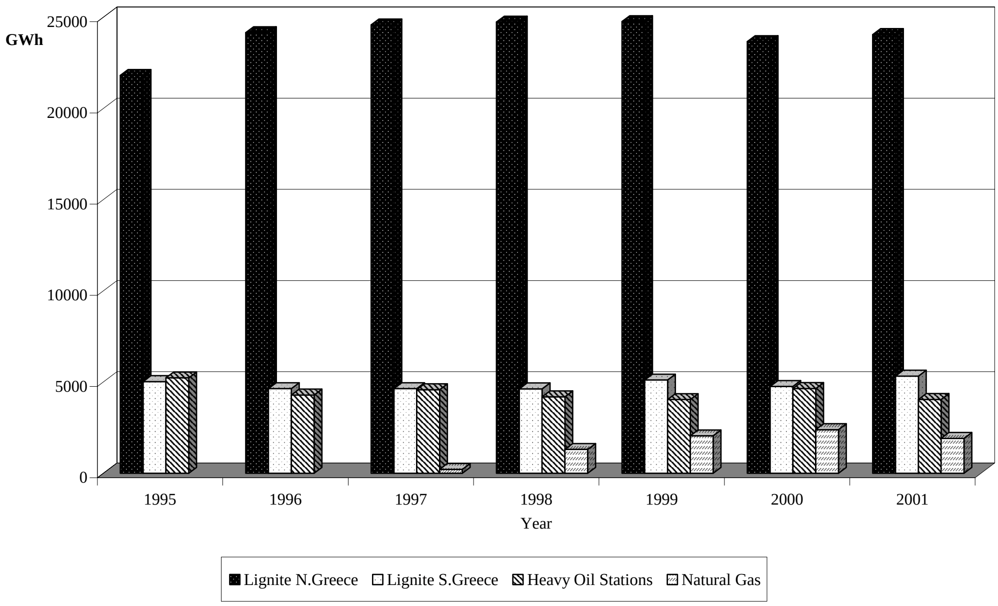

Figure 2: Fuel mix analysis for 1995-2001 net electricity production

2. Brief Presentation of Fossil Fuel Fired Power Stations

The Greek electricity sector is divided into two main branches. The first one contains the mainland electricity production network based on ten large-scale power stations[3], where local lignite, imported heavy oil and natural gas are used. The second branch includes 35 medium-small autonomous -diesel and heavy oil fired- power stations spread through out the Aegean Archipelago[7]. In this latter group one may include the medium sized -heavy oil fired- power stations of Crete and Rhodes. The figure (2) presents the evolution of the fuel mix used for the period 1995-2001, taking into account that 2002 values are not yet officially validated. In the present paper the mainland network is taken into consideration.

More precisely the mainland power stations can be categorized (2002) according to the fuel used as follows:

4050 MW using N. Greece Lignite
850 MW using S. Greece Lignite
360 MW using Natural Gas
837 MW using Heavy Oil

In addition, the lignite-fired stations are divided into north and south Greece installations, taking into consideration the important differences found into the physical characteristics of the fuel (lignite) used. More specifically, the north Greece lignite has higher specific calorific value (up to 50%) than south Greece lignite, while its sulphur content is found to be lower than the south Greece one. As a result the emission factors from each station may be quite different.

In the present analysis two heavy oil fired stations are also examined. Since the fuel used has specific standards, the emissions from both stations are almost similar. Finally the recently renovated natural gas fired station in Attica is included, while the new natural gas station at Komotini -started its operation during late 2002- is not taken into account.

3. Analysis of Air Pollutants Production

As already mentioned[8] the electricity generation sector in Greece is responsible for the production of a substantial part of the national air pollutants. In figure (3) one may examine the evolution of electricity sector air pollutant production for the period 1995–2001, based on official data[3][9].

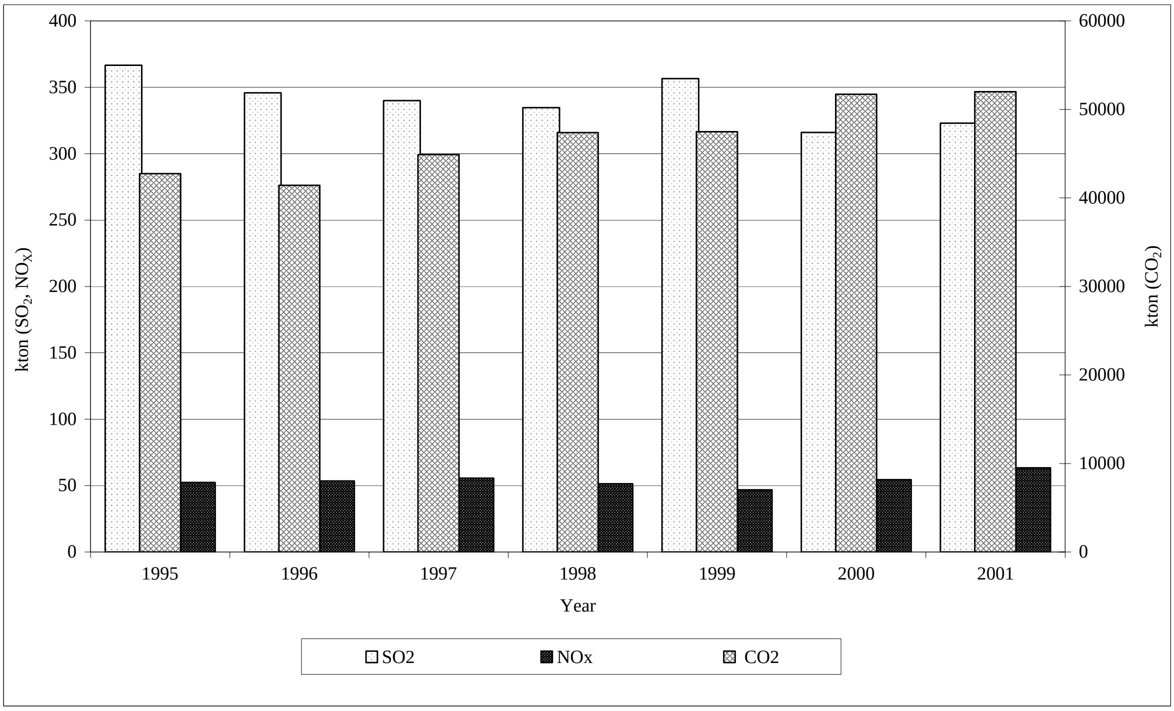

Figure 3: Evolution of electricity related air pollutants

Taking into consideration the fuels consumed during the period investigated and the emissions presented in figure (3), one may estimate the time evolution of the emission factors for each power station.

Subsequently, using the information collected, one has the opportunity to estimate the mean value (1995–2001) of the corresponding emission factors for each station and air pollutant, accompanied by their standard deviation values, figures (4), (5) and (6). Moreover the corresponding weighted mean factors for south and north Greece power stations are presented, so that direct comparisons can be made.

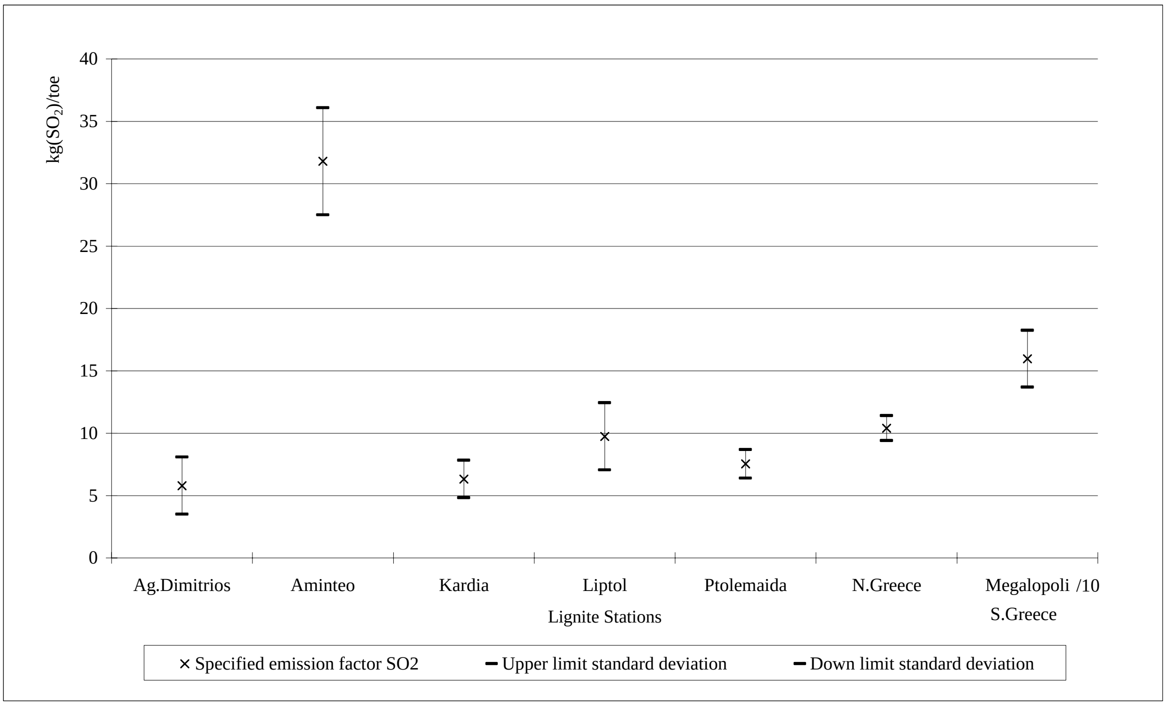

Figure 4: 1995-2001 mean SO_2 emission factor values for Greek lignite stations

Bear in mind that the calculation results for SO_2 and NO_X are based on official data concerning the fuel consumption and pollutants emitted. Thus, in figure (4) one may notice that the SO_2 emission factors from the north Greece stations are kept into much lower range than of the south Greece units. Moreover, the standard deviation of Megalopoli stations factor during 1995–2001 is found to be very high, due to the desulphurization unit that started its operation in 2000.

On the other hand, NO_X emission factors show the same behavior for all the lignite stations (see figure (5)). Finally, in figure (6) the CO_2 emission factors[10] are presented. Keep in mind that the wide variation of the factors numerical value is the result of the encountered variety in the carbon context of each lignite mine. In general the factors given here are quite higher than the corresponding international values[11]. However, this difference can be explained taking into account the extremely low heating value of the local lignite compared to internationally utilized values for brown or hard coal.

4. Estimating the Air Pollutants Emissions for the Next Decade

Taking into consideration the emission factors already calculated and projecting the electricity demand for the next decade the energy related emissions could be assessed. In the present study two different energy scenarios are examined. The first one is the officially expected basic scenario[12]. According to this scenario the electricity demand is increasing annually by 3%. This increase is to be covered by new gas fired power stations (total rated power 700 MW) and lignite fired units of 300 MW installed capacity. Meanwhile the capacity factor of the existing lignite, heavy oil and natural gas stations is slightly improved. On the other hand, the contribution of renewables is of minor importance, while the existing hydro power stations increase their production by (3.5%) during the next ten years. Finally, the wind parks contribution in the electricity production will not exceed the 1300 GWh up to 2010.

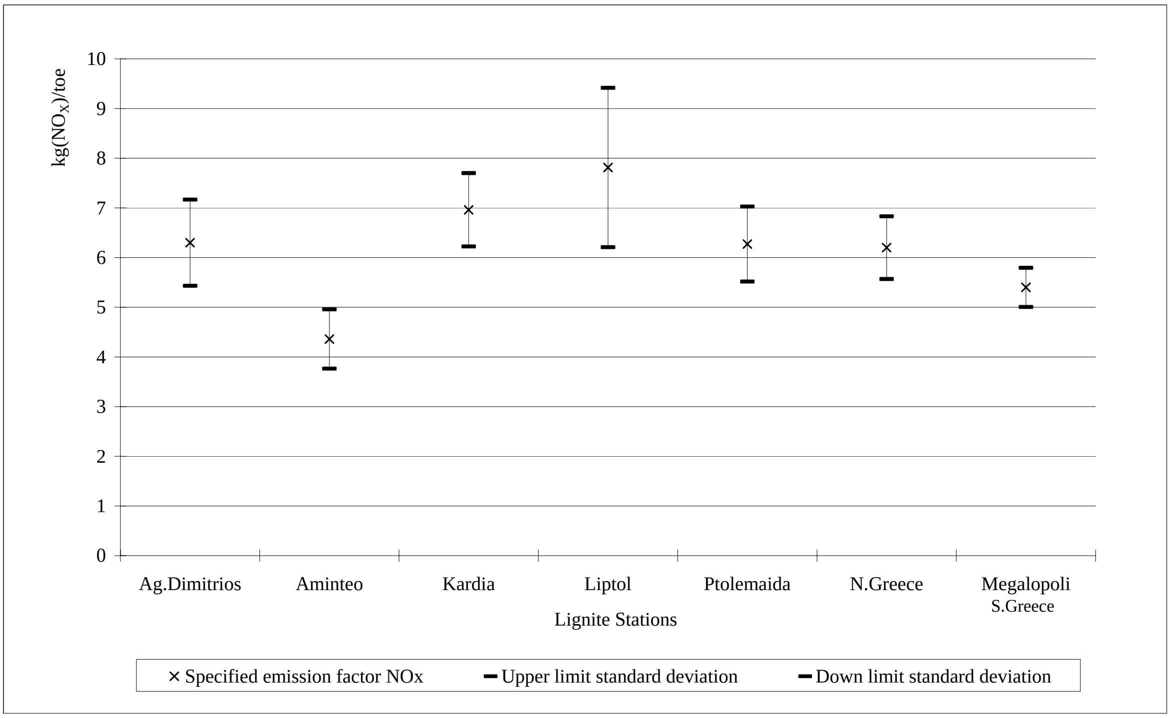

Figure 5: 1995-2001 mean NO_X emission factor values for Greek lignite stations

Time-mean CO_2 emission factors for Greek Linginte Stations

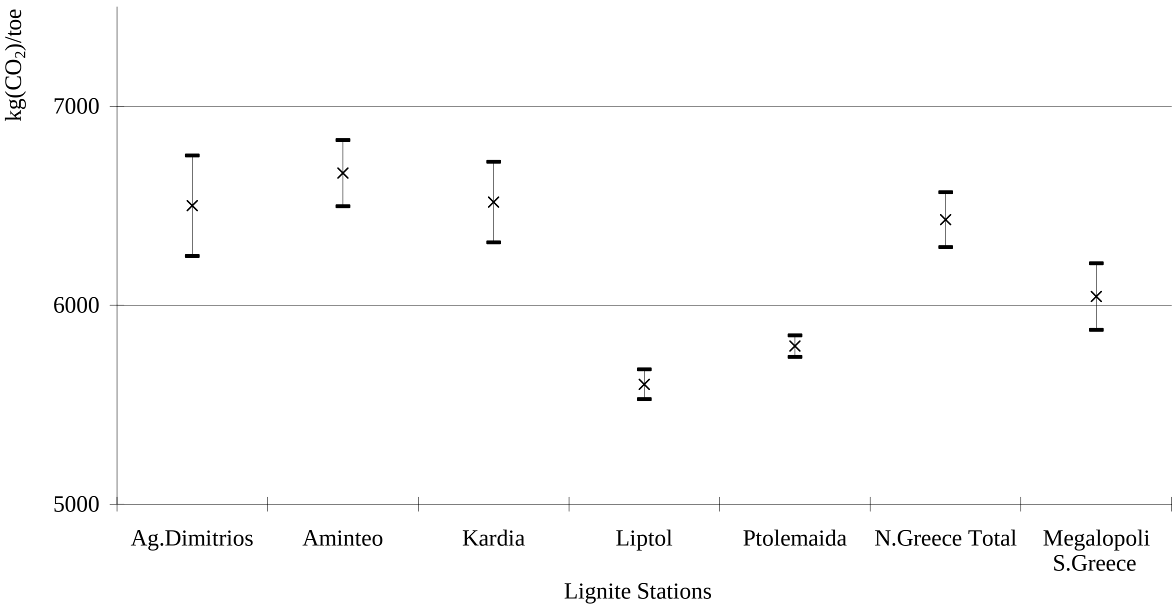

Figure 6: 1995-2001 mean CO_2 emission factor values for Greek lignite stations

Unfortunately, the above described scenario leads to substantial increase of energy related air pollutants. Precisely the NO_X and SO_2 emissions are increased by 18% and 13% respectively during the present decade. At the same time the CO_2 emissions amplification exceeds 20 % (see figure (7)).

As an alternative and financially acceptable solution one may evaluate scenario "B". According to this scenario[13], the energy policy adopted includes several environmental friendly choices. Thus the annual electricity demand increase is not going to exceed the 2.8% due to energy conservation measures applied in the industrial and tertiary sectors.

Furthermore, the lignite fired stations capacity is decreasing by 1% annually, while the heavy oil fired stations continue their operation in order to cover peak loads. The enlarged electricity demand is covered mainly by new gas fired power stations of 1300MW, based on combined cycle technology, while an extended utilization of renewable energy resources is expected. More precisely, wind parks are expected to reach 1500MW of installed capacity, while extra 350MW of biomass and geothermal power stations are scheduled to start their operation.

As a direct result of this option, the SO_2 emissions are slightly decreasing due to the partial substitution of lignite by natural gas. On the other hand the NO_X emissions do not present a remarkable diminution, as nitrogen oxides emission factor for natural gas is not negligible. Finally, CO_2 emissions are very slightly reduced up to 2005, due to the important penetration of renewable energy sources into the local fuel mix (see figure (8)). However, the continuous growth of electricity demand is gradually compensating this reduction, hence after 2005 the CO_2 production starts rising again.

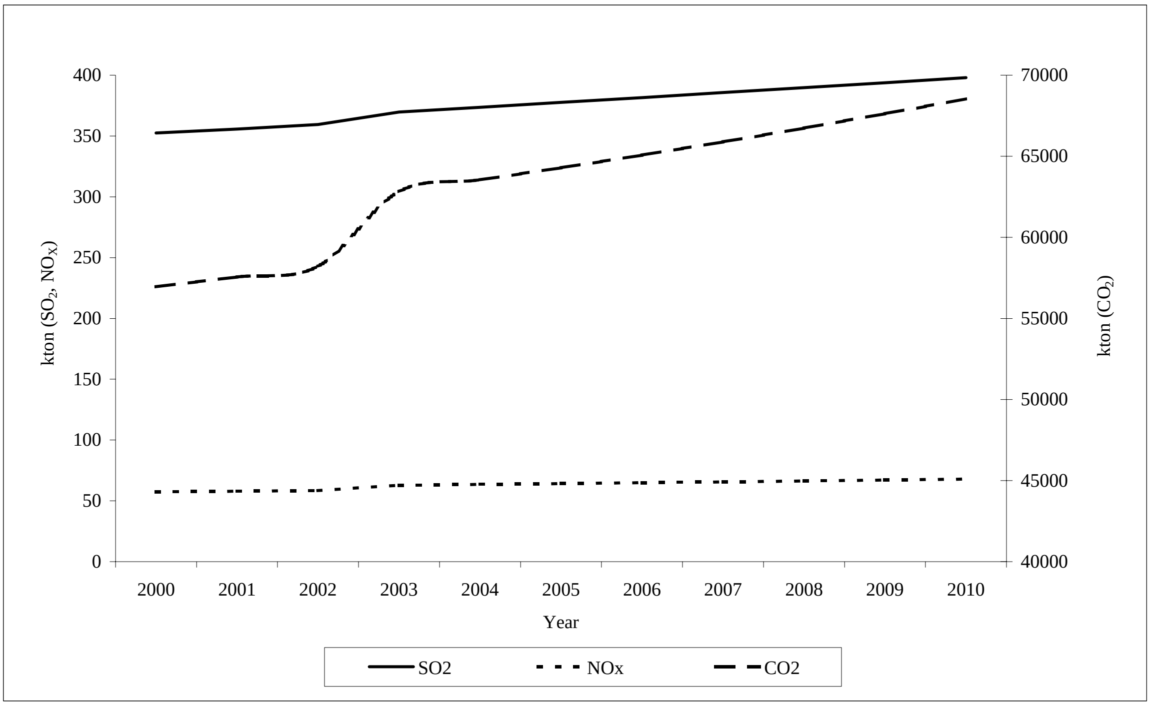

Figure 7: Estimated emissions for the basic scenario

5. Conclusions

The significant forecasted energy demand increase of the current decade should be covered either using N. Greece lignite or (and) imported natural gas. However, taking into consideration that no remarkable additional natural gas imports are possible without the existing infrastructure strengthening, the authors expect that the major electricity demand increase (2.0%-2.5%) is going to be covered by further exploitation of domestic lignite. On the other hand, the only possibility to exploit (using large-scale applications) the high wind potential of Greek mainland is by improving the national electrical network capability.

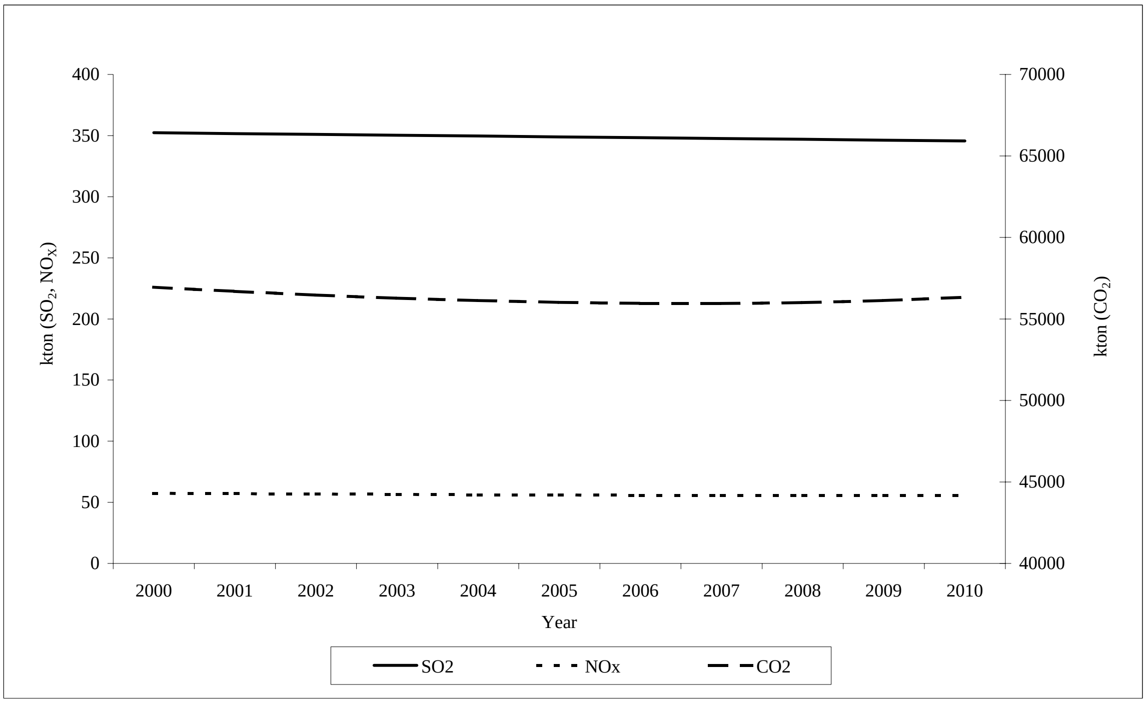

Figure 8: Estimated emissions for scenario "B"

In this context, an integrated and time-extensively analysis is presented concerning the national air pollutants emissions, resulting from the Greek electricity generation. The results presented are based on official data and analyse the SO_2, NO_x and CO_2 production on the basis of the fuel utilized. Among the most interesting results of the present survey is the continuous air pollutants production increase with time, attributed mainly on the electricity demand amplification and the national policy insist on using N. Greece lignite and imported natural gas.

This strategy is almost proven that leads to air pollution rise, which even if the environmentally friendly scenario -included in the 2nd National Program for Greenhouse Gases Prevention- is applied shall still be remarkable. On the other hand, only by introducing efficient energy saving measures in the industrial and the tertiary sector it will be possible to decelerate the annual electricity consumption escalation rate. Besides, a significant air pollution decrease may be realized in case that a considerable wind and hydropower penetration is realized in the national electricity generation.

Recapitulating, the negative evolution projected and the poor results of the 1st National Program for Greenhouse Gases Prevention, strongly question the efficiency and underline the necessity of extensive energy saving and renewable resources utilization during the application of the 2nd National Program. In the opposite case, our country has no chance on meeting the European target for Greenhouse gasses emission limitation, deteriorating at the same time the Greek citizens living quality due to the increased concentration of dangerous air pollutants.

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WASTE MINIMIZATION AND POLLUTION PREVENTION BY THE USE OF PRODUCTION PLANNING SYSTEMS

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Abstract

The objective of the present work is to investigate the potential of integrating the environmental factor in the industrial production planning systems, and suggest an efficient and easy approach to the pollution prevention and waste minimisation problem of the industrial units. More specifically, the present work deals with the identification of the relationships between the environmental and the production management parameters, as well as with the accommodation of the environmental constraints and the corresponding optimisation criteria in the well-established production planning systems. In addition, the present work identifies the most suitable type of production processes for implementing the proposed approach and highlights the key factors for its success.

Keywords: Waste; Pollution; Protection Planning; Environment

1. Introduction

The production of industrial goods and services involves the extraction of natural resources, their utilization in the manufacture of products, the disposal of waste, and the distribution, use and disposal (including reuse and recycling) of the final product. Environmental impacts can occur with varying degrees of risk along this entire industrial life cycle, and appear as local, regional, and/or global environmental problems. Although industry is a major user of natural resources and a direct or indirect source of pollution and other environmental impacts, it must remain a key partner in the common endeavour to achieve sustainable development[1]. The industry has the technology, know-how, resources and the entrepreneurial spirit to innovate, which can be used to achieve environmental goals and objectives. When the end-of-pipe approach was found to be incapable of abating industrial pollution and its impacts, the focus shifted backwards, on the industrial production and its processes. The emphasis is now on improving process efficiency, minimising effluents and optimising waste treatment and disposal practices. Pollution Prevention, that is according to EPA[2] the reduction or elimination of waste at the source through production integrated measures, has proved to be the best protection.

On the other hand, leading-edge companies have recognised that a pro-active environmental strategy may lead to innovative products and, by reducing the resources required for goods and services, businesses can achieve a serious competitive advantage. Consequently, a number of companies have started to show interest in modern concepts, such as Eco-Design, which aims at incorporating environmental considerations into product development, throughout the life cycle of a product (e.g. auto catalyst[3] or demolition debris recycling[4]) or service, and Eco-Efficiency. The production integrated environmental protection is of decisive significance and this is also reflected in the Integrated Pollution Prevention and Control Directive of the European Union (IPPC 96/61[5]), which aims at the prevention and minimisation of the risk to harm the environment as a whole. The IPPC in the industrial processes is realised through the Best Available Techniques (BAT), that are technical and organisational measures for the prevention of the emission of potentially polluting substances, otherwise to minimise such emissions to air, soil and water.

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Production-integrated environmental protection requires a very good and detailed knowledge of the parameters that affect the production and is implemented through various measures of different complexity and need for capital investment (figure (1)). These measures usually are:

- Technological changes for the avoidance and the minimization of emissions
- Changes in the technical specifications of the products and/or in the production processes
- Recovery and recycling of materials and substances
- Appropriate production management plans, since not only the technology itself, but also the way it is operated is very important

Given the business potential of reducing environmental impacts, it is clear that there is a need to identify the production process parameters that really affect the environment and how they affect it. Sometimes the first step for major environmental investments is to change the current production practices and to that effect, the Best Available Techniques suggested for each different industrial sector include, amongst others, the production organisation related measures. Major environmental issues in the production sector include reducing the consumption of energy and water, cutting emissions of solvents, nitrogen oxides and sulphur oxides, and minimising quantities of waste[6]. Good operating practices imply procedural, administrative and institutional measures that a company can use to minimise waste and emissions. Many of these measures are used in industry extensively as efficiency improvements and good management practices[7] rather than for environmental protection purposes and can often be applied with little or no cost in all the areas of a plant, including production, maintenance operations, and raw material and product storage.

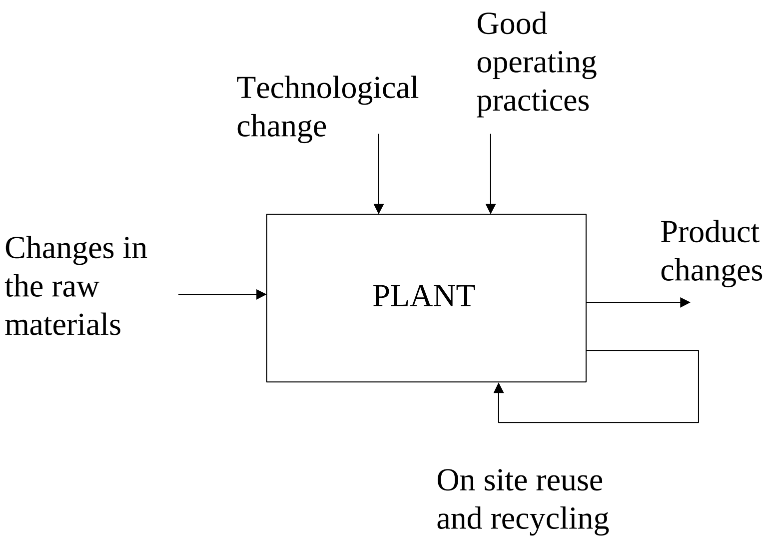

Figure 1: Measures for the production-integrated environmental protection

For the successful application of various soft production integrated environmental protection measures, it is important either to develop new decision support systems that take into account the correct relationships and interconnections between the traditional factors of production and the newly recognized environmental factor, or to extend the already existing, well established, tested and operating decision support systems to include the environmental factor. In this context, the present work provides a methodology that embodies the concepts of integral environmental protection in the production planning systems, in order to create or sustain competitive advantage for a manufacturing company. It is expected that this work will contribute to:

- the establishment of a methodological foundation for the integration of environmental considerations in production planning systems
- the understanding of the relationships between the well known conventional production management parameters and the environmental parameters of the system.

2. The State of the Art in the Production Planning Systems

Facing the increasing international competition, there is a growing need for planning tools in the industry that allow an efficient utilization of scarce resources. Therefore, today very significant progress has been achieved in the development and implementation of commercially available production management systems of varying complexity and functionality that support and improve the quality of decision-making in a wide spectrum of strategic and operational aspects and aim to obtain significant benefit in the form of increased productivity and resource utilisation.

In their wider and most modern version, the supply chain management systems address a full range of planning and scheduling applications from strategic planning to detailed plant scheduling and process optimisation, thus improving business decisions and coordinating production activities from raw materials to customers. These applications operate either as stand alone or integrated. They usually face either the whole range or some of the following problems:

- Strategic planning applications for the evaluation long range resource strategies.
- Decision support in the procurement of raw or intermediate materials, definition of the timing and volume of purchases, demand management.
- Evaluation of alternate ways of making the same product as well as co-product and by-product recipes.
- Tactical operations planning, capacity planning, inventory management planning.
- Scheduling problem that addresses the problem of detailed plant operation that satisfies the demands for different products under a number of constraints (time, limited resources, etc.).

Scheduling and planning are inherently optimization problems, the solution of which suggests the user how exactly to operate the facility. The parameters being considered include the available inventory, the capabilities and constraints of the manufacturing sites, the distribution network and production capacities, the demands and deadlines. The objectives may be to minimise costs or to maximize profits or any other optimisation criterion that the operation of the plant needs to follow. As part of the wider production planning systems, the scheduling problems may include a number of complicating features including shared intermediates, demands spread over the planning horizon, utility requirements, limited intermediate storage, sequence dependent cleaning. Scheduling suggests solutions to problems created by changes or upsets, as well as cost saving improvements by reducing changeover and inventory holding costs, or increasing effective capacity.

In general, the formal definition of the scheduling problem is as follows:
Given:

- A time horizon, a set of product orders, recipes for the required products, details on the availability of equipment, storage, raw materials, utilities or any other constraint

Determine:

- The allocation of operations in the units and the available resources, the timing of operations for each unit and the flow of material throughout the plant
-

So as to optimise one (or more) out of a wide range of possible optimization criteria, such as:

- Minimize the total delay, or the total operational cost, or the total changeover cost, or the total energy, water, raw materials consumption, or
- Maximise the total profit, or
- Optimise the operation of the wastewater treatment plant, in order to avoid disturbances in its operation.

Under the above definition, the production planning and scheduling are clearly optimization problems. Recent years have seen the emergence of general methodologies for their solution, based on a mathematical programming approach and providing considerable flexibility with regard to process structure and resource utilization[8][9]. A number of different problem classes, such as short term scheduling, campaign planning and scheduling and plant design can all be handled in a consistent manner. With the mathematical programming approach, a different number and type of constraints can easily be accommodated and a wide range of optimization criteria can be the driver for obtaining the best operational schedule. The input information to the above systems include several categories of data, such as product demands and inventories, product recipes, plant resources, maintenance schedules and the current status of plant equipment.

3. The Integration of Environmental Aspects in the Production Planning Systems

3.1 The matching of production planning with the environmental issues

In fact, the core objective of the production planning systems, i.e. the most efficient utilization of various resources, is also the underlying concept of the production-integrated environmental protection. As mentioned above, many systems have already been installed in the industry that apply quantitative methods to decision making for improved operational efficiency and profitability.

Therefore, it is promising to seek the opportunities for incorporating environmental considerations in the well established, familiar and already operating industrial production planning systems. Thus, the decision support methods of the production planning systems regarding logistics, allocation of resources and the manufacturing of goods will be exploited, taken also into account the environmental parameters of the plant in an integrated and not separate manner. Under this principle, environmental oriented planning of production systems can be realised[10]. Although the underlying decision problems are complex, systematic planning and control methodology has the capability for considerable environmental and economic benefits.

The question is how the main problems considered in the supply chain management systems, i.e. inventory management, product mix planning, scheduling and production control could be extended, in order to include environmental aspects. The matching of some conventional production planning with the corresponding environmental issues is indicated in Table I. The constraints usually involved in the production planning systems include:

- Mass balances throughout the system.
- Batch size restrictions due to the size and type of the equipment available. The equipment list should also include pollution processing equipment and wastewater treatment plants.
- Constraints in the quantities, timing and availability of the various resources required.

Certainly, to implement this approach a detailed analysis of the material and energy flow through the system is required, including mass balances for each substance and emphasizing the parameters that affect the environmental behavior of the system, such as the flowrate and timing of the liquid effluent discharges, the concentration of CO, CO_2, Nitrogen Oxides, CFCs, HCFs and halons, the emissions of Volatile Organic Compounds arising from solvents use, the consumption of resources and utilities, such as water, energy (oil, gas, electricity), steam, raw and auxiliary materials, the type and required quantities of solvents and, in wastewater streams parameters such as BOD, COD, SS, oils, N, P, metals, cyanides and chlorides. Moreover, process related restrictions within the overall production chain must be considered explicitly, e.g.:

- Solid and hazardous or special waste disposal
- Standards for emission to air, water and soil
- Product packaging
- Time dependent smog emissions
- Available capacities over time
- Chronological and/or process driven orders of jobs
- Maximum waiting times between two production units
- Energy and material supply limits over time

For example, for the solution of the product mix planning problem, the LP models usually used for the determination of the optimal production mix including the material and energy flows, must be extended by the additional inclusion of emissions to air, water and soils, their standards, and their environmental costs. As a result of this extension, energy and material demands, production amounts and capacity allocations of both production and emission reduction units can be obtained.

For the scheduling problem environmental oriented production rules could be an allocation according to minimal set-up emissions

- By the priority use of production units with greater efficiencies and less consumption and emission factors
- By avoiding unforced waiting times
- By avoiding high emission set-up measures
- By harmonising capacity utilisation

Table I: Matching of production planning functions with environmental issues

PRODUCTION MANAGEMENT FUNCTION	**CORRESPONDING ENVIRONMENTAL CONSIDERATION**
Strategic planning	High level decision making for pollution prevention and waste minimisation oriented choices in the product/ process development
Raw or intermediate materials procurement	Consideration of recycling and/or reuse capability, and disposal procedures
Inventory management	Eco-balancing for commodities sourcing
Demand management	Consideration of environmental objectives when determining orders
Product mix planning	Optimisation of the product mix respecting environmental standards
Capacity planning	Allocation of production across various plants by combining the production with the distribution problem, taking into account the environmental impacts of production and distribution
Scheduling	Use environmental oriented production rules
Production control	Consideration of variations in input and output flows of succeeding and preceding production units throughout the production chain

For an environmental oriented production planning procedure, additional information is necessary for each product, on specific material and energy consumption patterns and emission factors. By this, conventional priority rules for the allocation of jobs can be extended by environmental oriented rules, e.g. an allocation according to maximum waiting time related emissions or to minimal set-up emissions. Also, explicit constraints on environmental impact such as material and energy consumption, process waste generation, differences in production types, different types and amounts of emissions, their characteristics, their time dependency, different sources of emission generation and the operation of the recycling and reuse facilities can easily be incorporated in the production planning systems.

3.2 Special cases

Beyond these general statements, there are specific cases where production planning and scheduling issues have serious environmental dimensions and, therefore, the appropriate approach of the planning problem with explicit consideration of this environmental dimension will significantly improve the environmental behavior of the corresponding system.

Some of the waste generated in the industry is a consequence of process inefficiency, as is the case with part of the product changeover waste. Actually often the generation of this waste is processing-sequence dependent and there is a strong dependence of the setup and cleanup times of the product sequence in equipment items. This is a problem that can be faced with the generation of the appropriate schedules. Effluents generated in setup and cleanup tasks are a source of waste that can be significantly reduced with a proper schedule. In this case, the optimization criterion for the production scheduling should refer to the minimization of changeovers or changeover costs, in case they can be quantified. Thus, the product changeover costs need to be determined for each unit as a function of the intermediates processed. The sum of these values will need to be minimized in the final schedule. The strategy proposed may be easily adapted to include the operating costs dependent on units to tasks assignment. In these setup and cleanup subtasks, in addition to the involved cost, there are also treatment processes required for the intermediate remains and substances used. Another case is the one that the utilities consumption is either product sequence dependent, i.e. depends on the sequence of different products in the same equipment or storage facility, or allocation dependent, and i.e. varies with the specific assignment of products or processing tasks to production units.

Production planning cannot reduce the specific resource requirement of an individual processing step carried out in a particular piece of equipment. However, there may be scope to reduce the overall utility (resource) consumption by organizing the production, so that the most efficient equipment is used for each processing step and the most utility intensive processing tasks sequences are avoided[11]. Certainly this has to be satisfied against the need for timely satisfaction of customer orders. When production-planning systems are model based, the objective criteria and the constraints may easily be changed, in order to accommodate various environmental constraints as the ones mentioned above. Optimal mathematical formulation seeks to make the best use of resources minimizing the total cost of energy and changeover while satisfying all other constraints.

3.3 Optimization criteria

As far as the optimisation criteria are concerned, in case the optimisation criterion for scheduling determination is the total cost minimization, the utilities cost or the changeover cost may be hidden behind other, more significant in quantitative terms costs. However, in an environmentally oriented production planning system, these cost terms must be taken into account explicitly (e.g. environmental and social cost of energy[12]) and isolated from the other terms. Therefore, in the case of utilities cost minimization, the operating costs depended on units to tasks assignments should be determined in detail. For example, the use of the most harmful equipment from an environmental point of view could be assigned a very high / prohibitive operating cost allocation, thus minimizing the chance of this specific assignment. Another criterion, mainly depending on the system, may be the minimisation of the overall production time.

The modelling of the production planning and scheduling as optimisation problems and their solution through mathematical programming methods are the catalysts for the integration of the environmental factor in the production planning systems, since they facilitate the accommodation of any operational constraints expressing environmental considerations, as well as the inclusion of any optimisation criterion expressing environmental issues. Much significant work has been carried out for the development of algorithms and the corresponding systems for the solution of short–term or long–term planning of processing systems[13][14], that can easily accommodate a very large number of parameters, such as storage limitations, mixed production facilities, cleanup requirements, accommodation of batch and continuous processes, in addition to the possibility to include a variety of optimisation criteria.

3.4 Suitability and Success Factors

Although the approach of integrating environmental issues in the production planning systems can be applied in any industry, it will be most successful in cases where production planning is absolutely necessary for its operation, and more specifically to the multipurpose plants. Multipurpose plants are general-purpose facilities, where a variety of products can be produced by sharing the available equipment, raw materials and intermediates, utilities and production time resources. Multipurpose plants are advantageous if many different products are to be produced in relatively low volumes in a common facility. The operational flexibility in such plants is what makes them very attractive in the very rapidly changing today's market, but at the same time their operation is severely complicated by the need to take into account detailed production scheduling. The determination of product sequences, resource allocation, batch sizes and other schedule-related variables requires the solution of mathematical optimization models. Current trends in flexible manufacturing will result in even more complicated production facilities and customer requirements, rendering the traditional approaches increasingly inapplicable.

The environmental oriented production planning systems will mainly succeed in companies with well-established production practices and good availability of information on the details of the process streams. On the other hand, the effectiveness of these systems requires continuous monitoring, evaluation of the results achieved and exploitation of the evaluation results for the improvement of the system.

4. Implementation Methodology

A structured approach is necessary to identify, evaluate and implement the integration of production planning to environmental issues. The basic steps to be followed are:

- Detailed analysis of the existing production planning systems functions. It should be noted that the production planning system of the company may not necessarily be an advanced and sophisticated computer aided system, but a set of decisions made by the production planning department, supported by any type of system.
- Detailed analysis of the parameters, constraints and optimisation criteria involved in the existing production planning systems
- Detailed and quantitative analysis of all the environmental aspects, i.e. identification of all sources of waste and emission generation, investigation of the factors that influence the volume and the composition of the waste and emissions
- Matching between the environmental and production planning parameters
- Accommodation of all the environmental parameters in the production planning constraints and optimisation criteria

5. Conclusions

The proposed methodology is used to systematically identify and evaluate the environmental improvement opportunities through the integration of the environmental factor in the production planning systems. The application of such systems can show the effects of various operational and structural constraints on the environmental behaviour of the plant. In addition, the proposed approach will contribute significantly in the identification of the relationships between the environmental and the production planning parameters of the system. The improvements brought about through simple low or no cost changes in procedures will also provide a significant financial saving, since they will result in a more efficient use of raw materials, energy, water and resources in general.

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EVALUATION OF DOMESTIC-WASTE COLLECTION SYSTEM OF NIKAIA MUNICIPALITY. IMPROVEMENT PROPOSALS

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Abstract

In the majority of Greek large-cities, the collection and transportation process of domestic-waste is based on empirical information and personal standpoints, thus leading to a significant loss of time and resources. In this context, the present work initially evaluates the existing domestic-waste collection system of Nikaia municipality. For this purpose, several recently gathered data are analysed concerning the available domestic-waste collection equipment (e.g. existing pails, trucks, personnel etc.) and the corresponding routing. Accordingly, the present waste-collection plan for every town sector is investigated and revised, on the basis of current population and economic activities. In this way significant waste time reduction may be realized, contributing to the deterioration of related operational cost and improving the quality of services offered to the local citizens. On top of that, the replacement of existing waste-pails by new and larger ones is also examined, along with the reinforcement of the outdated waste collection trucks. The capital needed is not prohibitive, while additional savings may be possible by disposing the old-fashioned equipment. Finally, a cost-benefit analysis takes place in order to weigh the financial gains of such a revised system in comparison with the necessary amount invested. The calculation results clearly support the proposed modifications, while one should also consider the remarkable social benefits, resulting from the new management plan. Recapitulating, a thorough analysis of the existing domestic-waste collection process in Nikaia town leads to several interesting amelioration ideas. These proposals -if adopted and properly applied- should shortly payback the necessary investment capital, leaving remarkable gains and improving the services offered by the local authorities. Several additional urban municipalities may equally use this promising house-waste collection management plan, after certain minor modifications.

Keywords: Domestic Waste Collection; Economic Activity; Waste-Pail; Payback Period; Cost-Benefit Analysis; Management Plan; Routing

1. Introduction

In the majority of Greek cities, the collection and transportation process of domestic-waste is mainly based on empirical information and personal standpoints. This empirical procedure usually results in significant loss of time and resources[1][2]. In this context, the present work initially evaluates the existing domestic-waste collection system of Nikaia municipality. For this purpose, several recently gathered data[3] are analysed concerning the available domestic-waste collection equipment (e.g. existing pails, trucks, personnel etc.) and the corresponding routing[4].

Accordingly, the present waste-collection plan for every town sector is investigated and revised, on the basis of current population and economic activities[5]. In this way significant waste time reduction may be realized, contributing to the deterioration of related operational cost and improving the quality of services offered to the local citizens[6].

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Finally, a cost-benefit analysis takes place in order to weigh the financial gains of such a revised system in comparison with the necessary amount invested[8][9]. The calculation results clearly support the proposed modifications, while one should also consider the remarkable social benefits, resulting from the new management plan.

2. Present Situation

Nikaia municipality is located in West Attica, being one of the largest municipalities in the wider Athens area. According to the 2001 census, the permanent population of Nikaia is 113267 persons. Besides, the area is densely structured with increasing building activity. As a result, Nikaia's land-planning problems are similar to those presented in the majority of Greek cities. Inside Nikaia municipality boundaries, several crucial areas are located, like the General Hospital of Nikaia, the 3rd Cemetery of Athens, the Local Cemetery of Neapolis, the Stadium of Nikaia, the Stadium of Neapolis, the Katrakion Theatre, tenement houses etc. On top of that, a great number of avenues and roads traverse the municipality (e.g. P. Ralli, Gr. Labraki, Thivon), covering the main transportation burden. On balance, housing has been the main use of land, as the wider area has traditionally been a work force shelter.

For municipality waste collection purposes, Nikaia has been divided in 15 sectors, each containing two sub-sectors. For every sub-sector there is a separate gathering routing, taking place every two days (three times a week). Considering the numerous small waste-pails, the collection trucks are obliged to pass from almost every small road of the city, often twice a day, to face the habitants' needs. As a result, there is plenty of labour effort and time waste[5], leading to remarkable money loss. In this context, the Soft Energy Application & Environmental Protection Laboratory carried out an extensive evaluation study of the existing waste-collection system[3]. Hence, the most important findings are summarized below.

After a thorough and time-consuming investigation of the current waste collection equipment, see Table I, one may state the following:

- There are more than 12100 waste-pails in the city most of them (80%) belonging to the 240lt category.
- Recently a remarkable number (≈10%) of 660lt waste-pails were bought by the municipality.
- Only a very small number (92 out of 12107) of waste pails have a capacity of 1200lt.

Table I: Waste-Pails Distribution in Nikaia Municipality (2002)

Sectors	**120lt**	**240lt**	**330lt**	**660lt**	**1200lt**	**New 1200lt**
Sector 1	3	588	61	111	1	252
Sector 2	15	743	3	45	0	226
Sector 3	11	642	46	90	2	246
Sector 4	18	777	1	31	2	224
Sector 5	9	784	0	56	0	242
Sector 6	48	912	24	33	0	273
Sector 7	21	688	11	115	1	265
Sector 8	20	727	0	82	0	248
Sector 9	10	718	138	14	0	245
Sector 10	428	234	43	164	3	246
Sector 11	50	715	0	148	79	295
Sector 12	77	716	6	46	0	229
Sector 13	150	781	3	55	0	260
Sector 14	14	501	0	46	0	163
Sector 15	1	0	168	74	4	112
Total	**875**	**9.526**	**504**	**1.110**	**92**	**3526**

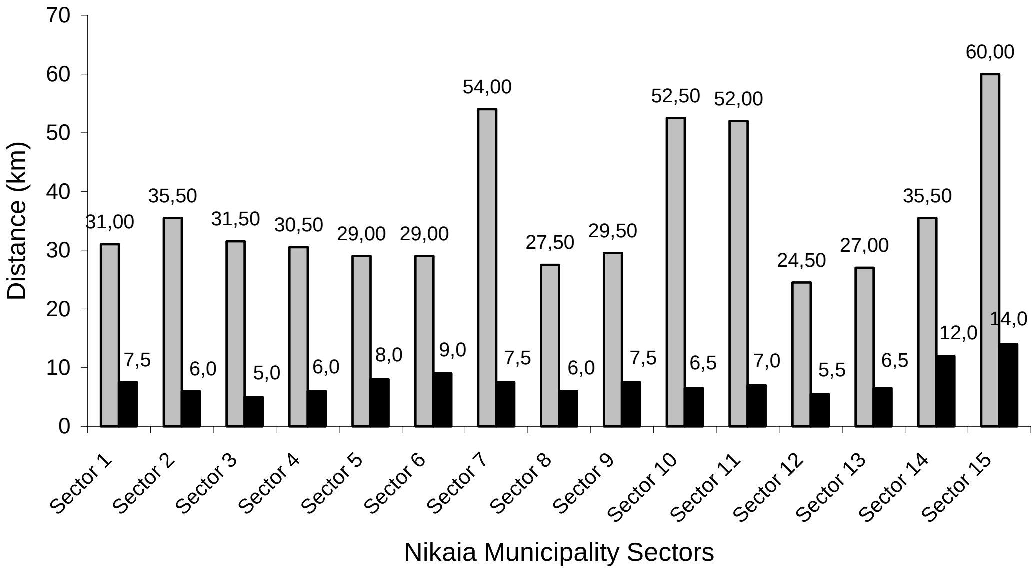

Figure 1: Covered Versus Collection Distance for Nikaia Waste Collection System

Due to the numerous waste-pails, only 55% of the working time is actually productive, while the rest is consumed by the existing traffic. More precisely, in Table II one has the opportunity to investigate the productive time versus the total operational time of the waste-collection group. On top of that, one may evaluate the real collection distance in comparison with the total distance covered by every collection group. As it is obvious from figure (1), the real collection distance represents only a small percentage (20%-30%) of the distance covered by the municipality waste collection trucks.

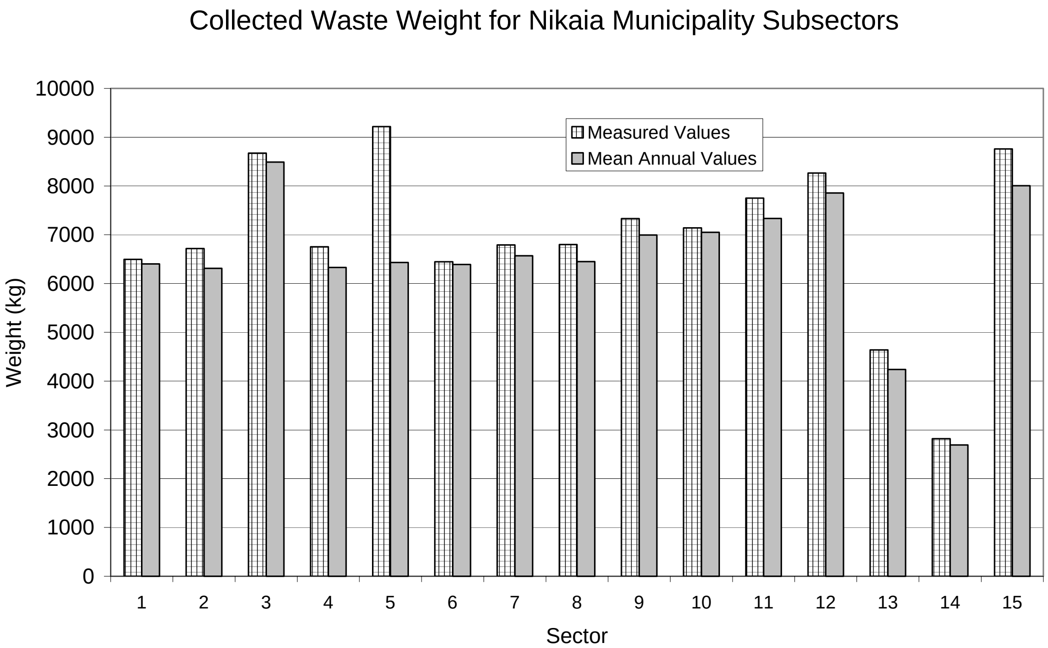

Figure 2: Mean Daily Collected Waste Analysis for Nikaia Municipality Sectors

Finally, using the information assembled by our research team[3][5][10], we demonstrate in figure (2) the geographical distribution of total waste weight in comparison with the mean annual data resulting from the terminal station weighting. Most sectors have an average daily collection weight between

6500kg and 8500kg. The only exceptions are sectors 13 and 14, while for the last one the total weight is less than 30% of the mean value. Finally, sectors 3 and 5 produce the largest part of the municipality wastes.

Table II: Waste Collection Procedure Main Operational Characteristics

Sectors	Operation Time (h:minutes)	Distance Covered (km)	Collection Time (h:minutes)	Collection Distance (km)
Sector 1	4:00	31,00	2:00	7,5
Sector 2	3:50	25,50	2:34	6,0
Sector 3	5:15	29,00	3:17	5,0
Sector 4	3:35	23,00	2:33	6,0
Sector 5	4:10	24,50	2:27	8,0
Sector 6	3:45	24,50	2:05	9,0
Sector 7	4:05	54,00	2:14	7,5
Sector 8	4:05	31,00	2:07	6,0
Sector 9	3:10	29,50	2:24	7,5
Sector 10	5:25	52,50	2:58	6,5
Sector 11	5:25	52,00	3:59	7,0
Sector 12	4:17	30,00	2:20	5,5
Sector 13	5:05	25,00	3:06	6,5
Sector 14	3:45	35,50	2:08	12,0
Sector 15	4:45	60,00	2:13	14,0

Table III: Main Urban Planning Data of Nikaia Municipality

Sectors	Blocks	Residents	Shops	Schools	Factories
Sector 1	62	1.762	238	1	115
Sector 2	117	2.348	263	4	58
Sector 3	88	2.476	226	8	42
Sector 4	107	2.284	358	0	42
Sector 5	192	4.302	606	7	88
Sector 6	88	2.736	203	3	32
Sector 7	52	1.816	101	0	21
Sector 8	79	1.738	169	7	34
Sector 9	151	3.376	367	1	71
Sector 10	67	1.874	237	2	28
Sector 11	56	1.996	213	2	12
Sector 12	74	2.226	104	6	23
Sector 13	67	2.016	86	3	15
Sector 14	63	1.412	28	1	14
Total	**1263**	**32.362**	**3.199**	**45**	**595**

Table IV: Analysis of Main Activities for Each Sector of Nikaia Municipality

Sector	Main Activity	Sector	Main Activity
1	Industrial-Commercial	9	Pure Residential
2	Pure Residential	10	Commercial
3	Pure Residential	11	Pure Residential
4	Commercial	12	Pure Residential
5	Residential-Commercial	13	Pure Residential
6	Pure Residential	14	Pure Residential
7	Pure Residential	15	Commercial
8	Residential-Commercial		

To get an unambiguous picture of the current situation in Nikaia municipality, one should examine the main activities taken place in each sector, see also Table III. According to data presented in Table III, sector 5 definitely contains the majority of the house residents and school buildings of the municipality. On the other hand, sectors 1 and 14 have the minority of the house residents, while sector 1 includes the majority of small industries of the municipality. Keep in mind that sector 15 is not a separate area, but represents the waste collection from the entire traffic axis of the region. In this context one may divide the existing city sectors according to their primary activity, Table IV. More specifically, sectors 2,3,6,7,9,11,12,13 and 14 are clearly residential regions. Sector 1 presents industrial and commercial activity, while all other sectors are basically commercial ones.

3. Proposed Improvements

Considering the information of Tables I-IV and figures (1) and (2), along with the increased waste load due to the incessant population increase of Nikaia and the 2004 Olympic Games activity[5], one may propose the following amelioration steps of the existing municipality waste collection system, i.e.:

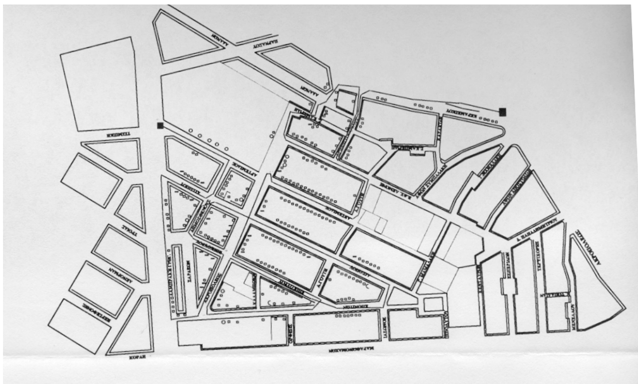

Figure 3: Proposed Collection Plan for Sector 13

- Replacement of the existing waste pails with larger ones of 1200lt capacity. According to the detailed analysis results, see also last column of Table I, almost 3530 new large waste-pails are required. The initial cost of new equipment varies between 300€ and 350€ (VAT included) per waste-pail.
- Disposal of small waste-pails to other smaller municipalities, at a 50% discount in comparison with the purchase value of new ones. The expected revenue is 300,000€ (±5%).
- Supply of two new waste-pails washing cars at a cost of 150,000€ (±5%) each.

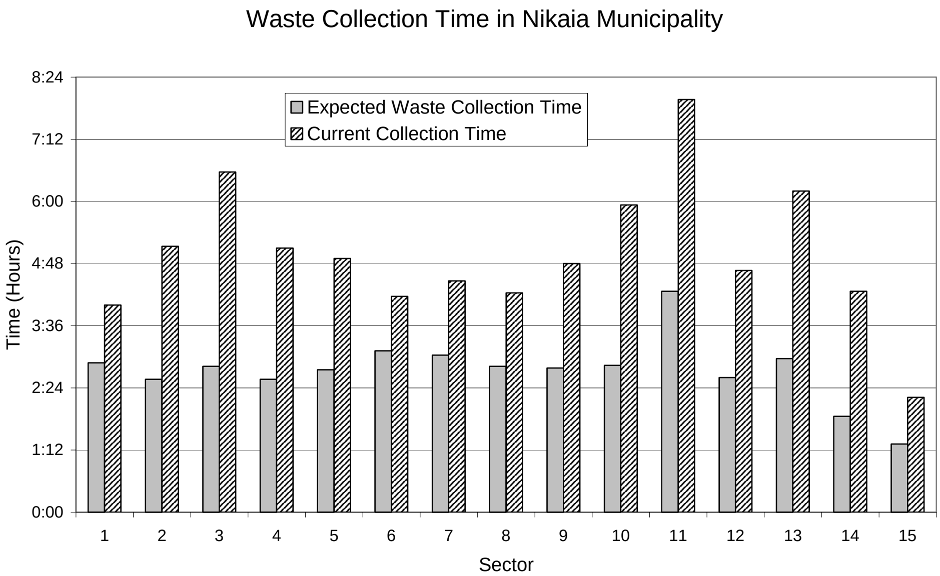

Figure 4: Comparison between Current and Expected Waste Collection Time

- Design of new waste collection routing and estimation of the time needed, based on the current needs of citizens and the installation of 3600 new large waste-pails. In figure (3) we present for example the new waste collection routing for sector 13, while in the next figure (4) we compare the measured -according to the existing system (Table II)- and the expected waste collection time on the basis of the proposed modifications. Using the official information concerning the existing system labour cost, the corresponding current annual value approaches the 1,250,000€. On the other hand, the labour cost of the proposed system does not surpass the 1,025,000€, including the operation of the two new waste-pails washing cars. Thus the expected operation cost savings are of the order of 225,000€ per year.

Recapitulating, one may use the above mentioned financial data in an integrated cost-benefit analysis in order to evaluate the viability of the proposed modifications.

4. Cost-Benefit Analysis Model

The total cost of a waste collection system includes[8][9] the invested initial capital "IC_o" for purchasing the necessary equipment and the corresponding maintenance and operation (M&O) cost "FC". The output of the system is the social satisfaction of a clean and healthy environment and the improvement of citizens' life quality. Since the system revenues cannot easily be quantified, the evaluation of the two waste collection systems should be carried out on the total cost basis.

Thus, the total operational cost "C_n" of a waste collection system after n-years of operation can be approached by the following relation:

$$C_n = IC_o \cdot (1+i)^n + FC_n \tag{1}$$

where:

$$FC_n = FC_o \cdot \left(\frac{1+g}{1+i}\right) \cdot \left[1 + \left(\frac{1+g}{1+i}\right) + \ldots + \left(\frac{1+g}{1+i}\right)^{n-1}\right] \cdot (1+i)^n \tag{2}$$

Keep in mind that "i" is the market capital cost, "g" is the annual inflation ratio of the M&O cost of the system and the subscript "o" is used to describe the specific time-point when the analyzed waste-collection system starts operating.

In order to compare the two waste-collection systems, one should use equations (1) and (2) for the two alternatives, considering that "IC_o" is zero for the already operating waste-collection system. Thus, using equations (1) and (2) for the two options under evaluation we get:

$$\Delta C_n = C_n^{old} - C_n^{new} = \left[(\delta FC) \cdot f - IC_o^{new}\right] \cdot (1+i)^n \tag{3}$$

where:

$$\delta FC = FC_o^{old} - FC_n^{new} \tag{4}$$

$$f = \left[1 + x + \ldots + x^{n-1}\right] \cdot x \tag{5}$$

and

$$x = \frac{1+g}{1+i} \tag{6}$$

As it is obvious from equation (3), the proposed investment presents financial advantage for the specific time-horizon "n-years" if "ΔC_n" is positive. Finally, one should not disregard the residual value of the equipment used at the end of the time-period analyzed, which is very low for the already old-fashioned equipment. In order to obtain calculation results in constant values, it is better to examine the following non-dimensional parameter:

$$BCR = \frac{\Delta C_n^*}{IC_o^{new}} = \frac{\Delta C_n}{IC_o^{new} \cdot (1+g)^n} = \left[(\frac{\delta FC}{IC_o}) \cdot f - 1 \right] \cdot \frac{1}{x^n} \qquad (7)$$

which compares the proposed revised waste-collection system money saving in constant values with the necessary capital to be invested (i.e. benefit to cost ratio or BCR).

5. Evaluation Results

Using the above described analytical model and the financial data of section 3, one has the opportunity to evaluate the financial behaviour of the two waste collection systems under investigation. Thus, the initial cost of the new equipment (including the amount received accumulated from old equipment disposal) is:

IC_o=(1,060,000-1,230,000)Euro

The corresponding annual M&O cost difference is:

δFC=(200,000-250,000)Euro

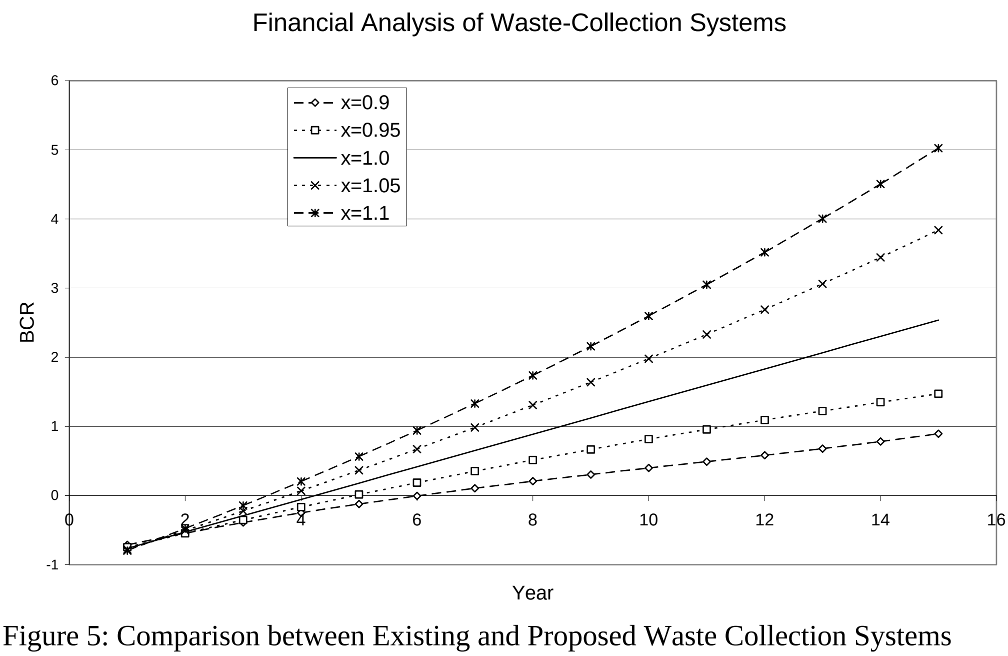

Figure 5: Comparison between Existing and Proposed Waste Collection Systems

Finally, values of the local market parameter "x" depends on the local market capital cost and the corresponding M&O cost annual inflation ratio. For the analysis completeness, one should treat "x" as an independent parameter, taking values between 0.90 and 1.10. Subsequently, the cost-benefit analysis calculation results are summarized in figure (5), where one has the opportunity to examine the new system payback period (i.e. BCR=0, equation (7)) versus operation time. As it is obvious, the payback period of the proposed system varies between 3.5 and 6 years, while the corresponding equipment service period exceeds the 15 years. Besides, the financial behaviour of the proposed solution is fairly influenced by the local market economic situation, if local market capital cost and M&O cost inflation rate take reasonable values, i.e. $g \leq 15\%$ and $i \leq 15\%$.

Recapitulating, the proposed renovation of the existing waste-collection system of Nikaia municipality is definitely positive, as far as its financial outcome is concerned. Bear in mind that no State or E.U. subsidization is taken into account during the evaluation process.

6. Conclusions and Proposals

A thorough analysis of the existing domestic-waste collection process in Nikaia town leads to several interesting amelioration ideas. The suggested revisions of the existing empirical waste-collection system are based on detailed information about the current situation and economic activity of the entire municipality. Besides, new improved computer based techniques are utilized to prepare the new waste-collection routing, without disregarding the peculiarities of each building block.

At the same time, these proposals -if adopted and properly applied- should shortly payback the necessary invested capital, leaving remarkable gains and improving the services offered by the local authorities. On top of that, it is almost obvious that several additional urban municipalities may equally use this promising house-waste collection management plan, after certain minor modifications.

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ENVIRONMENTAL IMPACTS OF WIND ENERGY APPLICATIONS: "MYTH or REALITY?"

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Abstract

Wind energy is the fastest growing energy sector for electricity production in various European countries. A substantial wind power penetration is also expected in the Greek energy market. This significant number of new wind turbines provokes serious reaction of local people, pretending important environmental impacts. For this purpose, an introductory survey is carried out to validate the real size of the wind energy applications impact on human societies and local ecosystems. During the present investigation, several important parameters, like visual impact, noise emissions, avian mortality, land usage and energy payback period-materials requirements are taken into account. On the other hand the wind energy contribution to air pollution reduction is also considered.

Keywords: Wind Energy; Environmental Impact; Noise Emissions; Avian Mortality; Visual Impact; Air Pollution; Land Use

1. Introduction

Aeolus, the ancient Greek god of winds, used to push sail-ships and move windmills for ages. Nowadays 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]. During the last five years, the development rate of installed capacity in individual countries varies between 15% and 75% per year (figure (1)). Thus, the original E.U. target for 4,000MW of wind power by 2000 has been almost doubled, while the new EWEA (European Wind Energy Association) target attains 40,000MW by 2010 and 100,000MW by 2020.

According to extensive wind potential studies all over Europe, the best wind resources are located in the upland regions of Ireland, Britain and Greece, where average wind speeds (at hub height) may overpass the 8÷11m/s. More precisely, in the Aegean Archipelago -a remote Hellenic area at the east side of the mainland- there exist several islands, which, along with the mainland coasts, possess high wind potential[2].

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 or locally extracted lignite (figure (2)), thus strongly contributing to environmental deterioration[3]. At the same time, the electricity production cost for the majority of the remote Greek islands is extremely high[4], approaching the value of 0.25Euro/kWh, while the fuel cost is responsible for almost 50% of the above-mentioned value. 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.[5].

Finally, in March 1997, the European Commission undertook the obligation to reduce total E.U. emissions of greenhouse gases (in comparison with 1990) by 8% before the year 2012. Wind energy provides one of the cheapest renewable energy opportunities, reducing CO_2 emissions caused by electricity generation[6].

***Kaldellis J.K., Kavadias K.A., Paliatsos A.G., 2003**, "Environmental Impacts of Wind Energy Applications: "Myth or Reality?", Fresenius Environmental Bulletin Jr, Vol. 12(4), pp. 326–337.*

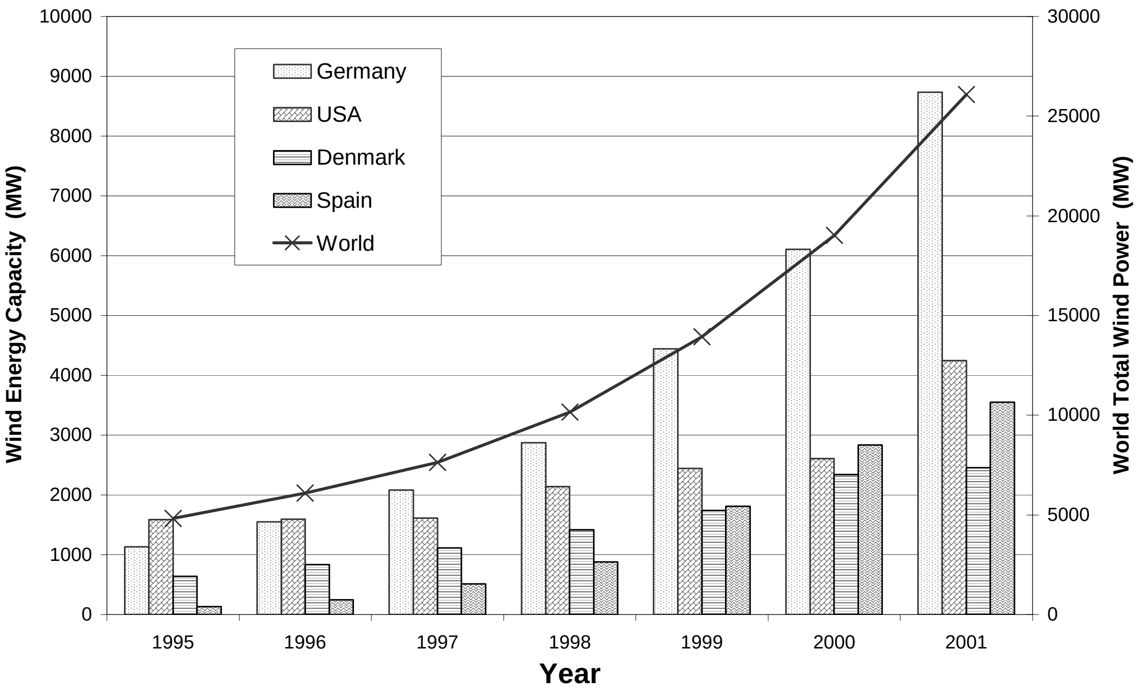

Figure 1: Evolution of wind power capacity in Europe and USA

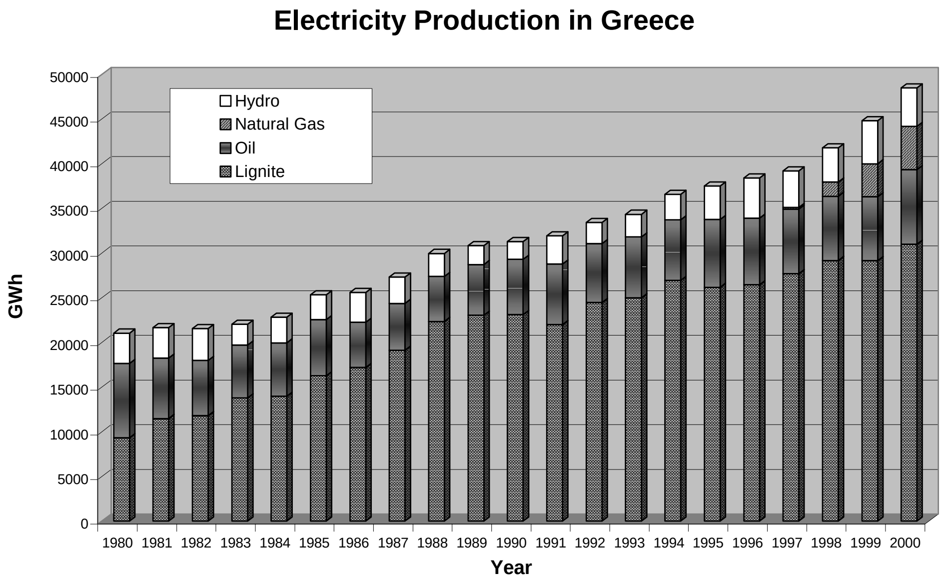

Figure 2: Time-evolution of electricity production profile in Greece

2. Position of the Problem

For all the above-mentioned reasons, the Greek State is strongly subsidizing private investments in the area of wind energy applications[7], either via the 2601/98-development law or the "Energy Operation 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%. Hence, during the last two years, a substantial increase (of more than

100%) of the existing wind power has been encountered, suddenly pushing the installed wind power of the country over the 250MW (figure (3)).

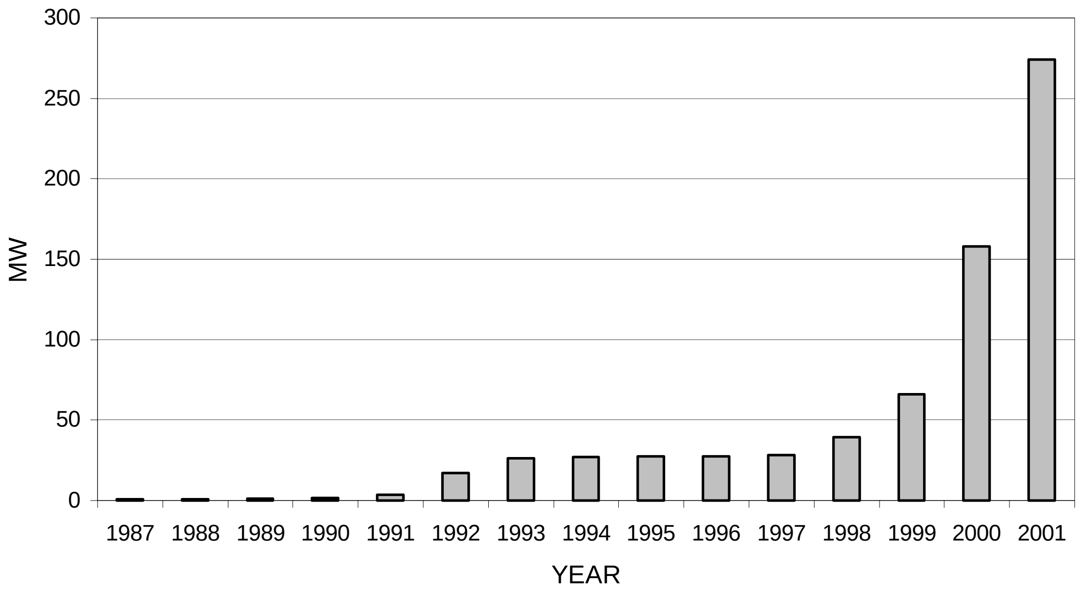

Figure 3: Installed wind power capacity in Greece

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 (Greek Regulatory Authority for Energy[8]). 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[9], which in some cases may even lead to cancellation of the complete wind power project, claiming important environmental impacts.

In this socio-techno-economic context, the RAE (Greek Regulatory Authority for Energy) decides -via international tenders- which companies have the ability to develop power stations, on a pure fiscal criteria basis. In view of this significantly scheduled wind power penetration (more than 1200MW have been accepted by RAE) in the local energy market and despite the expanded negative attitude of local societies encountered[10], an introductory investigation of the principal environmental impacts on the local societies-ecosystems is carried out, along with the techno-economic analysis regularly presented in similar cases[7]. The results obtained may be useful in any decision taken in the area of the European and local energy planning[11].

Generally speaking, public opinion surveys on both sides of the Atlantic are in strong support of the wind energy development[12]. Typically, two-thirds to three-fourths of those polled encourage wind development even in areas with existing wind turbines. Several states of USA, including California, Colorado, Michigan and Texas, defend the so-called "Green Power" program, concerning the electricity produced by a renewable (green-clean) energy source, see also[13]. Additionally, "Green marketing" is the practice where an electric utility (municipal or private) offers blocks of "Green Power" to customers to support the development of renewable resources. Customers arrange to purchase a certain amount of "Green Power" (actually energy in kilowatt-hours) per month, for which they commonly pay a small premium to completely or partly offset any higher cost of renewable power sources.

On the other hand, there also exist other groups that find wind turbines "*huge and noisy industrial machines damaging local amenity*". Besides, "visual intrusion" is one of the major factors determining opposition to wind energy (figure (4)). Many researchers believe[14][15] that people unconsciously realize that opposition on aesthetic grounds is subjective and is, therefore, often dismissed by public officials. They, then, rationalize their opposition by rising concerns such as noise, shadow flicker and birds, which can be objectively evaluated.

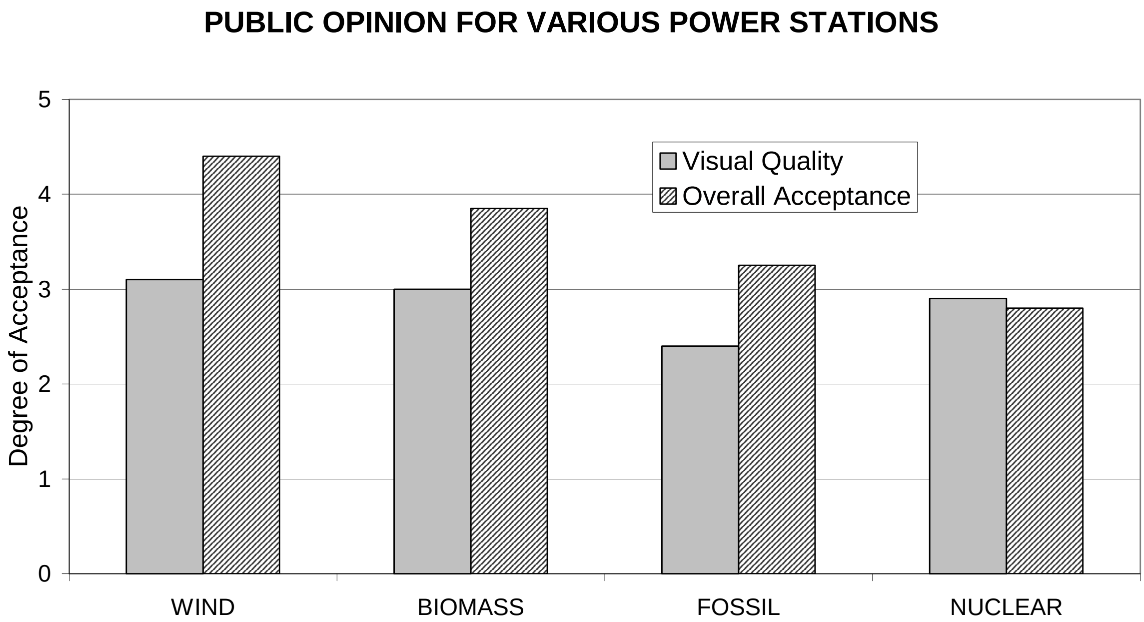

Figure 4: Public opinion for various power production alternatives[14]

To be objective, depending on the landscape characteristics, modern wind turbines -with a hub height of 60÷100 meters and a blade length of 30÷50 meters- form a visual impact on the scenery. However, in any case that man places structures in a terrain, its character immediately changes. Besides, it is a matter of taste -to a large extent- how people perceive that wind turbines fit into the landscape. Numerous studies[9][12] in many European countries revealed that people who live near wind turbines are generally more favorable towards them than city dwellers.

Another important aspect of wind turbines operation is the noise emission. From the human perception point of view, most people find it pleasant to listen to the sound of the waves at the seashore, called "white noise" (random emissions). On the contrary, a neighbor's radio produces some systematic content, which one's brain cannot avoid discerning and analyzing. If one generally dislikes his neighbor, he will no doubt be even more annoyed with that noise. That’s why sound experts define "noise" as "unwanted sound". According to this example, it is easy to conclude that the annoyance by wind turbine noise emissions is also a highly psychological phenomenon[23].

Therefore, in an attempt to obtain an unambiguous picture concerning the size and importance of the main environmental impacts of wind energy installations, the following topics are examined.

3. Visual Impact

Water and windmills have been in operation, during the last 800 years, all over Europe. Recently, wind turbines revived the matter of landscape aesthetics. They have been subject to hard criticism because they are "a new element" and because they are located in highly visible places in order to exploit wind conditions. 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 additions to the landscape. Thus, although a wind plant is clearly a man-made structure, what it represents "may be seen either as a positive or as a negative addition" to the landscape.

As already mentioned, the attitude towards wind energy is usually positive[9][12]. However, the knowledge that a wind turbine will actually exist within a five-miles distance from their home seems to make people slightly less positive, i.e. the "NIMBY" (Not In My Back Yard) phenomenon[16]. According to various researchers[10][12] a negative view of wind turbines on the landscape is the major factor determining opposition to wind energy applications.

Taking the above-described piece of information seriously into account, the industry has devoted considerable effort to carefully integrate the development of new wind-parks into the landscape. Computer-generated photomontages, animations and even fly-through, together with mapped zones of visual influence, provide objective predictions of appearance, e.g.[17][18].

One of the most significant methods to improve public acceptance has been visual uniformity; i.e. the rotor, nacelle and tower of each machine look similar. They don't need to be identical. Additionally, it is equally important all towers to be of consistent height, while steel towers are found more aesthetically pleasing than the lattice ones, more widely used in the U.S.A. Professional designers have been employed by several wind turbine manufacturers to enhance the appearance of their machines. Finally, if turbines are faulty, the public may perceive a wind farm to be unjustified -a waste of visual resources. Thus, when turbines don’t operate or are perceived as often broken, the public is far less likely to tolerate the turbines intrusion on the landscape.

Finally, a more objective case of visual impact is the effects of the periodic reflections (glinting) or interruption (shadow flicker) of sunlight from the rotor blades[19]. Wind turbines, like other tall structures, will cast a shadow (or a reflection) on the neighboring area when the sun is visible. This is a problem only when turbines are sited very close to workplace or dwellings and occur during periods of direct sunlight. These effects may be easily predicted and avoided by carefully considering the machine-site and the surface finish of the blades. A common guideline used in N. Europe is a minimum distance of 6-8 rotor diameters between the wind turbine and the closest neighbour. A house, 300 meters from a contemporary 600kW machine with a rotor diameter of 40 meters, will be exposed to moving shadows approximately 17-18 hours (out of 8760h) annually.

4. Noise

Sound emissions from wind turbines may have two different origins, i.e. mechanical noise and aerodynamic noise. Additional analysis reveals[20] that for most turbines with rotor diameters up to 20m the mechanical component is the dominant one, whereas for larger rotors the aerodynamic component is the significant one. More precisely, mechanical noise may originate in the gearbox, in the drive train (the shafts) and in the electrical generator of the wind turbine. It is true that machines constructed during the early 80s or earlier do emit some mechanical noise, which in most cases may be heard even up to a 200m distance from the turbine. Nowadays, no manufacturer considers mechanical noise as a problem any longer, since within five years mechanical noise emissions had dropped to half their previous level due to better engineering practices.

On the other hand, three main categories of aerodynamic noise sources[21][22] may be distinguished:

- Discrete low frequency noise at the blade passing frequency and its harmonics.
- Self induced noise due to direct radiation by the attached boundary layer on the rotor blade, due to flow field separation at the blade trailing edge and finally due to trailing edge instabilities involving quasi-discrete frequencies.
- Broadband noise due to interaction between the inflow turbulence and the rotor.

For almost all-existing commercial wind turbines operating under normal conditions, the most significant noise source is the self–induced noise of the blades. However, for very large wind turbines the interaction of the atmospheric turbulence with the rotor can become predominant, under certain conditions.

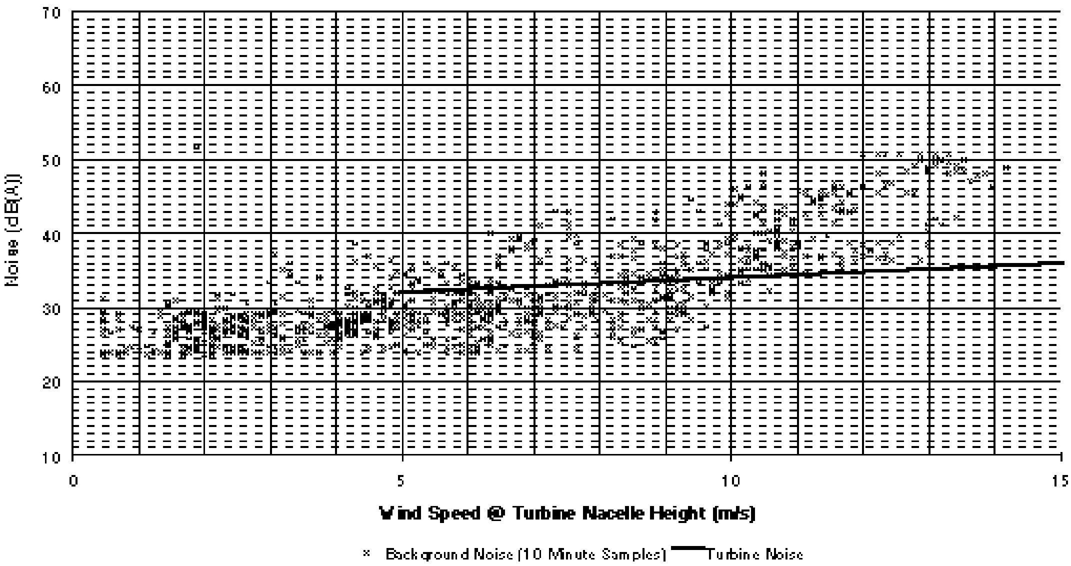

Figure 5: Background noise and turbine noise vs. wind speed[24]

Generally speaking, no landscape is ever completely quiet, since birds, animals and human activities create sound. Thus, when the wind hits different objects at a certain speed, it will start making a sound. From a technical point of view, as wind speed approaches the 6-7m/sec, the noise from the wind in leaves, shrubs, trees, masts etc. (background noise), will gradually mask any potential sound from wind turbines, (figure (5)). Of course, sound reflection or absorption from terrain and building surfaces may change the sound picture in different locations. The wind rose is therefore important to chart the potential dispersion of sound in different directions.

The dB(A) scale, used by public authorities around the world, measures the sound intensity over the whole range of different audible frequencies. As a matter of fact, it uses a weighting scheme, which accounts for the fact that the human ear has a different sensitivity (better at medium -speech range-frequencies) to each different sound frequency. Besides, the dB-scale is a logarithmic one. This means, that as the sound pressure (or the energy in the sound) is doubled the dB index increases by approximately three points (e.g. from 97dB(A) to 100dB(A)).

Other parameters being equal, sound pressure will increase with the fifth (4^{th} to 6^{th}) power of the speed of the blade relative to the surrounding area[20]. That is why modern wind turbines with large rotor diameters have very low rotational speed (figure (6)). On top of that, the energy in sound waves (and thus the sound intensity) will drop with the square of the distance from the sound source (figure (7)).

According to this fact, at one rotor diameter distance (~40m) from the base of a wind turbine emitting 100dB(A) one will generally have a sound level of 60dB(A), corresponding to a European clothes dryer, while four rotor diameters (170m) away one will have 44dB(A), corresponding to a quiet living room in a house.

Of course, in cases of two or more wind turbines located at the same distance from ones ears, the sound energy will double, increasing thus the sound level by 3dB(A). One will actually need ten wind turbines placed at the same distance from the measurement point, in order to perceive that the subjective loudness has doubled. Finally, the fact that the human ear (and mind) discerns pure tones more easily than (random) white noise must be taken into account when doing sound estimates.

Summarizing, sound pressure predicted or measured is typically around 96-101dB(A) (figure (6)) for commercial wind turbines. Thus, the sound pressure level at a distance of 40m from a typical machine is 50-60dB(A), about the same level as a conventional speech. A farm of ten wind turbines, with the nearest at a distance of 500m would create a sound level of about 42dB(A) under the same conditions, equivalent to the sound inside a quiet office.

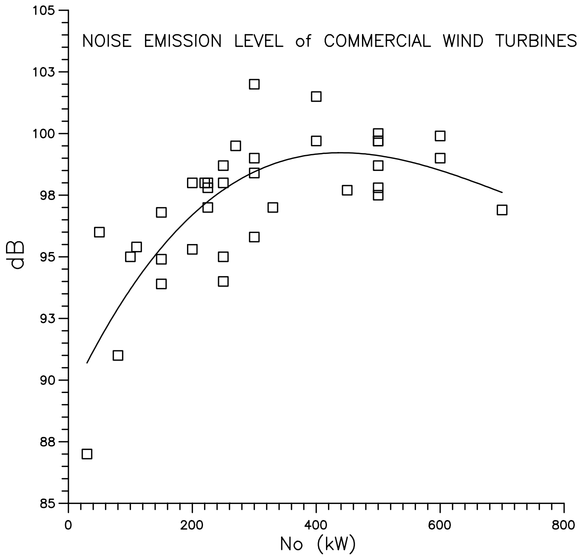

Figure 6: Noise emission level by contemporary wind turbines, market data

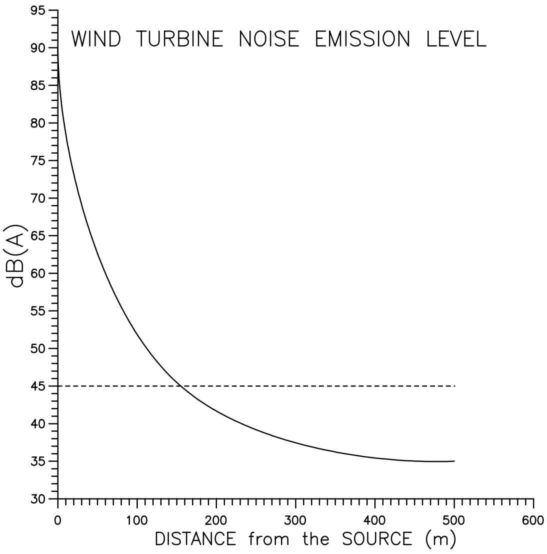

Figure 7: Noise emission changes vs. the distance from the wind turbine

Ten years ago, wind turbines were louder than they are today (figure (8)). Serious effort has been devoted for the creation of the present generation of quiet machines, paying detailed attention to both the design of the blades[26][27] to avoid boundary layer separation[28] and to mechanical parts of the machine. As a result, noise is a minor problem for modern carefully sited wind turbines.

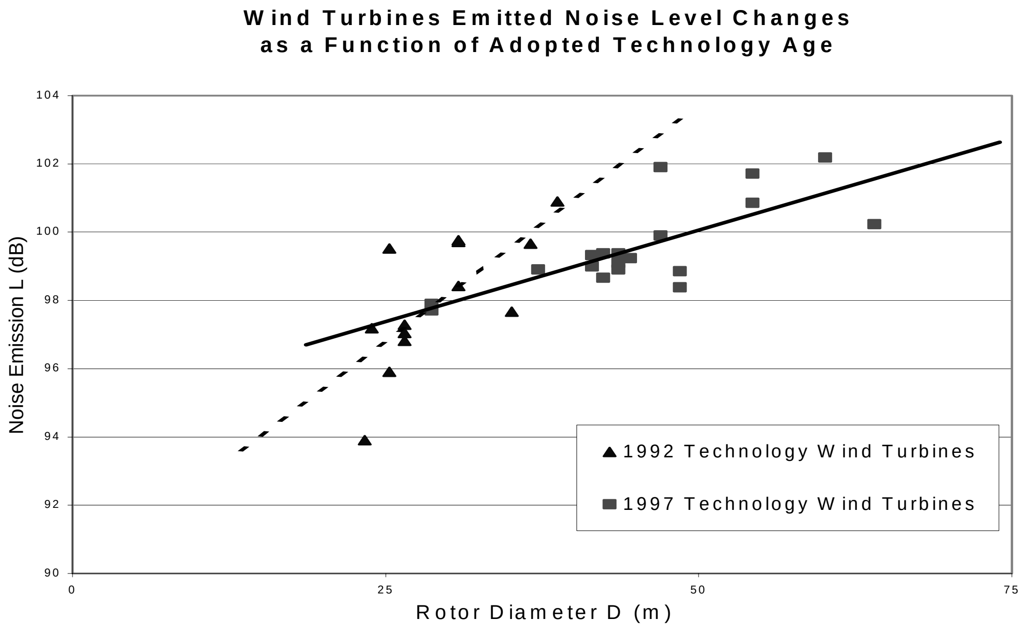

Figure 8: Wind turbine technology amelioration impact on noise emission[25]

5. Impact on Birds

Birds often collide with structures that they cannot easily detect, like high voltage overhead lines, masts, poles and windows of buildings. More than a few are also killed by moving vehicles. Accordingly, the impact of wind turbines on birds can be divided into:

- Direct impact, including risk of collision and effect on the breeding success.
- Indirect impact, including effects caused by disturbance from the wind turbines (noise and visual disturbance).

Studies in Germany, the Netherlands, Denmark and the UK conclude[29] that wind turbines do not pose any substantial threat to birds, since bird mortality due to wind turbines is only a small fraction of background mortality.

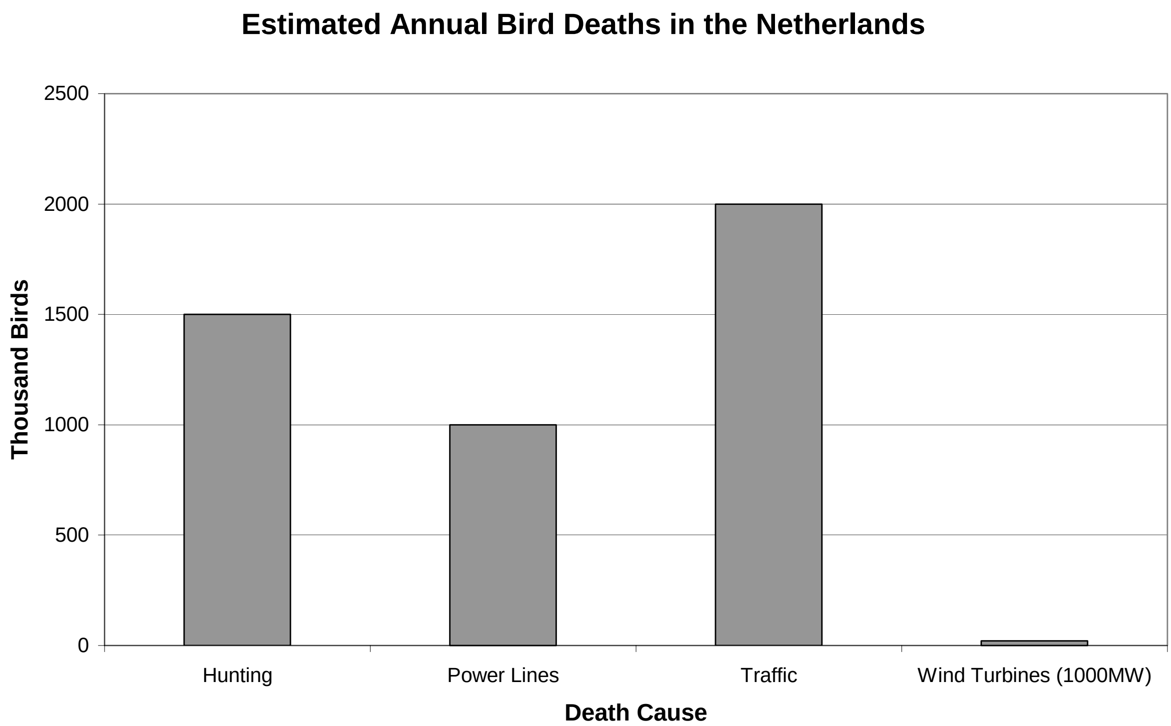

Figure 9: Bird mortality in the Netherlands[19]

In figure (9), the estimated number of annual bird deaths in the Netherlands from various man-made causes is presented[19]. According to the results given, more than **three hundred times** as many birds die from collisions with moving vehicles than with wind turbines and **seventy times** as many are killed by hunters. A parallel study in Denmark has estimated the maximum level of birds' collision with wind turbines to be in the range of 6-7 birds/turbine/year. Equivalently, 25,000 to 30,000 birds annually die from collision with wind turbines that produce enough electricity for 600,000 families. For comparison purposes, keep in mind that over one million birds are annually killed by traffic in Denmark.

Isolated examples have been reported, concerning significant damages on specific species, like geese and waders as well as golden eagles. For example, approximately three thousand cumulative bird deaths are related to the 625MW of installed wind power capacity at Altamont Pass each year, including 39 golden eagles[30]. However, in this area a "wind wall" of turbines on lattice towers is literally closing off the pass, while during the early development stages of wind farms practically no measures are taken to avoid this problem.

Another negative example[31] is referred to the Spanish wind farm of Tarifa, near the Strait of

Gibraltar, which is a major bird migration route. This problem could have been avoided if the special circumstances in this area had been properly taken into account during the planning process of the wind farm.

On the other hand, for the majority of wind power installations one can say that the birds get accustomed to wind turbines rather quickly and there are several examples of falcons nesting in cages mounted on wind turbine towers. Radar studies (during day and night) show[19] that birds tend to change their flight route some 100-200m upwind of the turbine and pass above or around it at a safe distance.

Summarizing, we can say that the "avian mortality" is a real problem for commercial wind power plants (e.g. one bird for 100MWh of electricity-consumption of 25 families) and every death is regretted. However, results should not be concluded by a few extreme cases of increased bird mortality. Besides, wind power industry and wind farm developers are taken seriously into account this issue, normally excluding new installations from bird-sensitive locations.

6. Land Use

The Achilles' heel of wind energy has always been the charge that it is too land-intensive. It is true that wind energy is diffuse (~500W/m^2), while collecting energy from wind requires turbines to be spread over a wide area. More precisely, turbines should be separated by at least five to ten rotor diameters, in order the wind strength to be reformed and the air turbulence created by one rotor not to harm another machine downwind.

Therefore, the amount of land needed varies from as little as 0.05km^2/MW for California's densely packed arrays of small old-fashioned wind turbines to the 0.15km^2/MW found in the openly spaced wind plants of northern Europe. As a rule of thumb, wind farms require 0.08 to 0.13km^2/MW or wind farm arrays occupy 50m^2 of land for every m^2 swept by the wind turbine's rotor[32]. Onshore wind farms have the advantage of dual land use, since the 99% of the area occupied by a wind plant can be used for agriculture or remain as natural habitat. Furthermore, part of the installations can be made offshore.

Table I: Land required per GWh of electrical energy for a 20-year period in Greece.

Production Technology	Maximum Land Required	Minimum Land Required
Wind Energy Installation	Medium Wind Potential V≈6m/s 1300m^2	High Wind Potential V≈9.5m/s 750m^2
Photovoltaic-Solar Station	North Greece (1400kWh/m^2) 2900m^2	Crete (1650kWh/m^2) 2200m^2
Lignite-Fired Thermal Power Station	Low Quality Megalopolis 9500m^2	Medium Quality Ptolemaida 6800m^2

As stated above, less than 5% of the wind park area would be physically occupied by wind turbines, electrical equipment and access roads. Wind turbine foundations, though about 50m in diameter, are normally completely buried, permitting any existing agricultural activity to extend right up to the tower base.

There is no evidence that wind farms interfere to any greater extent than this with arable or livestock farming. Modern wind plants use no more land than other means of energy generation, see also Table I. For direct comparison between wind energy and fossil fuels, the total fuel cycle in each case must be taken into account. For example, a wind plant in a moderately strong wind regime will use far less land than a coal mine and a conventional power plant, producing the same amount of electricity during a 20-year period.

Effects on other terrestrial ecosystem primarily result from construction activity, land take and hydrological disruption. The scale of these effects will depend on the type of ecosystem, drainage, construction techniques & timing and restoration practice. On typical flat on-shore sites, installation does not to any significant level affect vegetation or fauna. In almost all E.U. countries wind power developers are obliged to minimize any disturbance of vegetation under construction of wind farms in combination with road works etc., on sensitive sites as mountainous sites and offshore.

7. Energy Balance and Materials Requirements

Though wind turbines do use energy-intensive materials, such as steel, glass reinforced polyester (fiberglass), and concrete (for foundations), according to three separate European studies[19] they quickly repay the energy consumed in their construction. More precisely, modern wind turbines rapidly recover all the energy spent in manufacturing, installing, maintaining, and finally scrapping them. A typical wind farm reimburses its energy debt in 3 to 4 months, in contrast to photovoltaics that present an amortization time of almost seven years.

As expected, most of the energy used to manufacture the turbine is contained in the rotor and nacelle. But more than one-third of the total energy consumed by the wind turbine is contained in the concrete foundation and the tower of the machine. A detailed life-cycle analysis[19] of wind turbines is done by D.W.T.M.A., estimating the energy content in all components of a wind turbine, and the global energy content in all links of the production chain. The resulting estimated energy requirements of a typical Danish 600kW wind turbine during its 20-year lifetime are shown in Table II.

Table II: Specific energy demand during the operational life of a wind turbine.

Process	**Specific Energy (MWh/kW)**
Manufacture	0.880
Installation	0.228
Operation & Maintenance	0.358
Scrapping (Total)	-0.098
TOTAL	1.368

Manufacturing a state of the art 600kW wind turbine takes 3.2TJ, taking into account everything, from producing raw material to installing a ready to operate machine, including 20 years of operation & maintenance and decommissioning. In suitable locations, the wind turbine will generate 1.1 to 1.4GWh per year in its projected 20-year useful life.

According to the results obtained, at good sites, wind turbines pay for the energy in their materials within the first three to four months. Even at poor sites, energy payback occurs in less than one year.

A more extensive study was carried out in Germany examining wind turbines from 10kW to 3MW in size[33]. The analysis shows that even small wind turbines of 10-30kW took only a year to recover the energy spent in manufacturing, installing and decommissioning them, while turbines of 55kW took some six months to recover the corresponding energy spent.

A recent detailed study[34] concerning the material inputs of a wind farm is carried out for the Baix-Ebre wind farm in Spain, based on a life-cycle environmental impact assessment (LCA). Baix-Ebre wind farm comprises 27x150kW turbines on a high mountain ridge of Catalonia. While caution must be exercised with regard to this approach, as materials inputs may not be strictly proportional to installed capacity, the weights per MW give useful approximate generalized estimates, which are more widely applicable.

From the data gathered, it is clear that the material inputs required for a wind farm are dominated by the concrete (reinforced) for the turbine foundations and by the steel from which the turbine towers are fabricated. It is conceivable that a wind farm could, on reaching the end of its operating life, be refurbished by installing new nacelles and rotors on top of the existing towers and foundations. This would reduce the material inputs required for the "second generation" wind farm by well over 80%.

Lastly, if there is sufficient demand for the secondary raw materials, wind turbines can be regarded as being mainly composed of recyclable materials. The principal unresolved issue from an environmental perspective is the recycling of rotor blades[35].

Water use is another significant issue in energy production, particularly in areas where water is scarce. Conventional power plants use large amounts of water for the condensing portion of their thermodynamic cycle. Small amounts of water are used to clean wind turbine rotor blades in arid climates, to eliminate dust and insect build up, which otherwise deforms the shape of the airfoil and degrades performance[36]. According to calculation results wind power plants use less than 1/600 as much water per unit of electricity produced as nuclear does and approximately 1/500 as much as coal[37].

Finally, decommissioning will include the removal of all above ground elements of the development as a minimum, as well as the restoration of the original site. In most cases, the decommissioning costs can be recovered from the scrap value of the turbines and copper wiring from the project. Indeed, another significant environmental benefit of wind energy is that wind turbines can easily be decommissioned, in comparison with other generating technologies.

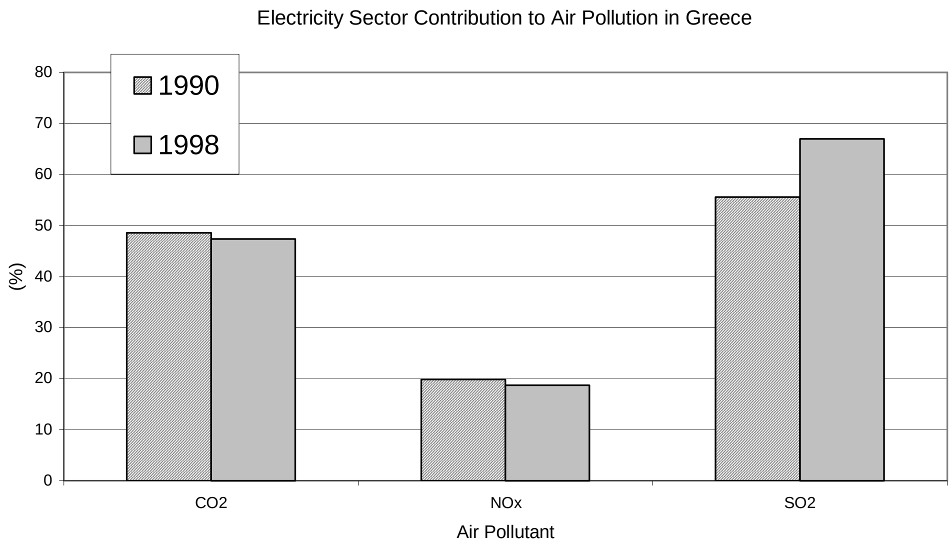

Figure 10: Electricity sector contribution to air pollution in Greece

8. Wind Energy Impact on the Diminution of Air Pollution

Air pollutants are primarily emitted from the various energy transformation processes based on fossil fuels. Today SO_2, NO_x, CO and volatile organic compounds (VOCs) are considered as the basic air pollutants, along with the CO_2, which is the result of using carbon as a fuel. These major pollutants may cause detriment at very different concentration levels, according to their toxicity factors[3]. Figure (10) presents the time varying contribution of the electricity production sector on the national annual production of the above pollutants. As it is obvious from the data of figure (10) electricity production is responsible for about 48% of the national CO_2 emissions, along with 68% of SO_2 and 20% of NO_x.

More specifically, according to recent research and official data[3][38], every MWh of electricity consumed in Greece is considered responsible for almost 18kgr of CO, 4.3kgr of NO_x, 6.4kgr of SO_2 and 1054kg 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 Greek society. Similar results[19] are also valid (Table III) for almost all E.U. country members.

Table III. Specific emissions (kg/MWh) from fossil-fuelled electricity plants vs. 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 IV one may compare[19] 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 IV. CO_2 Emissions (kg/MWh) from various electricity production technologies[19]

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
Wind	-	7	-	7
Small Hydro	-	10	-	10

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. According to damage cost derived using previous estimates of acidification[39], an optimistic value is approximately 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 III) 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 of wind energy production plants are only a very small percentage respectively to those from fossil-fuelled plants.

9. Conclusions

It is the author's articulated opinion that wind energy is a sufficient, mature, cost-effective and widely applicable technology, especially for the Greek socio-economic situation. However, in some exceptional occasions, remarkable negative environmental events are encountered. In order to explain and validate the real impact of wind energy applications on the environment, an introductory investigation is carried out, including visual impact, noise emissions, avian mortality, land use etc. Subsequently, the energy amortization period and the material requirements of a typical wind converter are estimated.

The main conclusions drawn from the above-presented study are that wind energy applications, especially during their first steps, impose -in a degree- unnecessary annoyance on human societies and local ecosystems. These spare accidents at no case characterize the contemporary wind energy technology. Besides, one should seriously take into consideration the undeniable contribution of wind energy to the air pollution prevention.

In this context, wind energy developers and turbine manufacturers have realized a lot during the twenty-years of their participation in the wind potential exploitation all over the world. Modern wind turbines are more quiet, safer, respect the landscape aesthetics, while special attention is paid during new project planning.

For all the above-mentioned reasons, the society -if properly informed- eagerly supports the efforts of wind power sector to fulfill the electricity demand with clean energy. It is common belief that wind turbines are not inherently dangerous. Therefore, every aspect of a wind plant should convey the sense that wind energy is more benign than other forms of energy. Of course, wind industry should continue placing the same effort on being a good neighbor as on being aerodynamic efficient, in order not only to maintain but also to increase the public acceptance of wind energy applications, all over the world. Recapitulating, the increase of wind energy penetration in the local fuel-mix is going to ameliorate the existing environmental situation without invoking the long and short-term hazards of thermal and nuclear power stations.

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NOISE AND VISUAL IMPACT OF WIND POWER STATIONS
WHAT IS THE PUBLIC OPINION IN GREECE?

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Abstract

During the last three years, the installed wind power in Greece has significantly risen from 40MW to almost 300MW. This important wind power ascension was based on remarkably sized contemporary wind turbines, concentrated in few relatively restricted geographical areas. In certain areas, however, this outstanding wind power penetration provokes serious local population reactions, which in several cases lead even to the complete wind power projects cancellation, by claiming important environmental impacts. More specifically, noise emission and visual impact are the most common complaints made by local people against wind turbines. In this context, an extensive study is carried out concerning the noise and visual impact of operating wind parks in Greece, allowing for the above-mentioned remarks. This survey is carried out in three separate phases -between 2000 and 2002- by different research groups, while the complete public opinion investigation and the results analysis validates the necessary scientific criteria. In the questionnaire, general questions were posed regarding acceptability of the operating wind parks in locality, along with more specialized questions concerning "visual intrusion" and "noise disturbance" of these wind power installations. The conclusions drawn are very characteristic of the public attitude towards wind power applications and may be useful to everyone related to the local energy planning procedures.

Keywords: Wind Energy; Public Opinion; Noise Impact; Visual Impact

1. Introduction

During the last three years, the installed wind power in Greece has significantly risen from 40MW to almost 300MW (figure (1)), after a long period (1993-1998) of stagnation, mainly due to the incomplete legislation frame and the insufficient infrastructure of the local electrical networks. This important wind power ascension was based on remarkably sized contemporary wind turbines, concentrated in few relatively restricted geographical areas, i.e. mainly on NE. Crete and S. Euboea[1]. On top of that, an increased number of wind projects are under development for the Peloponessos area, in an attempt to take advantage of the existing electrical network capabilities and the available infrastructure. In certain areas, however, this outstanding wind power penetration provokes serious local population reactions, which in several cases lead up even to the complete wind power projects cancellation, by claiming important environmental impacts[2]. More specifically, noise emission and visual impact are the most common complaints made by local people against wind turbines[3].

In view of this negative reaction, many researchers believe that "visual intrusion" and "noise disturbance" are the major factors determining opposition to wind energy, although opposition on aesthetic and vexatious grounds is characterized as subjective and is often dismissed by public officials. In this context, an extensive study is carried out concerning the noise and visual impact of operating wind parks in Greece, allowing for the above-mentioned remarks.

This survey is carried out in three separate phases -between 2000 and 2002- by different research groups, while the complete public opinion investigation and the results analysis validates the necessary scientific criteria. In the questionnaire, general questions were posed regarding acceptability of the operating wind parks in locality, along with more specialized questions concerning "visual intrusion" and "noise disturbance" of these wind power installations.

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Finally, comparisons with relative opinion surveys on both sides of Atlantic are also conducted, in order to improve the understanding of the public behaviour towards new energy production installations. The conclusions drawn are very characteristic of the public attitude towards wind power applications and may be useful to everyone related to the local energy planning procedures.

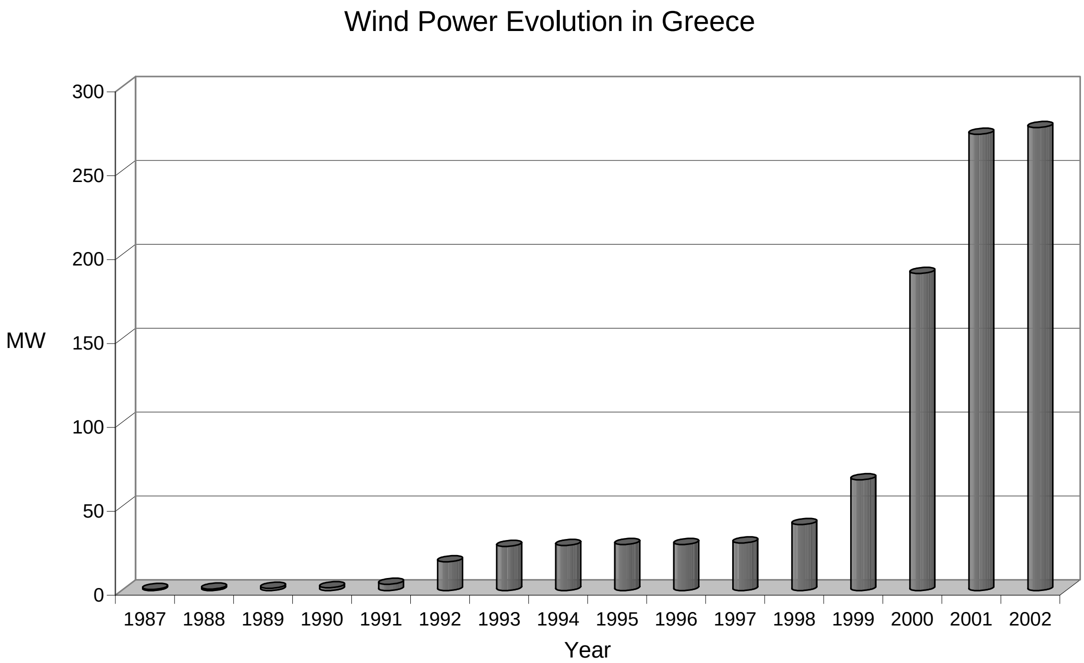

Figure 1: Time evolution of Greek wind power

2. Investigating Noise and Visual Impact of Wind Parks

Wind turbines have been subjected to hard criticism since they are usually located in highly visible places in order to exploit the available wind potential. However, 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 additions to the landscape. Thus, although a wind plant is clearly a man-made structure, what it represents may be seen either as a positive or as a negative addition to the landscape[4].

To be objective, depending on the landscape characteristics, modern wind turbines -with a hub height of 40÷80 meters and a blade length of 20÷40 meters- form a visual impact on the scenery. However, in any case that man places structures in a terrain, its character immediately changes. Besides, it is a matter of taste -to a large extent- the way people perceives wind turbines fitting into the landscape. Numerous studies[5][6] in many European countries revealed that people who live near wind turbines are generally more favorable towards them than city dwellers.

According to various researchers[7][8] a negative view of wind turbines on the landscape is the major factor determining opposition to wind energy applications. In this context, people disliking wind turbines unconsciously realize that opposition on aesthetic grounds is subjective, therefore rationalize their opposition by rising concerns such as noise, shadow flicker and birds, which can be objectively evaluated.

Another important aspect of wind turbines operation is the noise emission. From the human perception point of view, experts define "noise" as "unwanted sound". Hence, it is easy to conclude that the annoyance by wind turbine noise emissions is also a highly psychological phenomenon[9].

Sound emissions from wind turbines may have two different origins, i.e. mechanical noise and aerodynamic noise. Additional analysis reveals[10] that for most turbines with rotor diameters up to 20m the mechanical component is the dominant one, whereas for larger rotors the aerodynamic component is the significant one. Nowadays, no manufacturer considers mechanical noise as a problem any longer, since within last ten years mechanical noise emissions had dropped to half their previous level due to better engineering practices.

For almost all-existing commercial wind turbines operating under normal conditions, the most significant noise source is the self-induced noise of the blades. However, for very large wind turbines the interaction of the atmospheric turbulence with the rotor can become predominant under certain conditions.

Other parameters being equal, sound pressure will increase with the fifth (4^{th} to 6^{th}) power of the speed of the blade relative to the surrounding area[10]. That is why modern wind turbines with large rotor diameters have very low rotational speed. On top of that, the energy in sound waves (and thus the sound intensity) will drop with the square of the distance from the sound source. According to this fact, at one rotor diameter distance (~40m) from the base of a wind turbine emitting 100dB(A) one will generally have a sound level of 60dB(A), corresponding to a European clothes dryer, while four rotor diameters (170m) away one will have 44dB(A), corresponding to a quiet living room in a house. Of course, in cases of two or more wind turbines located at the same distance from one’s ears, the sound energy will double, increasing thus the sound level by 3dB(A).

Summarizing, sound pressure predicted or measured is typically around 96-101dB(A) for commercial wind turbines. Thus, the sound pressure level at a distance of 40m from a typical machine is 50-60dB(A), about the same level as a conventional speech. A farm of ten wind turbines, with the nearest at a distance of 500m would create a sound level of about 42dB(A) under the same conditions, equivalent to the sound inside a quiet office[11].

3. Registration of Local People Attitude

In order to investigate in depth the public attitude towards wind energy applications the Soft Energy Applications and Environmental Protection Laboratory of TEI Piraeus has first scheduled and subsequently conducted[12][13] a public survey in several representative Greek territories, presenting wind energy development interest. During the planning phase, emphasis is laid on the following topics:

- ✓ The degree of public knowledge about wind energy applications
- ✓ The public awareness about the environmental and macro-economic impacts of wind energy. Personal annoyance is also recorded
- ✓ The public attitude towards existing and new wind parks

The second subject to be clarified is the preparation of this research. According to the existing experience[5][6][14] there are several ways of conducting similar studies, like telephonic interviews, written questionnaires being mailed to a random sample, personal named or unnamed interviews etc. For increasing reliability and due to the country idiosyncrasy this last technique was selected. More specifically, during this survey the questionnaires were completed in the interviewer's sight, while the respondents filled in their name and phone, for confirmation purposes. The public response was encouraging, since almost one out of two of the persons asked answered the questions eagerly.

The last point to be arranged was the number of interviews needed to draw safe conclusions[15]. As it is obvious, the reliability of the results derived strongly depends on the size of approved sample used, since the outcome uncertainty is normally decreasing with the square root of the sample size. Due to the geographical diversity of the study and the manpower needed, a sample number in the range of 100 to 150 questionnaires was assumed acceptable, while 50 interviews were set as the lower limit.

Table I: Demonstration of the questionnaire used in the present public opinion survey

Question I	**What do you know about wind energy?**	
Possible Answers	a	It is obtained from the waves of the sea
	b	It is used in the solar heaters
	c	It is obtained from the wind
	d	It is obtained from nuclear plants
	e	I do not know
Question II	**The wind converters or wind turbines are usually used:**	
Possible Answers	a	in producing electric energy
	b	in marking regions
	c	for aesthetic reasons
	d	for televising purposes
	e	for other reasons
Question III	**Do you actually agree with the installation of Wind Turbines in your territory?**	
Possible Answers	a	YES, I do
	b	NO, I don't
	c	I would agree if only I had proof of their usefulness
	d	I am not interested in this matter
	e	I have no formed opinion
Question IV	**The wind converters or wind turbines of your territory:**	
Possible Answers	a	are visually annoying
	b	have no visual impact on me
	c	are not aesthetically right
	d	I have no opinion on their aesthetic impact
	e	make the area attractive
Question V	**The noise of the Wind Turbines in your territory:**	
Possible Answers	a	is too loud
	b	is too annoying
	c	does not actually disturb me
	d	is covered by the surroundings
	e	is pleasantly heard, in relation to their valuable energy

For the preparation of the questionnaire a large number of scientists collaborated, including statistics experts, sociologists and market survey experts. The relative questions to the subject investigated are summarized in Table 1, along with the possible answers. As it is obvious from Table I the first two questions asked guarantee that the people interviewed are familiar with the subject examined. According to the entire sample analyzed (417 questionnaires) 94% of the people interviewed are familiar with the basic wind energy principles (question I), while only 2% was not sure about the contributions of wind parks in the electrification effort (question II). Recapitulating, one may clearly state that the samples used have the necessary size to be statistically sound and credible, while the vast majority (≈95%) of the people questioned has quite a good idea about wind energy basic principles and wind power applications. The rest 5% is excluded from further analysis.

4. Survey Data Concerning Greek Wind Parks

In this paper emphasis is set to analyse the public opinion about visual and noise impact of existing wind power stations. For this purpose, two specific regions have been selected, presenting quite different attitude towards wind turbines. Hence, the first area investigated is the S. Euboea island. 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[1] of the public attitude towards wind turbines encountered in S. Euboea may be the remarkable concentration (≈120MW) of numerous large wind converters, in a relatively short time.

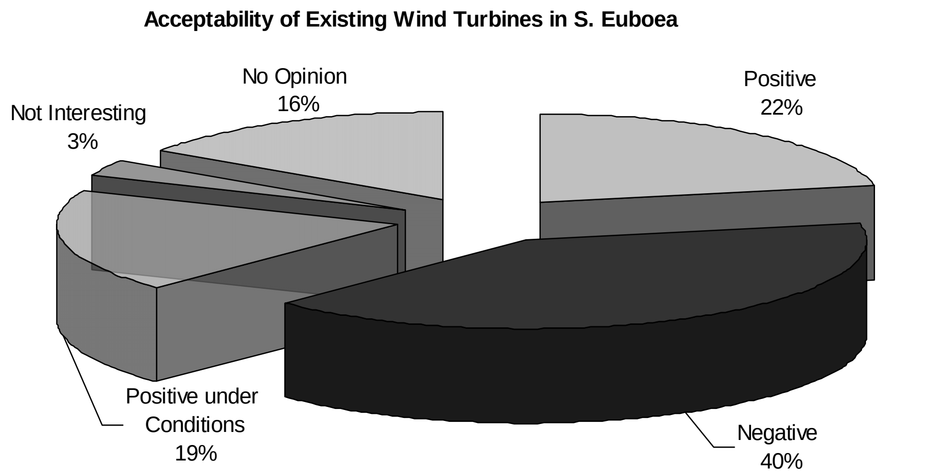

Figure 2: Public opinion towards wind parks

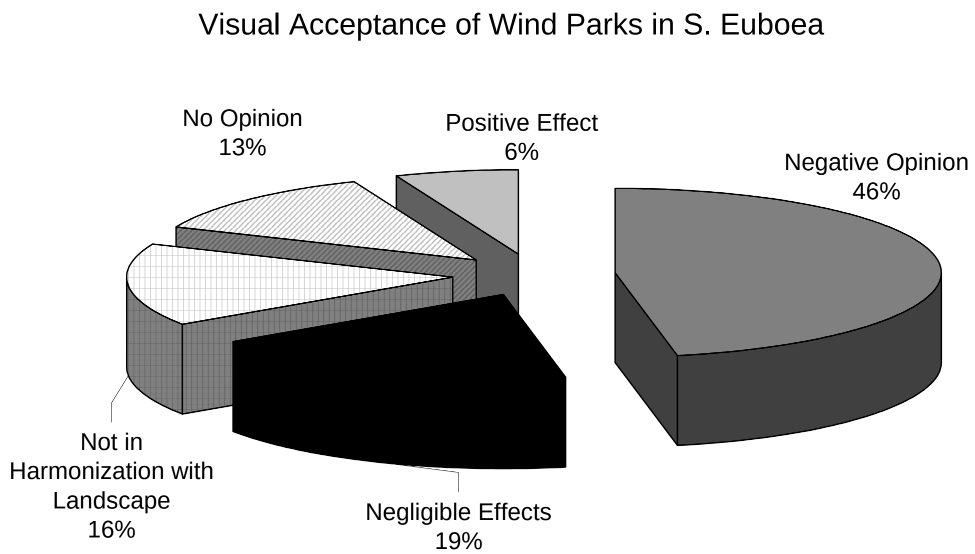

Figure 3: Wind turbines visual impact

Another interesting outcome of this 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 harmony with the landscape, figure (3). On the other hand only 6% likes 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.

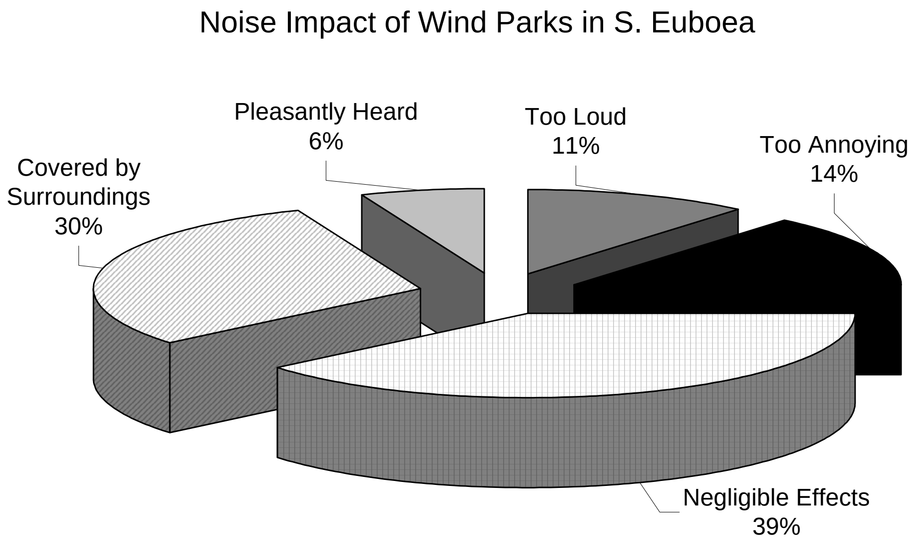

Figure 4: Wind turbines noise impact

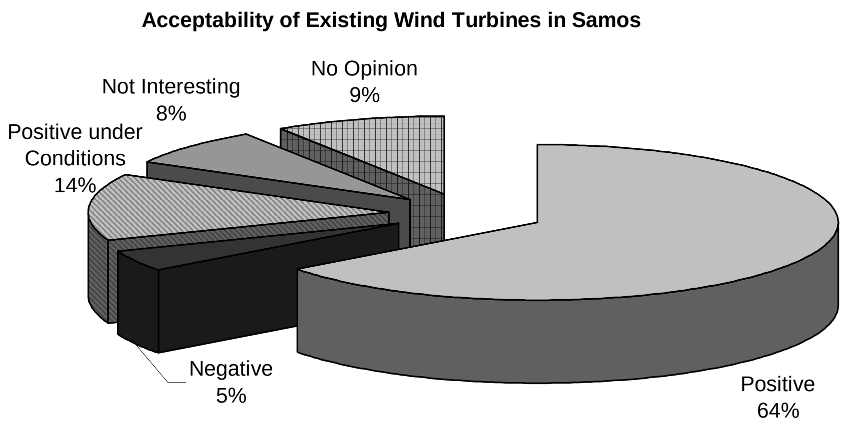

Figure 5: Public opinion towards wind parks

This is not exactly the case for the wind turbines noise impact upon the local people. It is interesting to mention that a quite smaller portion (25%) of the people questioned supports that the noise of the wind turbines in their territory is either too loud or too annoying, figure (4). Another 30% declares that any wind turbine noise is covered by the surroundings, while the rest habitants support that wind parks operation do not actually disturb them. On top of that, a small minority finds wind turbine sound emissions pleasantly heard, in relation to their valuable energy production.

The second area analysed is Samos island. 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 (5). Only a small minority (5%) was negatively expressed for the existing wind converters.

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 harmony with the landscape, figure (6). 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.

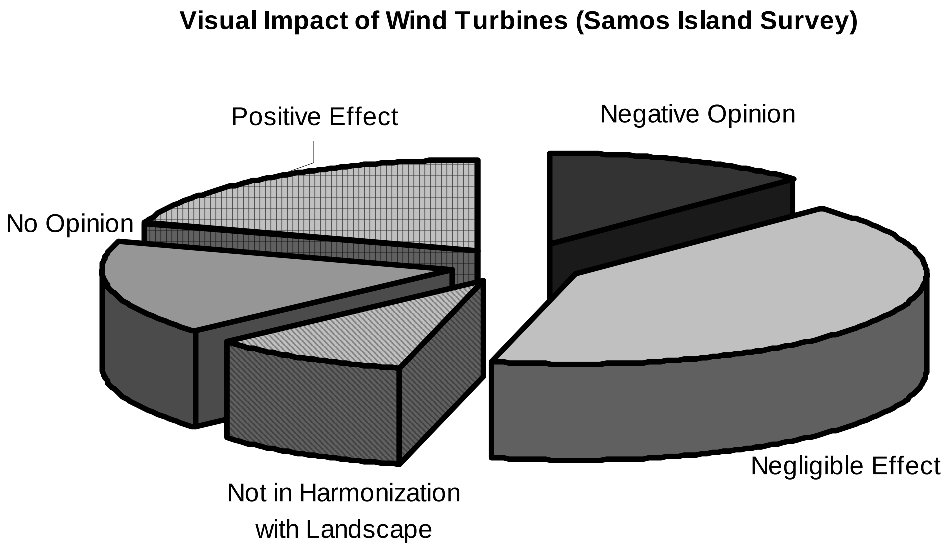

Figure 6: Visual impact of wind turbines

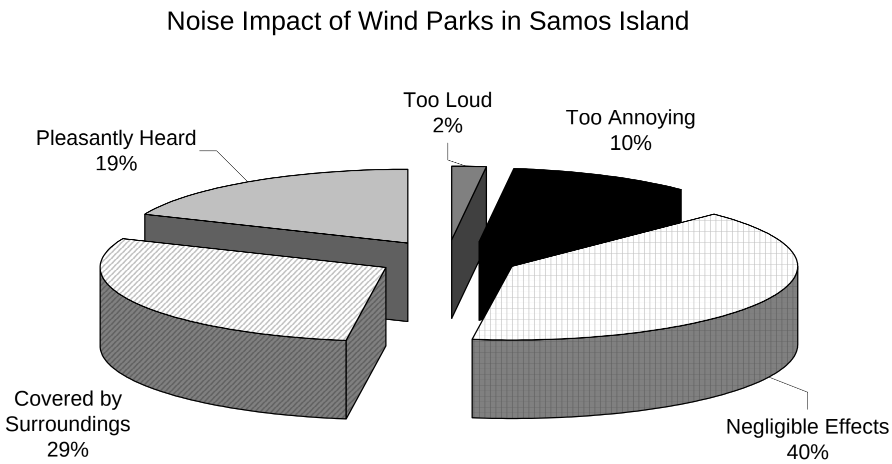

Figure 7: Wind turbines noise impact

A similar attitude is encountered concerning the noise impact of existing wind turbines, figure (7). More specifically, people finding wind turbines noise either too loud or too annoying represent the 12% of the sample, while an additional 29% believes that the corresponding emissions are masked by the surround (background) noise. On the other hand, the majority (40%) of the local people do not bothered by the wind turbines operation, while an additional 19% of the respondents state that the wind parks sound emissions can be characterized as pleasant in view of their useful energy production.

Summarizing the results of figures (2) to (7) one may state that there is a direct link between acceptance of wind power applications and claims about visual and noise impact due to their operation on the local societies. Generally speaking people disliking wind turbines express serious claims about their visual and noise annoyance on the surroundings. On the contrary, people accepting wind energy as a clean and sustainable energy resource do not seem to be remarkably disturbed by their operation.

In addition, it is important to mention that more people express negative attitude about wind turbines visual impact than about their noise emission. This fact is in accordance with the results of similar studies on both sides of Atlantic, figure (8). Thus, one may state that "visual intrusion" is one of the major factors determining opposition to wind energy, although noise disturbance can be more objectively measured.

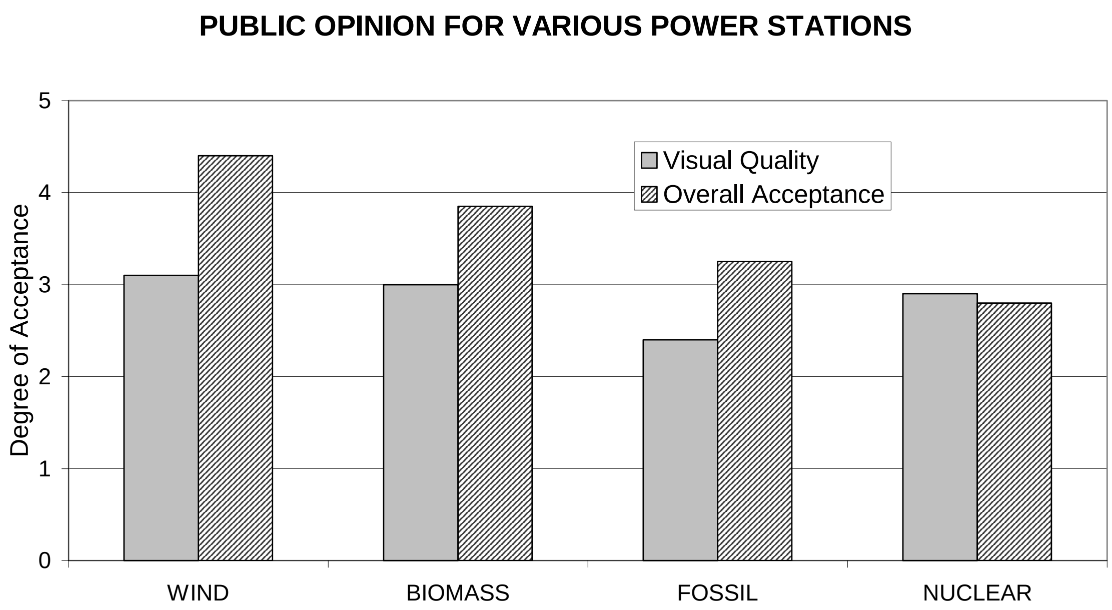

Figure 8: Public opinion for various power production alternatives[7]

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 and noise impact of existing wind turbines. According to the assessed results of recent public opinion surveys, realized during 2000-2002 concerning the social attitude towards existing wind parks, one may conclude that a remarkable part of the respondents declares 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.

In addition, a remarkable part of the people questioned declares noise impact of operating wind parks on the local societies. This reaction, although not so strong as the visual impact one, is more objective and may be supported in court. In this context, one may observe a direct relation between visual and noise impact and general public attitude towards wind power applications. More specifically, the vast majority of people disliking wind turbines declares visual and noise annoyance due to the operation of existing machines. On the other hand, a remarkable part of people accepting wind energy as an alternative and promising energy production option does state visual impact of existing wind parks. However, this is not the case for noise emission.

Taking into consideration the above described information, the authors believe that the conclusions drawn are very characteristic of the public attitude towards wind power applications in Greece and may be found necessary to everybody related to the local energy planning procedures. Of course, wind industry should continue placing the same effort on being a good neighbour as on being aerodynamic efficient, in order not only to maintain but also to increase the public acceptance of wind energy applications, all over the world.

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