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J.K. Kaldellis - K.A. Kavadias - H.A. Labridou

LABORATORY
OF SOFT ENERGY APPLICATIONS & ENVIRONMENTAL PROTECTION
TEI OF PIRAEUS

Contact address: Lab of Soft Energy Applications
and Environmental Protection
P. O. BOX 41046
12201 Athens, Greece.

Tel.: +30-210-5381237
Fax: +30-210-5381467

e-mail: sealab@gdias.teipir.gr
www.sealab.gr

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

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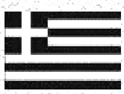

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3. Rational Management - Energy & Natural Resources Saving
4. Financial Evaluation of Investments
5. Development of New Technologies

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The Soft Energy Applications & Environmental Protection Lab instructs in the following subjects:

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3. Applications of Renewable Energy Sources **(RES II)**	***6th ″***
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5. Environment & Industrial Development **(ENV-ID)**	***2nd ″***
6. Basic Principles of Ecology **(BPE)**	***3rd ″***
7. Air Pollution – Pollution Prevention Technologies **(AP-PPT)**	***4th ″***
8. Turbomachines **(TURBO)**	***5th ″***
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In the context of its high quality educational and academic activities, the Soft Energy Applications & Environmental Protection Lab implements the **M.Sc in Energy** postgraduate course, in cooperation with the British Herriot-Watt University. The M.Sc course offers scientific knowledge and highlights potential professional opportunities in a wide range of subjects in the field of energy and environmental impacts of energy generation and consumption.

Research Areas

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

Published Results:

- **Kaldellis J.K., 2006**, "An Integrated Model for Performance Simulation of Hybrid Wind-Diesel Systems", *Renewable Energy Journal*, on-line available (10/10/06) in www.ScienceDirect.com.
- **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", *Journal of Applied Energy*, Vol.79/2, pp.127-144.
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2. "Estimation of Social - Environmental Cost in the Energy Production Sector"

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3. "Technological Progress in Wind Energy Market"

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Published Results:

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5. "Flow Field Prediction for High Speed Turbomachines"

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

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- **Nastos P.T., Paliatsos A.G., Priftis K.N., Kaldellis J.K., Panagiotopoulou-Gartagani P., Tapratzi-Potamianou P., Zachariadi-Xypolita A., Kotsonis K., Kassiou K., Saxoni-Papageorgiou P., 2006**, "The Effect of Weather Types on the Frequency of Childhood Asthma Admissions in Athens, Greece", *Fresenius Environmental Bulletin*, Vol.15/8b, pp. 936-942.
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15."Social Attitude Towards Wind Energy Applications in Greece"

Published Results:

- **Kaldellis J.K., 2006**, "Evaluation of Greek Wind Parks Visual Impact: Public Attitude and Experts' Opinion", *Fresenius Environmental Bulletin*, Vol.15/11, pp.1419-1426.
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***Research Projects under Development** (1/2)*

Participation in Research Programs (2002-2006)

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

***Research Projects under Development** (2/2)*

10. "***Optimisation of Water Systems in Islands with Limited Water Resources***", Research Program "Archimedes-II" supported by the Greek Ministry of Education
11. Hellenic/French Collaboration Research Program "Platon" entitled "***Advanced Techniques of Automation in Wastewater Treatment Plants***". (Accomplished)
12. "***Development of an Experimental Hybrid Plant based on a Wind Turbine - P/V Station Collaboration***", supported by T.E.I. of Piraeus (Accomplished)
13. "***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)
14. Program "***RENES-Unet***", for the Diffusion of Renewable/Soft Energy Applications in Greece and European Union
15. "***Techno-economic Study of Small Hydro Power Stations***", supported by the private company EMPEDOS SA
16. "***Water Pumping Storage Systems for Crete Island***", in collaboration with the Technical University of Crete and the Enercon Hellas SA
17. "***Desalination System Based on Gas-Turbines Exhausted Gases***" supported by PPC and Crete Municipalities Union
18. "***NATURA-2000***", supported by the Greek Ministry of Environment, Physical Planning and Public Works
19. "***Natural Gas Cogeneration Opportunities in Urban Areas***", in collaboration with the Municipality of Nikaia
20. "***Energy Saving in TEI Buildings***", supported by TEI of Piraeus

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PART ONE

WIND ENERGY APPLICATIONS

MAXIMUM WIND ENERGY CONTRIBUTION IN AUTONOMOUS ELECTRICAL GRIDS BASED ON THERMAL POWER STATIONS

J.K. Kaldellis
Laboratory of Soft Energy Applications & Environmental Protection
Mechanical Eng. Dept., Technological Education Institute of Piraeus

Abstract

Greek islands cover their continuously increasing electricity demand on the basis of small autonomous thermal power stations. This electrification solution is related with increased operational cost and power insufficiency, especially during summer. On the other hand, the stochastic behaviour of the wind and the important fluctuations of daily and seasonal electricity load in almost all Greek islands pose a substantial penetration limit for the exploitation of the high wind potential of the area. In this context, the present study is concentrated on developing an integrated methodology which can estimate the maximum wind energy contribution to the existing autonomous electrical grids, using the appropriate stochastic analysis. For this purpose one takes into account the electrical demand probability density profile of every island under investigation as well as the operational characteristics of the corresponding thermal power stations. Special attention is paid in order to protect the existing internal combustion engines from unsafe operation below their technical minima as well as to preserve the local system active power reserve and the corresponding dynamic stability. In order to increase the reliability of the results obtained, one may use extensive information for several years. Finally, the proposed study is integrated with an appropriate parametrical analysis, investigating the impact of the main parameters variation on the expected maximum wind energy contribution.

Keywords: Autonomous Electrical Networks; Electricity Production; Thermal Power Stations; Wind Energy; Wind Penetration Constraints; Maximum Wind Energy Contribution

1. Introduction

Most Greek islands cover their continuously increasing electricity demand using small autonomous thermal power stations, based on oil-consuming internal combustion engines. This electrification solution is related with increased operational cost[1], while in several cases the existing infrastructure cannot fulfil the excessive power demand during the summer period[2]. On the other hand, most islands possess high wind potential, thus wind energy may be an economic attractive solution for the urgent electrification problem of their habitants[3].

Unfortunately, the stochastic behaviour of the wind and the remarkable fluctuation of daily and seasonal electricity load, in almost all island grids, leads to substantial wind energy penetration limits[4][5], especially during the low consumption periods of the year. In fact, the island electrical networks manager (i.e. the Greek Public Power Corporation or PPC) defines an instantaneous upper wind energy penetration limit in order to protect the local grid stability in case that the wind energy production is suddenly zeroed. This, up to now empirically chosen value, permits the operating thermal power units to replace the wind power contribution without overloading problems or electrical system voltage and frequency fluctuations.

The proposed study is concentrated on developing an integrated methodology which can estimate the maximum wind energy contribution to the existing autonomous electrical grids on the basis of stochastic analysis. For this purpose one takes into account the electrical demand probability density profiles of every island under investigation as well as the operational characteristics of the corresponding thermal power stations[6]. In order to increase the reliability of the results obtained, one may use extensive information for several years. Finally, the proposed study is integrated with an appropriate parametrical analysis, investigating the impact of the main parameters variation on the expected maximum wind energy contribution.

The methodology developed is accordingly applied to the island of Crete, which is one of the most interesting case studies[7][8] concerning the incorporation problems of wind parks in an autonomous electrical network.

2. Electrical Load Analysis

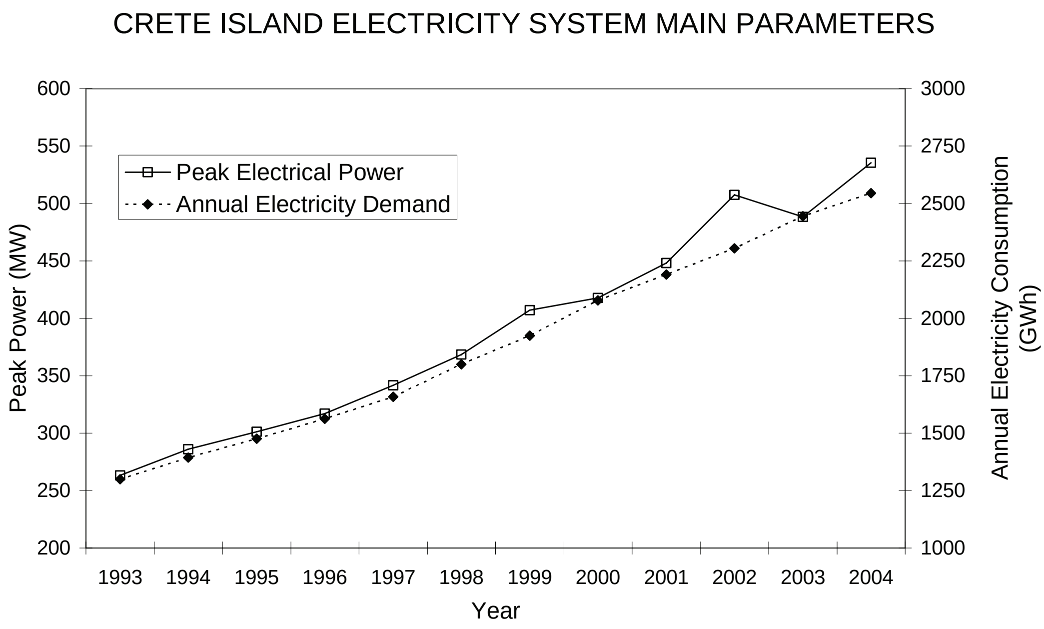

Figure 1: Time evolution of the Crete island electricity system main parameters

As already mentioned, the electricity demand in most Greek islands, including Crete, presents a significant annual increase, approaching annually the 7% during the last decade, figure (1). As a result the annual energy consumption during 2004 surpassed the 2550GWh in comparison with the modest 280GWh of 1975. On top of this, due to the increased tourism, a high seasonal variation of electricity demand is encountered, see also figure (2). More precisely the mean monthly electricity demand in the summer (≈250GWh) is more than 50% higher than the corresponding winter one (≈150GWh). Consequently, there is a considerable electricity generation diversification between the year periods (i.e. summer versus other seasons), which seriously affects[9] the wind energy penetration in the local network.

Using the available time-series of the load demand one may estimate the corresponding load probability density profile, figure (3). As it results from figure (3) the corresponding load demand (for 2004) varies between N_{min} (≈130MW) and N_{max} (≈550MW), while the average annual value is N_{aver} (≈280MW). Using the resulting cumulative probability distribution, figure (4), it is obvious that the load demand ranges mainly (≈95%) between 160MW and 400MW.

In order to face the above described load demand the local electricity generation system is based on twenty-six (26) oil-fired thermal power units located mainly near Chania and Heraklion, Table I. Recently, two internal combustion engines (2x51MW) started their operation in the new-built Atherinolakkos power station.

Table I: Crete island electricity generation system, end of 2004

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

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

Taking into account that Crete electricity generation system is based on diesel or heavy oil powered engines, Table I, these units should not be allowed operating below a certain limit, in order to avoid increased wear and maintenance requirements. This limit is mentioned as the "technical minimum" of each engine, hence the minimum output power of the "in operation" thermal units "N_{dmin}" is calculated as:

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

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

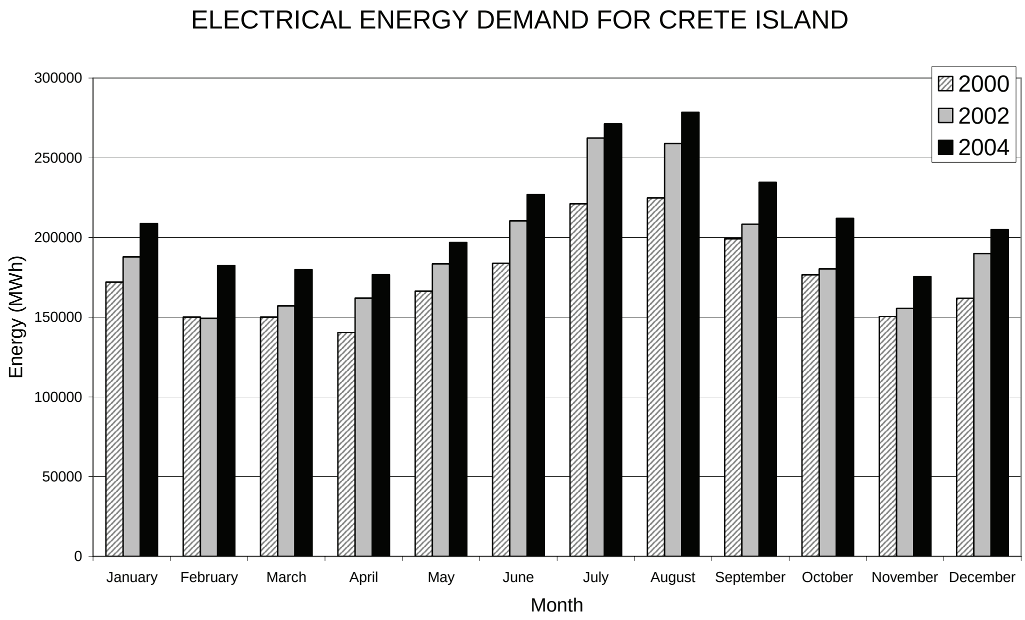

Figure 2: Monthly variation of electrical energy demand for Crete Island (2000-2004)

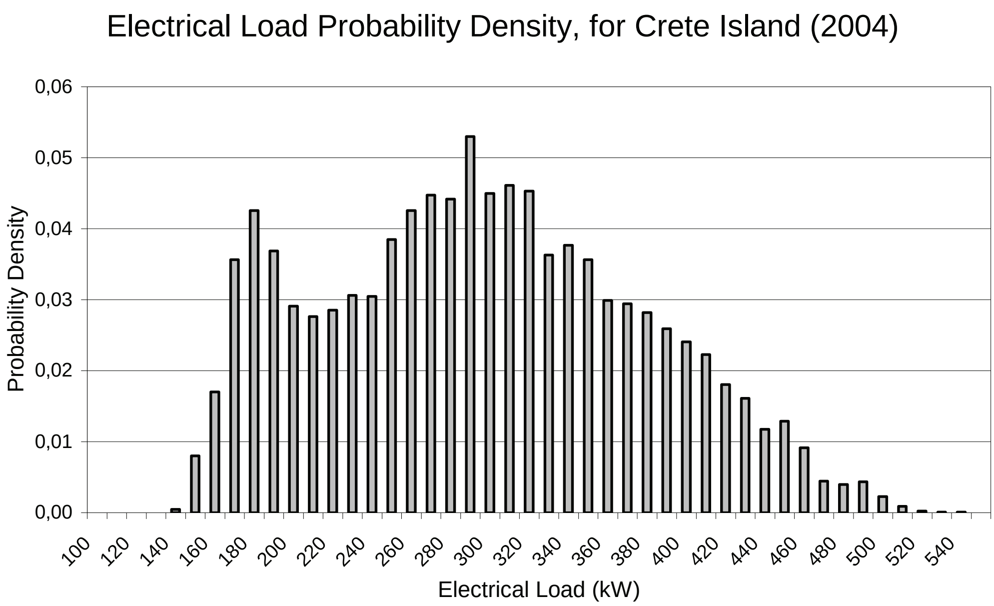

Figure 3: Probability density profile of electrical load demand for Crete island

In addition, due to the stochastic behaviour of the wind one cannot disregard the probability of an unexpected loss of a significant part of the "in operation" wind parks. To avoid (or to minimize) loss of load events[10][11] in similar situations, the local system operator should maintain full spinning reserve in the thermal power units, which suffices to cover the total load demand. For minimum fuel consumption operation, each thermal power unit should operate near the minimum fuel consumption point "N_{di}^{opt}", otherwise additional fuel consumption should be imposed. On the other hand, if "N_{di}^{max}" is the maximum permitted outlet power of the thermal unit "i" for a short time operation (1min to 10 min) in order to have enough time to start additional thermal engines, then the maximum active power reserve[12] of the local system is given as:

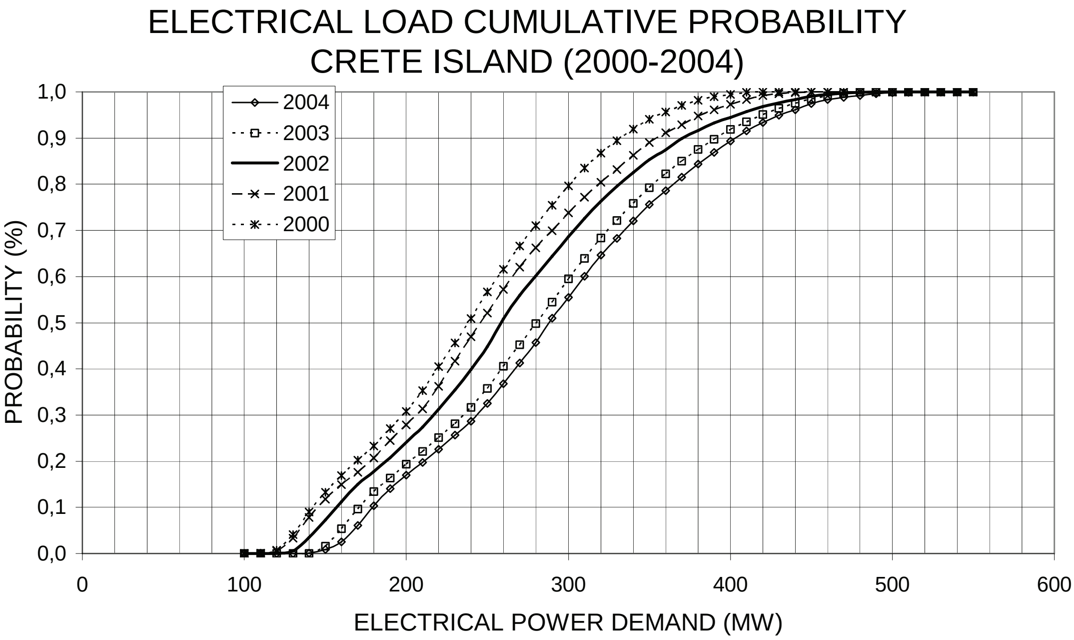

Figure 4: Electrical load cumulative probability distribution for Crete island (2000-2004)

$$N_{RESV} = \sum_{i=1}^{i=i_{max}} \left(N_{d_i}^{max} - N_{d_i}^{opt} \right) = \sum_{i=1}^{i=i_{max}} (\varepsilon_i - \tau_i) \cdot N_{d_i}^{*} \quad (2)$$

where "ε_i" and "τ_i" are the maximum power and optimum operation coefficients. In order to avoid the problems described, the maximum permitted wind power penetration is bound by the following relation:

$$N_w \le N_{RESV} = \sum_{i=1}^{i=i_{max}} (\varepsilon_i - \tau_i) \cdot N_{d_i}^{*} \quad (3)$$

For practical applications, assuming that the coefficients "ε_i" and "τ_i" are almost the same for all engines in operation, the equation (3) is transformed to the more simplified and widely used equation (4), i.e.:

$$N_w \le \left(1 - \frac{\tau}{\varepsilon} \right) \cdot N_L = \lambda_1 \cdot N_L \quad (4)$$

where "N_L" is the instantaneous load demand.

Finally, the fluctuations of a wind farm output power are normally compensated by equal magnitude variations of the output of the "in operation" units. In order to avoid annoying system frequency excursions and increase wear of the existing thermal power units an additional penetration limit is also imposed, dictated by the instantaneous rate that the "in operation" units can compensate any power deficit of the system. This dynamic penetration limit[13], expressed by the factor "s", is characteristic of the local electrical network and the spatial distribution and the type of the system wind turbines[14]. Generally speaking, this limit is selected by the system operator (incorporating also subjective/personal attitude) and is up to now empirically set in the range of 20% to 40%. In case of emergency this value may drop down to 15% or even zeroed[9]. In this context, the dynamic penetration constraint is expressed as:

$$N_w \leq s \cdot \sum_{i=1}^{i=i_{max}} N^*_{d_i} = \frac{s}{s+\tau} \cdot N_L = \lambda_2 \cdot N_L \quad (5)$$

3. Maximum Wind Energy Penetration in Autonomous Electrical Networks

On the basis of the analysis of section (2), the maximum absorbed wind energy "$N_w^*(t)$" by the local electrical system can be estimated according to the following equations, i.e.:

$$\text{If} \quad N_L(t) \leq N_{d_{min}}(t) = \sum_{i=1}^{i=i_{max}} k_i \cdot N^*_{d_i} \quad \text{then} \quad N^*_w = 0 \quad (6)$$

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

$$\text{If} \quad N_{d\,min}(t) \leq N_L(t) \leq (1+\lambda) \cdot N_{d\,min}(t) \quad \text{then} \quad N^*_w = N_L(t) - N_{d\,min}(t) \quad (7)$$

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

$$\lambda = \min\{\lambda_1, \lambda_2\} \quad (8)$$

Finally,

$$\text{If} \quad N_L(t) \geq (1+\lambda) \cdot N_{d\,min}(t) \quad \text{then} \quad N^*_w \leq \lambda \cdot N_L(t) \quad (9)$$

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

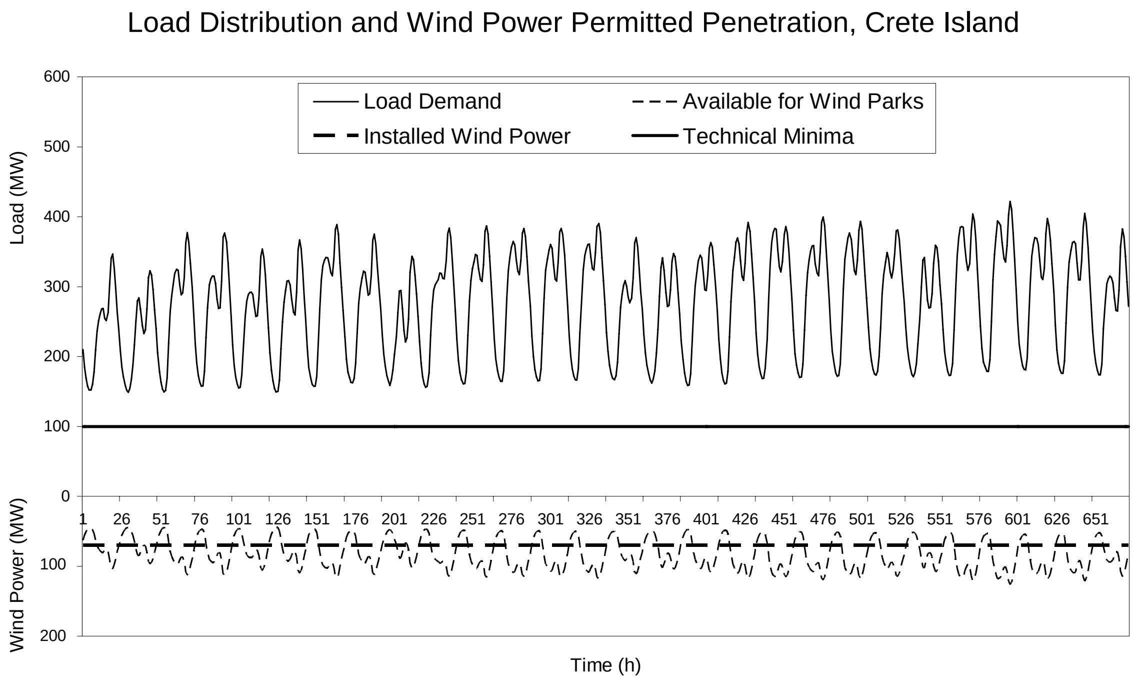

Figure 5: Electrical load demand and wind power penetration time-series, Crete island

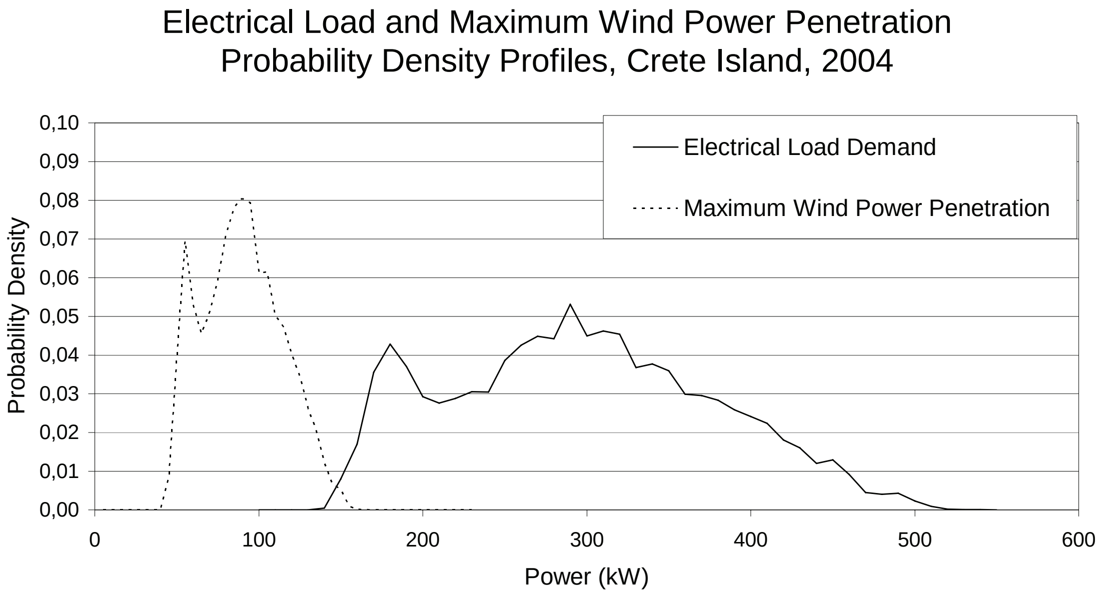

Figure 6: Electricity load demand and maximum wind power penetration probability density profiles for Crete island

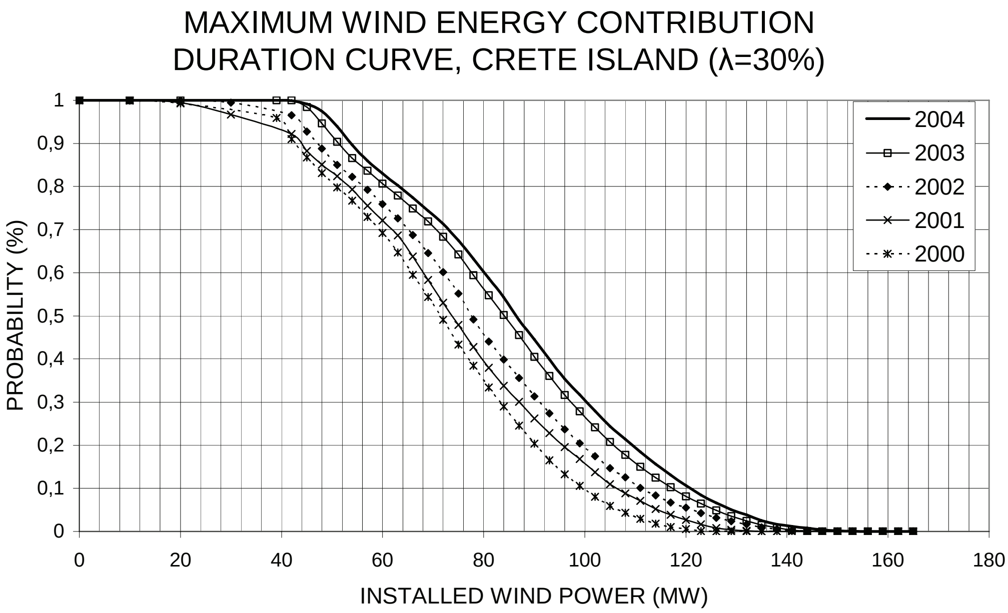

Figure 7: Time-evolution of maximum wind energy contribution duration curve, Crete island

Applying the proposed analysis on the load time-series of the Crete island electrical system, one may estimate the resulting maximum wind energy penetration time-series in the local grid, see for example figure (5). Accordingly, one may reproduce the corresponding maximum wind energy penetration probability density profile, figure (6), as well as the cumulative probability distribution, figure (7). According to figure (6) the wind power absorption varies between 42MW and 160MW, while the most common wind power demand is between 80MW and 100MW. More specifically, wind power values less than 50MW are required (figure (7)) during the 95% of the year, hence if the output power of the existing wind parks is up to 50MW, the wind energy yield would be absorbed for the 95% of the hours of the year. Subsequently, if the available wind power is 60MW the possibility of absorbing the entire wind energy production decreases to 83%. This fact means that the additional 10MW are required only for the 12% of the year.

A more clear-cut picture of the installing additional wind power influence is given in figure (8), where one may find the relation between the maximum capacity factor "CF^*" of the wind parks imposed by the local network (i.e. under the theoretical assumption that the existing wind parks operate all-year at rated power) versus the corresponding rated power of the existing wind turbines. According to the results obtained the "CF^*" value decreases slowly between 40MW and 100MW and more rapidly after the 100MW.

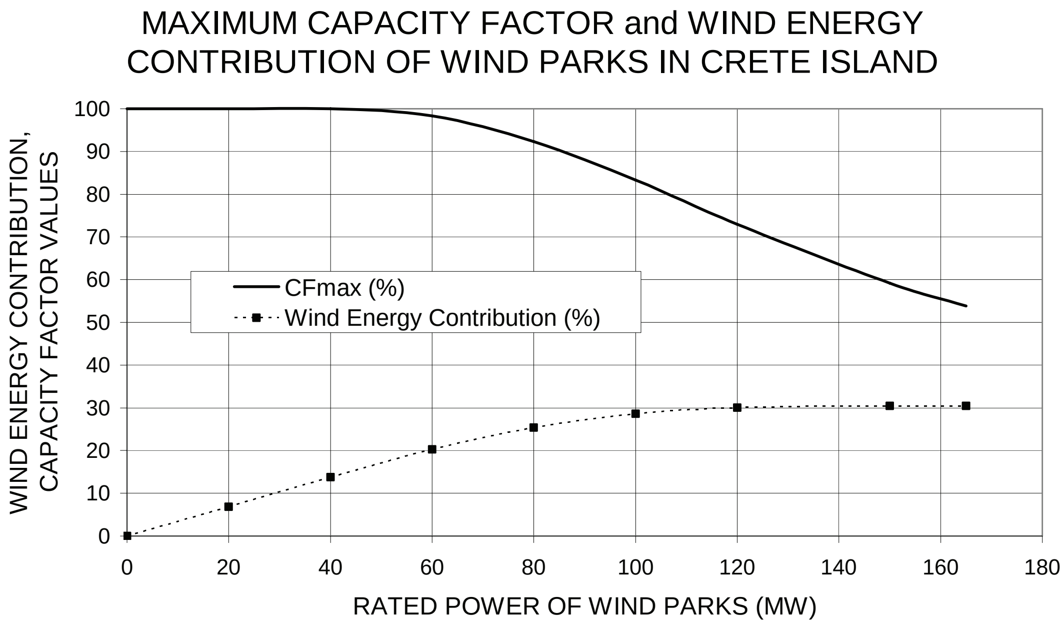

Figure 8: Maximum wind energy contribution and capacity factor distributions of wind parks in Crete island

Finally, one may estimate the maximum wind energy contribution to the local electricity demand as a function of the rated power of the existing wind parks, figure (8). As it is obvious from the results depicted, the maximum wind energy contribution tends asymptotically to 30.5% as the installed wind power approaches the 165MW. However, the major wind energy contribution is realized for much lower wind power, i.e. 100MW. In this case, one should not exceed the 100MW, since for higher wind power values the expected wind energy increase is very slow while the corresponding maximum capacity factor decreases remarkably.

4. Impact of Time on Maximum Wind Energy Penetration

Taking into consideration the significant electricity demand increase encountered in Crete island, figure (1), it is interesting to examine the evolution of the maximum wind power penetration in the local grid, in the course of time. Keep in mind that in this way one may forecast the corresponding maximum wind energy contribution in the near future.

For this purpose the electrical load demand for the period 2000-2004 is utilized, see also figure (4). In this figure one may find the cumulative probability of the electrical load of Crete island to exceed a given value. For example, while the possibility of the load demand being inferior to 400MW is 99.5% for the year 2000, the corresponding value for 2004 is only 89.3%. Additionally, one should also mention that the minimum load demand is higher than 100MW for all the five-year period investigated, hence the minimum load demand of the system is higher than the technical minima of the existing thermal engines.

The application results of the section three analysis for Crete island are included in figure (7). According to the information obtained one may state the following:

- For 2003 and 2004 the local system can absorb 40MW of wind power for the entire year.
- This is not the case for 2000 to 2002, since during this period the corresponding wind power values vary between 16MW and 24MW.
- The installed wind power that guarantees an acceptable (e.g. 80%) wind energy absorbance possibility increases from 51MW in 2000 to 63MW in 2004.
- The installation of wind parks with rated power higher than 100MW (the current installed wind power is approximately 100MW) present maximum wind energy absorbance possibility equal to 10% for the load profile of 2000 and 31.7% for the one of 2004.
- Finally, the maximum wind power penetration in the Crete island network is 123MW for 2000 and 150MW for 2004.

Summarizing, it is obvious that only a slight increase of the maximum wind power penetration is encountered in the course of time, which for an 80% absorbance probability is approximately 2MW per year. In fact, this wind power increase is practically negligible, in comparison with the corresponding peak load demand of the island. Hence, taking into consideration that in the island already operate almost 100MW of wind power, it is almost certain that any new wind power addition in the next five years would be utilized by only 50% of the year, the maximum. Thus, the only way to increase remarkably the wind energy contribution, in order to fulfil the corresponding load demand, is by using the appropriate energy storage installations[1] along with parallel applications of wind energy e.g. desalination[15][16]. Otherwise, the island wind power is going to stagnate just above the 100MW[3].

5. Parametrical Analysis of Maximum Wind Energy Penetration

In an attempt to better understand the parameters affecting the value of the maximum wind energy contribution in an autonomous electrical network, we proceed to analyze the impact of the local thermal power stations technical minima as well as the influence of the upper participation limit "λ" -set by the local system manager- on the numerical value of the corresponding wind power participation.

According to the analysis of section two the technical minima of the system depend on the number of thermal units in operation (i.e. i_{max} of equation (1)) and the technical minimum of each internal combustion engine of the system. Excluding the annual maintenance period of the engines, the local system technical minimum is approximately 100MW. Taking into account that the minimum annual load demand is higher than this value, it is evident that in any case the thermal units operate above their technical minimum.

Hence, it is quite rational that any decrease of the system technical minima does not influence the maximum wind penetration probability profile, figure (9). On the contrary, as the system technical minima increase to 120MW, there is a slight decrease of the probability of wind energy absorbance for installed rated power less than 50MW. In this context, for the present situation, where the existing wind power approaches the 100MW, there is no practical influence of the local system technical minima on the wind energy absorbance possibility.

Subsequently, the impact of the upper participation limit "λ" on the corresponding wind energy contribution should be investigated as a function of the installed wind power in Crete island. As already explained, see equations (4), (5) and (8), the exact value of "λ" is dictated by the characteristics of the existing internal combustion engines on the basis of the local system "active power reserve" and the corresponding "dynamic stability". In this context, the value normally applied in similar situations[12] varies between 20% and 40%.

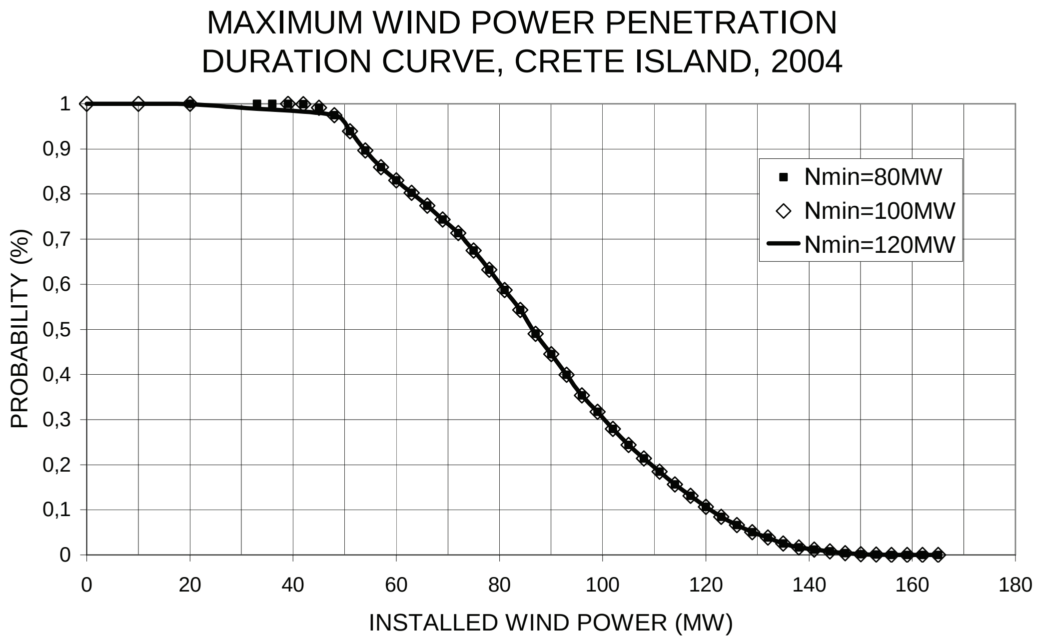

Figure 9: The impact of local electrical system technical minima on the maximum wind energy contribution to cover the Crete island electrical load demand

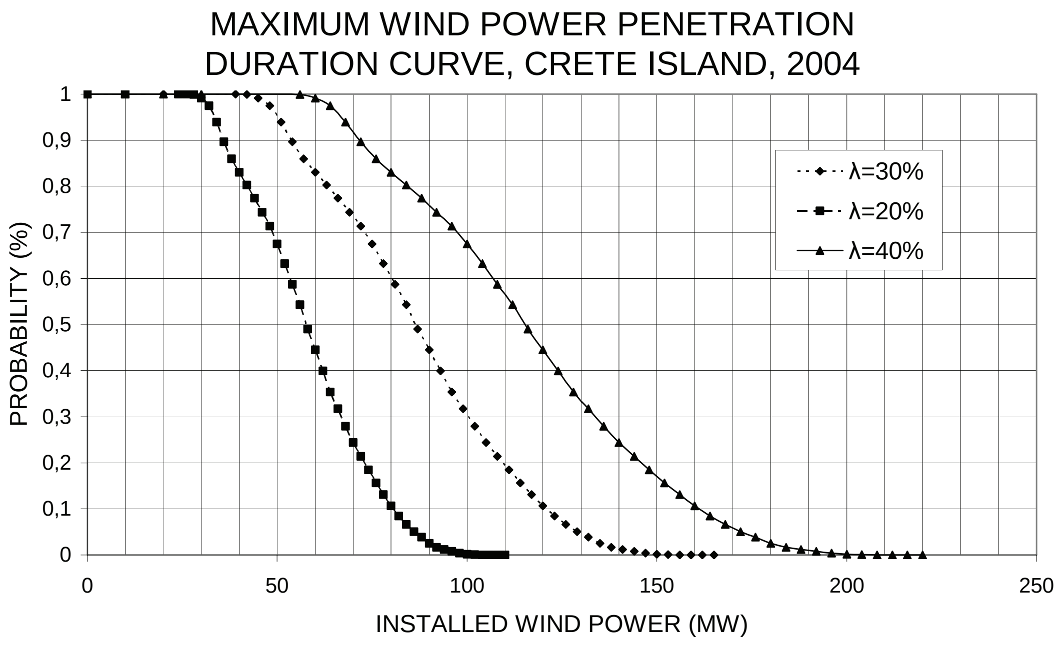

Figure 10: The impact of local electrical system upper wind power participation limit on the maximum wind energy contribution to cover the Crete island electrical load demand

Using the calculation results of figure (10) one should underline the significant influence of the "λ" value on the wind energy penetration probability profile. More precisely, there is considerable wind power penetration amplification as the "λ" value increases. For example, the wind power that guarantees 80% annual wind energy absorbance for λ=40% is almost twofold the corresponding value for λ=20%. In fact, an almost linear variation may be established between the maximum wind power penetration and the corresponding "λ" value, for any probability level of figure (10).

Recapitulating, it is important to note that the maximum wind energy contribution in the local autonomous electrical networks strongly depends on the upper participation limit defined by the local system operator, while it is practically unaffected by the exact value of the "in operation" thermal engines technical minima.

6. Conclusions

An integrated numerical method, able to estimate the maximum wind energy penetration in a given autonomous electrical network is presented, based on stochastic analysis of the available load demand time-series. More precisely, the calculation method developed estimates the maximum wind energy contribution on the basis of the information provided by the system operator concerning the corresponding load demand and the operational status of the existing thermal power stations. For this purpose extensive data for a five-year long period are analyzed, using the appropriate mathematical tools.

The calculation results indicate that if the present situation does not change there is a very strict limit for the wind power participation in the island autonomous electrical systems, which is slightly modified in the course of time. More precisely, the maximum wind energy contribution to the Crete island network can hardly exceed the 100MW for the next five years, while the rated power of the already in operation wind parks is almost 100MW. The direct result of this outcome is the stagnation of new wind power investments during the next years. Only by finding complementary applications of the wind energy (e.g. desalination or hydrogen production) or by building appropriate energy storage installations it is possible to further increase the wind energy participation in similar autonomous electrical markets.

Additionally, one of the most interesting findings of the present analysis is that the main parameter, which controls the maximum wind power penetration, is the corresponding upper participation limit that the local electrical utility imposes in order to eliminate any grid instability problems. Thus, by applying a better wind energy production-demand management plan it is possible to remarkably increase the wind energy contribution.

Recapitulating, it is important to note that the proposed methodology gives us the capability to estimate the maximum wind energy contribution to any autonomous electrical network, on the basis of the operational parameters of the existing thermal power units. The same methodology can be equally well applied to large electrical grids with high wind energy penetration.

Using this model, one may state that the present situation imposes a quite narrow limit for the wind energy contribution to fulfil the electrical needs of the local societies. Unfortunately, this situation is going to be worsening during the next years, while the possibility of new wind parks to be erected in these islands is minimal. Only by planning and applying an integrated new strategy, concerning the incorporation of new wind power in the local networks, including complementary activities, appropriate energy storage installations and improved electrical load management, will be possible to significantly contribute to solving the severe problem of the continuously increasing electricity demand of autonomous islands on the basis of clean and cost effective wind energy applications.

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EVALUATION OF STATE AND PRIVATE WIND POWER INVESTMENTS IN GREECE ON THE BASIS OF LONG-TERM ENERGY PRODUCTIVITY

J.K. Kaldellis, K.A. Kavadias, A.G. Paliatsos[1]
Laboratory of Soft Energy Applications & Environmental Protection
Mechanical Eng. Dept., Technological Education Institute of Piraeus
[1]General Department of Mathematics, Technological Education Institute of Piraeus

Abstract

Since the early eighties Greek State has started an ambitious -for that period- wind energy exploitation program, via the State directed Public Power Corporation. This twenty five-year long effort faces serious obstacles and drawbacks, nowadays reaching an installed State wind power capacity of not more than 40MW. On the other hand, private wind energy production stations rated power exceeds the 450MW, although the existing legislation frame has been only recently activated. In this context, the present work is devoted to analyze the life-long energy production of State owned and private wind power installations located in nearby regions in view of the available data. Among the most interesting results of this study is the unusual intense time-variation of the encountered wind energy production, not justified by the corresponding wind potential changes. Besides, the technical availability of most State wind parks has been rather low in spite of the significant improvement during the last years.

Keywords: Wind Park; Energy Production, Private Investments; PPC; Capacity Factor; Time-evolution

1. Introduction

In the early eighties Greek State started an ambitious -for that period- wind energy exploitation program, via the State directed Public Power Corporation (PPC)[1][2]. This twenty five-year long effort faces serious obstacles and drawbacks, nowadays reaching an installed State wind power capacity of not more than 40MW, figure (1).

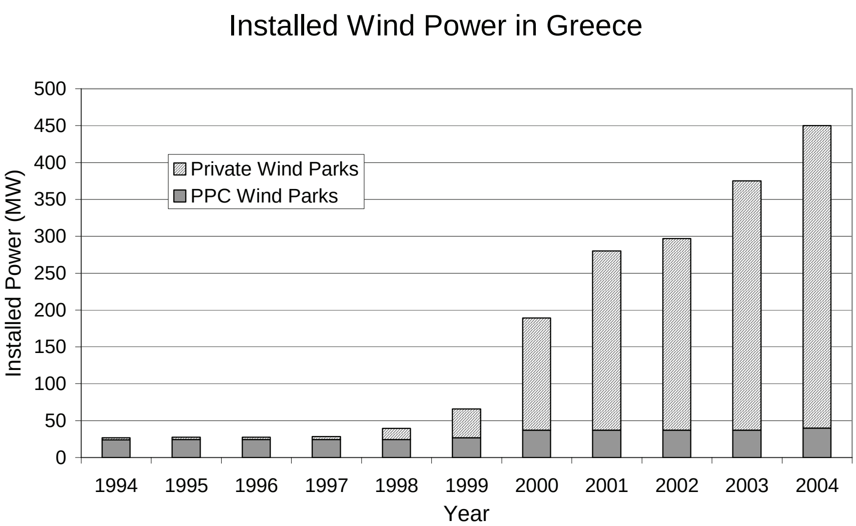

Figure 1: Wind power time evolution in Greece

Since 1994, when the Greek parliament voted for the new Renewables' Law, the PPC domination in local electricity market has been argued[3]. In fact, according to the 2244/94 Law, private investors were allowed to create electricity production stations on the basis of renewable energy sources exploitation and sell their energy yield to the local electrical network at a specific price[4].

Consequently, in a few years private wind energy production stations rated power exceeded the 450MW, figure (1), although the existing legislation frame had been really activated only by the end of 1998, when the first private wind park was installed in Crete island[5].

In this context, the present work is devoted to analyzing the life-long energy production of State owned and private wind power installations located in nearby regions in view of the available data[6]. To be more precise, one should take into consideration that individual wind converters have been operating in Greece since 1985, under the previous legal frame, belonging mainly to small private companies, municipalities or Hellenic Telecommunications Organization[7]. Recapitulating, emphasis is laid on investigating the time-variation of the encountered wind energy production, in order to evaluate the performance of the installed wind turbines[8].

2. Historical Evolution of Greek Wind Power Stations

According to the available official information, the first Greek wind park was created in Kithnos island, in 1982. This park was a 5x20kW pilot wind project, based on two-bladed MAN (Aeroman) wind converters of the first generation. These machines were replaced in 1990 by 5x33kW wind turbines of the same manufacturer. Between 1982 and 1990 no significant State wind energy activity was encountered, excluding two ineffective installations in Mikonos (1x108kW Micon) and Karpathos (1x175kW HMZ) islands, which soon presented major failures that finally suspended their operation[8]. On the other hand, during the same period a few small enterprises and municipalities have been showing increased interest[7] in installing their own wind turbines, on the basis of the existing legislative frame (i.e. Law 1559/85). This law permitted individuals to install wind turbines in order to cover their own electricity consumption. Only the excess energy could be sold to the local grid at low price.

Despite the strict constraints of this law a small number (seven) of private wind turbines were installed throughout Greece[1], mainly due to the financial support by European funds. Besides, at the end of 1980's the Hellenic Telecommunications Organization started an ambitious -for that period- effort to install small wind turbines of approximately 100kW rated power in order to cover the electricity requirements of specific remote telecommunication stations. In this context, seven (7) medium-sized (for that period) wind turbines were erected in selected Aegean Sea islands. Despite the most of these wind turbines good performance, the program was abandoned during the early 1990's, mainly due to insufficient maintenance support.

During the end of 1980's and the beginning of 1990's two municipality companies created their own wind parks which have been operating since then. In fact the first installation, located in Chios Island (Vrontades municipality) since 1989, contains two Nordtank wind turbines of 150kW rated power, i.e. 2x150kW. The second installation, which started its full operation in 1995, belongs to Mytilene municipality (Lesvos island). Initially it was based on two Windmaster-300kW (HMZ) wind turbines, while in 1997 an additional wind turbine (Micon-225kW) was installed. The above mentioned installations, which do not belong to PPC, are the only ones operating continuously for more than ten-years. During the same period, two additional wind turbines have been installed in Crete island by the municipality of Anogia (Rethimnon) -150kW rated power- and the municipality of Sitia -500kW rated power-. The first wind turbine has early presented major failure due to insufficient lightning protection, while the other has been operating until now with fair performance. Finally, one 75kW wind turbine was also installed in Naxos (Cyclades) island by the local agricultural cooperation. This engine has been out of order during the last years.

In the meantime a significant number of wind projects had been realized[8] during 1990-1993 by PPC, taking into account that 122 commercial wind turbines were installed throughout Aegean Archipelago under the financial support of E.C. This remarkable -for that period- activity includes[2] the installation of:

a. 24x55kW Windmatic 15S and 26x100kW Windmatic 19S wind converters
b. 36x225kW Vestas V-27 wind turbines. Another 9 machines -initially designated for Lesvos island- were finally installed in 1999, after a long-lasting legal dispute with local authorities
c. 34x300 HMZ/Windmaster wind turbines, constituting the two (17+17) largest wind parks of that period in the entire Mediterranean region and
d. 2x500 Tacke TW-500 machines, being by far the biggest engines in Greece at that time.

At the end of 1999 the installed wind power in Greece hardly was 60MW. Since then, a considerable number of wind turbines have been erected[5], mainly in Euboea and Crete island, while recently this activity is being concentrated in the mainland[9], e.g. Thrace, Peloponnesus etc.

As it is obvious from the brief historical presentation of the Greek wind power installations, a limited number of wind parks possess energy generation data for a remarkable time period.

3. Wind Park Energy Production Analysis

Using previous authors work[10][11], one may state that the exact value of a wind park energy yield is a function of the local wind potential, the existing atmospheric conditions (temperature, pressure, humidity, level of turbulence etc.), being also strongly depended on the specific power curve of the machine used, i.e. N=N(V) -output power versus wind speed "V". More precisely, the net energy output "E" of a wind park over a time period "Δt" (e.g. Δt=8760hours per year and "E" is given in kWh/year) based on "z" similar engines of rated power "N_o" is given as:

$$E = CF \cdot z \cdot N_o \cdot \Delta t \tag{1}$$

where the capacity factor "CF" is expressed[10][11] as the product of the mean technical availability factor "Δ" and the mean power coefficient "ω" of the installation, i.e.:

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

The mean power coefficient "ω" -expressing the time (yearly)-averaged energy production during an hour per kW of the machine nominal power ("V_C" cut-in and "V_F" cut-out wind speed of a machine)- is defined[7][8][10] by the following equation, i.e.:

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

where the probability density function "f(V)" describes the local wind potential. In general, "f(V)" is expressed using the well known Weibull distribution, however the accuracy of the results will be improved if detailed wind speed measurements are available.

It is interesting to note that according to equations (1) and (2), the relative variation of the annual energy yield of every wind power-station may be expressed as:

$$\frac{dE}{E} = \frac{d(\Delta t)}{\Delta t} + \frac{dz}{z} + \frac{dN_o}{N_o} + \frac{d\omega}{\omega} + \frac{d\Delta}{\Delta} \tag{4}$$

Thus, according to equation (4) the energy yield of a wind park should depend on the annual variation of "Δt" (Δt=8760h/year except during the leap years where Δt=8784h/year), the wind turbines number of each wind park examined (usually dz=0) and the rated power of each wind turbine (slightly affected by the aging). Taking into consideration that the variation of all these parameters is limited (or zero) one finally gets from equation (4):

$$\frac{dE}{E} \cong \frac{d\omega}{\omega} + \frac{d\Delta}{\Delta} = \frac{d(CF)}{CF} \quad (5)$$

Recapitulating, one may state that the major annual energy production variation depends primarily on the mean power coefficient and the mean technical availability time evolution. In the following, one may estimate the expected "CF" variation by using the available long-term wind energy production data. As it is obvious from equation (5), any significant energy production discrepancy between the expected theoretical and the realized value should be attributed to the technical availability deviation from the reference value, e.g. Δ_{ref}=90%.

4. Energy Production Analysis of North Aegean Sea Wind Parks

The first private wind park installed in Chios island, see also figure (2), was the one of the municipality of Vrontados, started its operation in July 1989. This wind park was based on two similar wind turbines of 150kW. In figure (3) one may find the corresponding energy yield of this wind park for a considerable time period. More specifically, the capacity factor of the installation presents significant time-variation, while the long-term average value is approximately 15%. Note that serious problems were encountered during 1991, zeroing the corresponding electricity generation.

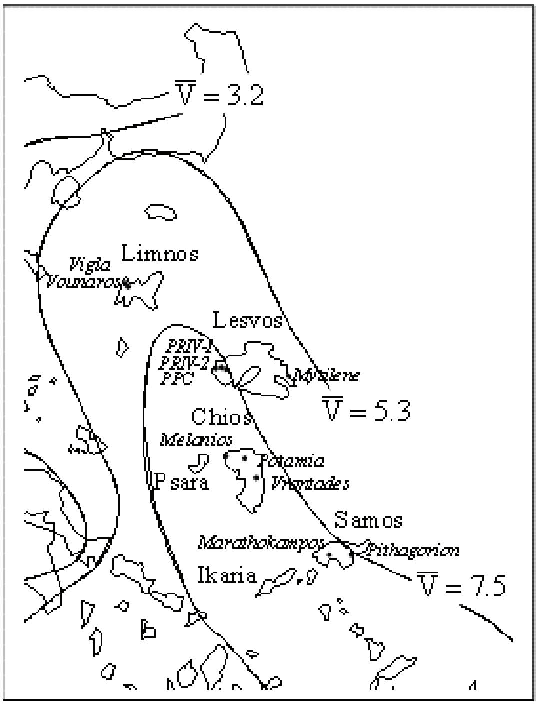

Figure 2: Wind parks locations in N. Aegean

In Chios island also operate, since 1992, another three wind parks belonging to the Greek PPC. More precisely the first one has been installed at Potamia and contains ten (10) WM-100 wind turbines of 100kW rated power. The second one is located at Melanios and includes eleven (11) V-27 wind turbines of 225kW rated power. Finally, the third wind park has been created in Psara island, a very small island NW of Chios. This wind park is based on nine (9) V-27 wind turbines, while the local electrical grid is connected with the one of Chios island. In figure (4) one may find the capacity factor time-evolution for these three wind parks along with the one of Vrontades municipality, for the period 1998-2001, where official data are available.

According to the available data the Melanios wind park presents the best energy generation performance (i.e. 4-year average CF value equal to 29.8%), while Psara wind park also presents quite high energy yield (average CF≈27.3%). On the other hand Potamia and Vrontades capacity factor values are considerably lower than the ones of the previous installations. Finally, in figure (5) one may compare the energy generation performance of the above mentioned wind parks for 2004. According to the most recent available official data the capacity factor values of all wind parks present similar time-evolution. However, Melanios and Psara "CF" values are much higher than the ones of Potamia and Vrontades installations.

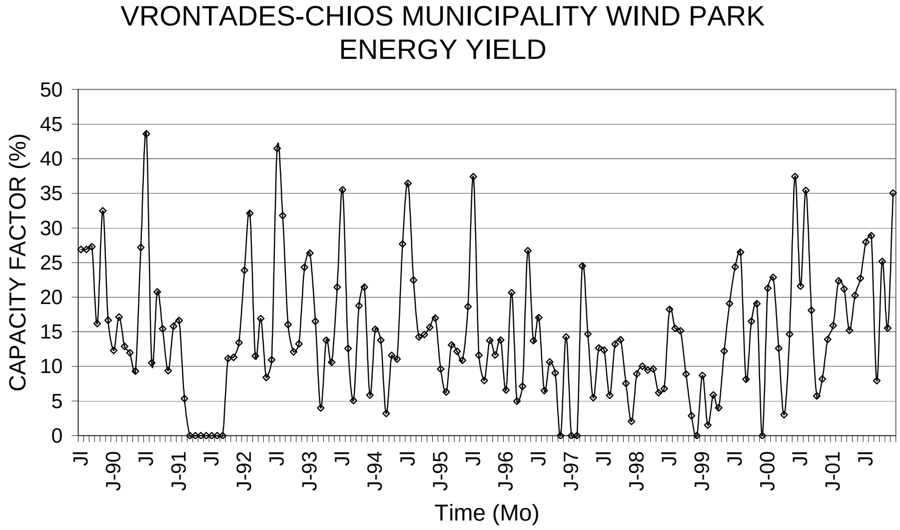

Figure 3: Time-evolution of Vrontades wind park energy yield (1989-2001)

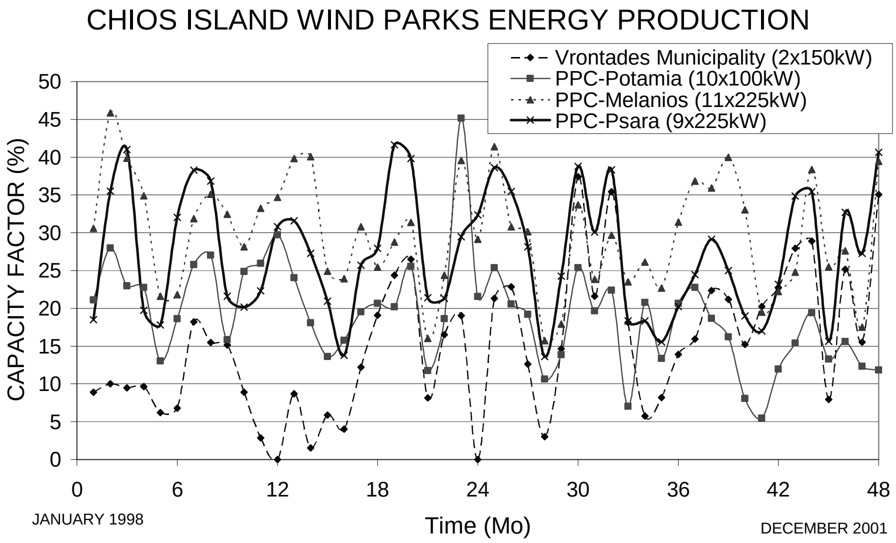

Figure 4: Energy yield comparison between wind parks of Chios island (1998-2001)

Subsequently, one should analyze the energy performance of the wind park of Mytilene municipality. This wind park was created in 1994 and started its full operation in 1995. During 1997 its rated power had been increased from 600kW to 825kW. According to the official data of the 1995-2004 decade the calculated capacity factor value was strongly varying between 5% and 25%, while the corresponding long-term average value was slightly above 12.5%, figure (6). During 2003 major failures of the two HMZ-300 wind turbines were encountered, hence the second wind turbine was completely destroyed.

In 1999 nine V-27 wind turbines were installed by PPC at the west part of the Lesvos island, constituting a wind park of 2025kW rated power. These wind turbines were operating for two years with very good energy production performance. However, during 2002 major problems appeared, leading one of the machines to complete destroy, while three other turbines presented serious malfunctions. These problems were solved in 2004, while since then the wind park has been operating with only eight (8) wind turbines.

Recently, two private wind parks (4200kW and 3000kW) started their operation in the west part of the island. The performance of these installations is presented in figure (7) along with the "CF" variation of PPC and Mytilene municipality wind parks for 2004. According to the official data[4] the two new-erected private wind parks show excellent performance, since their annual average CF values exceed 40%. On the other hand, the corresponding "CF" values of the other two wind parks are less than 17%.

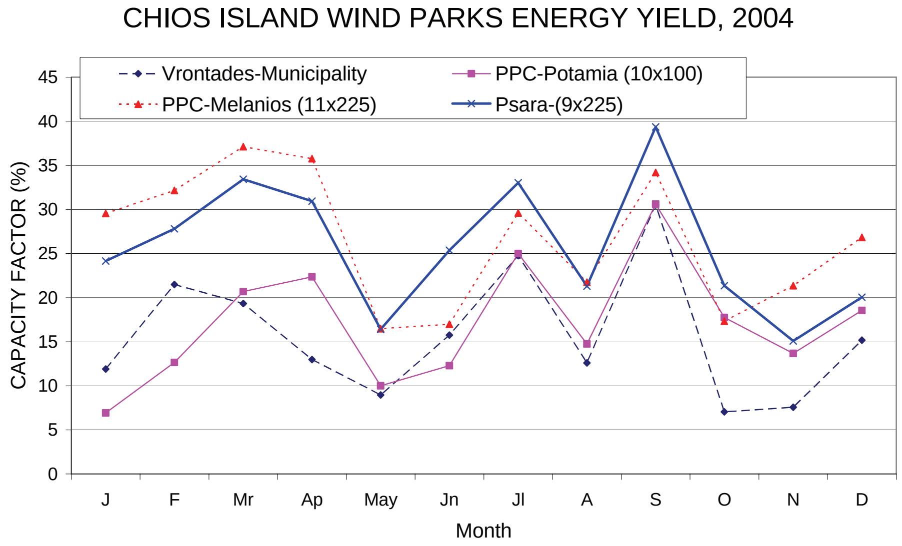

Figure 5: Detailed "CF" comparison for Chios island wind parks, 2004

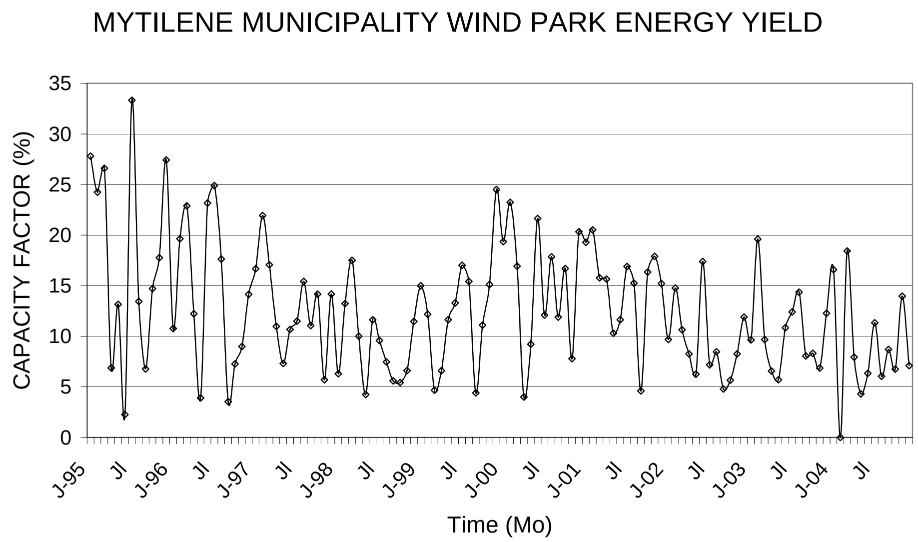

Figure 6: Time-evolution of Mytilene wind park energy yield (1995-2004)

In order to present a clear-cut picture of the energy performance of the existing wind parks in the N. Aegean area, one may investigate the capacity factor time-evolution of all PPC wind parks operating in Lemnos, Lesvos, Chios, Samos and Ikaria islands, figure (2), for the 2000-2004 period. The above mentioned wind turbines can be separated in two subgroups.

The first one includes the WM-55 and WM-100 wind turbines manufactured by the Danish company Windmatic at the end of 1980's. Using the information of figure (8) one may notice the considerable "CF" variation between these five wind parks during the same year. In fact, Ikaria and Samos (Marathokampos) wind parks present the highest "CF" values, while acceptable and gradually increasing may be characterized the energy performance of Limnos-Vounaros installation. Besides, the total annual energy yield of all the power stations investigated seems almost constant during the 2000-2003 period (CF≈24%) and only during 2004 the corresponding value drops to 22%.

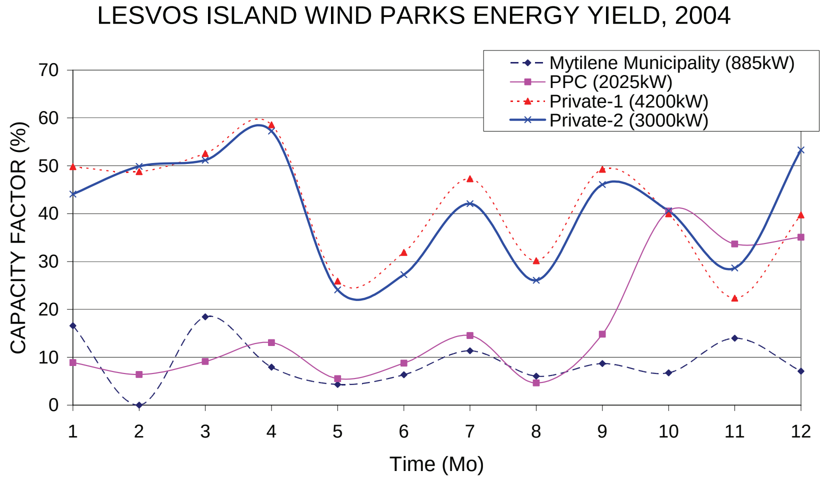

Figure 7: Detailed "CF" comparison for Lesvos island wind parks, 2004

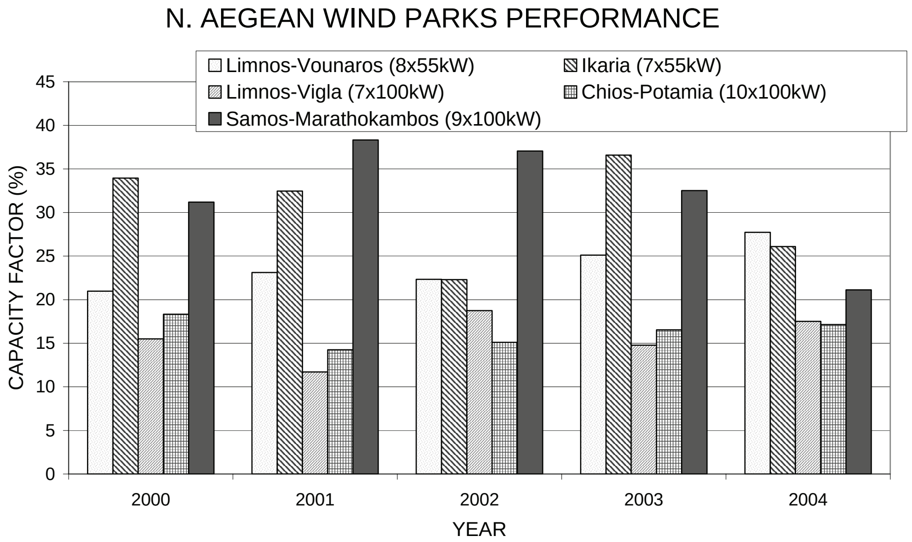

Figure 8: Performance of wind parks based on WM-15S and WM-19S wind turbines

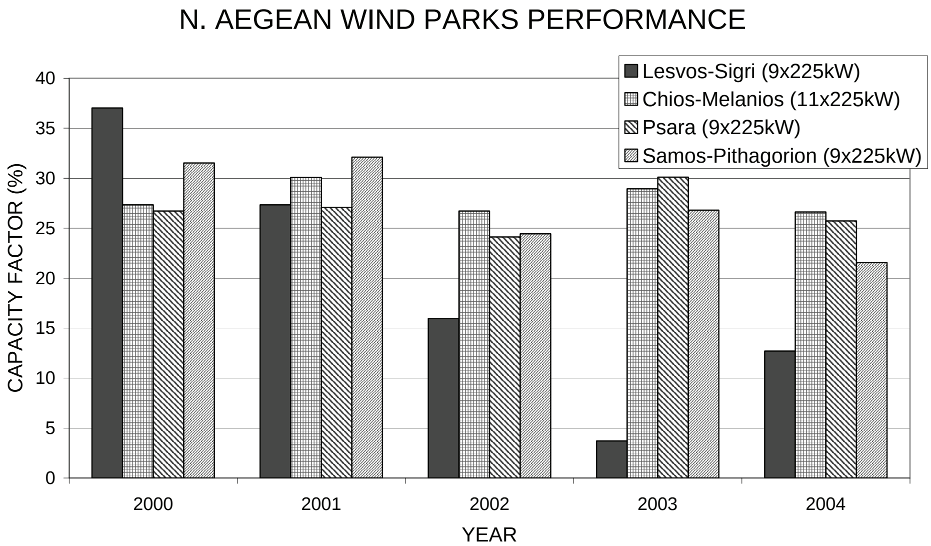

Figure 9: Performance of N. Aegean wind parks based on V-27 (225kW) wind turbines

The second group contains the V-27 wind turbines (rated power 225kW) manufactured also by the Danish company Vestas at the beginning of 1990's. These wind turbines, located in Chios-Melanios, Psara, Samos-Pithagorion and recently in Lesvos, present quite better performance, figure (9), than the first group. In fact the average annual CF value is approximately 30% for 2000 and 2001. However, after the problems appearing in Lesvos wind park the corresponding CF value drops to 25%.

5. Conclusions

An attempt is made to investigate the energy generation performance of the existing wind parks using available long-term official data. Among the most interesting results of this study is the unusual intense time-variation of the encountered wind energy production, not justified by the corresponding wind potential changes. Besides, the technical availability of most wind parks erected during the previous decades has been rather low in spite of the significant improvement encountered during the last years.

On the contrary, most private wind parks show remarkable capacity factor values, despite the fact that they have been installed in regions with lower wind potential than PPC wind parks. Finally, all the conclusions drawn should be examined in details under the recent situation being formed in the new liberalized European electricity market.

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RISK EVOLUTION DURING A WIND PARK INVESTMENT REALIZATION

J.K. Kaldellis, E. Kondili[1], K.A. Kavadias
Laboratory of Soft Energy Applications & Environmental Protection
[1] Optimisation of Production Systems Lab
Mechanical Eng. Dept., Technological Education Institute of Piraeus

Abstract

During the last ten years, wind energy proved to be a mature electricity production sector. In Greece, on the other hand, the installed capacity hardly surpasses the 500MW, while most domestic financial organizations characterize wind park investments as high-risk projects. The present study investigates the risk evolution during the entire procedure of a new wind-park investment, based on the experience gained from several projects planned and implemented during the last decade. It is important to note that all financial organizations estimate their contribution -and the interest rate offered- on the basis of the investment expected risk. Hence, during the wind park implementation procedure, several technical and commercial considerations should be taken into account, in order one or more sites suitable for the new development to be chosen. Subsequently, important parameters strongly affecting the realization of the investment include also constraints and incentives based on the existing national and European legislative frame, environmental impact considerations, constraints related with the archeological and historical heritage, military-telecommunication installations and airports in the candidate areas as well as the social attitude towards wind exploitation projects. Finally, the financial possibilities of a wind power station play a dominant role on the project total risk; hence they should thoroughly be taken into consideration.

Keywords: Risk Impact; Wind Park; Investment; Interest Rate; Social Attitude

1. Introduction

During the last ten years, wind energy proved to be a mature electricity production sector, since the annual development rate of installed capacity in individual countries reaches 40%, while the total installed capacity in Europe exceeds the 40,000MW[1]. In Greece, on the other hand, the installed capacity hardly surpasses the 500MW[2], see figure (1), while most domestic financial organizations insist on characterizing wind park investments as high-risk projects[3].

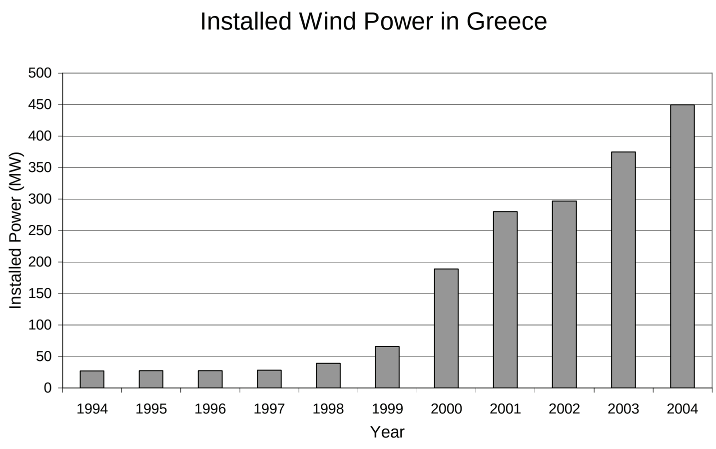

Figure 1: Wind power time evolution in Greece

The present study investigates the risk evolution during the entire procedure of a new wind-park investment, based on the experience gained from several projects planned and implemented during the last decade[4]. It is important to note that all financial organizations (banks, private investors etc.) estimate their contribution -and the interest rate offered- on the basis of the investment expected risk[5].

Hence, during the wind park implementation process, several technical and commercial considerations should be taken into account, in order one or more sites suitable for the new development to be chosen. Among the factors involved one should include the accurate assessment of the wind potential, the examination of the local electricity distribution system, the study of local road network and the consideration of potential sites ownership[6].

Subsequently, important parameters strongly affecting the implementation of the investment also include constraints and incentives based on the existing national and European legislation, environmental impact considerations[7], constraints related with the archeological and historical heritage, military-telecommunication installations and airports in the candidate areas as well as the social attitude towards wind exploitation projects[8].

During the last decade, several wind-based projects have faced serious obstacles due to the above-mentioned reasons[9], while even more plans were totally abandoned either from the beginning or during their initial stages. Finally, the financial performance of a wind power station plays a dominant role on the project total risk[10]; hence it should thoroughly be taken into consideration.

2. Risk Impact on the Wind Park Economic Performance

As already mentioned, the wind power sector's rapid growth and prospects are attracting more and more attention from institutional and private investors[11]. Hence, many investors are starting to take a serious look at this new market as projects become bigger and require utility-scale financing. For example, typical wind power investments have an average size of 20MW, hence the capital required is approximately 20M€.

Two major factors that dominate the financial behaviour of similar projects are the risk related with the project implementation and the time required for the installation erection. Keep in mind that these two factors are often interacting with each other, hence their involvement is quite complex. In fact both parameters affect the capital cost or the return on investment required. More specifically, the investment cost "C_n" of a wind power installation consists of[12] the initial installation cost "IC_o" (turnkey value), as well as the maintenance and operation cost, "FC_n+VC_n", see also Appendix One. Therefore, one may write the following relation (all quantities being functions of time):

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

Accordingly, the initial cost "IC_o" includes the market price of the "z" machines constituting the wind park under investigation and the corresponding installation cost, all values expressed at the time point "t_o" at which the wind power investment starts its operation. 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:

$$\alpha + \beta = 1 - \gamma \tag{2}$$

where "γ" is the subsidy percentage by the Greek State (γ=30%-40%), according to the existing development law for the renewable energy applications.

Generally speaking, any investment involves two different kinds of risk, i.e. the "market risk" and the "unique risk". Although one cannot avoid market risk, which stems from the uncertainties of the whole economy, this is not the case for the unique risk, since it relates to a specific project. In general, these two kinds of risk have different names each, hence for example market risk is also called "non-diversifiable risk" and unique risk is found as "diversifiable risk".

More specifically, wind power project risks can be also classified[13] into the following categories:

- Development and construction risks including all aspects of installing wind turbines
- Financial risks relate to the terms and availability of financing options
- Production risks incorporating wind variability, efficiency losses and curtailments
- Operational risks taking into account maintenance costs over the lifetime of the project
- Regulatory risks involving permitting, changes in legislation and changes in tax benefits

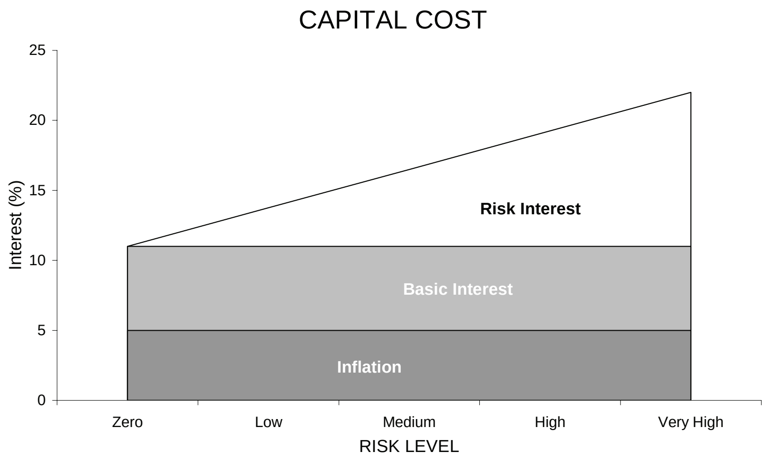

Figure 2: Wind energy investments capital cost components vs. risk level

The relative importance of these categories will vary throughout the life of the project. Development, construction and financing risks appear at the early stages of the investments, while production, operations and regulatory risks extend throughout the life of the project (operation risk). Sometimes the investors may have to pay a market premium to hedge these risks, since the premiums may enable more predictable results and ensure the access to competitive financing. In this context, the capital cost consists of three component parts, i.e. time preference (i_b), inflation rate (g) and risk premium (Δi), figure (2), thus:

$$i = i_b + g + \Delta i(r) \tag{3}$$

The third component of equation (3) is the risk premium. It is important to mention that risk is related rather to the nature and the time-horizon of an investment than to the size of the project. On the other hand, the areas of risk in general, as they are perceived by organizations that finance the development of a wind park project, include completion risk, technology risk, energy production risk, operating risk, financial risk and country risk[14]. Modern portfolio theory suggests a quantitative relationship between risk parameter "r", appropriately defined, and a lender's required rate of return, properly adapted for the local market[15]. According to the existing experience, the time-horizon of a project influences significantly the risk premium, especially for medium and high-risk investments. Note that for mature financial markets a straight-line relationship between "Δi" and "r" can be established for investments characterized by low or medium risk ($r \le 1.3$). This is not the case for high-risk projects and economical markets under expansion. Recapitulating, one should mention here that the present study is focused on the risk related to the project implementation.

3. Risk-Related Wind Park Implementation Activities

The development of a wind park is a complicated project that consists of several important phases, figure (3), including:

- Site Selection
- Project Feasibility Analysis
- Investment Evaluation
- Planning Application
- Construction
- Commissioning-Initial Operation

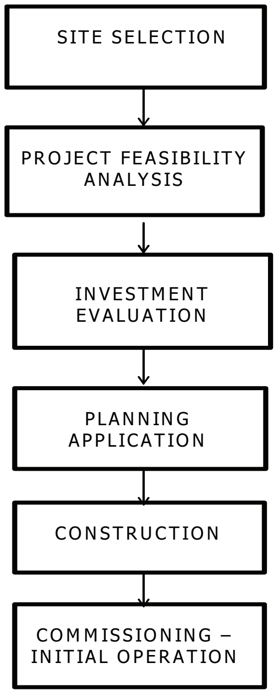

Figure 3: The main phases of a wind energy project

The site selection process is a vital determinant and is mainly based on the available information concerning the wind potential, the local electricity distribution network, the existing infrastructure (road network, access constraints etc.), the land ownership, the financial and financing possibilities, the environmental considerations and the attitude of the local society towards similar investments. At this stage most of the work is carried out using general information.

The project feasibility analysis includes wind resource assessment (based on site measurements and computer models applications), existing land uses (discussion and agreement with the landowners), assessment of ground suitability (for wind turbines foundation, erection and access roads creation), electrical connection possibility and expected cost (local grid capacity, distance between the wind park and the connection substation) and environmental impact assessment. At this point one should determine the project scale, i.e. the potential number and size of wind turbines to be installed. In the meantime, during this phase one should request for the "*Wind Park Production Permission*" from the RAE (Greek Regulatory Authority of Energy) and the Ministry of Development, figure (4).

As far as the environmental impact assessment is concerned, one should investigate matters related to visual and noise impact (especially for locations near domestic dwellings), impact to the existing flora and fauna, proximity with microwave, TV, radar or radio transmissions, as well as with civil and military airports. On top of this, areas with increased ecological importance or high security areas are usually excluded. Finally, special attention should be paid to the opening of a creative discussion with local authorities and local communities. This activity is very sensitive and may determine the entire project success. According to figure (4), one should collaborate with several Organizations and Ministry Departments in order to obtain the *Installation Permission*.

In the meantime, the potential investors should prepare their proposal and the corresponding business plan in order to submit for investment subsidy. At the moment there are two different possibilities. Therefore one may apply for investment subsidy either to the Ministry of Economy via the current Development Law (e.g. 3299/2004) or to the Ministry of Development, via the Operational Program of Competitiveness. In both cases there are specific requirements that the investment and the investor should fulfill. The subsidy percentage is quite high varying between 30% and 45%, according to the characteristics of each project.

After the successful completion of the first two phases, one may assume that the proposed wind power station is commercially viable and environmentally acceptable. Thus, during the investment evaluation phase one should select the most appropriate number and wind generator type and face all the maters related with the environmental considerations. The major topics that should seriously be considered are the visual, noise and landscape assessment. Accordingly, the fauna and flora existing on the selected site (permanent or seasonal) should be considered in relation to the loss of habitat, to their sensitivity to disturbance and to their importance which may be identified in the national and local legislation. As already mentioned, regions of high ecological sensitivity are normally excluded from similar interventions. On top of these, one should carry out the appropriate studies and activities concerning archaeological and historical importance of the area, the impact on water resources, the potential interference with the telecommunication systems, the aircraft safety etc. At the end of this phase one should definitely obtain the "*Installation Permission*" as well as the "*Environmental Terms Approval*".

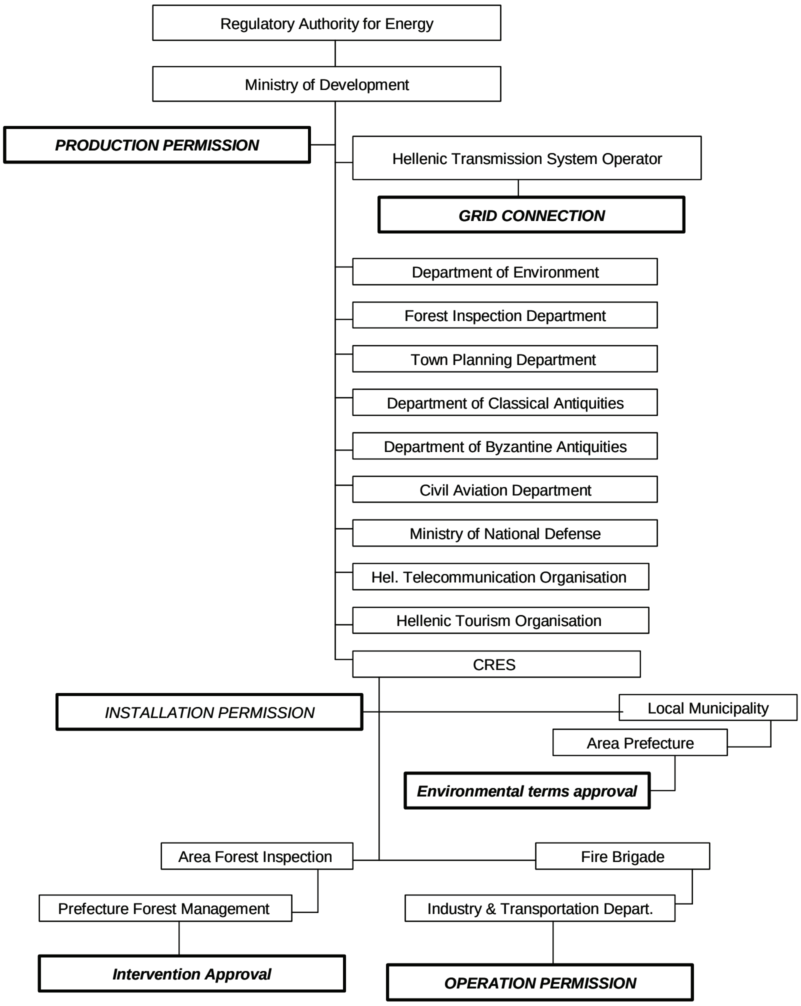

Figure 4: The officially implementation procedure of a new wind park

During the planning application phase, the detailed technical, commercial and environmental assessments should have been undertaken. Besides, the investment consortium should be finalized, while the approval of the project subsidy by the local authorities is also expected. As it is obvious, the project implementation team defines the detailed application procedure using the existing software. Additionally, the expected financial behavior of the project is simulated, under selected techno-economic scenarios, while at the same time the negotiations with banks and financing institutions should result to a preliminary agreement. One of the most important topics to be solved during this phase is the agreement between the potential equipment supplier, including terms of payment, engines purchasing and guarantees. Responsibility for and allocation of risks are crucial to contract negotiations. The best arrangements assign financial responsibility for risks to the party or parties with the best ability to manage them. Finally, at the end of this phase one should obtain the "*Intervention Approval*", figure (4).

During the construction phase one should take into account the existing transport access studies, the detailed electrical and civil engineering planning, the environmental considerations and the requirements set by the corresponding electrical grid owner. In view of the various subcontractors required for a wind park project the coordination, planning and management of the site construction works is vital. Besides, discrepancies may occur when specification details in one section of the contract do not match with those in another. More specifically, the project developer should ensure that all contractors are aware of and abide by the requirements of the planning conditions and the agreed environmental measures. On top of these, the project developer should concentrate his efforts in the time-effective resolution of construction issues, being also in continuous liaison with the project owner and the local authorities. During the design development phase it is often useful to have the owner’s representative review and comment on the contractor’s design documents. Finally, the developer should ensure that on-site and off-site works are undertaken with minimum disruption to the local residents.

After the wind park erection, the installation is ready for operation. For this purpose the wind turbines manufacturer and the wind park developer start the power station initial-trial operation. At this point it is important to mention that developers, owners and operators of wind energy projects are responsible for the wind park satisfactory operation of the project throughout its service period (lifetime). When the testing operation of the installation is satisfactorily completed, including the connection with the local electrical network, the wind park owner receives the wind park "*Operation Permission*", after the corresponding plant inspection by the Greek Public Power Corporation experts.

Summarizing, all these phases require the completion of a wide range of activities including:

- Wind measurements and meteorological assessment in general
- Preliminary technical energy analysis and financial evaluation
- Site identification and appraisal
- Investment decision
- Site acquisition
- Continuous liaison with the project owner
- Liaison with the local government and the local community
- Land development and site design
- Environmental impact assessment and constraints analysis
- Project financing analysis covering revenues and operating cost predictions, construction costs, project finance and taxation
- Social impacts assessment
- Transport access studies
- Grid connection assessment and power purchase negotiations
- Liaison with the network provider for the physical grid connection
- Continuous contact and follow up of the formal permitting procedures
- Detailed electrical and civil engineering
- Preparation of specification and tender documentation for the electrical equipment and installation works
- Tender review and negotiations for the electrical equipment supply, electrical installation works
- Contracting of construction
- Contract administration
- Coordination, planning and management of the site construction works
- Resolution of construction issues
- Commissioning and starting up of the plant
- Review of commissioning and quality assessment documents

For the successful implementation of the project, all the above elements need to be coordinated and interact appropriately to balance and optimise the economic, environmental and planning drivers of the project.

4. Quantification of Risk during the Project Implementation Activities

In the following, an attempt is made to quantify the risk involved as well as the capital required for the above mentioned activities. In essence, risks affect what is most important to owners, contractors and operators, i.e. profitability. Typical risks for a wind farm project include[16]:

- ✓ Cost/schedule overruns
- ✓ Interface issues between the construction and M&O phase of the project
- ✓ Variations in design (either conceptual or detailed)
- ✓ Force majeure
- ✓ Defective design/workmanship-materials and
- ✓ Changes in the law-regulations.

Table I indicates the capital required, the risk involved and the average and the maximum values of the duration for each of the project activities. According to the existing experience, the first three activities demand relatively low capital to be spent; however they present very high risk, depending on the wind potential quality and the infrastructure of the potential site. After the investment decision, normally one out of five cases is accepted (the proportion mentioned decreases as the number of wind power installations is expanding), one should obtain the potential site ownership and begin the land development and site design. The next activities include the various official permissions required (figure (4)), the environmental impact assessment, the project financing opportunities, the grid connection and electrical power purchase agreement, which present also quite high risk. Accordingly, one should realize the planning, coordination and management of the site construction works, as well as the detailed electrical and civil engineering infrastructure preparation along with the negotiations with the equipment suppliers. Even at this stage there is a considerable risk, especially concerning the project completion timing, taking into account that the local climate and the social attitude of the nearby communities are significant factors. During the construction stage the risk is fairly low, especially if a positive public attitude has been achieved and the wind park developer manages a suitable resolution of the various construction issues. Finally, the testing operation and the commissioning and starting up of the plant present a minimum risk, while the greater part of the invested capital has been spent.

Table I: Wind Park Investment Tasks and Development Cost

TASKS / ACTIVITIES	**CAPITAL (k€/MW) REQUIRED**	**RISK**	**DURATION (years)**	
			Average	**Maximum**
Wind measurements and meteorological assessment in general	1.5-5.0	Very high	1	3
Preliminary technical energy analysis and financial evaluation	1.0-2.0	Very high	0.1	0.5
Site identification and appraisal	1.0-2.0	Very high	0.1	1
Investment decision (Milestone)			Up to here (1 year total)	Up to here (3 years total)
Site acquisition	5.0-20.0	Very high	0.2	0.5
Land development and site design	2.0-4.0	Very high	0.3	0.6
Energy Authorities / Production Permission	2.0– 5.0	Very high	0.2	0.6
Environmental impact assessment and constraints analysis	2.0-5.0	High	0.3	0.75
Project financing analysis	3.0-10.0	High	0.3	1

TASKS / ACTIVITIES	CAPITAL (k€/MW) REQUIRED	RISK	DURATION (years)	
			Average	Maximum
Social impacts assessment	1.0-5.0	High	0.2	2
Transport access studies	1.5-3.0	Moderate	0.1	0.3
Grid connection assessment and power purchase negotiations	1.5-3.0	Moderate	0.3	1.5
Liaison with the network provider for the physical grid connection	1.0-2.0	Moderate	0.1	0.3
Continuous contact and follow up of the formal permitting procedures	3.0-5.0	Moderate-Low	During the entire Project	
Installation Permission (milestone)			Up to here (1.5 year total)	Up to here (3 years total)
Detailed electrical and civil engineering, preparation of specifications	3.0-10.0	Moderate-Low	0.3	0.6
Tender documentation for the electrical equipment and installation works	2.0-3.0	Low	0.3	0.6
Tender review	1.0	Low	0.1	0.3
Negotiations for the electrical equipment supply, electrical installation works	1.0-3.0	Moderate-Low	0.2	1
Coordination, planning and management of the site construction works	10.0-20.0	Low	0.6	1.5
Contract administration	2.0-3.0	Low	1	3
Contracting of construction	Non specified	Moderate-Low	0.6	1.5
Resolution of construction issues	Non specified	Moderate-High	0.3	1.5
Commissioning and starting up of the plant	Non specified	Moderate-Low	0.2	0.5
Review of commissioning and quality assurance documents	Non specified	Low	0.1	0.3
Test operation	Non specified	Low	0.1	0.3
Continuous liaison with the project owner	Non specified	Moderate-Low	During the entire Project	
Liaison with the local government and the local community	Non specified	Moderate	During the entire Project	

Summarizing, one may state the following for a wind park development in Greece:

- ✓ The time required for the erection of a typical wind park is approximately three (3) years, with two (2) years being the absolute minimum. In several cases, the complete project duration exceeds four (4) years or even five (5) years in special occasions.

- ✓ Approximately 50% of the candidate projects are abandoned before the investment decisions, either due to lower wind potential available than the expected one or due to the prohibitive infrastructure improvement requirements.
- ✓ A considerable part of the projects (20%) fails due to land possession problems or serious environmental constraints or negative public attitude towards the wind energy applications.
- ✓ A remarkable share of wind energy projects face serious financing or management problems, usually sold to other investors. In this case, the vast majority of these projects are finally implemented, unfortunately with a remarkable time delay.
- ✓ A small number of projects are postponed or cancelled during the construction stage, either due to poor management or financing or due to public reaction during the power station construction.
- ✓ The risk weighted average development cost exceeds the 100,000€/MW to be installed, while in specific cases values up to 140,000€/MW have been reported.
- ✓ The entire project implementation cost is in the range of 650,000€/MW up to 950,000€/MW.

5. Discussion and Proposals

Using the information presented it is almost obvious that the creation of a new wind power station is a rather complicated project demanding the contribution of several experts[17]. Of course during the high risk stages of the project the capital required is rather low, while on the other hand the initial phases are the most time consuming. In fact, in figure (5) one may find a typical project plan based primarily on the data included in Table I. As it is obvious from this figure, the maximum duration of the wind park erection depends mainly on the site appraisal and acquisition, on the permissions acquirement procedures and finally on the construction activities.

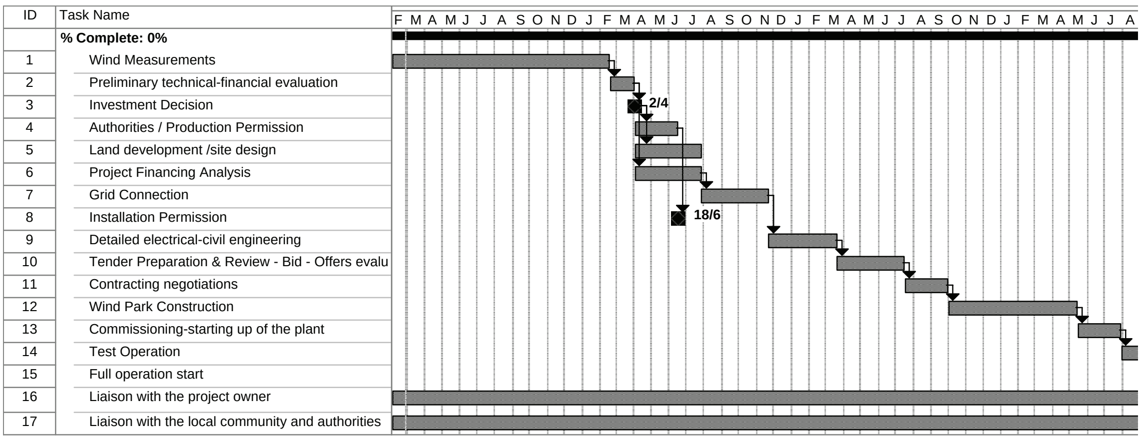

Figure 5: Typical implementation plan of a new wind park

In this context, one may state that by using the available wind potential data and the appropriate numerical codes and improving the contacts with the local authorities one may minimize the project preparation time required. Besides, using an optimum project management time-table and taking advantage of the existing professional software it is possible to decrease remarkably the time for project construction and commissioning. As already mentioned, the weather impact may be dominant, while special attention should be paid to avoid unnecessary disturbance to the social and political environment.

As far as the risk allocation is concerned, parties involved should also determine risk in terms of probability of occurrence and potential loss effect. Some low frequency but high value risks (e.g. catastrophic risks) can be covered by insurance. Besides, the party that is best able to control the events giving rise to the risk should bear the consequences.

Finally, in figure (6) one may demonstrate the evolution of the project implementation risk along with the capital requested during the project development phases. It is interesting to note that these two quantities vary inversely, i.e. during the high risk stages the capital required is minimal, while, as the risk is decreased, the capital needs are significantly amplifying.

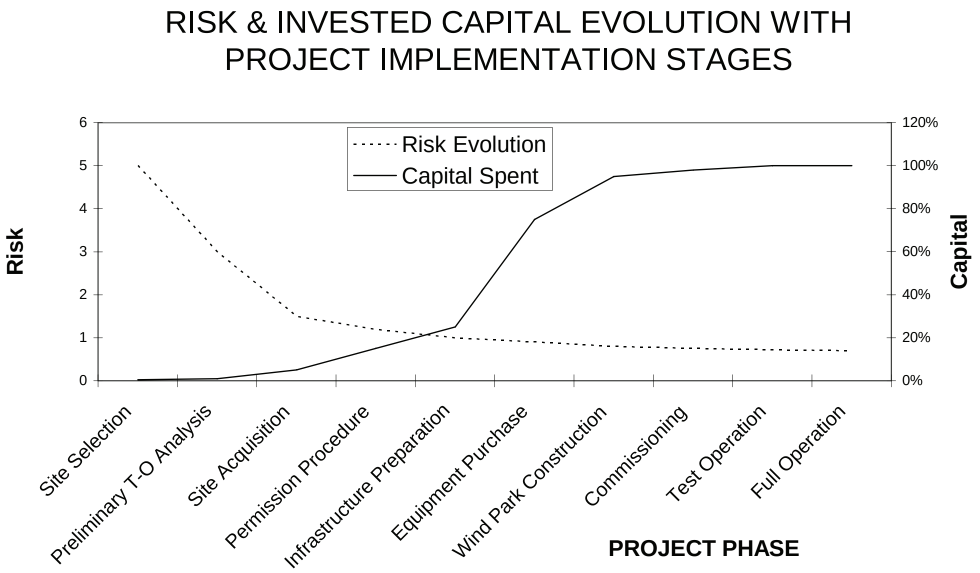

Figure 6: Risk and spent capital evolution with a wind park project implementation phases

6. Conclusions

The wind power investments are no more small scale individual projects. On the contrary, installations up to 250MW are under development. Usually, a typical wind power installation size is approximately 20MW, hence there is a need for professionals to develop and operate the entire project. The proposed study investigates the risk evolution during the entire procedure of a new wind-park investment, presenting the most reliable information from the local market.

It is important to note that according to the above presented analysis, significant risk is encountered only during the early phases of the project, when the capital requirement is minimal. Subsequently, when high capital is needed the risk is fair. At this point one cannot disregard that up to now the State does not practically facilitate the projects implementation, taking into account the rather complicated and sometimes confusing existing legislation. In other cases, local people sometimes object the erection of wind parks in their areas, either due to poor information or due to inconsiderate behavior of the developers.

Summarizing, one should point out that the wind energy projects accomplishment requires highly professional design and implementation, especially due to their case dependent character. In this way one may minimize the risk impact, taking also into consideration the experience from the existing project realization. Thus, if the Greek society wants clean and cost competitive wind energy based electricity, it is necessary to encourage professional wind parks development, taking into account that similar investments are quite promising, since they present low pay-back period, considerable State subsidy and guaranteed (via State controlled agreements) electricity production disposal.

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APPENDIX

Initial Cost

$$IC_o = P_r \cdot z \cdot N_o \cdot (1 + f) \qquad \text{(A-1)}$$

$$P_r(t_o) = \left[f_N(\nu) + c_\infty \cdot \left(1 + \varepsilon_1 \cdot e^{-\varepsilon_2 \cdot (t_o - 1990)}\right)\right] \cdot \sigma_p(z) \qquad \text{(A-2)}$$

with "N_o" the rated power of wind turbines used and c_∞=700Euro/kW, ε_1=0.7 and ε_2=0.125.

$$\nu = \frac{N_o}{N_o^*(t_o)} \qquad \text{(A-3)}$$

$$N_o^*(t_o) = A_N \cdot e^{B_N \cdot (t_o - 1990)} \tag{A-4}$$

with A_N=226.12, B_N=0.1786.

$$f_N = 566 \cdot e^{-\nu/0.35} - 132.5 + 100 \cdot \nu \tag{A-5}$$

$$\sigma_p(z) = 1.08 - 0.08 \log(z) \tag{A-6}$$

$$f = f_o \cdot \sigma_f \tag{A-7}$$

with "f_o" from relative (site depending) diagrams[12][18].

$$\sigma_f(z) = -0.075 \cdot (\log(z))^2 - 0.075 \cdot \log(z) + 1.15 \tag{A-8}$$

Fixed M&O Cost

$$FC_n = FC_{n-1} \cdot (1 + i_n) + (m_n \cdot IC_o) \cdot \prod_{j=1}^{j=n} \left(1 + g_j^m\right) \tag{A-9}$$

$$m_n(t) = m_o(t_o, z) \cdot \left[1 + \frac{\xi(\tau)}{m_o}\right] + \delta \tag{A-10}$$

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.)[12]. 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 [18]. 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.

Variable M&O Cost

$$VC_n = IC_o \cdot \sum_{k=1}^{k=k_o} r_k \cdot \sum_{l=1}^{l=l_k} \left\{ \left[\prod_{j=1}^{j=l \cdot n_k} \left(1 + g_j^k\right) \cdot \left(1 - \rho_j^k\right) \right] \cdot \left[\prod_{j=l \cdot n_k}^{j=n} \left(1 + i_j\right) \right] \right\} \tag{A-11}$$

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[19]. 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:

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

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 (12) describe the annual change of the price and the corresponding technological improvement level for the "k-th" major component of a wind converter[12][18]. 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 behavior 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.

PART TWO

HYBRID SYSTEMS

COST-BENEFIT ANALYSIS OF REMOTE HYBRID WIND-DIESEL POWER STATIONS: CASE STUDY AEGEAN SEA ISLANDS

J.K. Kaldellis, K.A. Kavadias
Laboratory of Soft Energy Applications & Environmental Protection
Mechanical Eng. Dept., Technological Education Institute of Piraeus

Abstract

More than one third of world population has no direct access to interconnected electrical networks. Hence, the electrification solution usually considered is based on expensive, though often unreliable, stand-alone systems, mainly small diesel-electric generators. Hybrid wind-diesel power systems are among the most interesting and environmental friendly technological alternatives for the electrification of remote consumers, presenting also increased reliability. More precisely, a hybrid wind-diesel installation, based on an appropriate combination of a small diesel-electric generator and a micro wind converter, offsets the significant capital cost of the wind turbine and the high operational cost of the diesel-electric generator. In this context, the present study concentrates on a detailed energy production cost analysis in order to estimate the optimum configuration of a wind-diesel-battery stand-alone system used to guarantee the energy autonomy of a typical remote consumer. Accordingly, the influence of the governing parameters -such as wind potential, capital cost, oil price, battery price and first installation cost- on the corresponding electricity production cost is investigated using the developed model. Taking into account the results obtained, hybrid wind-diesel systems may be the most cost-effective electrification solution for numerous isolated consumers located in suitable (average wind speed higher than 6.0m/s) wind potential regions.

Keywords: Hybrid Wind-Diesel Station; Stand-Alone System; Cost-benefit Analysis; Energy Production Cost; Variable Maintenance Cost; Sensitivity Analysis

1. Introduction

Most European and North American consumers cover their electrification needs by large capacity and robust interconnected electrical networks, supported by nuclear and fossil fuel-fired power stations of considerable size (e.g. 1000MW). In these cases the free market competition leads to reliable network operation and minimum production cost[1], achieving unit electricity costs of generation down to 0.03€/kWh. On the other hand, United Nations estimate[2] that almost two billion people have no direct access to electrical networks. Hence, their only electrification possibility should be based on autonomous stand-alone systems[3][4]. Otherwise one should invest on expensive[5] grid-extensions, whenever possible.

In actual fact, the great majority of rural consumers had no other choice than small diesel-electric generators, while only in limited cases small wind converters, photovoltaic generators or micro-scale hydro systems contribute in the electricity generation[6][7][8][9]. The utilization of diesel engines presents minimum first installation cost[10] but substantial maintenance and operation cost; see for example figure (1). On the contrary, wind power installations are capital intensive, presenting however low M&O cost[11]. As a result, one may find an appropriate combination of a small diesel-electric generator and a micro wind converter that guarantees the remote consumer electrification at a rational (minimum) initial and long-term cost[12][13][14]. Such a system may also use an appropriate battery bank, in order to improve the system reliability. The extreme cases of such a generalized stand-alone solution appear to be either the diesel-only (no wind turbine and/or energy storage) or the stand-alone wind power (zero diesel-oil contribution) configuration. The possibility of biofuel utilization is not included here[15].

Kaldellis J.K., Kavadias K.A., 2007, *"Cost-Benefit Analysis of Remote Hybrid Wind-Diesel Power Stations: Case Study Aegean Sea Islands", Energy Policy Journal, vol.35, pp.1525-1538.*

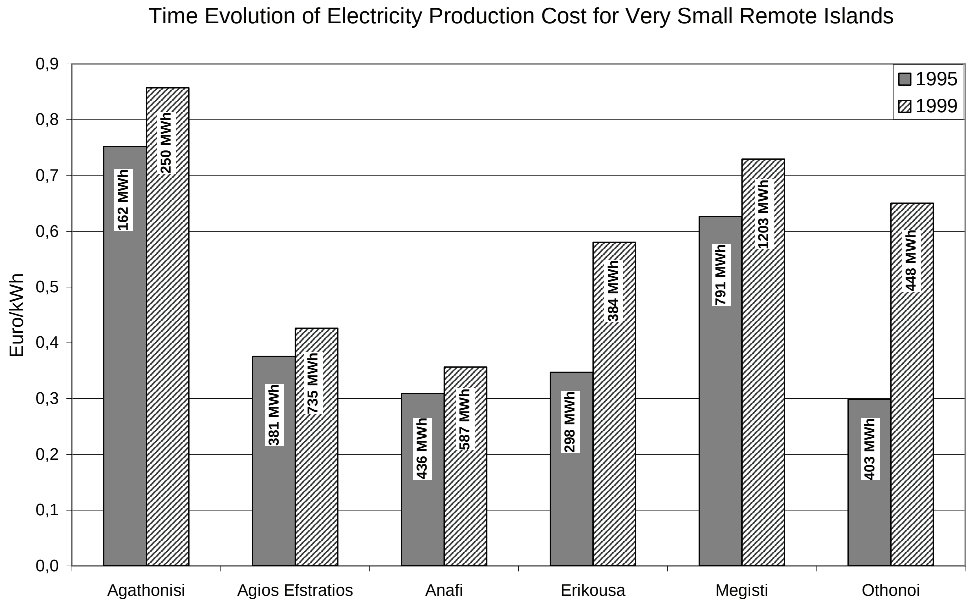

Figure 1: Electricity production cost time-evolution for remote consumers located in small Greek island

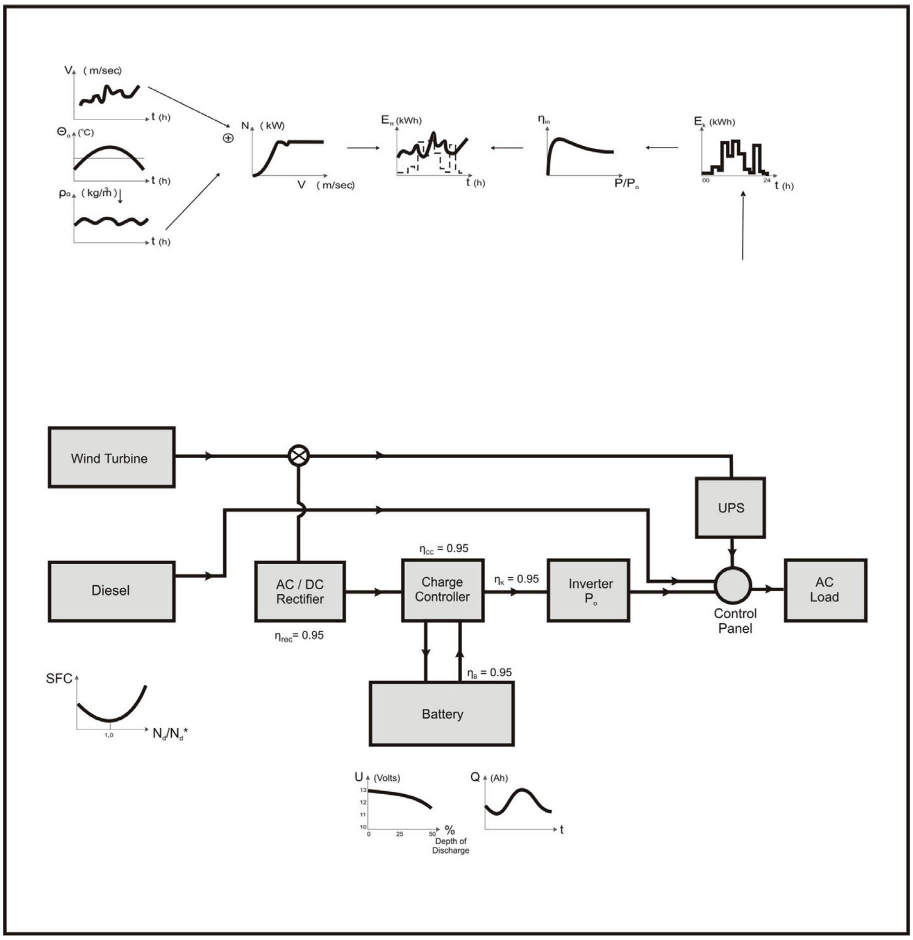

Figure 2: Proposed autonomous wind-diesel hybrid system

In this context, the present study is concentrated on a detailed cost-benefit analysis[9][11] of an optimum sizing wind-diesel-battery stand-alone system used to meet the electrification requirements of a typical remote consumer, generation capacity up to 15kW. Accordingly, the corresponding electricity production cost value is predicted using an integrated methodology and is subsequently compared to existing electrical market price. Finally, an extensive sensitivity analysis is carried out in order to improve the proposed analysis reliability.

2. Proposed Solution

Based on previous works by the authors[3][4][14] a representative small wind-diesel-battery stand-alone power system (up to 15kW) able to meet the electricity requirements of remote consumers consists of (figure (2)):

a. A micro wind converter of rated power "N_o" (kW)
b. A small internal combustion engine of "N_d" (kW), able to meet the consumption peak load demand "N_p" (i.e. $N_d \geq N_p$)
c. A lead-acid battery storage system with total capacity of "Q_{max}", operation voltage "U_b" and maximum depth of discharge "DOD_L"
d. An AC/DC rectifier of "N_o" kW and U_{AC}/U_{DC} operation voltage values
e. A DC/DC charge controller of "N_o" rated power, charge rate "R_{ch}" and charging voltage "U_{CC}"
f. A UPS (uninterruptible power supply) of "N_p" (kW), frequency of 50Hz, autonomy time "δt" and operation voltage 220/380V
g. A DC/AC inverter of maximum power "N_p" (kW) able to meet the consumption peak load demand, frequency of 50Hz and operational voltage 220/380V

This system should be capable of facing a remote consumer's electricity demand (e.g. a four to six member family), with rational first installation and long-term operational cost. The specific remote consumer investigated is basically a rural household profile (not an average load taken from typical users) selected among several profiles provided by the Hellenic Statistical Agency[3], see also [16] and [17]. In order to minimize the electricity requirements of the remote consumer special emphasis is laid on the efficient and rational use of the available energy resources. In this context, the numerical load values vary between 30W (refrigerator load) and 3300W. According to the consumption profile approved, the annual peak load "N_p" does not exceed 3.5kW, while the annual energy consumption "E_y" is around 4750kWh per year.

Additionally, the corresponding wind potential and ambient temperature and pressure are also necessary[18] to integrate the system sizing calculations. Finally, the operational characteristics of all components (e.g. wind power curve at standard day conditions, diesel-electric generator specific fuel consumption, inverter efficiency, battery bank characteristic etc.) composing the stand-alone system under investigation are also required, figure (2).

For estimating the appropriate configuration of the proposed wind-diesel hybrid system, three governing parameters should be defined: the rated power "N_o" of the wind turbine used, the battery maximum necessary capacity "Q_{max}" and the annual mass fuel flow consumption "M_f". Working this problem out, the already presented[3] computational algorithm "WINDREMOTE-II" is extended to include a small diesel-electric generator. This new numerical code "WIND-DIESEL I" is used to carry out the necessary parametrical analysis on an hourly energy production-demand basis, targeting to estimate the wind turbine rated power "N_o" and the corresponding battery capacity "Q_{max}", given the annual permitted oil consumption "M_f"; see also figure (3). More specifically, given the "M_f" value and for each "N_o" and "Q_{max}" pair, the "WIND-DIESEL I" algorithm is executed for all the time-period selected (e.g. one month, six-months, one year or even for three years), while emphasis is laid on obtaining zero-load rejection operation.

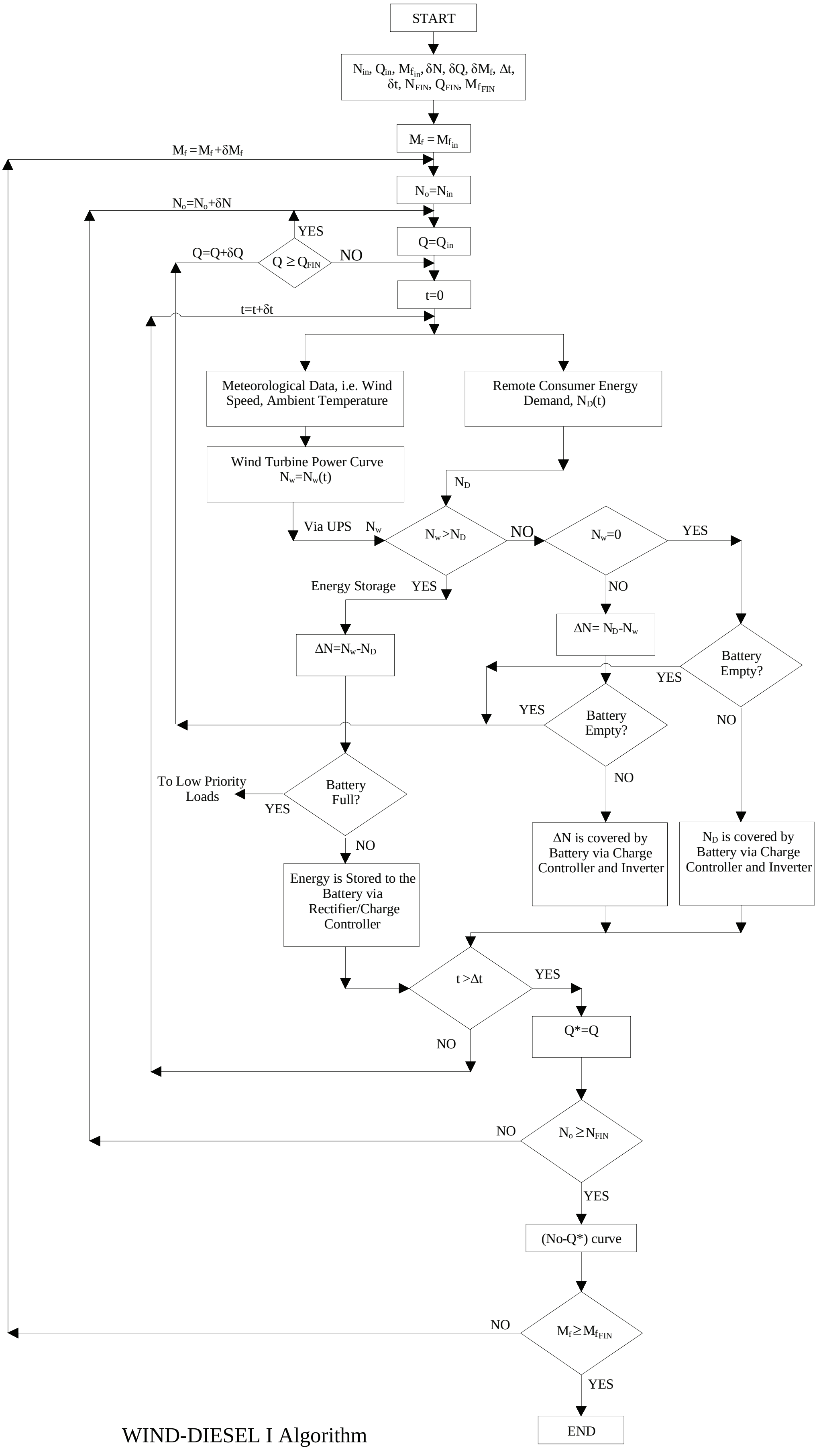

Figure 3: WIND-DIESEL-I algorithm.

3. Electricity Production Cost

The present value of the entire investment cost of a stand-alone wind-diesel power system (after -n years of operation) is a combination[11][9] of the initial installation cost and the corresponding maintenance and operation cost, also considering the investment residual value; all quantities expressed in present (constant) values.

3.1. First Installation Cost

As already acknowledged in previous works[11][19], the initial investment cost "IC_o" includes the market (ex-works) price of the installation components (i.e. wind turbine, IC_{WT}; battery, IC_{bat}; diesel generator, IC_d and electronic devices IC_{el}, including inverter, UPS, rectifier and charge controller cost) and the corresponding balance of the plant cost, expressed as a fraction "f" of the wind turbine market price. Thus one may write:

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

Using the market analysis data of Appendix One, equation (1) finally reads:

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

3.2. Maintenance and Operation Cost

During long-term operation, the maintenance and operation (M&O) cost can be split[9][11] into the fixed "FC_n" and the variable "VC_n" maintenance cost. In the present analysis, the fixed M&O cost also considers the fuel cost consumed by the diesel-electric generator. Generally speaking, the annual fixed M&O cost can be expressed[19] as a fraction "m" of the initial capital invested, furthermore including an annual inflation rate equal to "g_m" describing the annual changes of labor cost and the corresponding spare parts, embracing also any lubricants consumption.

Subsequently, the fuel consumption cost results by the annual diesel-oil quantity consumed "M_f", the current fuel price "c_o" and the oil price annual escalation rate "e". Thus one gets:

$$FC_n = m \cdot IC_o \cdot \left[\frac{1+g_m}{1+i} + \left(\frac{1+g_m}{1+i} \right)^2 + \ldots + \left(\frac{1+g_m}{1+i} \right)^{n-1} + \left(\frac{1+g_m}{1+i} \right)^n \right]$$
$$+ c_o \cdot M_f \cdot \left[\frac{1+e}{1+i} + \left(\frac{1+e}{1+i} \right)^2 + \ldots + \left(\frac{1+e}{1+i} \right)^{n-1} + \left(\frac{1+e}{1+i} \right)^n \right] \qquad (3)$$

where "i" is the return on investment index.

The variable maintenance and operation cost "VC_n" mainly depends[11] on the replacement of "k_o" major parts of the installation, which have a shorter lifetime "n_k" than the complete installation. Using the symbol "r_k" for the replacement cost coefficient of each "k_o" major part (battery, diesel-electric generator, rotor blades, etc.) the "VC_n" term can be expressed as:

$$VC_n = IC_o \cdot \sum_{k=1}^{k=k_o} r_k \{ \sum_{l=1}^{l=l_k} [(1+g_k) \cdot (1-\rho_k)]^{l \cdot n_k} \cdot (1+i)^{(n-l \cdot n_k)} \} \qquad (4)$$

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

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

while "g_k" and "ρ_k" describe the mean annual change of the price and the corresponding technological improvement level for the k-th major component of the system. In the present analysis one may take into account the diesel-electric generator and the battery bank replacement every "n_d" and "n_b" years respectively (e.g. $n_d \approx 4 \div 6$ and $n_b \approx 5 \div 7$ years). Applying equation (4), one finally gets:

$$VC_n = IC_o \cdot \Psi \tag{6}$$

with:

$$\begin{aligned}
&\Psi = 0 && \text{for } n \le n_d = 5\\
&\Psi = r_d \cdot \left(\frac{1+g_d}{1+i}\right)^{n_d} && \text{for } n_d + 1 \le n \le n_b = 7\\
&\Psi = r_d \cdot \left(\frac{1+g_d}{1+i}\right)^{n_d} + r_b \cdot \left(\frac{1+g_b}{1+i}\right)^{n_b} && \text{for } n_b + 1 \le n \le 2n_d = 10\\
&\Psi = r_d \cdot \left(\frac{1+g_d}{1+i}\right)^{n_d} + r_d \cdot \left(\frac{1+g_d}{1+i}\right)^{2n_d} + r_b \cdot \left(\frac{1+g_b}{1+i}\right)^{n_b} && \text{for } 2n_d + 1 \le n \le 2n_b = 14\\
&\Psi = r_d \cdot \left(\frac{1+g_d}{1+i}\right)^{n_d} + r_d \cdot \left(\frac{1+g_d}{1+i}\right)^{2n_d} + r_b \cdot \left(\frac{1+g_b}{1+i}\right)^{n_b} + r_b \cdot \left(\frac{1+g_b}{1+i}\right)^{2n_b} && \text{for } 2n_b + 1 \le n \le 3n_b = 15\\
&\Psi = r_d \cdot \left[\left(\frac{1+g_d}{1+i}\right)^{n_d} + \left(\frac{1+g_d}{1+i}\right)^{2n_d} + \left(\frac{1+g_d}{1+i}\right)^{3n_d}\right] + r_b \cdot \left[\left(\frac{1+g_b}{1+i}\right)^{n_b} + \left(\frac{1+g_b}{1+i}\right)^{2n_b}\right] && \text{for } 2n_d + 1 \le n \le n_{max} = 20
\end{aligned} \tag{7}$$

where "$r_d.IC_o$" is the diesel-electric generator and "$r_b.IC_o$" is the battery replacement cost in present values, while "g_d" and "g_b" describes the diesel-electric generator/battery purchase cost mean annual change (inflation rate).

3.3. Energy Production Cost

Using the above analysis and considering that the proposed wind-diesel system produces approximately "E_y" kWh per year, one may estimate the corresponding energy production cost by dividing the present value of the installation total cost with the corresponding electricity production. In this context the total cost is given as:

$$C_n = IC_o \cdot \left[(1-\gamma) + m \cdot x \cdot \frac{x^n - 1}{x-1} + \frac{c_o \cdot M_f}{IC_o} \cdot y \cdot \frac{y^n - 1}{y-1} + \Psi\right] - Y_n \tag{8}$$

where:

$$x = \frac{1+g_m}{1+i} \tag{9}$$

and

$$y = \frac{1+e}{1+i} \tag{10}$$

Similarly, "Y_n" represents the residual value of the investment, attributable to amounts recoverable at the "n" year of the stand-alone system 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.

Finally, "γ" is the subsidy percentage (e.g. 30%-40%) by the Greek State, according to the current development law (e.g. 3299/04) or the corresponding National Operational Competitiveness Program[9][19].

Taking also into account the analysis presented by the authors[20], concerning the current electricity marginal production cost "ce", one gets the following equations provided that the net present value of the investment becomes equal to the corresponding residual value (NPV=Yn, where "Yn" may be equal to zero) after n years of operation, i.e.:

$$c_e = IC_o \cdot \frac{1-\gamma}{E \cdot z \cdot \frac{z^n - 1}{z-1}} + m \cdot IC_o \cdot x \cdot \frac{\frac{x^n - 1}{x-1}}{E \cdot z \cdot \frac{z^n - 1}{z-1}} + c_o \cdot M_f \cdot y \cdot \frac{\frac{y^n - 1}{y-1}}{E \cdot z \cdot \frac{z^n - 1}{z-1}} + \frac{\Psi}{E \cdot z \cdot \frac{z^n - 1}{z-1}} - \frac{Y_n}{E \cdot z \cdot \frac{z^n - 1}{z-1}} \quad (11)$$

where:

$$z = \frac{1+p}{1+i} \quad (12)$$

and "p" is the produced electricity price mean annual escalation rate, e.g. p=3%.

Bear in mind that the proposed model also includes the diesel-only solution (i.e. $IC_o=\varphi.N_d$, $N_o=0$, $r_b=0$, $M_f=M_{max}$) as well as the zero-diesel configuration (i.e. $IC_d=0$, $r_d=0$, $M_f=0$).

4. Results for Typical Wind Potential Cases Studies

The above-presented analysis is being applied to typical remote consumers located in selected representative areas, on the basis of their wind potential, see also figure (4). Thus, the first case investigated concerns a remote consumer living in a medium-sized island of the Cyclades complex, i.e. Andros island located in the middle of the Aegean Sea. The island has one of the best wind potential in Greece ($\overline{V} \approx 9.5$m/s), since the minimum monthly average wind speed "$\overline{V}$" exceeds the 6.5m/s; figure (5). At the same time, the probability density function distribution validates that the possibility of wind speed values below 4.0m/s (calm spells) in the area is slightly above 15% on long-term measurements basis.

Using the analysis of chapter 3, figure (6) demonstrates the energy production cost of the examined stand-alone system (rated power up to 15kW) for a ten-year service period of the installation. According to the results obtained, for each "M_f" value there is a minimum production cost point, which corresponds on a specific system configuration (N_o, Q_{max}) that guarantees the remote consumer energy autonomy with minimum electricity production cost. Also one may observe that, by increasing the contribution of the diesel-oil, remarkable cost-decrease is initially encountered. However after a 500kg/year value, the corresponding electricity production cost starts increasing, underlining the existence of an optimum configuration. At the same figure, one may find the diesel-only and the wind-power ($M_f=0$) stand-alone systems, both presenting a quite higher operational cost. Finally, the optimum stand-alone system electricity production cost is below 0.5€/kWh, a value directly comparable with the operation of bigger diesel-only autonomous power stations in several Greek islands; see also figure (1). The situation is slightly improved for a 20-year time period operation, figure (7), since even the wind-power stand-alone solution ($M_f=0$) is more financially attractive than the diesel-only installation.

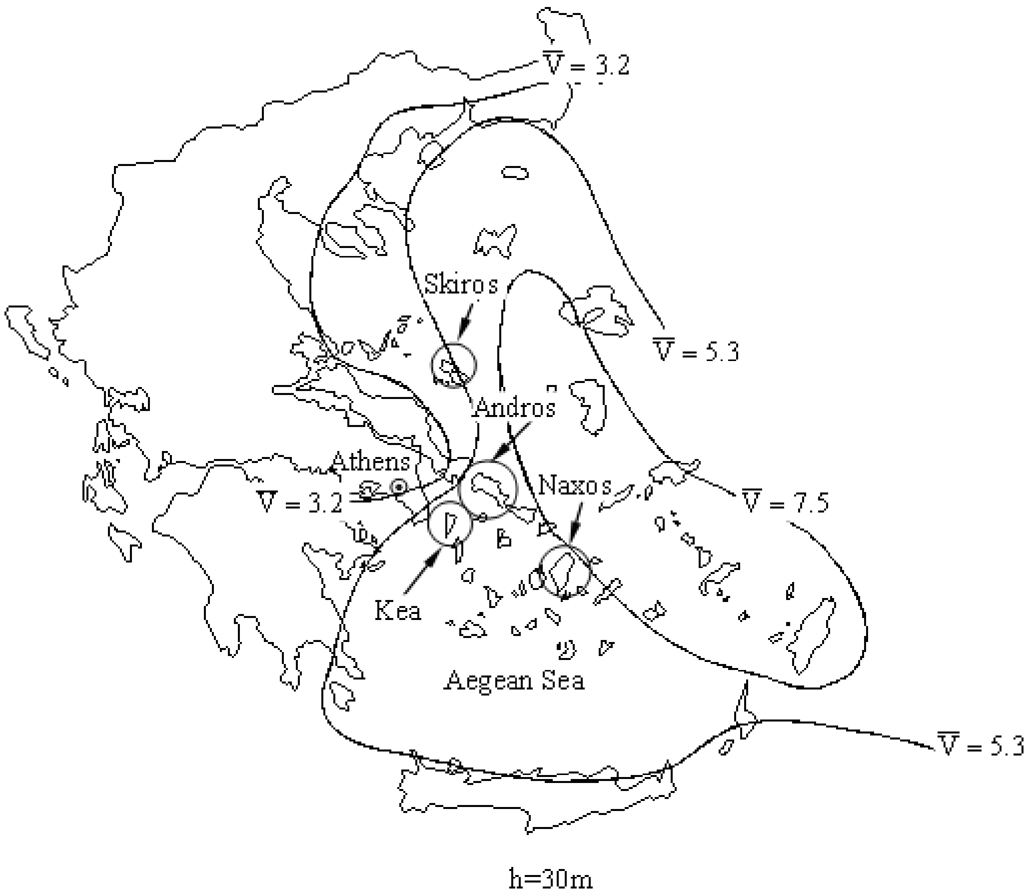

Figure 4: Wind potential map for Aegean Sea area at 30m height

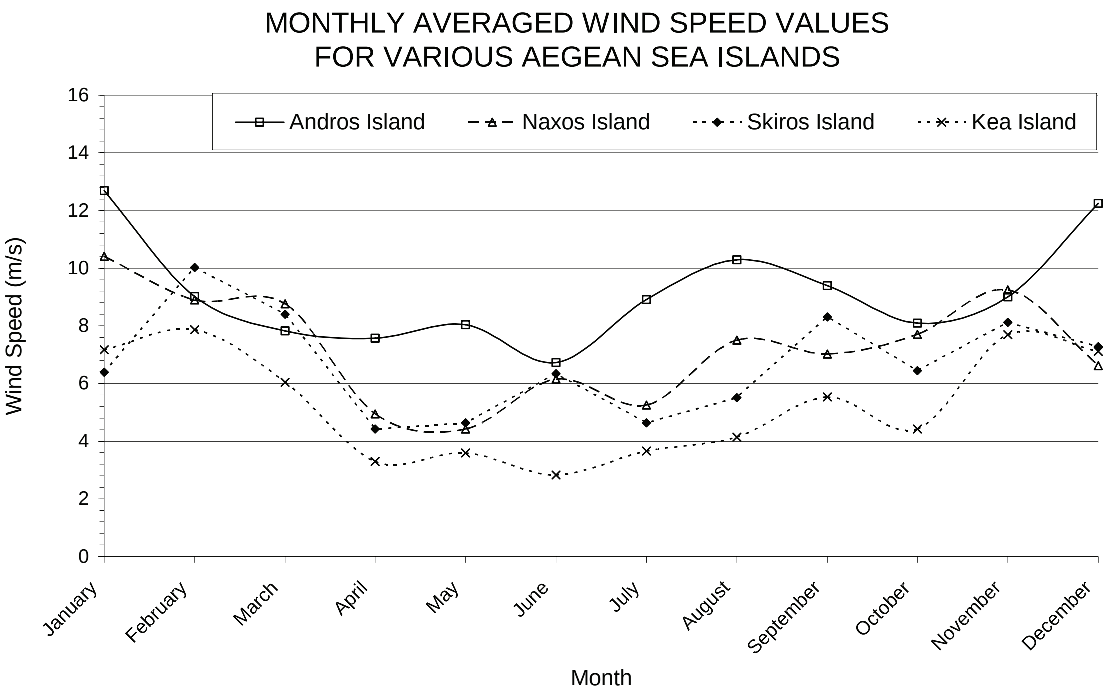

Figure 5: Wind speed values at various Aegean Sea islands

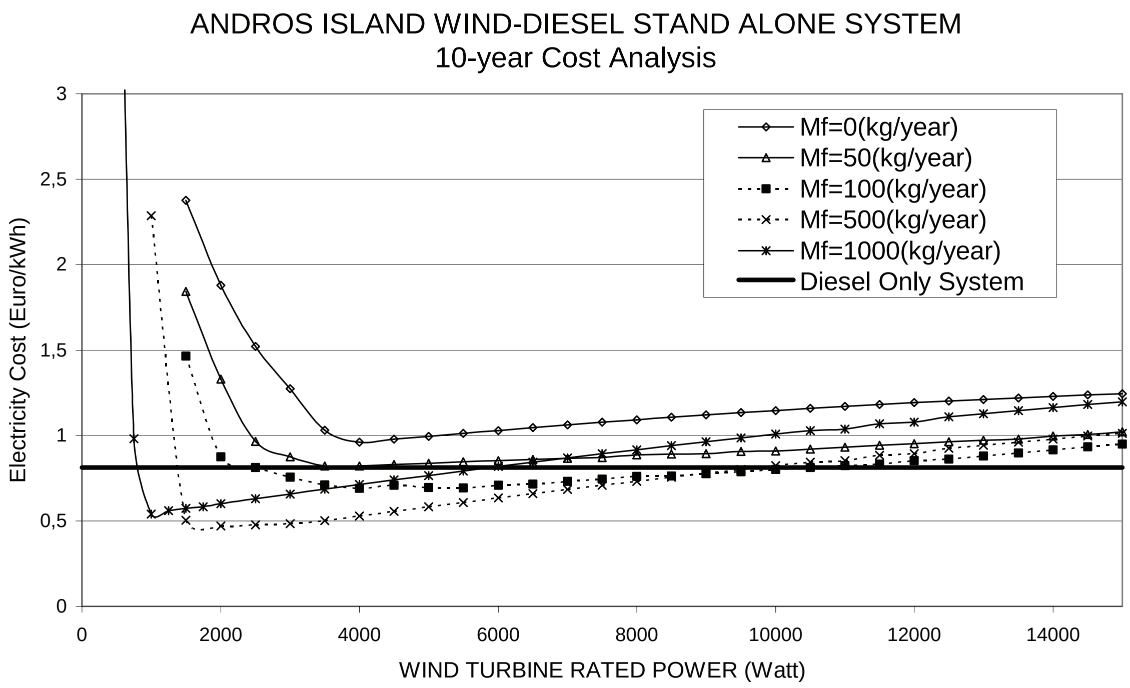

Figure 6: Ten-year electricity production cost of a wind-diesel hybrid system, Andros island

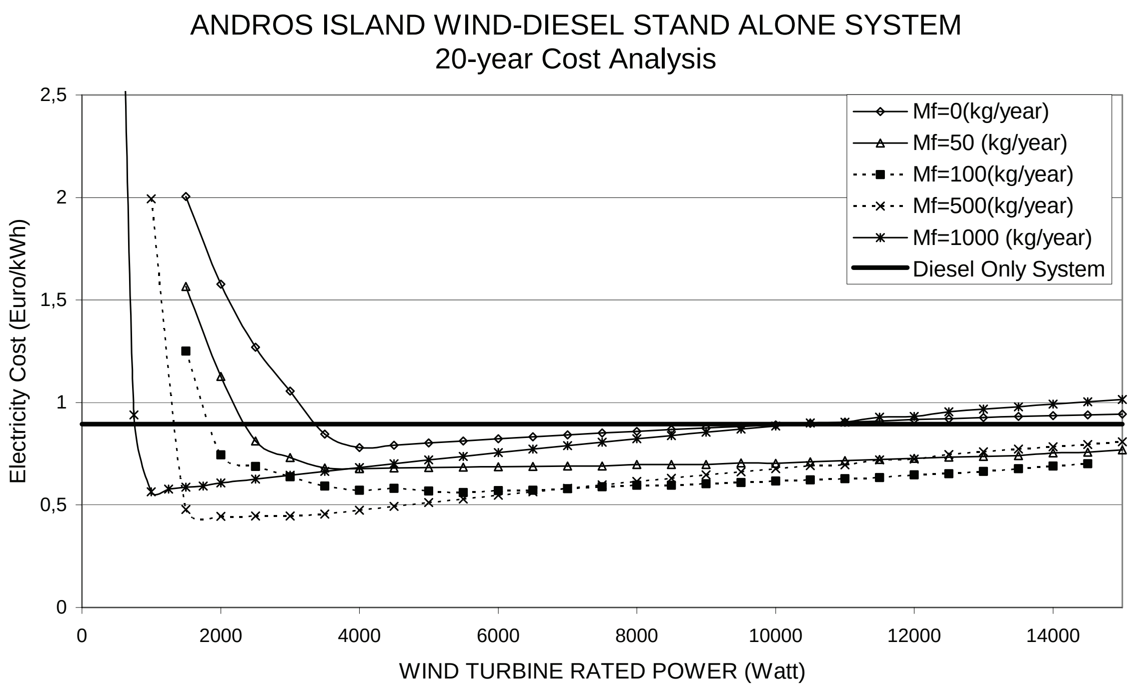

Figure 7: Twenty-year electricity production cost of a wind-diesel hybrid system, Andros island

The second case analyzed is also a remote consumer living in a medium-sized island of the Cyclades complex, i.e. Naxos island located in the middle of the Aegean Sea; figure (4). The island has an outstanding wind potential, since in several locations the annual mean wind speed exceeds 7.5m/s, at 10m height. In figure (5), the measured monthly averaged wind speed values are cited for a one-year time period. Applying the same analysis on a stand-alone system located in Naxos island, we get the calculation results of figure (8), where one may find the 10-year electricity production cost for several energy autonomous configurations. As in figure (6), the electricity production cost presents a minimum point for each diesel-oil penetration level, while the corresponding cost decreases as the diesel-oil contribution increases. This picture is inversed after a minimum electricity cost point is reached. On top of this, one may observe that the wind power (M_f=0) and the diesel-only systems are more expensive than the optimum configuration, while the corresponding minimum cost solution approaches the value of 0.61€/kWh. This value is higher than the Andros optimum solution (0.47€/kWh) due to the lower wind potential of the Naxos island.

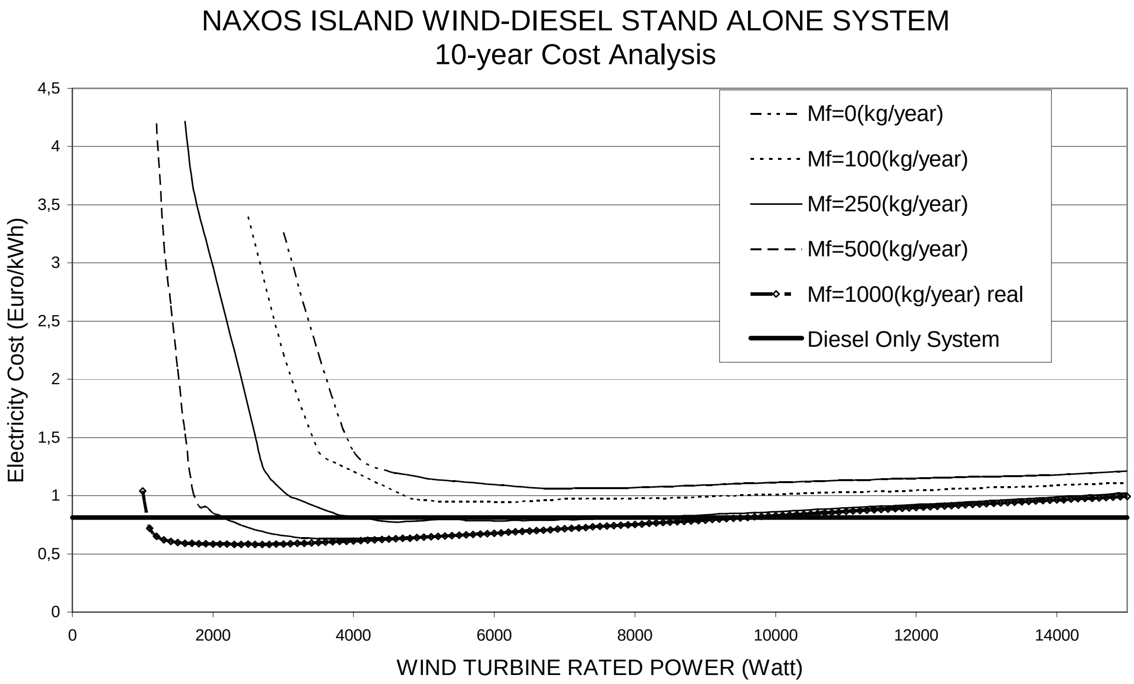

Figure 8: Ten-year electricity production cost of a wind-diesel hybrid system, Naxos island

The third case analyzed concerns a remote consumer living in the island of Skiros, a small island of NW Aegean Sea, belonging to the Sporades complex, figure (4). The island has a medium-strong wind potential, taking into consideration that the annual mean wind speed approaches the 6.8m/s at 10m height. Figure (5) presents the measured monthly averaged wind speed values for a one-year time period. Accordingly, in figure (9) one has the opportunity to see the corresponding medium term (i.e. for ten years) electricity production cost distributions for numerous stand-alone configurations. According to the calculation results, the electricity production cost decreases as the diesel-oil penetration rises, approaching the minimum value of 0.65€/kWh for 1200kg of diesel-oil annual consumption. The optimum configuration cost is almost 20% lower than the diesel-only system. On the other hand, a wind power stand-alone system (i.e. M_f=0) is much more expensive than the proposed solution, due to the considerable calm spells of the area.

The last case investigated is a remote consumer located in Kea island. Kea is a relatively medium-low wind potential area close to Athens. The corresponding wind potential although quite lower than the one of Andros, is good enough (annual mean wind speed ≈6.0m/s; figure (5)) to feed contemporary wind turbines for electricity production. In this case, the possibility of wind speed being less than 4.0m/s (zero wind production) is quite remarkable (≈45%). Therefore the maximum calm spell period of the island is approximately 170 hours (almost one week).

The calculation results of the proposed analysis, regarding stand-alone wind-diesel systems operating in Kea island, are summarized in figure (10). According to the results obtained, the 10-year electricity production cost is considerably diminished as the contribution of the diesel-oil increases. The minimum operation cost is achieved by accepting the consumption of almost 1200kg/year of diesel-oil. In any case, due to the low wind potential of the area, the corresponding minimum production cost exceeds the 0.80€/kWh. This value is slightly beneath the diesel-oil operation production cost. The situation is more encouraging in cases of 20-year operation, where the proposed wind-diesel system is definitely less expensive than the diesel-only solution.

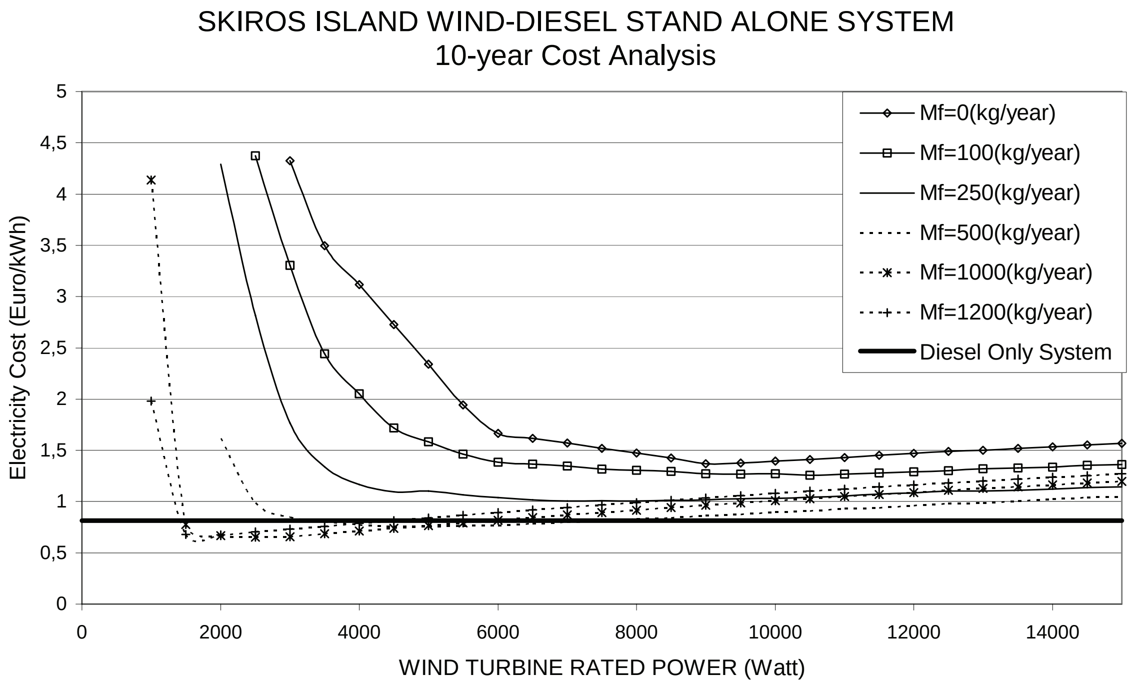

Figure 9: Ten-year electricity production cost of a wind-diesel hybrid system, Skiros island

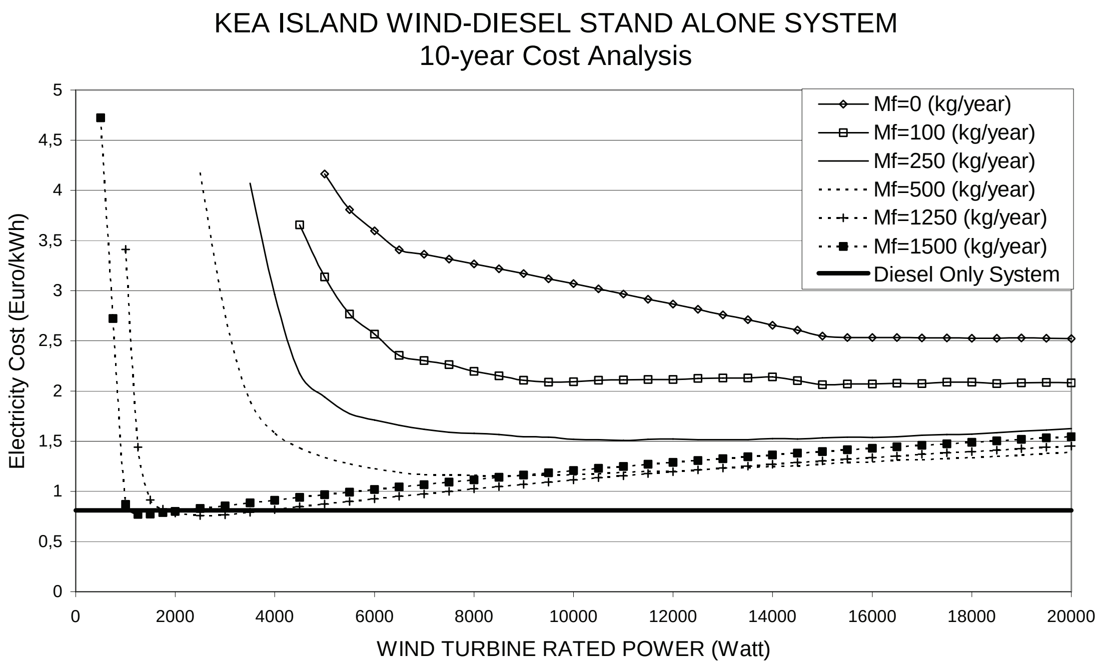

Figure 10: Ten-year electricity production cost of a wind-diesel hybrid system, Kea island

Recapitulating, the proposed wind-diesel-battery stand-alone system is actually a financially viable electricity generation solution, properly adopted to meet the electrification needs of remote consumers located throughout Aegean Sea. In fact, the electricity production cost is quite lower than the corresponding cost of diesel-only installations; see also figure (1). Bear also in mind that the production cost significantly reduces as the available wind potential becomes more intense. In this context, the 10-year minimum operation cost for Kea island is almost 0.8€/kWh while the corresponding value for Andros island is 0.47€/kWh.

5. Parametrical Analysis

In the following, the impact of the key parameters on the electricity production cost of a wind-diesel stand-alone system is examined as a function of the annual diesel-oil consumption. For this purpose, the central values of the problem governing parameters are included in Table I.

Table 1: Central values of the main parameters used in the presented sensitivity analysis

Parameter	Symbol	Numerical Value	Units
Annual mean wind speed (Andros Island)	$\bar{V}$	9.5	m/s
Return on Investment	i	8	%
Diesel-oil current price	c_o	1.5	€/kg
Diesel-oil price annual escalation rate	e	6	%
Lead-acid battery purchase cost coefficient	ξ	5.04	€/Ah
Initial investment cost	IC_o	Appendix One	
Fixed M&O cost coefficient	m	2	%
Local market annual inflation rate	g	2	%
Electricity price annual escalation rate	p	3	%

5.1. Wind Potential

As stated above, several representative types of wind potential are investigated in the present study; see also figure (5). According to the results obtained, the wind potential impact is dominant, figure (11), since the corresponding electricity production cost remarkably decreases as the wind potential improves. This difference is getting greater for low diesel-oil penetration, while after the value of M_f=1000kg/year all distributions are convergent towards Kea island curve. It is important to make a note of the significant difference between the Andros and Kea islands, since -in anticipation of M_f=600kg/year annual diesel oil consumption- the electricity production cost in Kea is more than double the corresponding value of Andros. Finally, one may easily conclude that as the available wind potential becomes more intense, the minimum electricity-production cost-point is moving towards a lower diesel-oil contribution.

5.2. Return on Investment Index

Generally speaking, the return on investment depends on the local market economic wealth and more precisely on the existing investment opportunities, timing of repayment, risk of the investment or any government subsidies. In addition, its numerical value varies with the inflation rate of the economy, in order to obtain positive inflation-free return on investment index. According to the data of figure (12) -concerning the electricity production cost of a wind-diesel system situated in Andros island; see also Table I- the return on investment index is directly proportional to the electricity generation cost value. Besides, the return on investment index has a greater influence on low diesel-oil penetration cases, due to the bigger initial capital invested. On the other hand, for diesel-only installations the corresponding impact is minimized. Finally, for each 1% increase of the return on investment index, the corresponding electricity production cost increase is approximately 0.006€/kWh, for diesel-oil annual consumptions beneath 600kg/year.

5.3. Current Diesel-oil Price

The exact value of the current diesel-oil price takes into account not only its market price, but also its transportation and storage cost, which is quite high for stand-alone consumers located in remote islands. In this context, high prices lead to relatively higher electricity production cost values, especially in cases of significant diesel-oil contribution, figure (13). As a result, the impact is dominant on diesel-oil penetrations exceeding the 1000kg/year, while it is almost negligible for annual diesel-oil consumptions beneath 200kg/year, underlining thus the fossil-fuel independency of similar stand-alone systems based mainly on renewable energy sources.

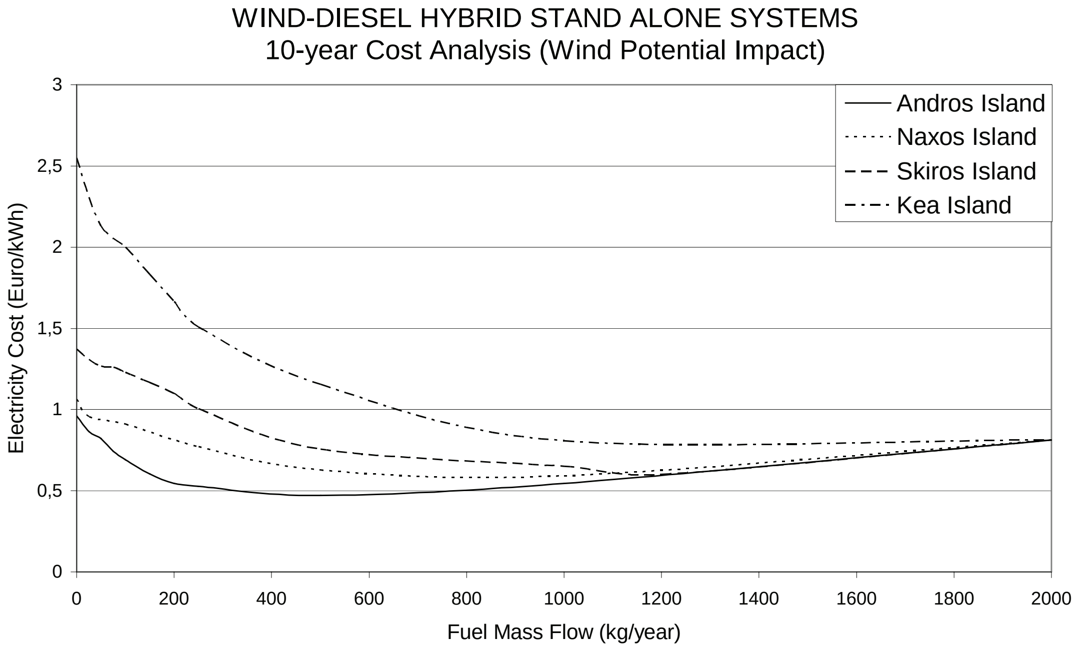

Figure 11: Wind potential impact on the electricity production cost of a wind-diesel hybrid stand-alone system

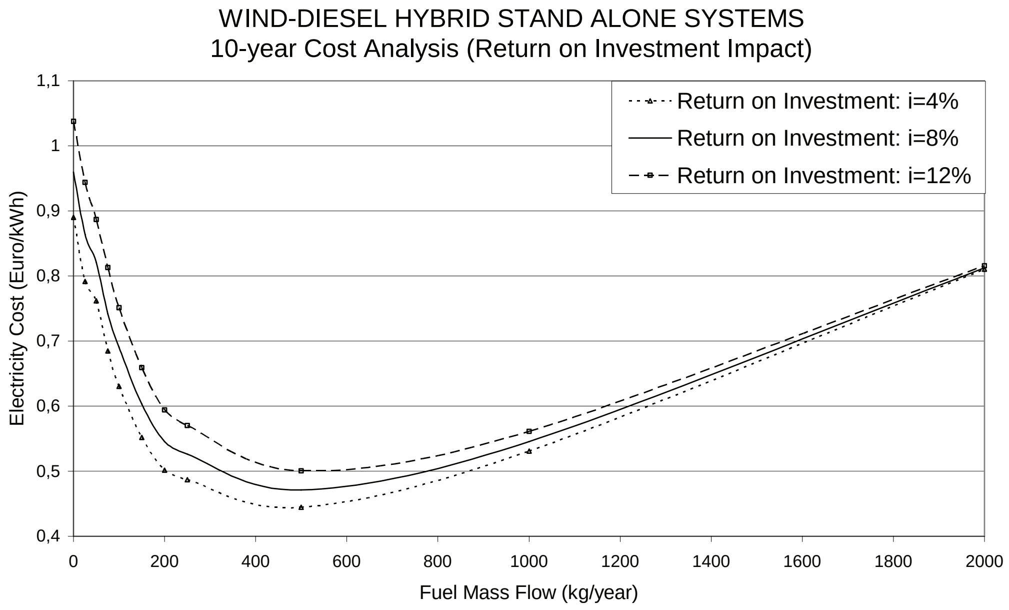

Figure 12: Return on investment index impact on the electricity production cost of a wind-diesel hybrid stand-alone system

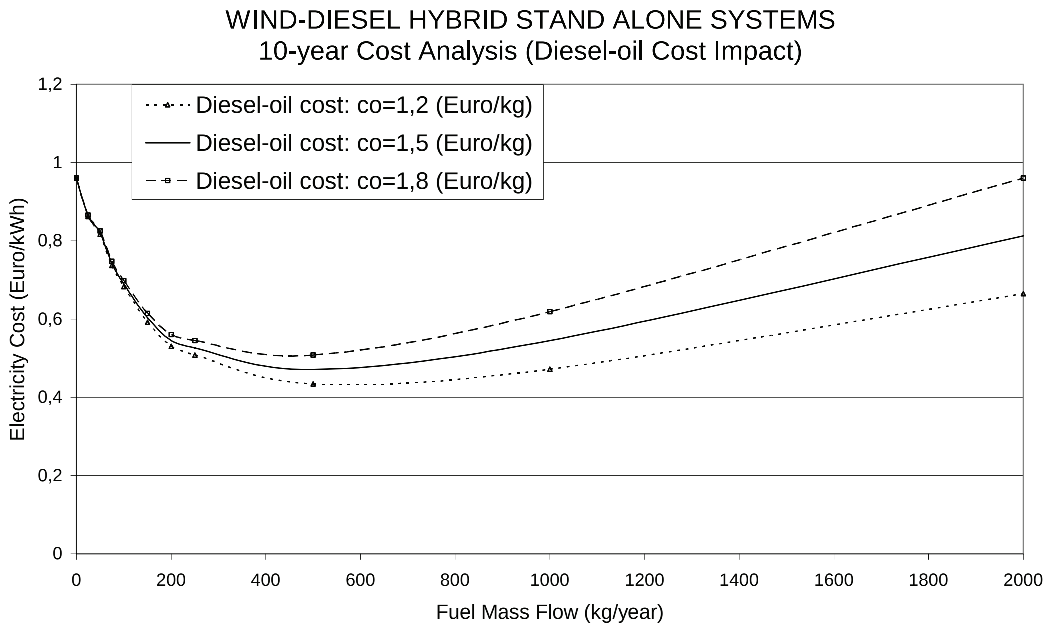

Figure 13: Diesel-oil current price impact on the electricity production cost of a wind-diesel hybrid stand-alone system

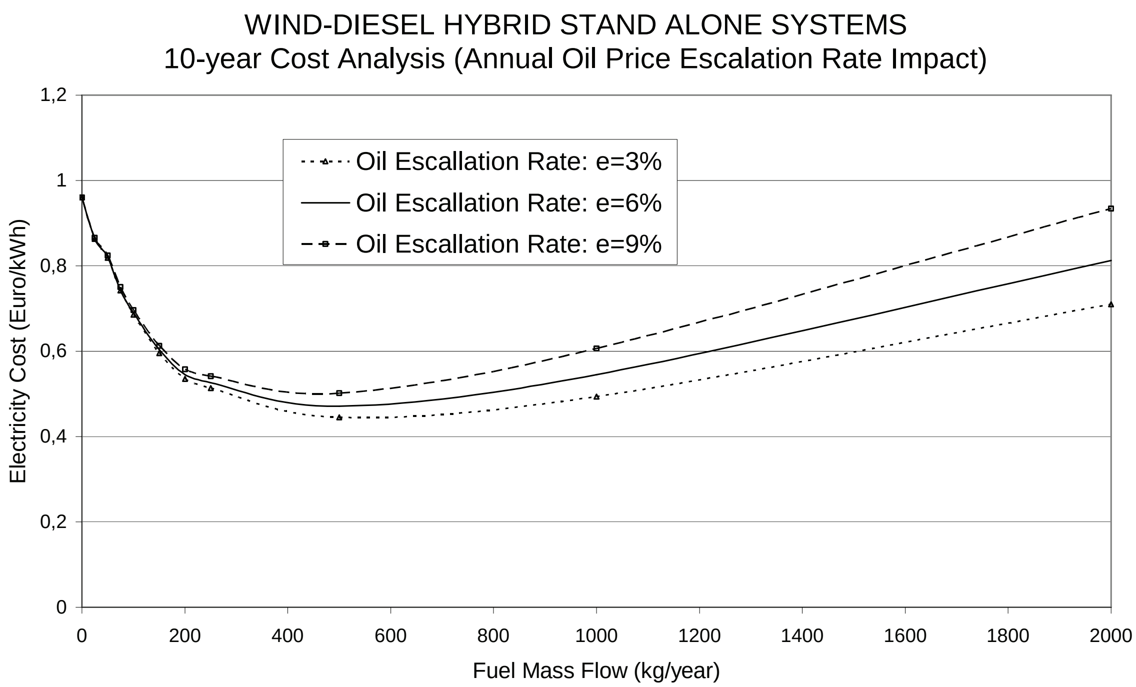

Figure 14: Diesel-oil price annual escalation rate impact on the electricity production cost of a wind-diesel hybrid stand-alone system

5.4. Diesel-oil Price Annual Escalation Rate

The term "diesel-oil price annual escalation rate" is hereby used to describe the gradual changes of the diesel-oil price annually. As it is obvious from figure (14), regarding the Andros island, the electricity production cost of the stand-alone system investigated is strongly influenced by the corresponding annual escalation rate, in cases of considerable diesel-oil annual consumption. More precisely, the electricity production cost is increased as the diesel-oil escalation rate is amplified. Thus, for each 3%

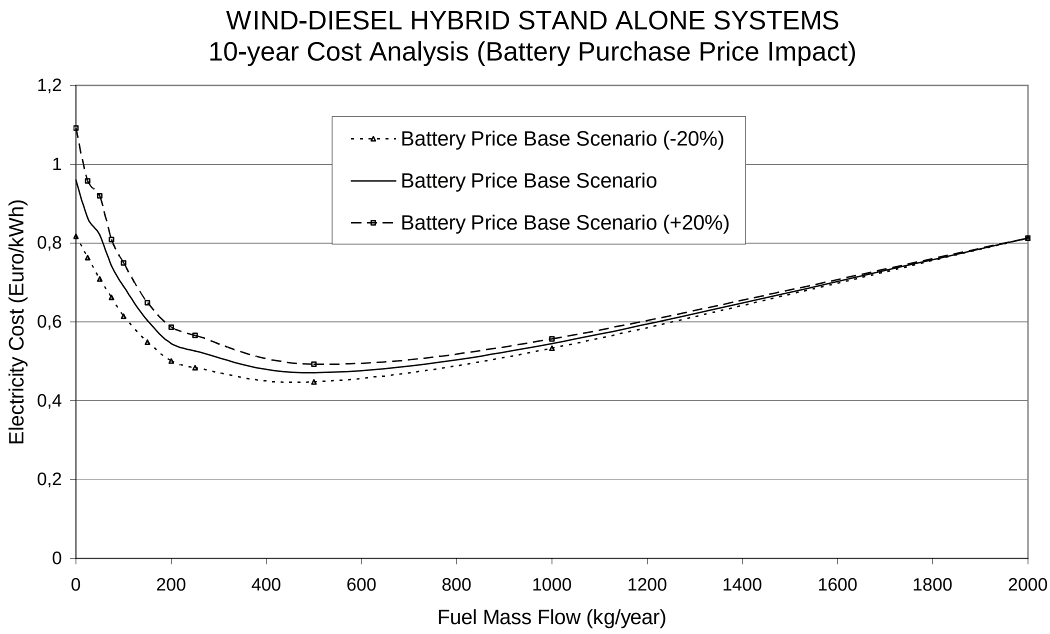

Figure 15: Battery bank purchase price impact on the electricity production cost of a wind-diesel hybrid stand-alone system

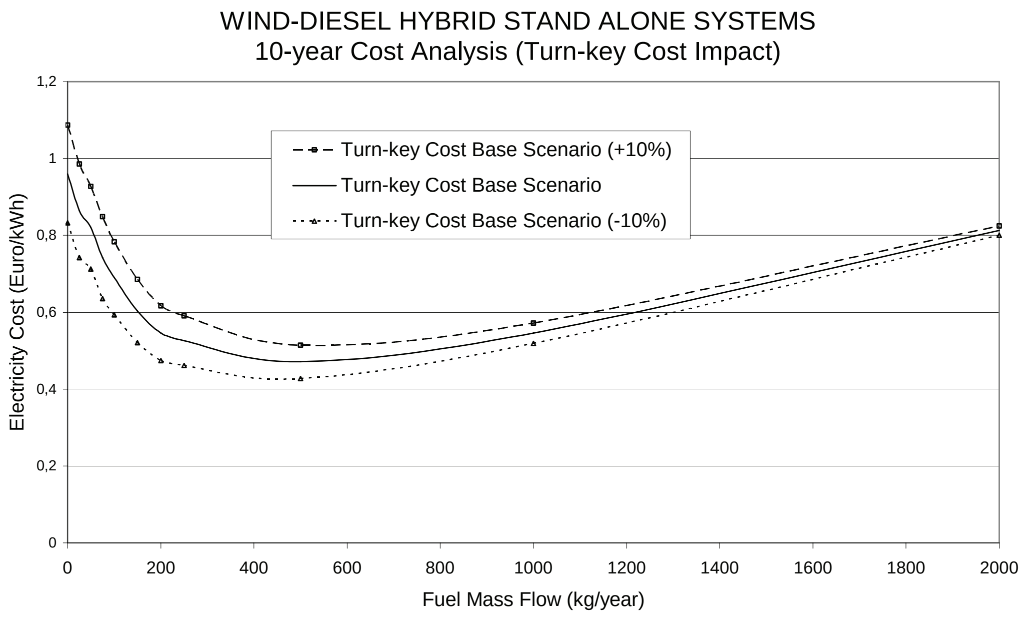

Figure 16: Investment turn-key price impact on the electricity production cost of a wind-diesel hybrid stand-alone system

increase of the "e", the corresponding "c_e" increase is almost 0.1€/kWh. On the contrary, zero impact is encountered on annual diesel-oil consumption beneath 200kg/year.

5.5. Battery Ex-Works Price

The battery bank is one of the most important components of stand-alone systems, putting in storage the wind energy surplus of high wind speed periods, in order to cover the energy deficit in low-wind speed and high-load demand cases. On the other hand, a typical lead-acid battery should be replaced every five to seven years; each substitution requiring a remarkable amount of money. The battery price impact becomes more important when the diesel-oil contribution to electricity generation is low (less than 500kg/year); figure (15). As expected, the electricity production cost gets lower as the battery price is also low. On the other hand, the battery cost impact is zeroed as the annual diesel-oil consumption tends to the diesel-only solution.

5.6. Installation Turnkey Cost

The initial investment cost (turnkey cost) includes the ex-works price of the equipment needed (wind turbines, battery bank, electronic equipment, etc.) and the corresponding installation cost. The application of new technological achievements and the economies of scale decrease most system components' prices in the international market. However, several parameters have to be taken into account, in order to foresee the future evolution of the ex-works prices in the local market. According to the results of the present analysis, figure (16), the electricity production cost grows as the turnkey cost of the installation increases. This impact is higher for medium-low diesel-oil penetration (up to 600kg/year) while for higher diesel-oil contribution the corresponding influence is quite restrained. In this context, the electricity production cost decreases by almost 0.07€/kWh for the Andros stand-alone system for each 10% diminution of the installation turnkey cost.

6. Conclusions

An integrated energy production cost analysis of typical wind-diesel hybrid systems is presented. In this context, the configuration of the proposed wind-diesel power system is described first, including the lead-acid battery storage system and the necessary electronic devices. Accordingly, an expert-type computational algorithm is presented, in order to estimate the hybrid station dimensions that guarantee the installation energy autonomy for a desired period.

The main part of the analysis is devoted to develop a complete electricity production cost model, considering not only the first installation but also the fixed and variable maintenance and operation cost, including diesel-oil consumption cost and battery replacement expenses every 5 to 7 years. Subsequently, the proposed methodology is applied to four typical wind potential cases, possessing annual mean wind speed values between 6.0m/s and 10m/s. For all cases investigated, the predicted electricity production cost is favourably compared with real electricity production cost data, resulting from the operation of existing autonomous diesel-only power stations. Finally, a quite extensive sensitivity analysis is carried out, in order to demonstrate the impact of the main techno-economic parameters on the energy production cost of optimum sized wind-diesel hybrid power stations.

In view of the uncertain future concerning the oil worldwide prices and the continuous air pollution increase, a progressive interest in hybrid power stations is taking place in many regions worldwide. Taking into account the extensive results obtained, hybrid wind-diesel systems may be the best cost-effective electrification solution for numerous isolated consumers, located in regions with fairly good (mean wind speed greater than 6.0m/s) wind potential. On top of this, subsidy possibilities -granted for example by local authorities or via European Union funds- should greatly increase the economic attractiveness of similar environmental friendly electricity production applications.

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APPENDIX

First Installation Cost of a Hybrid Wind-Diesel System in Greece

- Small wind turbine (rated power N_o) ex-works price "IC_{WT}":

$$IC_{WT} = \left(\frac{a}{b + N_o^x} + c \right) \cdot N_o \tag{A-1}$$

a= $8.7x10^5$ (Euro/kW)
b= 621
x= 2.05
c= 700 (Euro/kW)

- Diesel-electric generator (rated power N_d) ex-works price "IC_d":

$$IC_d = \phi \cdot N_d \tag{A-2}$$

φ= 150-250 (Euro/kW)

- Lead-acid battery bank (24 Volt, DOD_L=75%, Rated Storage Capacity Q_{max}) purchase cost "IC_{bat}":

$$IC_{bat} = \xi \cdot Q_{max}^{1-\omega} \tag{A-3}$$

ξ= 5.04 (Euro/Ah)
ω= 0.078

- Electronic devices (including inverter "N_p", UPS "N_p", rectifier "N_o", charge controller "N_o") ex-works cost "IC_{elec}":

$$IC_{elec} = \lambda \cdot N_p^{1-\tau} + B \cdot N_o \tag{A-4}$$

λ= 483 (Euro/kW)
τ= 0.083
B= 380 (Euro/kW)

- Balance of the plant cost "f•IC_{WT}"

f= 0.15 to 0.25

AN INTEGRATED MODEL FOR PERFORMANCE SIMULATION OF HYBRID WIND-DIESEL SYSTEMS

J.K. Kaldellis
Laboratory of Soft Energy Applications & Environmental Protection
Mechanical Eng. Dept., Technological Education Institute of Piraeus

Abstract

Stand-alone hybrid systems have turned into one of the most promising ways to handle the electrification requirements of numerous isolated consumers worldwide. The proposed wind-diesel-battery hybrid system consists of a micro wind converter, a small diesel-electric generator -basically operating as a back up energy production system- and a lead-acid battery bank that stores the wind energy surplus during high wind speed periods. In this context the present work is focused on presenting a detailed mathematical model describing the operational behavior of the basic hybrid system components, along with the representative calculation results based on the developed mathematical model. Accordingly, an integrated numerical algorithm is built to estimate the energy autonomy configuration of the hybrid system under investigation. Using the proposed numerical algorithm, the optimum configuration selection procedure is verified by carrying out an appropriate sensitivity analysis. The proposed methodology may equally well be applied to any other remote consumer and wind potential type, in order to estimate the optimum wind-diesel hybrid system configuration that guarantees long-term energy autonomy.

Keywords: Hybrid System; Optimum System Sizing; Wind-Diesel; Energy Balance; Battery Capacity; Energy System Modeling

1. Introduction

Stand-alone hybrid systems have turned into one of the most promising ways to handle the electrification requirements of numerous isolated consumers worldwide, including country houses, remote farms, shelters, telecommunication stations, small islands, light houses etc. In several interesting research papers one may find useful information concerning the design, operation and financial performance of similar installations[1][2][3][4][5].

In this context, wind-diesel hybrid systems using also an appropriate energy storage device (usually a lead-acid battery) are based on a micro wind converter and a small diesel-electric generator, mainly operating as a back up energy production system, while a battery bank is used to store the wind energy surplus during high wind speed and low consumption periods. These systems, if sized properly, combine:

a. Rational first installation cost, as the diesel-electric generator significantly decreases the required battery capacity,

b. Low operational cost, given that the wind turbine is the main electricity production source and

c. Improved reliability, on account of the three independent power sources that may cover the load demand of the installation.

Considering the capabilities of similar hybrid systems and the increased research interest[1][2][3][4][5][6][7][8], this paper attempts a detailed description of a stand-alone wind-diesel hybrid system performance, based on an analytical model equipped to simulate energy balance and operational status of the main system components. Using the proposed model one has the ability to estimate the appropriate wind turbine rated power and battery bank capacity, given the available fuel quantity that guarantees the energy autonomy of a remote consumer for a desired time period.

2. Analytical Description of the Proposed Hybrid System Components

A typical wind-diesel hybrid system (figure (1)) able to meet the electricity requirements of isolated consumers comprises of:

i. A micro wind converter
ii. A small internal combustion engine driving an electric generator
iii. A lead-acid or a Ni-Cd battery bank
iv. Several electronic devices

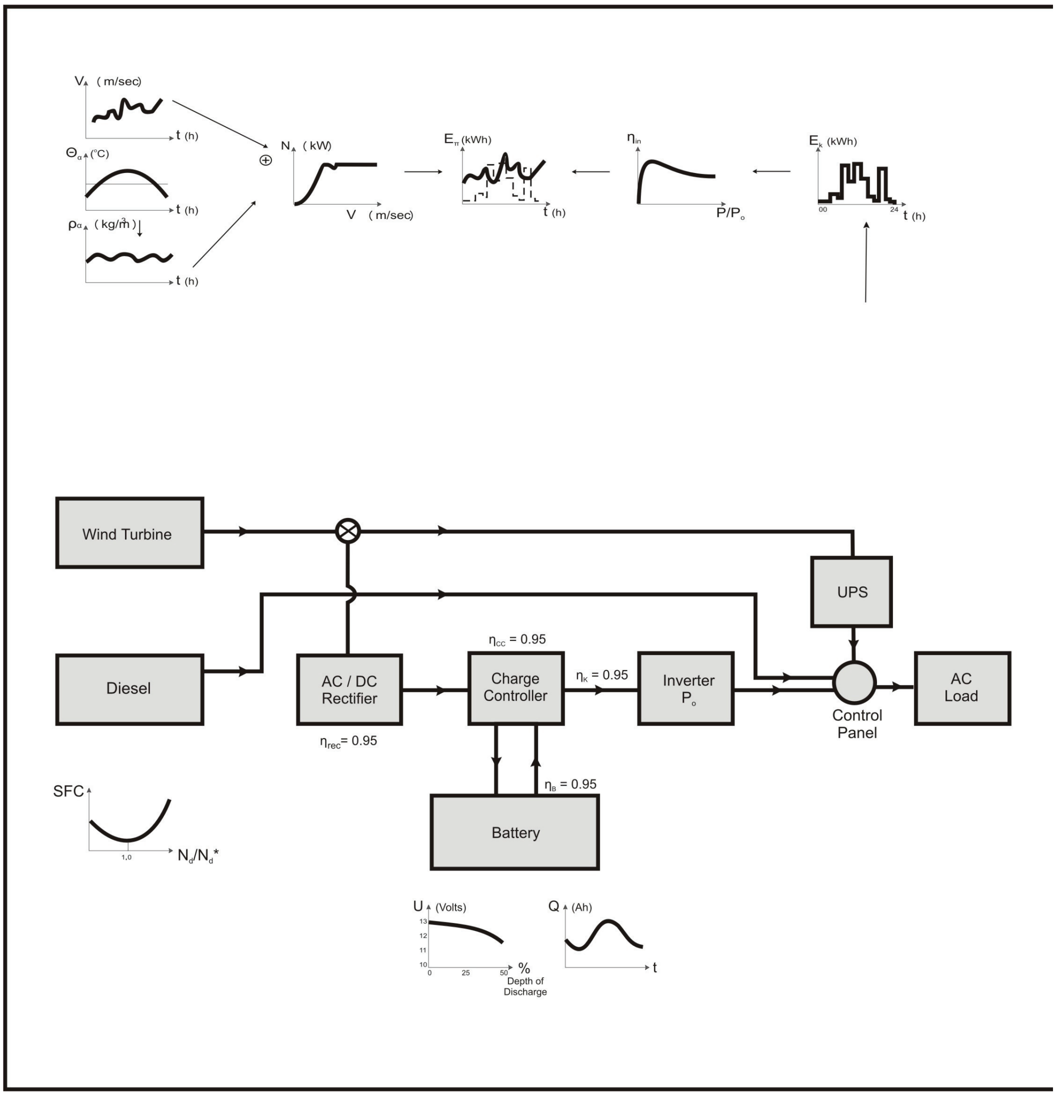

Figure 1: Proposed autonomous wind-diesel hybrid system

More specifically, in the following one may find all necessary parameters and corresponding equations used to simulate the operational behavior of the hybrid system main components, see also Table I.

2.1. Wind Turbine

In similar applications a low cost fixed pitch-three bladed micro wind converter[9] of rated power "N_o" is normally utilized as the primary energy production source. The output of the turbine depends[10] on the wind speed value "V" at hub height, the manufacturer's power curve "$N_w=N_w^*(V)$" at standard day conditions and the air density at the installation area, thus:

$$N_w(V) = \frac{\rho}{1.2215} \cdot N_w^*(V) \qquad (1)$$

Bear in mind that the air density value depends on the ambient temperature and pressure as well as on the corresponding air humidity[10].

Table I: Available information of the Hybrid System major components

Basic Hybrid System components	Major parameter of the Analysis	Value Range	Other parameters affecting the solution
Wind Turbine	Wind turbine rated power	0-15000W	Wind speed, Air density
Internal Combustion Engine-Electric Generator	Annual oil consumption	0-2000kg per year	Rater power of the generator, Specific fuel consumption
Battery	Maximum battery capacity	0-50000Ah	Operation voltage, Maximum depth of discharge

The corresponding wind turbine generator is usually of the induction type with operational slip ranging between 2% and 10%. The generator frequency variation should attentively be kept minimum; otherwise supplementary electronic devices (e.g. UPS, i.e. uninterrupted power supply system) might protect the consumer frequency.

2.2. Internal Combustion Engine-Electric Generator

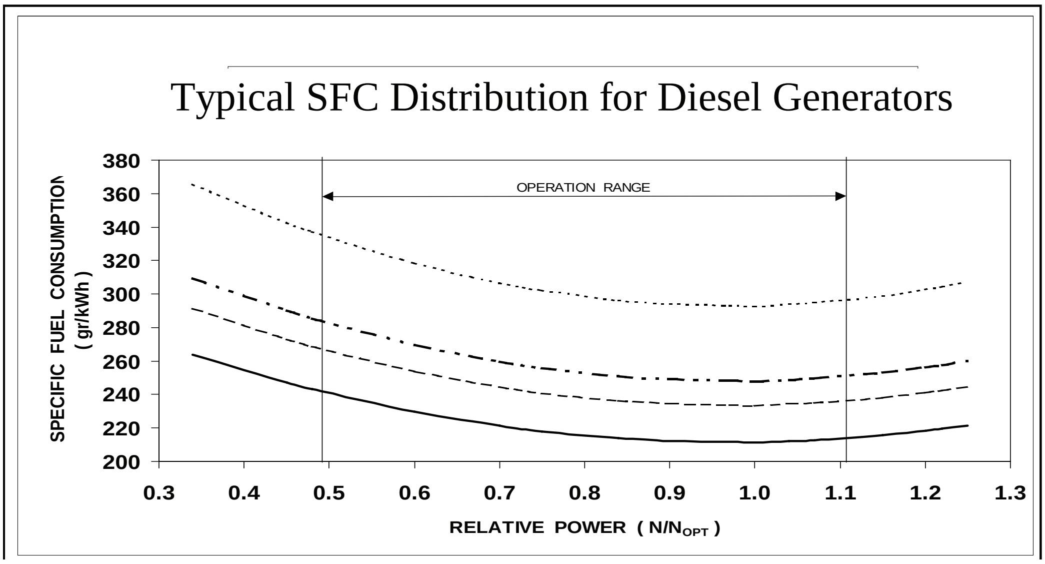

Figure 2: Diesel-electric generators SFC curve

In most stand-alone applications a naturally aspirated diesel generator[11] operating at a constant speed and driving a suitable electric generator is used to cover the electricity requirements of the installation. The rated power "N_D^*"of the engine should be able to face the consumption peak load demand "N_p" increased by an appropriate safety coefficient (e.g. ≈1.3), hence:

$$N_D^* \geq N_p \qquad (2)$$

while close attention should be paid on selecting an appropriate (see figure (2)) specific fuel consumption "SFC" of the diesel engine, especially under partial loading "$N_D \neq N^*_D$" of the engine, i.e.:

$$SFC = SFC\left(\frac{N_D}{N_D^*}\right) \qquad (3)$$

in order to minimize the corresponding fuel consumption. Bear in mind that even at zero load, diesel generators fuel consumption is almost 30% of the corresponding fuel consumption at rated power. On top of this, it is recommended to avoid the diesel engine operation below 30% of full load for long periods, in order to avoid serious maintenance problems, like chemical corrosion and glazing[11].

For the estimation of the mass fuel rate "m_f" of the diesel generator one may write:

$$m_f = SFC \cdot N_D \tag{4}$$

Thus, the total oil consumption over a given period ($t_o \div t_o + \Delta t$) is given as:

$$M_f = \int_{t_o}^{t_o+\Delta t} m_f \cdot dt \tag{5}$$

In the present application the diesel-electric generator is used as a back-up electricity production source, thus the generator starts automatically when the battery voltage drops below a certain critical value (or the corresponding depth of discharge "DOD" surpasses a pre-described value) or the load demand exceeds the sum of the wind turbine and the battery bank (via the system inverter) output.

2.3. Battery Bank

There are several different energy storage alternatives, like flywheels, hydraulic storage, water pumping, battery storage even fuel cells[12]. In similar size applications, a lead-acid battery normally accumulates the available energy surplus to be used during periods of inadequate wind.

More precisely, the battery size is given in units of the time-period that the storage can cover the average load without the contribution of other power sources. Hence, the battery bank used is defined by the installation's hours of energy autonomy "h_o", the corresponding operation voltage "U_b" and the maximum permitted depth of discharge "DOD_L". In several cases instead of "h_o" one may use the maximum battery capacity "Q_{max}", which results by the hours of energy autonomy as:

$$Q_{max} = h_o \cdot \frac{E_y}{8760} \cdot \frac{1}{\eta_{dsc} \cdot (DOD_L) \cdot U_b} \tag{6}$$

with "E_y" being the annual energy consumption of the installation and "η_{dsc}" the efficiency of the battery energy production branch, including battery discharge loss, line loss, inverter loss etc. It is important to mention that the "DOD_L" value is strongly related[12][13] to the life duration (operational cycles-"n_c") of the batteries, e.g.

$$DOD_L \cdot n_c \approx (1200 \quad \text{to} \quad 1500) \tag{9}$$

During the normal operation the battery capacity varies between "Q_{min}" and "Q_{max}", i.e.:

$$Q_{min} \le Q \le Q_{max} \tag{7}$$

where:

$$Q_{min} = (1 - DOD_L) \cdot Q_{max} \tag{8}$$

Bear in mind that the battery voltage "U_b" is not constant, as it depends on the charge condition of the battery, along with the ambient or battery cell temperature "θ", i.e.:

$$U_b = U_b(Q;\theta) = U_b(DOD;\theta) \tag{10}$$

where:

$$DOD = 1 - \frac{Q}{Q_{max}} \leq DOD_L \tag{11}$$

Accordingly, the useful energy content of the battery at a specific time point "t_o" is expressed in view of equation (10) as:

$$E_b = \int_{Q_{min}}^{Q} U_b \cdot dQ' = Q_{max} \cdot \int_{DOD}^{DOD_L} U_b \cdot d(DOD') \tag{12}$$

Finally, the maximum charging and discharging power values are determined either by the charge controller charge current "I_{ch}", i.e.:

$$N_{ch} = U_{cc} \cdot I_{ch} \tag{13}$$

or by the inverter maximum power value "N_p". In equation (13), "U_{cc}" is the charge controller output voltage, being normally one to three volts higher than the corresponding battery voltage value.

Recapitulating, the overall efficiency of the energy storage branch includes the rectifier and charge controller losses, the standing losses owing to the battery self-discharge, losses of the line connecting the storage branch apparatus and the inverter loss.

2.4. System Electronic Devices

For the undisturbed operation of the hybrid system under investigation an AC/DC rectifier of nominal power equal to wind turbine rated power "N_o" is necessary to convert the incoming three-phase AC voltage "U_{AC}" from the wind turbine excess power to a nominal "U_{DC}" corresponding to DC current accepted by the system batteries.

The output of the AC/DC rectifier enters a DC/DC charge controller of "N_c" rated power that charges the system batteries with a charging voltage "U_{cc}", slightly higher than "U_b". The corresponding charge rate "R_{ch}" depends on the charge voltage and the battery charge current, while the discharge rate is defined by the battery voltage and the corresponding discharge current[14]. Finally, the excess energy is directly rejected into a water-heating dump-load by the controller, since no other low priority loads exist.

The battery energy production branch is integrated by an appropriate DC/AC inverter[15] converting the DC output of the batteries into standard 50Hz current of operational voltage 220/380V. The maximum power "N_p" of the inverter should be capable of meeting the consumption peak load demand, while its maximum efficiency equals "η^*_{inv}". During partial load "N_d" a typical inverter efficiency curve is shown in figure (3), i.e.:

$$\eta_{inv} = f\left(\frac{N_d}{N_p}\right) \leq \eta^*_{inv} \tag{14}$$

Finally, an uninterruptible power supply (UPS) of rated power "N_p", frequency 50Hz and operational voltage 220/380V, is also applied to guarantee the wind turbine output reliability for the consumer devices. The UPS autonomy time "δt" (e.g. $\delta t \approx 1$-2min) should be adequate to facilitate the other power devices (battery-inverter, diesel-electric generator) in meeting the consumption load on occasions of sudden low wind energy production.

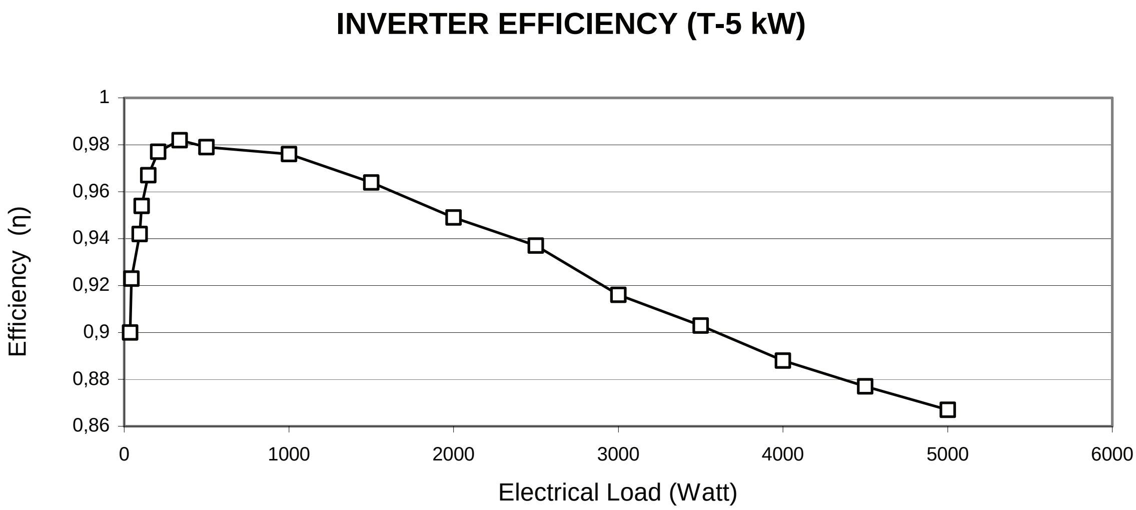

Figure 3: Typical 5kW inverter efficiency evolution

Bear in mind that the diesel switches on only when the wind turbine and the storage branch cannot cover the load demand, since the system power control should ensure that the load demand is always satisfied, i.e.:

$$N_w + N_{INV} + N_D \geq N_d(t) \qquad \forall t \tag{15}$$

in case of 100% system reliability required (excluding "Force Majeur" events).

Due to the battery bank existence, the system power control should activate the diesel generator only in case of deep battery discharge (i.e. $DOD \rightarrow DOD_L$) to prevent this particular occasion and ensure an unbroken load supply. In this manner, the diesel engine ignition and the frequency instability are minimized, therefore considerably limiting the diesel generator damaging.

3. Hybrid System Operation Modes

During the long lasting operation of the wind-diesel hybrid system under investigation one may meet the following situations:

i. The wind turbine production is higher than the load demand, i.e.:

$$N_w(t) \succ N_d(t) \tag{16}$$

thus the energy surplus "$\delta N(t)$" expressed as:

$$\delta N(t) = N_w(t) - N_d(t) \tag{17}$$

is stored via the AC/DC rectifier (efficiency "η_r") and the charge controller (efficiency "η_{cc}") at the battery bank, i.e.:

$$\Delta E(\Delta t) = \int_{t_o}^{t_o+\Delta t} (\delta N(t) \cdot \eta_r \cdot \eta_{cc}) \cdot dt \tag{18}$$

The corresponding battery capacity increase is given as:

$$\Delta Q(\Delta t) = \frac{\Delta E(t)}{U_b(Q_o)} \tag{19}$$

excluding the case that Q_o=Q_{max}, where this energy amount is forwarded to low priority loads. Thus:

$$Q(t_o + \Delta t) = Q_o + \Delta Q(\Delta t) \leq Q_{max} \tag{20}$$

ii. The wind turbine output is less than the load demand, i.e.:

$$N_w(t) \leq N_d(t) \tag{21}$$

thus the energy deficit "δ'N(t)" expressed as:

$$\delta' N(t) = N_d(t) - N_w(t) \tag{22}$$

is covered:

iia First, by the battery storage bank under the assumption that:

$$DOD \leq DOD_1 \tag{23}$$

In this case the battery capacity decrease is given as:

$$\Delta' Q(\Delta t) = \frac{\Delta' E(t)}{U_b(Q_o)} \tag{24}$$

where:

$$\Delta' E(\Delta t) = \int_{t_o}^{t_o+\Delta t} \left(\frac{\delta' N(t)}{\eta_{dch} \cdot \eta_{inv}} \right) \cdot dt \tag{25}$$

with "η_{inv}" and "η_{dch}" the inverter and the battery discharge efficiency, respectively. In this case one gets:

$$Q(t_o + \Delta t) = Q_o - \Delta' Q(\Delta t) \tag{26}$$

iib If equation (23) is not validated, the energy deficit (including line loss "η_{line}") is covered by the diesel-electric generator (see also eq.(4)) in expense of the oil reserves "δm_f" of the installation, i.e.:

$$\delta m_f(\Delta t) = \int_{t_o}^{t_o+\Delta t} \frac{\delta N'(t)}{\eta_{line}} \cdot SFC\left(\frac{\delta' N(t)}{N_d^*} \right) \cdot dt \tag{27}$$

and

$$M_f(t_o + \Delta t) = M_f(t_o) + \delta m_f(\Delta t) \tag{28}$$

under the restriction that:

$$M_f(t_o) \le M_{f\,max} \tag{29}$$

iic On the occasion that both equations (23) and (29) are not valid, the first degree battery protection limit is violated and the energy deficit is covered by the battery storage branch (see equations (24) to (26)), under the condition that:

$$Q_o \ge Q_{min} \quad \text{or} \quad DOD(t_o) \le DOD_L \tag{30}$$

iii. In the extreme case that neither equation (29) nor equation (30) is validated, load rejection takes place. Thus, given that the zero-load rejection operation is desired, the rated power of the wind turbine or the battery bank capacity should be increased under the specific (predefined) maximum annual diesel-oil consumption value.

4. Optimum Hybrid System Configuration Algorithm

In an attempt to estimate the exact hybrid system dimensions that guarantees one-year energy autonomy of a typical remote consumer, a new numerical algorithm is devised. The proposed algorithm calculates the required wind turbine size "N_o" and the corresponding battery capacity "Q_{max}" that ensures the system energy autonomy for a given annual diesel oil quantity "M_{fmax}". The proposed algorithm (WIND-DIESEL II) consists of the following steps:

i. For every region analyzed (e.g. Naxos island) and for a specific annual diesel-oil quantity available (M_{fmax}), select the wind turbine rated power "N_o" taking values from a specific numerical range, Table I.
ii. Accordingly, select a battery capacity starting from a minimum value, Table I. A maximum battery capacity limit also exists.
iii. For every time-point of a given time-period (with a specific time-step) estimate the wind energy produced "N_w" by the wind turbine, considering the existing wind speed, the ambient density and the selected wind turbine power curve.
iv. Compare the wind energy production with the isolated consumer energy demand "N_d". If any energy surplus occurs ($N_w>N_d$), the energy is stored to the battery system and a new time point is analyzed (i.e. proceed to step iii). Otherwise, proceed to step (v).
v. Since ($N_w \le N_d$), the energy deficit (N_d-N_w) is covered by the energy storage subsystem, if the battery capacity is higher than a given limit (i.e. $Q>Q_1$ or $DOD<DOD_1$). If this is not the case, proceed to step (vi). Accordingly proceed to step (iii).
vi. In this case the energy deficit (N_d-N_w) is covered by the diesel generator in the expense of diesel oil reserves, if any (i.e. $M_f<M_{fmax}$). Otherwise proceed to step (vii). Accordingly proceed to step (iii).
vii. The energy deficit (N_d-N_w) is finally covered by the energy storage branch, violating the first-degree battery protection restriction (i.e. $Q<Q_1$), if the battery is not near the lower capacity permitted limit ($Q>Q_{min}$). Accordingly proceed to step (iii). In case the battery is practically empty, the battery size is increased by a given quantity, if the battery maximum capacity limit is not exceeded. Then repeat the complete analysis from the beginning, step (iii). If the maximum battery size is reached a new wind turbine rated power is selected, while the calculation is restarted from step (ii).

Bear in mind that during the algorithm execution the annual diesel oil quantity varies between two extreme values, i.e.:

$$0 \le M_{f\,max} \le M_{f\,upper} \tag{31}$$

where:

$$M_{f\ upper} = E_y \cdot SFC \ \ (kg / year) \tag{32}$$

Also, the wind turbine rated power takes values between:

$$N_{min} \le N_o \le 15000 \ \ (Watt) \tag{33}$$

with:

$$N_{min} = \frac{E_y}{8760 \cdot CF \cdot \eta_{ups}} \tag{34}$$

where "CF" is the mean annual capacity factor of the installation and "η_{ups}" is the efficiency ($\eta_{ups} \approx 95\%$) of the UPS. The maximum value (15kW) is taken as the upper limit of the micro wind converters category, considering also the corresponding purchase cost.

On the basis of the first installation cost, the battery capacity values are also bounded as:

$$0 \le Q_{max} \le 50000 \ \ (Ah) \tag{35}$$

while one should not disregard the area needed for the installation of the batteries as well as the increased maintenance needs, Table I.

5. Application Results

By using the above-presented mathematical model-numerical algorithm, one may estimate the energy balance and the profile of the main performance parameters for a typical wind-diesel hybrid installation located in Naxos island of Aegean Archipelago. The installation under investigation is based on a 6kW wind turbine, a diesel generator of 5kW, while the battery storage capacity (24V, DOD_L=75%, DOD_1=40%) is taken equal to 5000Ah. In addition, the maximum available annual diesel-oil quantity is taken equal to 100kg/y (i.e. M_{fmax}=100kg/y), compared with the 2000kg/y diesel oil consumption of a diesel-only installation used to fulfill the energy requirements of the same remote consumer.

The proposed hybrid installation concerns the electricity demand of a typical remote consumer (4-6 member family); see for example[16][17]. Three representative weekly electricity consumption profiles are selected on an hourly basis, 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[18]. In figure (4), the most realistic electricity load demand profile for this typical family is presented 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.

The electricity consumption, in association with the available wind speed values[19] and the corresponding ambient conditions (temperature, pressure and humidity) needed for the air density estimation are the main inputs defining the energy behavior of the hybrid system examined.

In this context, Naxos is a medium-sized island (18000 habitants, area of 428km²) of central Aegean Sea belonging to the Cyclades complex, located in the middle of the Aegean Archipelago. The local terrain is very intense, including several rocky mountains with relatively sharp slopes. The island has an outstanding wind potential, as in several locations the annual mean wind speed exceeds 7.5m/s, at 10m height. In figure (5), the measured monthly averaged wind speed values are cited for an one-year time period along with the corresponding standard deviation, while the entire year hourly-mean wind speed time series is also demonstrated in figure (6). According to the data presented, there are two relatively large low wind speed periods during the entire year, i.e. between the 18th and 20th week of April and between the 26th and 27th week of July. These time periods, along with the time period belonging to the 35th week of the year are those strongly testing the energy autonomy condition of the stand-alone hybrid system.

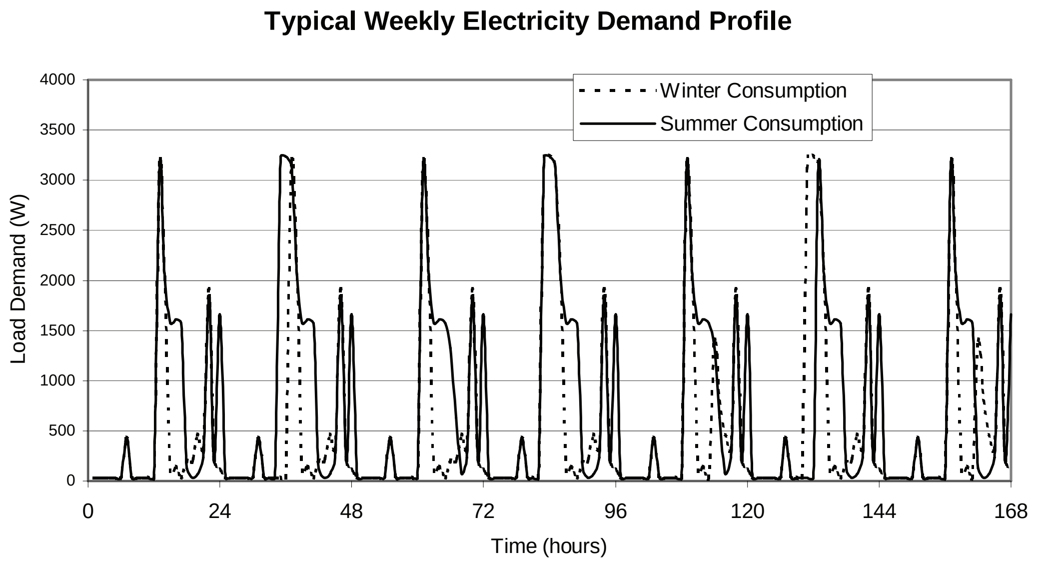

Figure 4: Typical electricity demand profile of the remote consumer analyzed

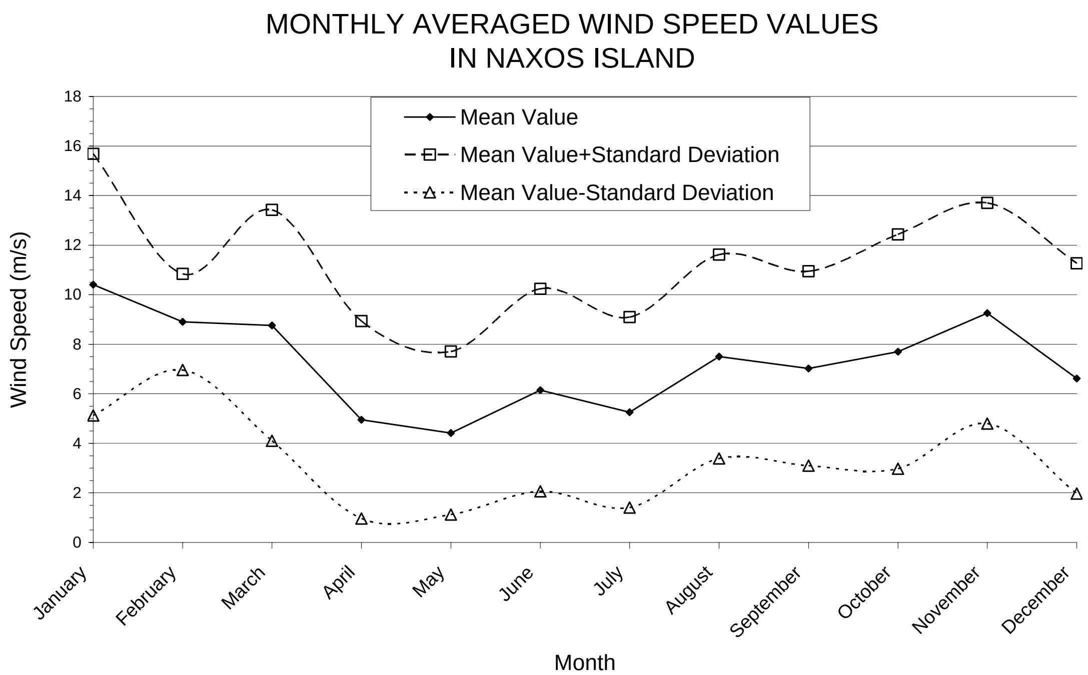

Figure 5: Wind speed values at Naxos island

Applying the analysis of section 3 to the above-described installation for these low-wind-speed winter and summer weeks, we get several interesting calculation results, included in figures (7) to (10). More specifically, figures (7) and (8) present the installation load demand (negative y-axis) during the selected winter and summer weeks (20th and 27th) of relatively low wind potential, see also figure (6), along with the corresponding wind energy production (positive y-axis). In the same figures one may also find the diesel-electric generator contribution, while the corresponding energy surplus/deficit results by comparing the energy production with the energy demand. Subsequently, in figures (9) and (10) one may observe the battery capacity distribution versus time along with the corresponding diesel oil reserves (right hand axis) and the energy deficit/surplus time series.

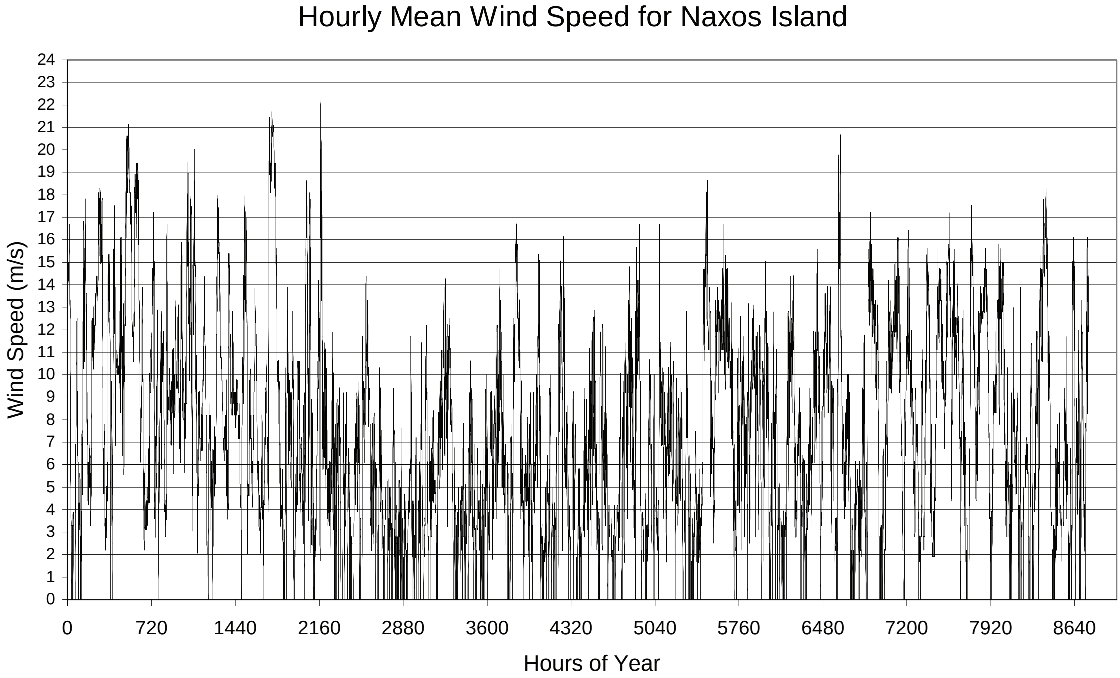

Figure 6: Hourly mean wind speed at Naxos island

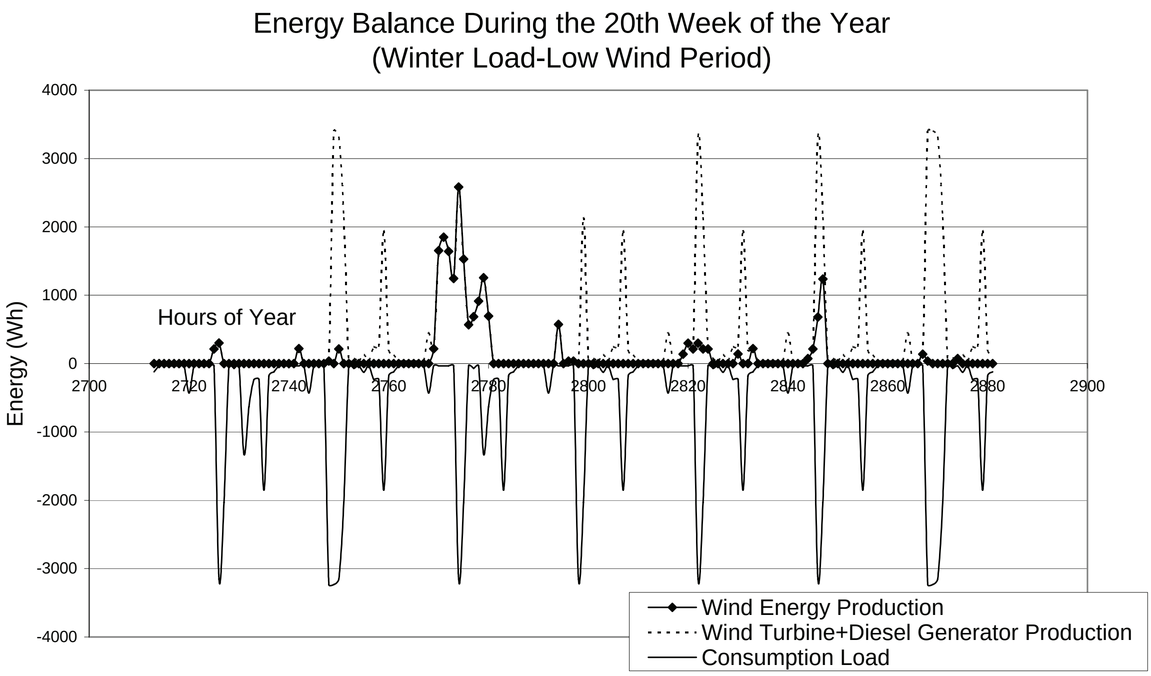

Figure 7: Energy production-demand profiles for a low wind winter week

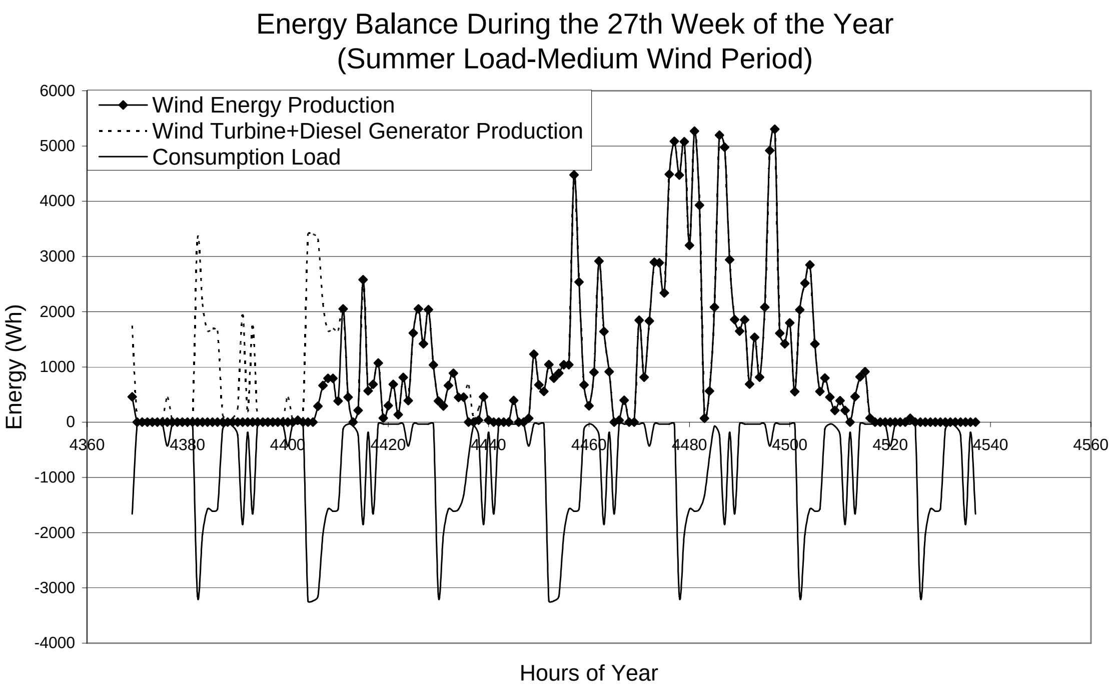

Figure 8: Energy production-demand profiles for a low wind summer week

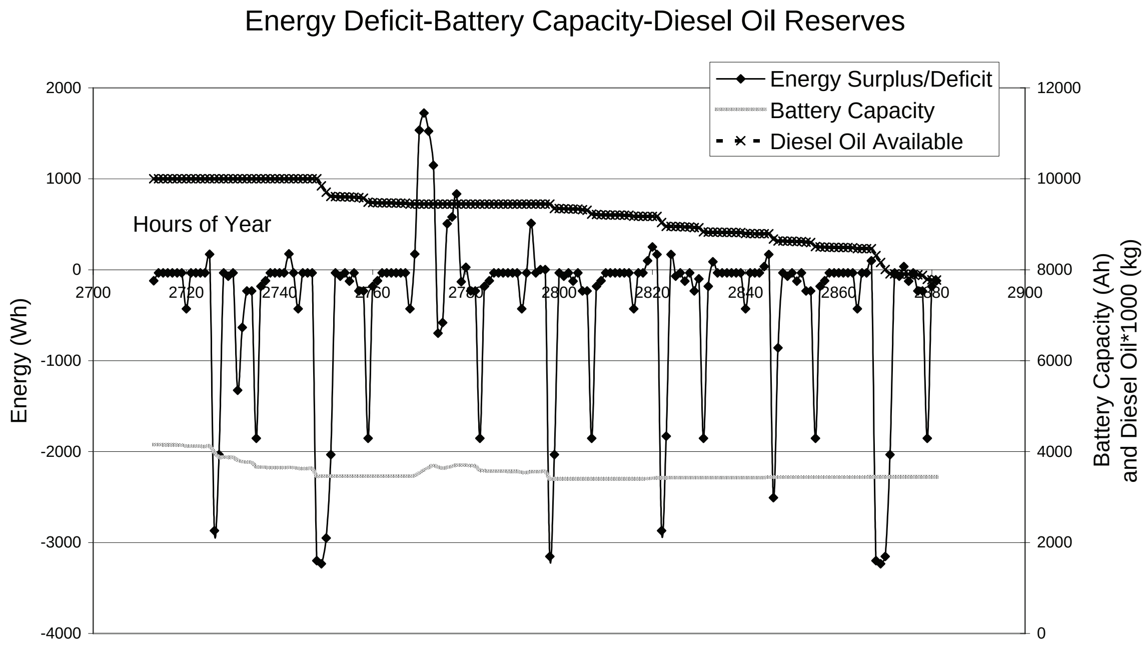

Figure 9: Battery capacity-diesel oil-energy deficit for a low wind winter week

At this point, it is interesting to mention that during the 20th week (figure (7)) the diesel-electric generator covers the energy deficit in expense of the diesel oil reserves (figure (9)), especially during the second half, since the wind turbine production is quite low excluding a ten hours period (2770-2780), where the corresponding wind energy production just exceeds the 2kW (wind turbine rated power 6kW). According to the results of the figure (9), the battery capacity is constantly low approaching the first battery limit value ($DOD \approx DOD_1 = 3000Ah$).

During the second week examined the problem appears at the beginning and the end of the period examined, figure (8), since the wind energy production is zeroed. Bear in mind that due to the previous relatively large low-wind period (i.e. the 26th week of the year) the system battery bank is near the first DOD limit, figure (10), hence the energy deficit is totally covered by the diesel-electric generator. On the other hand, after the mid-period of the 27th week the wind turbine loads the battery bank, thus the energy deficit of the last part of this week (figure (8)) is covered without additional diesel oil consumption.

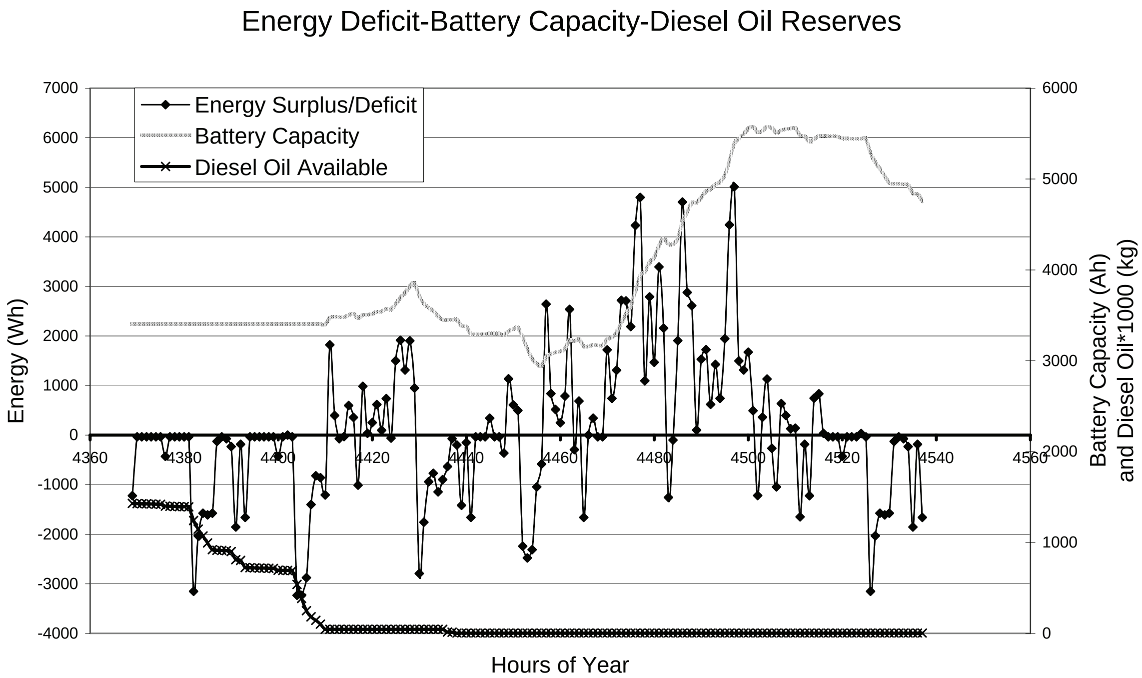

Figure 10: Battery capacity-diesel oil-energy deficit for a low wind summer week

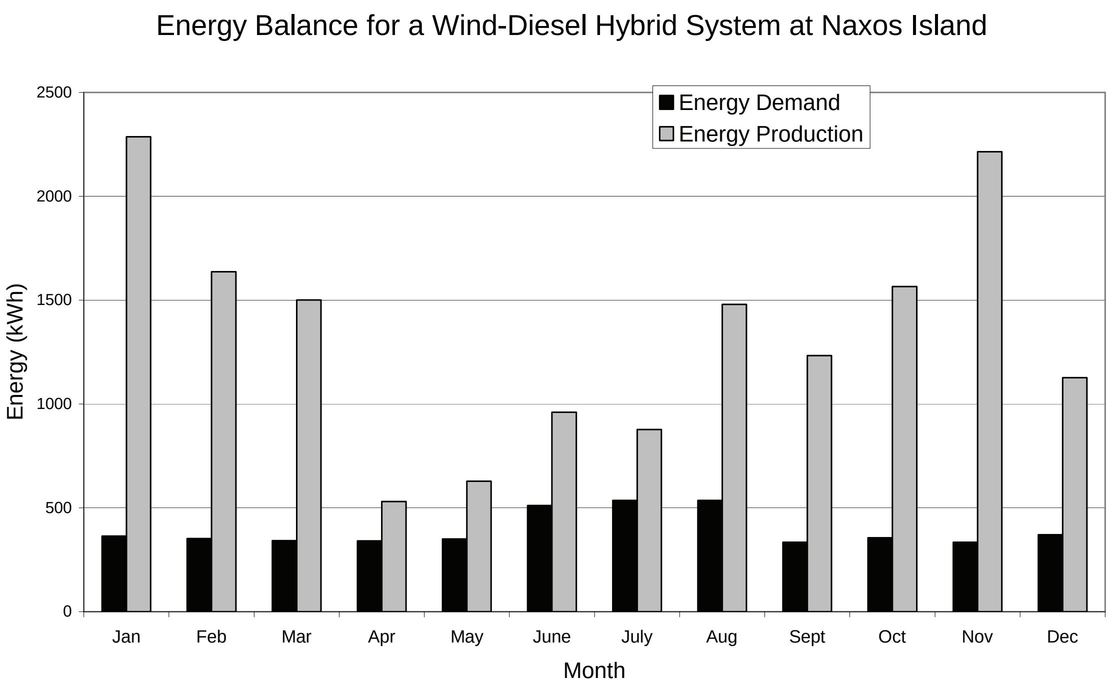

Figure 11: Monthly energy balance for a Wind-Diesel Hybrid system at Naxos island

Finally, in figure (11) one may compare the system energy production (wind turbine + diesel-electric generator) with the installation energy demand for every month of the year, see also figure (6). Obviously, there is a remarkable energy surplus in most months of the year, while during April and May the energy surplus is minimum (considering the system -especially the storage- loss), underlining the fact that the hybrid system is practically optimum sized, under the zero load rejection pre-condition[20].

6. Sensitivity Analysis of the Proposed Solution

In the following, the above-described optimum configuration algorithm along with the corresponding mathematical model of section 3, are applied in order to estimate the optimum hybrid system size for a remote consumer case (figure (4)) situated is Naxos island, where yearlong wind speed data exist. The corresponding maximum fuel quantity available is assumed here equal to 100kg/y. The calculation results are demonstrated in figure (12). It is important to mention that in this section we want to prove that every point (N_o-Q_{max}) belonging to the curve DE guarantees one-year's energy autonomy of the specific consumer under examination, with the minimum system dimensions.

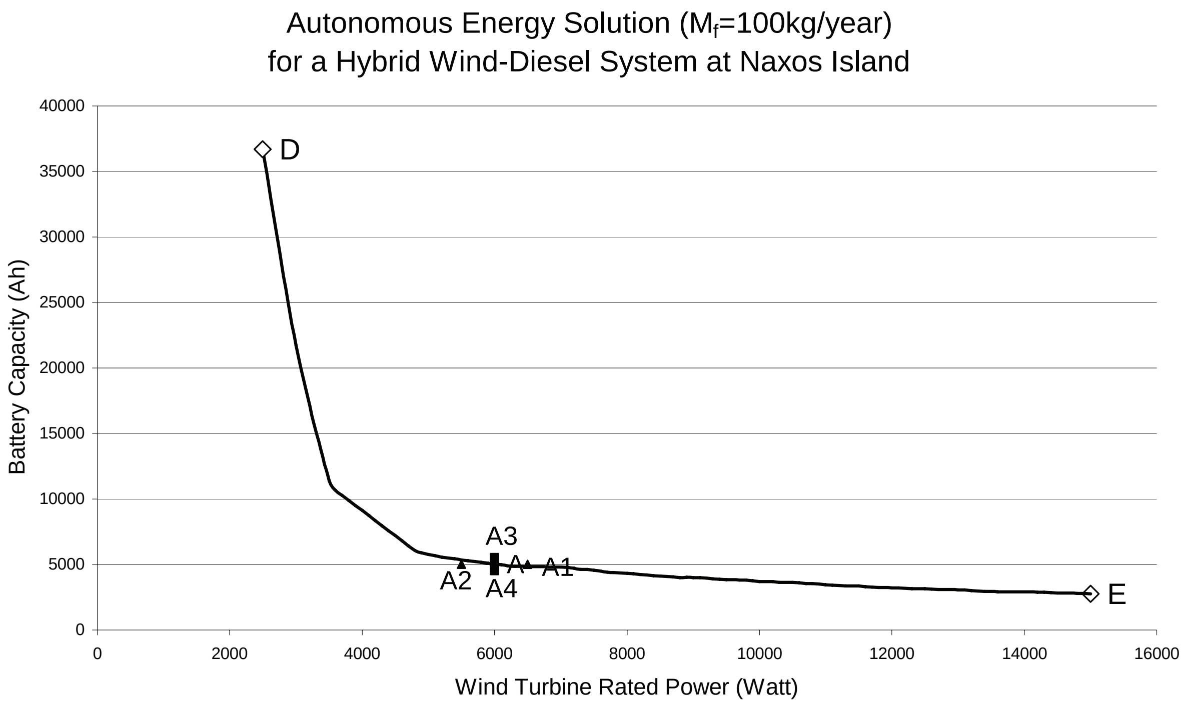

Figure 12: Energy autonomous configuration for a Wind-Diesel Hybrid system, Naxos island

For this purpose, by selecting a typical point A (N_o=6kW, Q_{max}=5000Ah) of curve (DE) in figure (12) one may see the corresponding energy deficit/surplus for the 27th summer week of the year, figure (13). Accordingly, by increasing the wind turbine rated power by 500W (point A1 of figure (12)) we get the corresponding energy deficit/surplus distribution in comparison with the one of point A, figure (13). According to the results of figure (13) the energy deficit of the hybrid system remains the same (at low wind speed the wind energy production is practically zero), while the energy surplus of point A1 is slightly higher than the one of point A. On the contrary, the energy surplus of point A2 (wind turbine rated power 500W less than the one of point A) is somewhat lower than the production of point A. In figures (14) and (15) one has also the opportunity to compare the time distribution of the hybrid system battery capacity and the residual diesel oil quantity concerning the operation of the hybrid system for the 27th week of the year and for the configurations regarding the points A, A1 and A2 of figure (12).

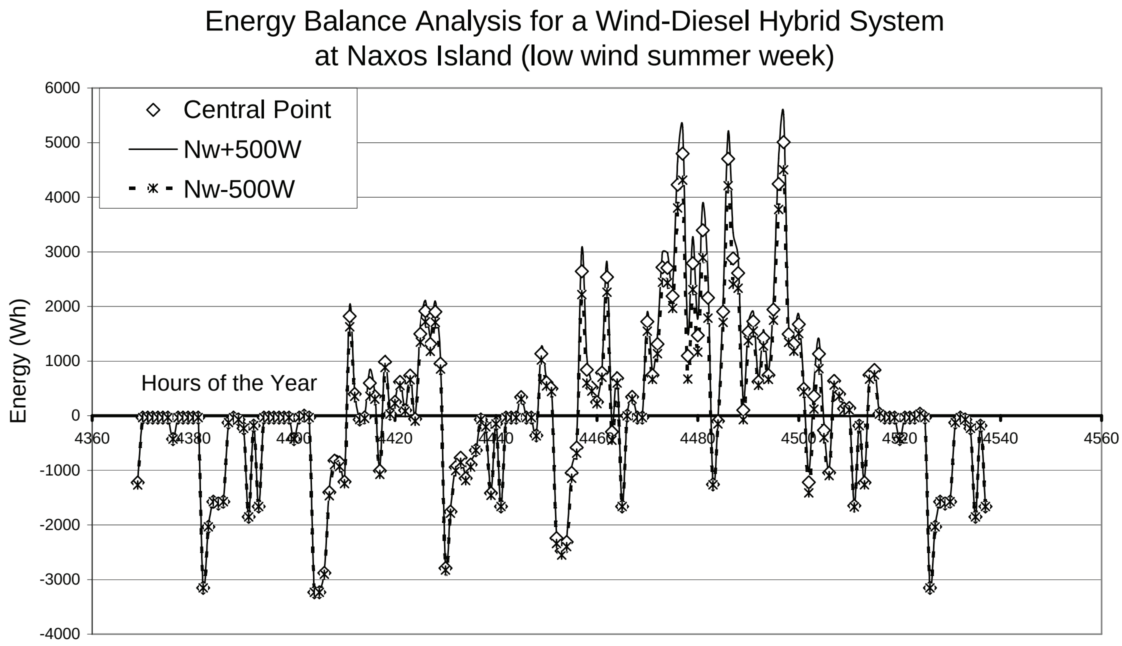

Figure 13: Energy balance of a Wind-Diesel Hybrid system at Naxos island

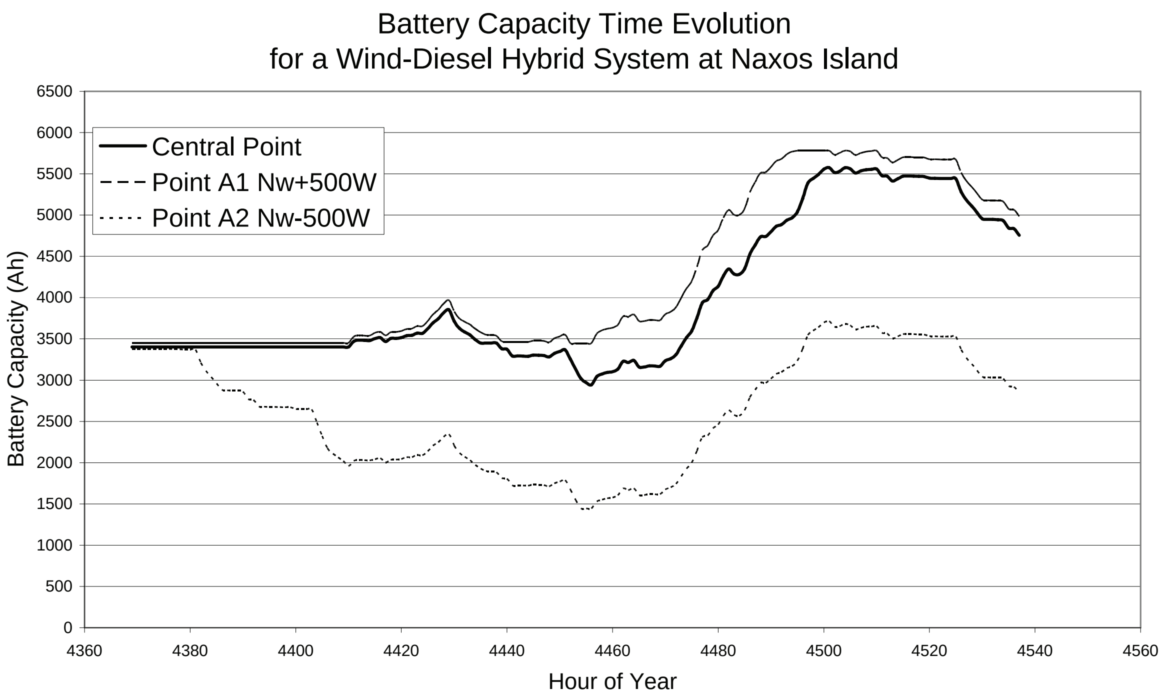

Figure 14: Battery capacity time evolution of a Wind-Diesel Hybrid System at Naxos island

According to the results of figure (14) the battery capacity of point A2 is quite lower than the one of point A, violating the maximum DOD limit (i.e. Q_{min}=1500Ah) and leading to load rejection. On the other hand, the battery capacity distribution of point A1 is slightly higher than the one of point A. Subsequently, in figure (15) we present the time distribution of the residual diesel oil quantity for the 27th week of the year analyzed and for the three hybrid system configuration corresponding to points A, A1 and A2. As it is obvious, the residual diesel oil quantity is practically zero at the beginning of the week for the hybrid system of point A2. On the contrary, only the hybrid system corresponding to point A1 reserves a small diesel oil quantity at the end of the 27th week, while this is not the case for the point A configuration.

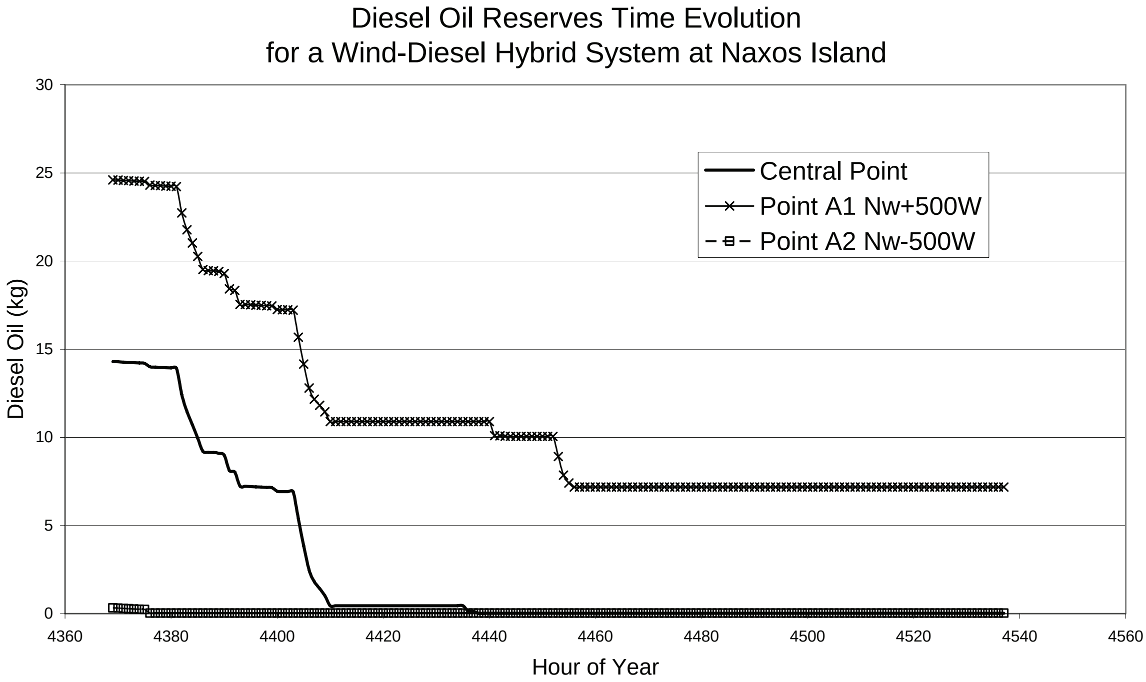

Figure15: Diesel oil quantity time evolution of a Wind-Diesel Hybrid system at Naxos island

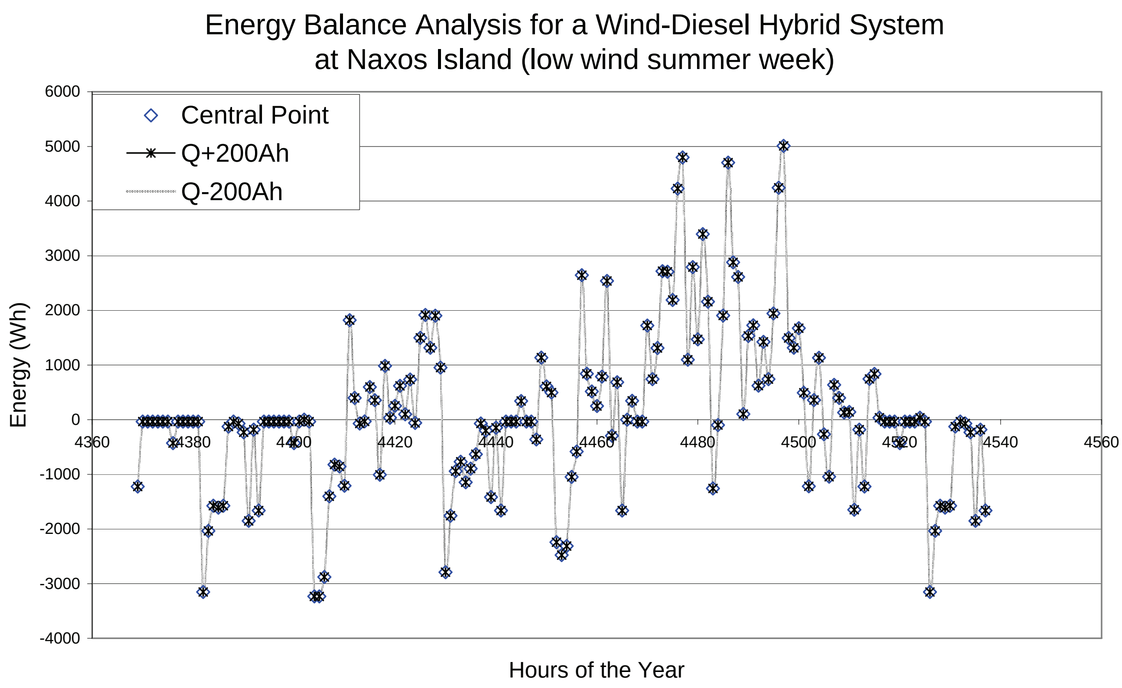

Figure 16: Energy balance of a Wind-Diesel Hybrid system at Naxos island

Repeating the same investigation for points A3 and A4 of figure (12), corresponding to hybrid systems similar to the ones of point A but having 200Ah bigger and lower battery capacity respectively, we get figures (16) to (18). These figures present the energy surplus/deficit, the battery capacity and the residual diesel oil distributions versus time for the same (27th) week of the year. As expected, the energy surplus/deficit is not remarkably influenced by the battery capacity used, figure (16). However, the battery capacity at the specific week examined of point A3 is higher than the one of point A.

Similarly, the distribution of point A4 is lower than the corresponding one of point A, figure (17). Finally, the residual diesel-oil quantity is zeroed during the 27th week of the year first for the point A4, next for the point A and lastly for the point A3, figure (18).

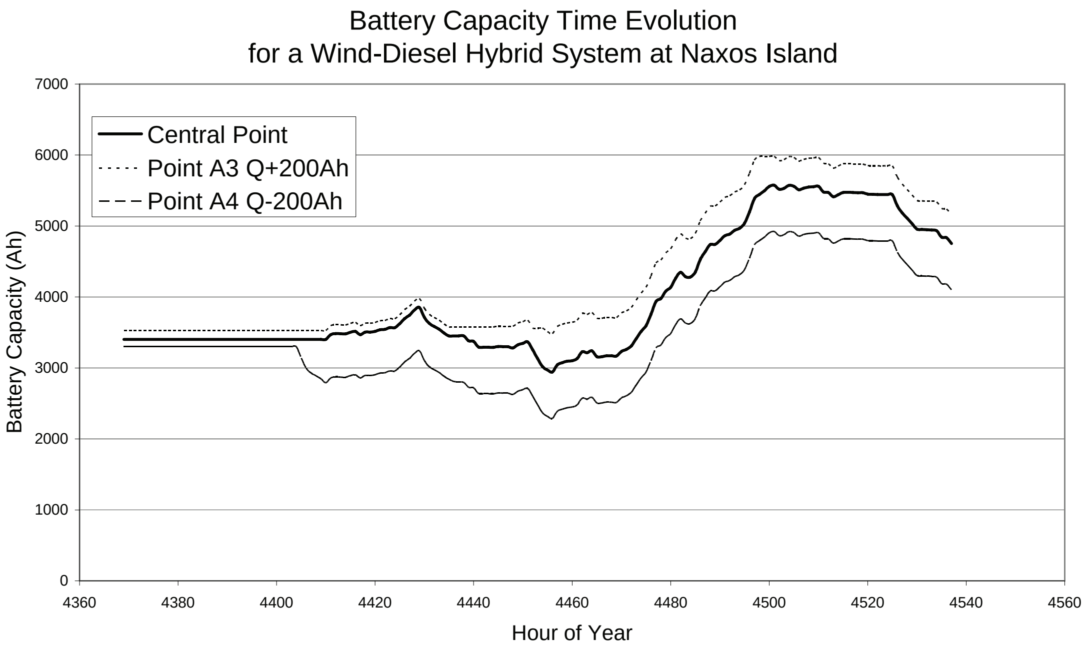

Figure 17: Battery capacity time evolution of a Wind-Diesel Hybrid system at Naxos island

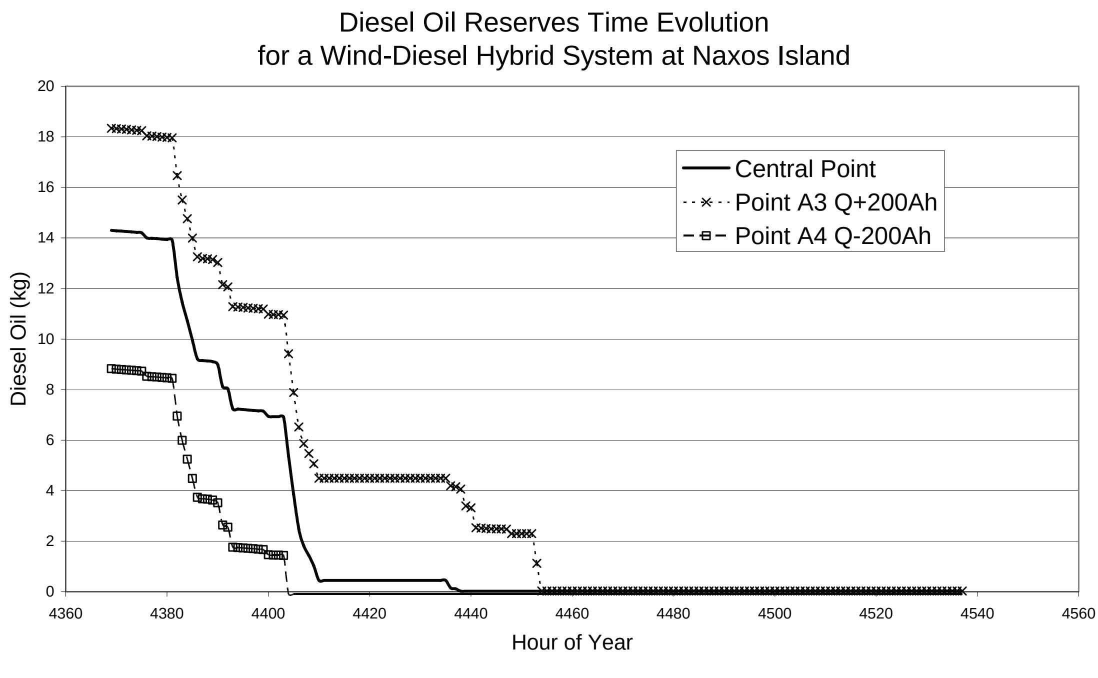

Figure 18: Diesel oil quantity time evolution of a Wind-Diesel Hybrid system at Naxos island

Recapitulating, according to the sensitivity analysis carried out it is obvious that every point belonging to the curve (DE) guarantees the installation examined energy autonomy for the time period analyzed (e.g. one year), while all the points belonging to the (N_o-Q_{max}) area under this curve represent undersized hybrid systems, which cannot guarantee the desired energy autonomy of the system. On the other hand, all points over the curve (DE) represent oversized hybrid systems retaining dimensions larger than required. For selecting the best points on the curve (DE) an optimization criterion should be provided[20], i.e. minimum first installation or ten-years operation cost, etc.

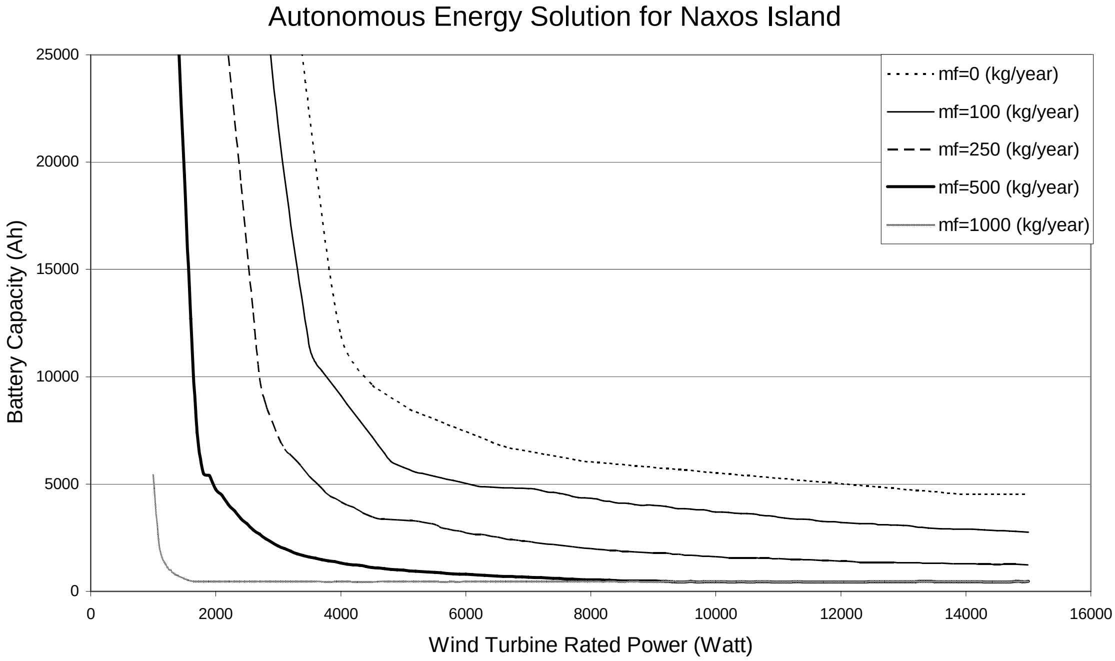

Figure 19: Energy autonomous configuration for a Wind-Diesel Hybrid system, Naxos island

These calculations can be repeated for several "M_{fmax}" values (see equations (31) and (32)) and the corresponding results are summarized in figure (19). As it is rational, the dimensions of the wind turbine and the battery bank are considerably reduced as the diesel-oil contribution in the system energy balance increases. Besides, for relatively high diesel-oil contribution (M_{fmax}≥250kg/y) the impact of the wind turbine rated power stops to influence the battery bank size after a certain point (e.g. N_o≥1.5kW for M_{fmax}=1000kg/y). On the other hand, before this value is reached there is a significant battery capacity diminution with a relatively small wind-turbine rated-power increase.

7. Conclusions

Taking into consideration the scientific interest concerning the capabilities of hybrid wind-diesel-battery systems with energy storage to fulfill the remote consumers' electrification needs, a detailed mathematical model describing the operational behavior of the basic hybrid system components is presented.

Accordingly, an integrated numerical algorithm is built in order to estimate the energy autonomous configuration of the wind-diesel-battery hybrid system under investigation. For this purpose, the optimum configuration selection procedure, adopted in the proposed numerical algorithm, is verified by carrying out an appropriate sensitivity analysis of the points belonging to the energy autonomous solution curve. Finally, a complete energy-autonomous three-dimensional surface may be predicted, considering that every point of this surface -i.e. wind turbine rated power, battery bank capacity and annual diesel-oil consumption- guarantees the remote consumer's energy-autonomy for the entire time-period examined.

Recapitulating, by incorporating an appropriate cost-benefit model, the proposed methodology may equally well be applied to other remote consumers and wind potential types, in order to predict the optimum wind-diesel hybrid system configuration that guarantees long-term energy autonomy, minimizing the consumption of imported oil and the corresponding environmental impacts.

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OPTIMUM SIZING OF A STAND-ALONE WIND-DIESEL SYSTEM ON THE BASIS OF LIFE CYCLE COST ANALYSIS

J.K. Kaldellis, K.A. Kavadias
Laboratory of Soft Energy Applications & Environmental Protection
Mechanical Eng. Dept., Technological Education Institute of Piraeus

Abstract

An autonomous wind-diesel system is one of the most interesting and environmental friendly technological solutions for the electrification of remote consumers or even entire rural areas. The proposed wind-diesel-battery hybrid system consists of a micro wind converter, a small diesel generator -basically operating as a back up energy production system- and a lead-acid battery bank that stores the wind energy surplus during high wind speed periods. The primary objective of this current study is to determine the optimum dimensions of an appropriate stand alone wind-diesel system, able to cover the energy demand of remote consumers, under the restriction of minimum life-cycle cost. For this purpose an integrated cost-benefit model is developed from first principles, able to estimate the financial behaviour of similar applications on a long-term operational schedule. In the proposed algorithm, besides the first installation cost, one takes into account the fixed and variable maintenance and operational cost, including fuel escalation and local market inflation rate. According to the results obtained for representative island territories, a properly sized stand-alone wind-diesel system is a motivating prospect for the energy demand problems of numerous existing isolated consumers all around Europe.

Keywords: Hybrid Wind-Diesel Station; Stand-Alone System; Cost-benefit Analysis; Energy Production Cost

1. Introduction

Official statistics estimate that almost two billion people have no direct access to electrical networks, 500,000 of them living in European Union and more than one tenth of them in Greece[1][2]. An autonomous wind-diesel system is one of the most interesting and environmental friendly technological solutions for the electrification of remote consumers or even entire rural areas[3][4][5]. The primary objective of this current study is to determine the optimum dimensions of an appropriate stand alone wind-diesel system, able to cover the energy demand of remote consumers located in typical Greek territories using long-term measurements, under the restriction of minimum life-cycle cost. In most previously published works the system configuration selection was based on a minimum first installation cost analysis only, diminishing the contribution of wind turbines in the energy production plan.

For this purpose an integrated cost-benefit model is developed from first principles, able to estimate the financial behaviour of similar applications on a long-term operational schedule. In the proposed algorithm, besides the first installation cost, one takes into account the fixed and variable maintenance and operational cost, including fuel escalation and local market inflation rate. It is important to note that using the proposed analysis one may prove that wind-based stand-alone systems, including a properly sized battery, lead to significant reduction of the fuel consumption in comparison with a diesel-only installation, also protecting the diesel generator from increased wear.

Special emphasis is put on investigating the impact of the operational (service) period of the installation on the corresponding energy production cost. According to the results obtained, a properly sized stand-alone wind-diesel system is a motivating prospect for the energy demand problems of numerous existing isolated consumers all around Europe.

Kaldellis J.K., Kavadias K.A., 2006, *"Optimum Sizing of a Stand-Alone Wind-Diesel System on the Basis of Life Cycle Cost Analysis", European Wind Energy Conference 2006, Athens, Greece.*

2. Proposed Solution-Optimum Sizing Algorithm

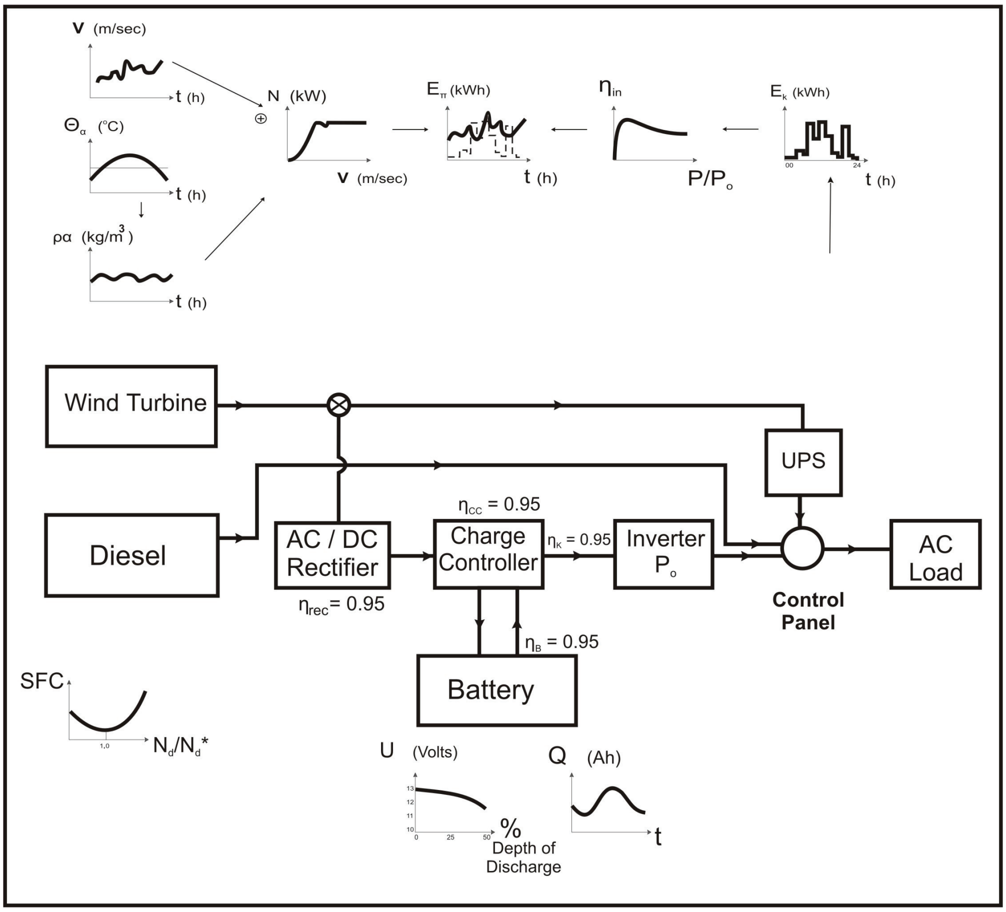

Figure 1: Proposed autonomous wind-diesel hybrid system

The proposed wind-diesel-battery hybrid system[2][6] consists mainly of a micro wind converter, a small diesel generator -basically operating as a back up energy production system- and a lead-acid battery bank, that stores the wind energy surplus during high wind speed periods, along with the necessary electronic devices. More specifically the proposed system includes (figure (1)):

a. A micro wind converter of rated power "N_o" (kW)
b. A small internal combustion engine of "N_d" (kW), able to meet the consumption peak load demand "N_p" (i.e. $N_d \geq N_p$)
c. A lead-acid battery storage system with total capacity of "Q_{max}", operation voltage "U_b" and maximum depth of discharge "DOD_L"
d. An AC/DC rectifier of "N_o" kW and U_{AC}/U_{DC} operation voltage values
e. A DC/DC charge controller of "N_o" rated power, charge rate "R_{ch}" and charging voltage "U_{CC}"
f. A UPS (uninterruptible power supply) of "N_p" (kW), frequency of 50Hz, autonomy time "δt" and operation voltage 220/380V
g. A DC/AC inverter of maximum power "N_p" (kW) able to meet the consumption peak load demand, frequency of 50Hz and operational voltage 220/380V

This system should be capable of facing a remote consumer's electricity demand (e.g. a four to six member family), with rational long-term operational cost. The specific remote consumer investigated is basically a rural household profile (not an average load taken from typical users) selected among several profiles provided by the Hellenic Statistical Agency[7], see also [8] and [9]. More precisely, the numerical load values depend (figure 2) on the year period examined and vary between 30W (refrigerator load) and 3300W. According to the consumption profile approved, the annual peak load "N_p" does not exceed 3.5kW, while the annual energy consumption "E" is around 4750kWh.

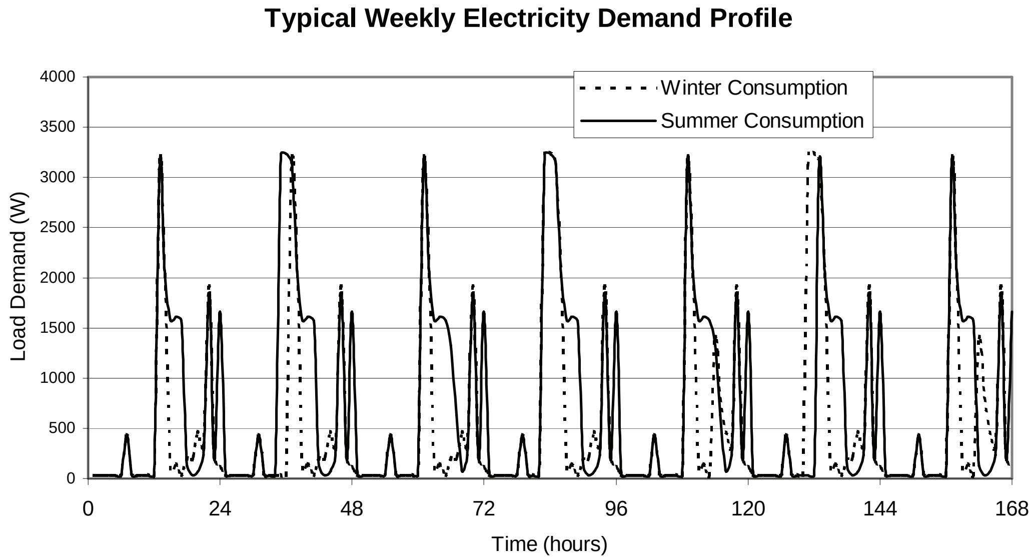

Figure 2: Typical electricity demand profile of the remote consumer analyzed

Additionally, the corresponding wind potential and ambient temperature and pressure are also necessary to integrate the system sizing calculations[10]. Finally, the operational characteristics of all components (e.g. wind power curve at standard day conditions, diesel-electric generator specific fuel consumption, inverter efficiency, battery bank characteristic etc.) composing the stand-alone system under investigation are also required, figure (1).

During the system operation, the following energy production scenarios exist:

- ✓ Energy (AC current) is produced by the micro wind converter and sent directly to the consumption (often via the UPS in order to avoid undesired voltage-frequency fluctuations)
- ✓ Energy is produced (AC current) by the small diesel-electric generator and is forwarded to the consumption
- ✓ The energy output of the wind turbine (not absorbed by the consumption-energy surplus) is transformed to DC current (via AC/DC rectifier) and subsequently is stored at the batteries via the charge controller
- ✓ The battery is used to cover the energy deficit via the charge controller and the DC/AC inverter

For estimating the appropriate configuration of the proposed wind-diesel hybrid system, three governing parameters should be defined: the rated power "N_o" of the wind turbine used, the battery maximum necessary capacity "Q_{max}" and the annual diesel-oil consumption "M_f". Working this problem out, the already presented[6] computational algorithm "WINDREMOTE-II" is extended to include a small diesel-electric generator. This new numerical code "WIND-DIESEL I" is used to carry out the necessary parametrical analysis on an hourly energy production-demand basis, targeting to estimate the wind turbine rated power "N_o" and the corresponding battery capacity "Q_{max}", given the annual permitted oil consumption "M_f"; see also figure (3). More specifically, given the "M_f" value and for each "N_o" and "Q_{max}" pair, the "WIND-DIESEL I" algorithm is executed for all the time-period selected (e.g. one month, six-months, one year or even for three years), while emphasis is laid on obtaining zero-load rejection operation. After calculating the appropriate (M_f, N_o, Q_{max}) combinations that guarantee the stand-alone system energy autonomy, one may proceed to evaluate the proposed wind-diesel installation financial behavior.

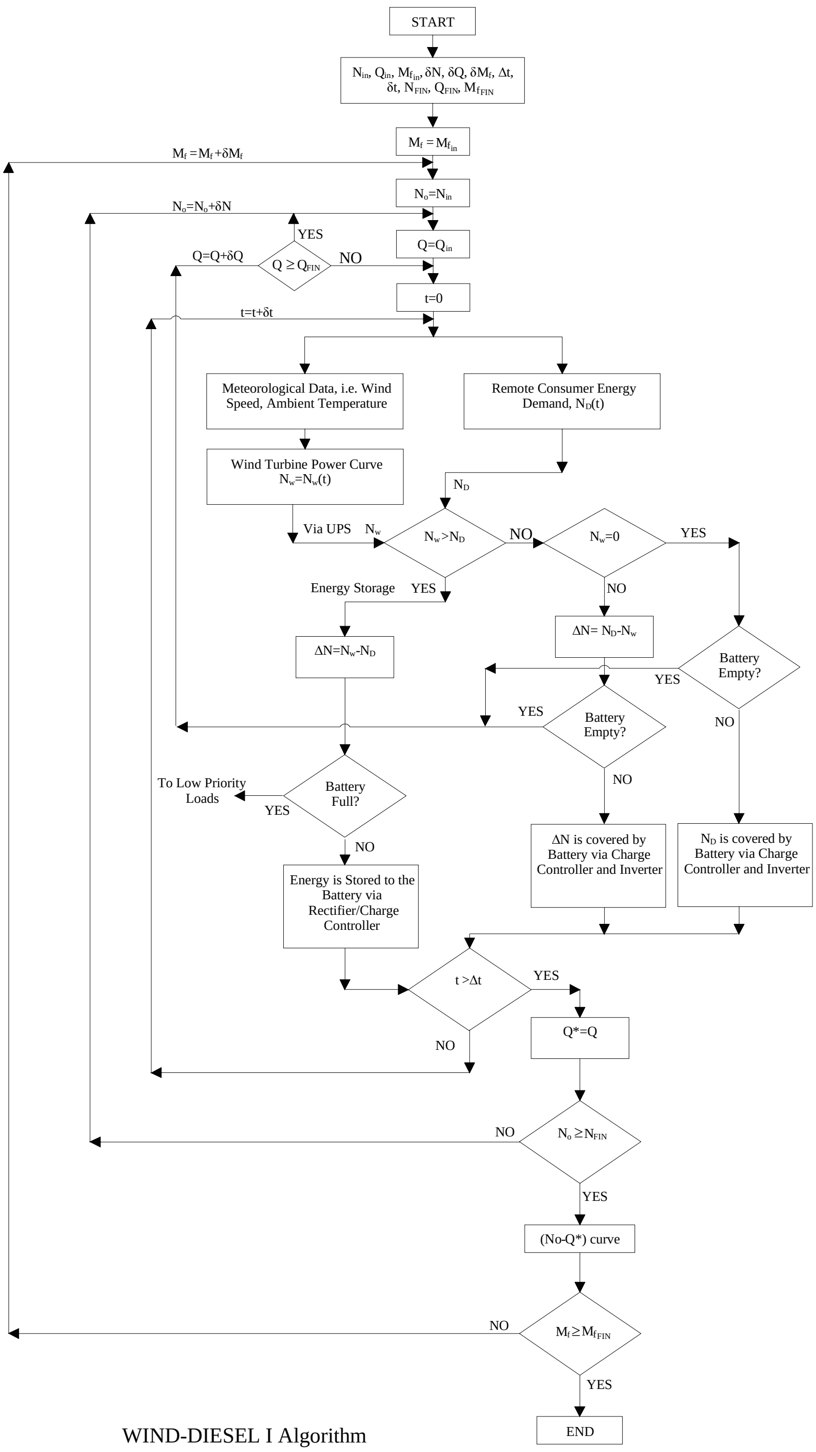

Figure 3: WIND-DIESEL-I algorithm

3. Life Cycle Cost Model

The present value of the entire investment cost of a stand-alone wind-diesel power system during its life cycle (i.e. after -n years of operation) is a combination[11][12] of the initial installation cost and the corresponding maintenance and operation cost, also considering the investment residual value; all quantities expressed in present (constant) values.

3.1. First Installation Cost

As already acknowledged in previous works[10][11], the initial investment cost "ICo" includes the market (ex-works) price of the installation components (i.e. wind turbine, ICWT; battery, ICbat; diesel generator, ICd and electronic devices ICel, including inverter, UPS, rectifier and charge controller cost) and the corresponding balance of the plant cost, expressed as a fraction "f" of the wind turbine market price. Thus one may write:

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

Using the market analysis data, equation (1) finally reads:

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

where the numerical values of the parameters appearing in equation (2) are given in Table I.

3.2. Maintenance and Operation Cost

During long-term operation, the maintenance and operation (M&O) cost can be split[10][11] into the fixed "FC_n" and the variable "VC_n" maintenance cost. In the present analysis, the fixed M&O cost also considers the fuel cost consumed by the diesel-electric generator. Generally speaking, the annual fixed M&O cost "FC^{WT}"can be expressed[13] as a fraction "m" of the initial capital invested, furthermore including an annual inflation rate equal to "g_m" describing the annual changes of labor cost and the corresponding spare parts, also embracing any lubricants consumption.

Subsequently, the fuel consumption cost "FC^D" results by the annual diesel-oil quantity consumed "M_f", the current fuel price "c_o" and the oil price annual escalation rate "e". Thus one gets:

$$FC_n = FC_n^{WT} + FC_n^D = m \cdot IC_o \cdot \left[\frac{1+g_m}{1+i} + \left(\frac{1+g_m}{1+i} \right)^2 + \ldots + \left(\frac{1+g_m}{1+i} \right)^{n-1} + \left(\frac{1+g_m}{1+i} \right)^n \right]$$

$$+ c_o \cdot M_f \cdot \left[\frac{1+e}{1+i} + \left(\frac{1+e}{1+i} \right)^2 + \ldots + \left(\frac{1+e}{1+i} \right)^{n-1} + \left(\frac{1+e}{1+i} \right)^n \right] \quad (3)$$

where "i" is the return on investment index.

The variable maintenance and operation cost "VC_n" mainly depends[10][11] on the replacement of "k_o" major parts of the installation, which have a shorter lifetime "n_k" than the complete installation. Using the symbol "r_k" for the replacement cost coefficient of each "k_o" major part (battery, diesel-electric generator, rotor blades, etc.) the "VC_n" term can be expressed as:

$$VC_n = IC_o \cdot \sum_{k=1}^{k=k_o} r_k \{ \sum_{l=1}^{l=l_k} \left[(1+g_k) \cdot (1-\rho_k) \right]^{l \cdot n_k} \cdot (1+i)^{(n-l \cdot n_k)} \} \quad (4)$$

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

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

while "g_k" and "ρ_k" describe the mean annual change of the price and the corresponding technological improvement level for the k-th major component of the system. For practical purposes, one may use the coefficient "h_k" in order to describe the combined impact of "g_k" and "ρ_k", using the following relation:

$$1+h_k=(1+g_k)\cdot(1-\rho_k)=1+(g_k-\rho_k)-g_k\cdot\rho_k\approx 1+(g_k-\rho_k) \tag{6}$$

In the present analysis one may take into account the diesel-electric generator and the battery bank replacement every "n_d" and "n_b" years respectively (e.g. $n_d \approx 4\div 6$ and $n_b \approx 5\div 7$ years). Applying equation (4), one finally gets:

$$VC_n = IC_o \cdot \Psi \tag{7}$$

with:

$$\begin{aligned}
&\Psi = 0 \qquad \text{for } n \le n_d = 5\\
&\Psi = r_d\cdot\left(\frac{1+h_d}{1+i}\right)^{n_d} \qquad \text{for } n_d+1\le n\le n_b=7\\
&\Psi = r_d\cdot\left(\frac{1+h_d}{1+i}\right)^{n_d}+r_b\cdot\left(\frac{1+h_b}{1+i}\right)^{n_b} \qquad \text{for } n_b+1\le n\le 2n_d=10\\
&\Psi = r_d\cdot\left(\frac{1+h_d}{1+i}\right)^{n_d}+r_d\cdot\left(\frac{1+h_d}{1+i}\right)^{2n_d}+r_b\cdot\left(\frac{1+h_b}{1+i}\right)^{n_b} \qquad \text{for } 2n_d+1\le n\le 2n_b=14\\
&\Psi = r_d\cdot\left(\frac{1+h_d}{1+i}\right)^{n_d}+r_d\cdot\left(\frac{1+h_d}{1+i}\right)^{2n_d}+r_b\cdot\left(\frac{1+h_b}{1+i}\right)^{n_b}+r_b\cdot\left(\frac{1+h_b}{1+i}\right)^{2n_b} \qquad \text{for } 2n_b+1\le n\le 3n_b=15\\
&\Psi = r_d\cdot\left[\left(\frac{1+h_d}{1+i}\right)^{n_d}+\left(\frac{1+h_d}{1+i}\right)^{2n_d}+\left(\frac{1+h_d}{1+i}\right)^{3n_d}\right]+r_b\cdot\left[\left(\frac{1+h_b}{1+i}\right)^{n_b}+\left(\frac{1+h_b}{1+i}\right)^{2n_b}\right] \qquad \text{for } 2n_d+1\le n\le n_{max}=20
\end{aligned} \tag{8}$$

where "$r_d.IC_o$" is the diesel-electric generator and "$r_b.IC_o$" is the battery replacement cost in present values, while "h_d" and "h_b" describe the diesel-electric generator/battery purchase cost mean annual change (inflation rate) combined with the corresponding technological improvement rate, see equation (6).

Table I: Proposed Values for the First Installation Cost Parameters of equation (2)

	Variable	Proposed Value		Variable	Proposed Value
a	Wind Turbine Cost Coefficient	$8.7\mathrm{x}10^5$	ξ	Battery Cost Coefficient	5.0377
b	Wind Turbine Cost Coefficient	621	ω	Battery Cost Coefficient	0.0784
c	Wind Turbine Cost Asymptotic Value	700	φ	Diesel-electric Generator Specific Cost	150€/kW
x	Wind Turbine Cost Exponent	2.05	λ	Electronic Equipment Cost Coefficient	483.57
f	First Installation Cost Coefficient	0.15	τ	Electronic Equipment Cost Coefficient	0.083
B	Electronic Equipment Cost Coefficient	380Euro/kW			

3.3. Life Cycle Energy Production Cost

Using the above analysis and considering that the proposed wind-diesel system produces approximately "E" kWh per year, one may estimate the corresponding energy production cost by dividing the present value of the installation total cost with the corresponding electricity production. According to the above presented equations, it is obvious that the energy production cost of the installation strongly depends on the service period of the installation; see for example equation (8). In this context the total cost function is given as:

$$C_n = IC_o \cdot \left[(1-\gamma) + m \cdot x \cdot \frac{x^n - 1}{x - 1} + \frac{c_o \cdot M_f}{IC_o} \cdot y \cdot \frac{y^n - 1}{y - 1} + \Psi \right] - Y_n \quad (9)$$

where:

$$x = \frac{1 + g_m}{1 + i} \quad (10)$$

and

$$y = \frac{1 + e}{1 + i} \quad (11)$$

Similarly, "Y_n" represents the residual value of the investment, attributable to amounts recoverable at the "n" year of the stand-alone system 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.

Finally, "γ" is the subsidy percentage (e.g. 30%-40%) by the Greek State, according to the current development law (e.g. 3299/04) or the corresponding National Operational Competitiveness Program[10][13].

Taking also into account the analysis presented by the authors[12], concerning the current electricity marginal production cost "ce", one gets the following equations provided that the net present value of the investment becomes equal to the corresponding residual value (NPV=Yn, where "Yn" may be equal to zero) after n years of operation, i.e.:

$$c_e(n) = \frac{IC_o}{E} \cdot \left[\frac{1-\gamma}{z \cdot f_z(n)} + m \cdot \frac{x \cdot f_x(n)}{z \cdot f_z(n)} + \frac{\Psi(n)}{z \cdot f_z(n)} \right] + \frac{c_o \cdot M_f}{E} \cdot \frac{y \cdot f_y(n)}{z \cdot f_z(n)} - \frac{Y_n(n)}{E \cdot z \cdot f_z(n)} \quad (12)$$

where:

$$z = \frac{1 + p}{1 + i} \quad (13)$$

and "p" is the produced electricity price mean annual escalation rate, e.g. p=3%. Besides, the functions "$f_x(n)$, $f_y(n)$ and $f_z(n)$" can be expressed by the following generalized form:

$$f_w = \frac{w^n - 1}{w - 1} \qquad \text{where } (w = x, y, z) \quad (14)$$

Bear in mind that the proposed model also includes the diesel-only solution (i.e. IC_o=φ.N_d, N_o=0, r_b=0, M_f=M_{max}) as well as the zero-diesel configuration (i.e. IC_d=0, r_d=0, M_f=0).

4. Analysis of the Parameters Involved

According to the above presented analysis, the main parameters involved in the electricity production cost procedure are the local market capital cost (x,y,z), the corresponding M&O inflation rate (x), the oil price annual escalation rate (y) and the electricity price annual escalation rate (z). On top of this, one should not disregard the impact of the capital cost as well as the influence of the annual change of prices/technological status of specific hybrid station major components on the variable M&O cost, equations (6) to (8).

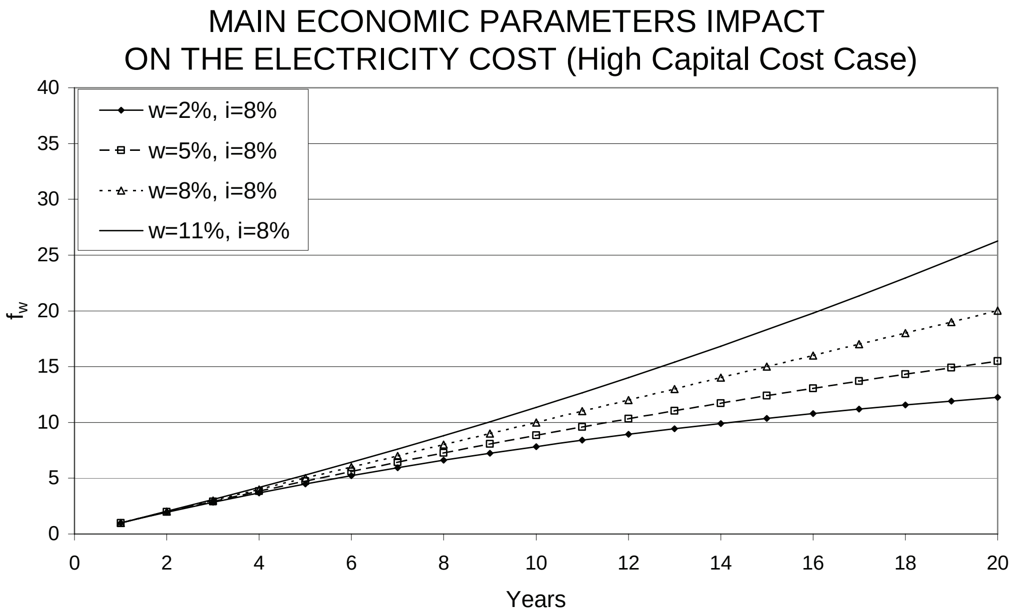

Figure 4: Time evolution of parameter "f_w", equation (14) for high capital cost scenario

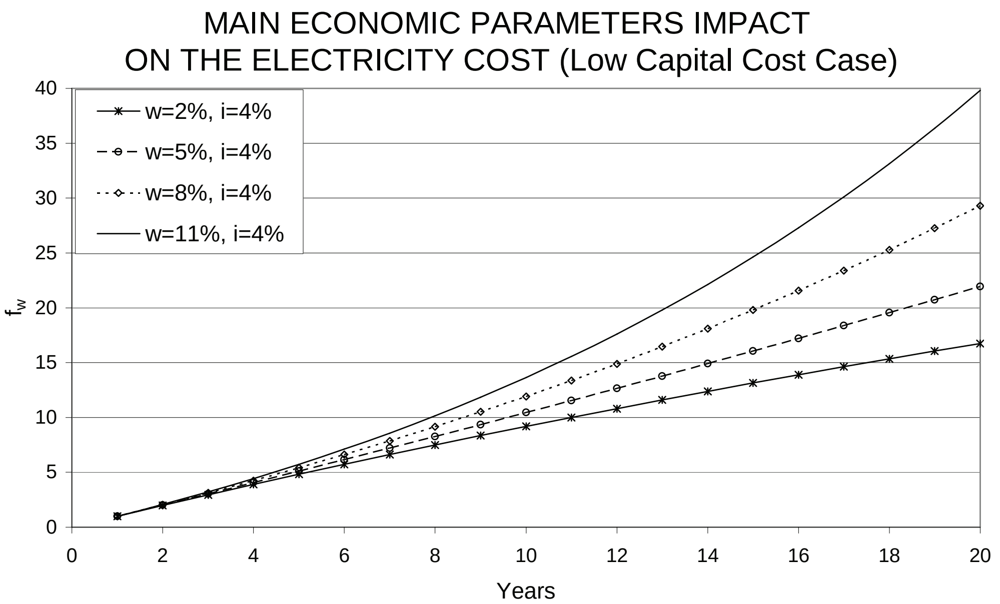

Figure 5: Time evolution of parameter "f_w", equation (14) for low capital cost scenario

Generally speaking, the capital cost describes the annual amount of money that one should pay for using loan-capital. This amount depends on the local market economic wealth, the timing of repayment and the risk of the investment, while its numerical value varies with the inflation rate of the economy, in order to obtain positive inflation-free values. For practical calculation purposes long-term annual mean values are utilized here, see also [13], hence a low (i=4%) and a high (i=8%) capital cost analysis cases are examined, figures (4) and (5).

The term "diesel-oil price annual escalation rate" takes into account not only the oil market price, but also its transportation and storage cost, which is quite high for stand-alone consumers located in remote islands. Taking into consideration the highly unstable international oil-market situation one should use a wide-range of "e" values, i.e. 2%≤e≤12%.

The inflation rate expresses the tendency of everyday life cost to increase in the course of time. Thus, the M&O cost inflation rate "g_m" describes the annual escalation of the M&O cost, in view of the annual changes of labour cost and the corresponding spare parts. Generally speaking, M&O cost inflation rate follows the market inflation rate tendency, being usually one or two percentage units lower[13].

Finally, the electricity price annual escalation rate is used here to describe the annual rate of change of the electrical energy (and power) market prices. This specific value depends on the existing electricity production situation in the local market (is assumed to follow the local market price variation), hence it also depends on the local government policy as well as on the existing legislative frame.

The impact of all these parameters is described in figures (4) and (5) as a function of the hybrid station operation period, for a low and a high capital cost scenario. More precisely, in these two figures one may find the time evolution of the parameters "f_x", "f_y" and "f_z" (see equations (10), (11), (13) and (14)) with the operation time of the installation. In both cases, the "f_w" achieves quite high values (up to 25 for i=8% and up to 40 for i=4%), seriously affecting the first and the third term of equation (12). In order to obtain a preliminary qualitative picture of the expected electricity production cost, let us assume that x≈y≈z. Then equation (12) reads:

$$c_e(n) = \frac{IC_o}{E} \cdot \left[(1-\gamma-\upsilon) \cdot \xi(n) + \Psi(n) \cdot \xi(n) \right] + m \cdot \frac{IC_o}{E} + \frac{c_o \cdot M_f}{E} \tag{15}$$

where:

$$\xi(n) = \frac{1}{z \cdot f_z(n)} \tag{16}$$

and

$$\upsilon = \frac{Y_n}{IC_o} \tag{17}$$

As it results from equation (15), one may state as a first order approximation that the initial capital invested and the variable M&O cost terms are mainly affected by the operational period and the local market economy parameters.

5. Application Results

The proposed analysis is being applied to typical remote consumers located in a small island of N. Aegean Sea, i.e. the island of Skiros. More precisely, Skiros is a small island of NW Aegean Sea, belonging to the Sporades complex. The island has a medium-strong wind potential, taking into consideration that the annual mean wind speed approaches the 6.8m/s at 10m height[14]. Figure (6) presents the measured monthly averaged wind speed values for a one-year time period.

Applying the "WIND-DIESEL I" algorithm of figure (3), one may estimate the corresponding year-long energy autonomous configuration for various diesel-oil annual quantities available, see figure (7). According to the results obtained, there is a considerable battery capacity diminution by accepting a small (100kg/y) diesel-oil consumption, representing approximately 5% of the annual diesel-only system fuel consumption, i.e. 2000kg/year. A significant battery capacity decrease is also encountered by accepting 250kg/y diesel-oil consumption. In fact, the utilization of 250kg/y of oil should guarantee system energy autonomy using a reasonably small wind turbine (i.e. less than 5kW) and a fair battery capacity. For bigger diesel-oil quantities the battery capacity is fairly reduced, excluding the configurations based on very small wind turbines, i.e. rated power below 3kW.

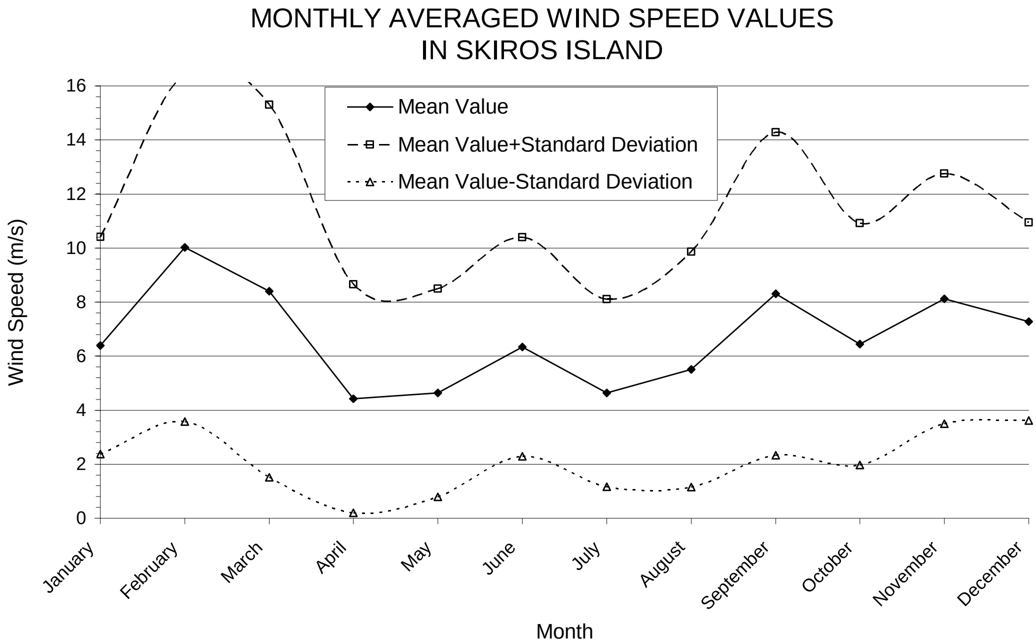

Figure 6: Wind potential at Skiros island

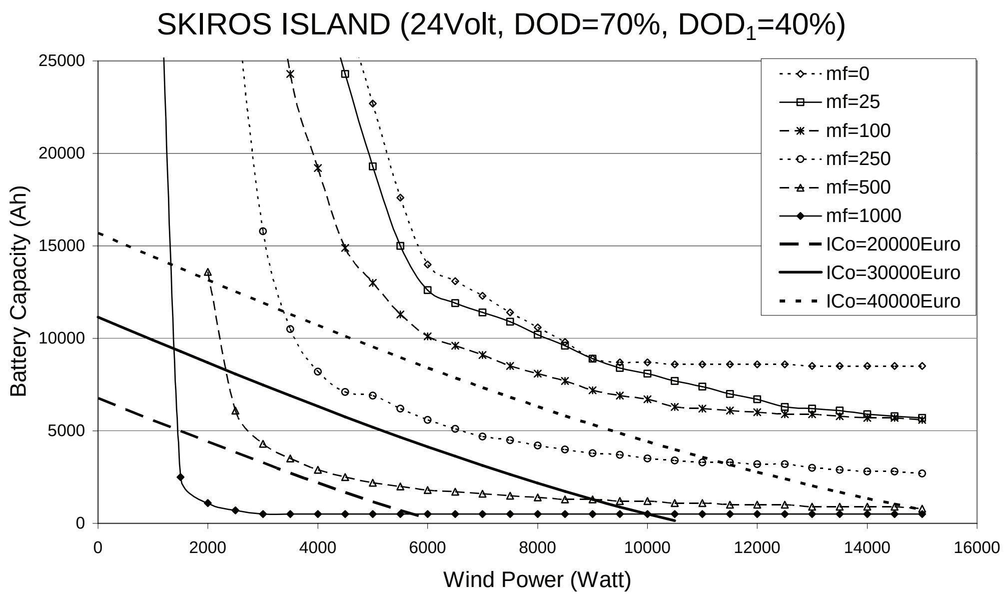

Figure 7: Energy autonomous configurations of the proposed hybrid wind-diesel system

In the next figures (8) and (9) one may find the calculated electricity production cost variation as a function of the wind turbine rated power, for 5, 10, 15 and 20 years of the hybrid system operation and for a low (Mf=100kg/y) and a high (Mf=500kg/y) annual diesel oil contribution. In both cases one may observe that there is a remarkable electricity cost decrease with the increase of the installation service period, especially in cases of high fossil fuel participation.

Accordingly, in figure (10) we demonstrate the minimum electricity production cost distribution versus the annual oil quantity consumed for various operational periods of the installation. After a thorough investigation of figure (10) one may state the following:

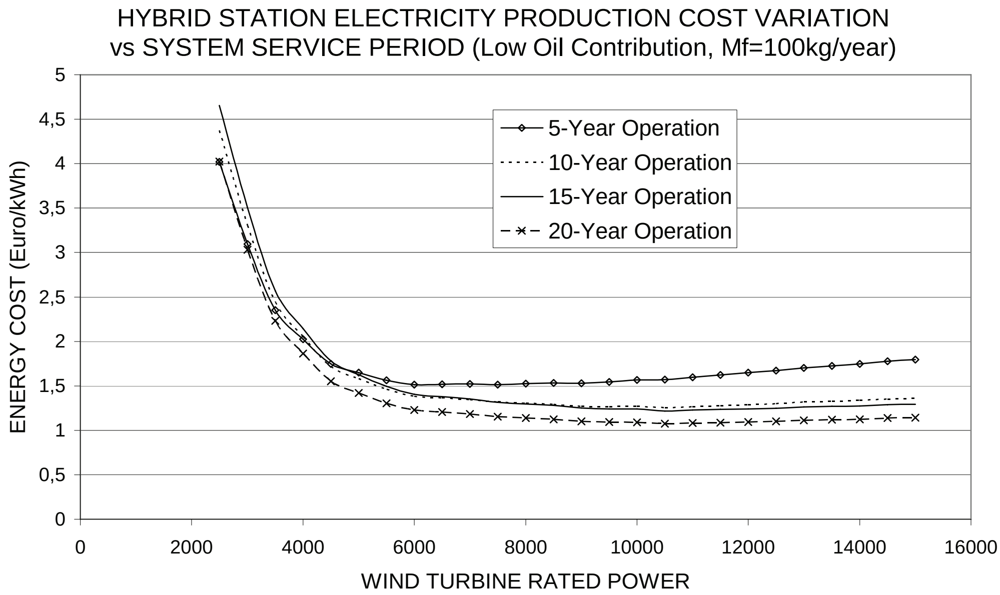

Figure 8: Electricity production cost values for variable hybrid system service periods

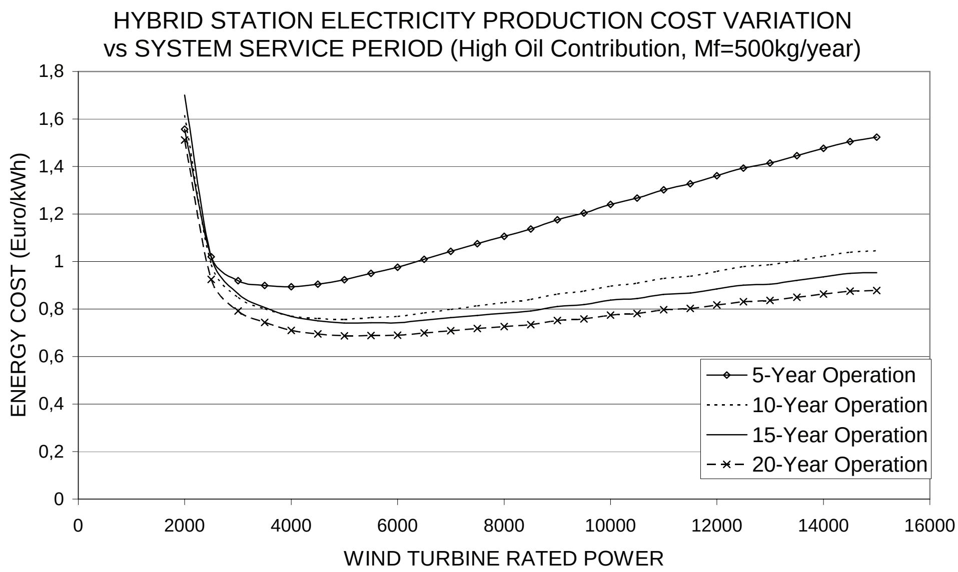

Figure 9: Electricity production cost values for variable hybrid system service periods

- For zero (wind only) or low diesel-oil contribution cases there is a considerable cost decrease between five (5) and ten (10) years and between fifteen (15) and twenty (20) years of system operation.
- On the contrary, the cost decrease between ten (10) and fifteen (15) years is quite small, due to the increase of the variable M&O cost contribution, e.g. replacement of the necessary major components of the installation.
- The minimum electricity production cost is remarkably decreased between the fifth and the tenth year of operation of the system, figure (11), being accordingly almost constant up to the twentieth year of operation.
- There is a significant optimum annual oil consumption decrease (approx. 300kg/year) when the desired service period of the hybrid station increases from five to twenty years (figure (12)), leading also to remarkable environmental benefits.

- In all cases examined, the optimum life cycle electricity production cost of the wind-diesel system investigated is slightly above 0.6€/kWh, being quite lower than the corresponding value of the already operating small thermal power stations in several tiny Greek islands[15].

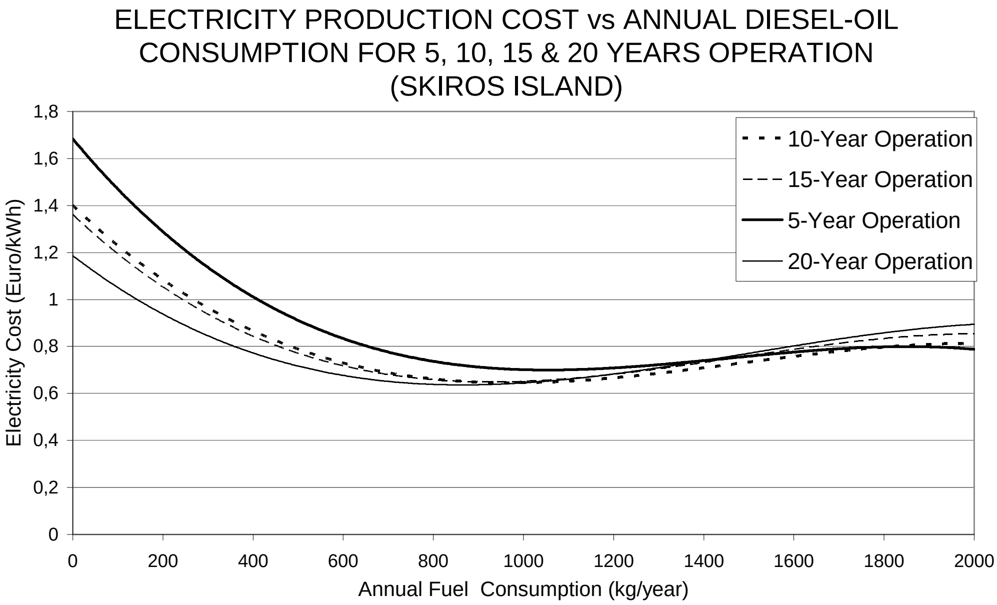

Figure 10: Life cycle hybrid system minimum electricity production cost vs annual diesel-oil consumption

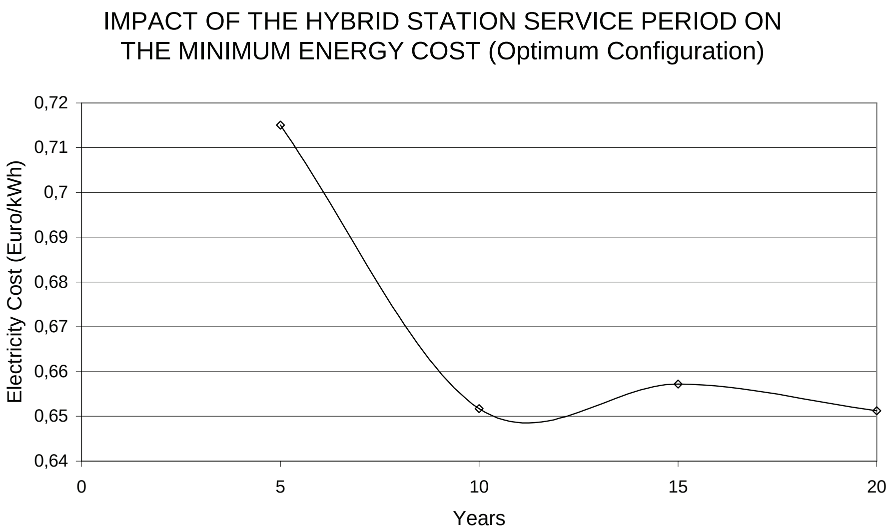

Figure 11: Minimum life cycle electricity production cost variation

6. Conclusions

An integrated cost-benefit model is developed from first principles, able to estimate the financial behaviour of an energy autonomous hybrid wind-diesel-battery system on a long-term operational schedule. For this purpose one should first define the optimum dimensions of the proposed system, able to cover the energy demand of remote consumers, under the restriction of minimum life-cycle cost. The main parameters to be predicted are the wind turbine rated power, the corresponding battery capacity and the annual oil consumption required in order to guarantee energy autonomy of the entire stand-alone installation. Accordingly, a total electricity production cost calculation model is

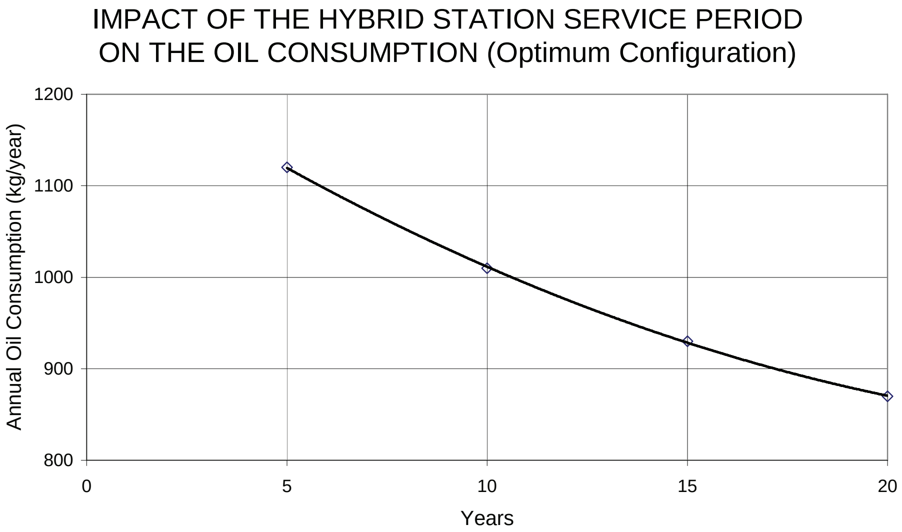

Figure 12: Annual diesel-oil consumption for the optimum hybrid system configuration

developed, taking explicitly into consideration the desired service period of the complete installation. Finally, the application of the complete analysis on a selected typical island region indicates that the proposed hybrid system is a reliable and a cost effective solution for the electrification of numerous isolated consumers.

According to the results obtained, one should point out the remarkable diesel-oil consumption decrease as the desired service period of the hybrid station increases, in order to minimize the corresponding life cycle electricity production cost. In any case, the estimated long-term electricity production cost of the proposed hybrid system is considerably lower than the current operational cost of several existing small autonomous thermal power stations throughout Aegean Archipelago. Recapitulating, one may definitely state that a properly sized stand-alone wind-diesel system is a motivating prospect for the energy demand problems of numerous existing isolated consumers all around Europe.

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PART THREE

ENERGY STORAGE

MAXIMIZING WIND GENERATED ELECTRICITY WITH HYDRO STORAGE: CASE STUDY CRETE

J.K. Kaldellis, K.A. Kavadias, D.E. Papantonis[1], G.S. Stavrakakis[2]
Laboratory of Soft Energy Applications & Environmental Protection
Mechanical Eng. Dept., Technological Education Institute of Piraeus
[1]Laboratory of Hydraulic Turbomachines, National Technical University of Athens
[2]Dept. of Electronics and Computer Engineering, Technical University of Crete

Abstract

A vital problem encountered in Greek islands within the Aegean Archipelago is insufficient electricity generation. Wind generated electricity appears to be a fiscally viable solution, as the area has excellent wind potential. Yet despite the technological improvement, the penetration of substantial wind power to autonomous electrical grids is still limited, mainly due to existing technical barriers. One of the most interesting autonomous electrical network cases is the island of Crete. Here, with an excellent wind potential, about 180 wind turbines of 120MW total installed rated-capacity are in operation or under construction. However, even in this relatively strong electrical system, grid instability and mismatching of supply and demand have led to significant wind energy rejection. This "split" wind power corresponds to an annual financial loss of income of 30,000€ per MW of wind power installed. The present study seeks an integrated methodology with pumped-hydro storage for maximizing the contribution of wind energy in the Crete electricity supply. In addition, the objective is to improve grid stability. An analysis of the wind-hydro electricity production cost is presented and compared with the corresponding operational cost of the existing thermal power plants.

Keywords: Wind Energy; Hydro Storage; Wind-Hydro; Electricity Generation; Cost-Benefit Analysis

NOMENCLATURE

c_o	minimum acceptable price of the wind-hydro electricity generation (€/kWh)
E	annual electricity generation by the proposed hybrid station (kWh)
EC_n	energy input cost (€)
e	produced energy price annual escalation rate (%)
FC_n	fixed maintenance & operation cost of the proposed station over an n-year period (€)
$f_{i,ii}$	auxiliary functions concerning parameters "g" and "e", see also equations(4) and (6)
g	maintenance & operation cost annual inflation rate (%)
IC_n	future value of the initial investment cost after n-years (€)
IC_o	autonomous hybrid system total initial cost (€)
i	local market capital cost (%)
m	maintenance and operation cost coefficient (%)
N_G	local network electricity load (kW_e)
N_H	rated power of the hydro turbines of the proposed station (kW)
N_{min}	technical minima of thermal power stations of the network (kW_e)
N_{WT}	permitted wind power penetration (kW_e)
N_w	rated power of the wind parks belonging to the entire wind-hydro station (kW)
n	operational years of the installation
Pr	reduced turnkey price of the installation (€/kW)
q	ratio between the rated power of the hydro turbines and the wind parks of the station
R_n	proposed power station revenues over an n-year period (€)
R_o	proposed power station annual revenues present value (€)
r	ratio of the rejected wind energy financial value (in comparison with c_o)
t	time

***Kaldellis J.K., Kavadias K.A., Papantonis D.E., Stavrakakis G.S., 2006,** "Maximizing Wind Generated Electricity with Hydro Storage: Case Study Crete", Wind Engineering Journal, vol.30(1), pp.73-92.*

x	viability ratio, i.e. ratio of annual revenues divided by the investment initial cost
Y_n	residual value of the investment after n years of operation (€)
Z	wind-hydro station energy cost divided by the hydro turbines relative to wind turbines size
γ	State subsidization percentage (%)
ε	annual wind energy rejection per MW of operating wind power ((MWh/year)/MW)
η^*	total energy transformation coefficient of the entire wind-hydro system
λ	upper wind energy participation limit in the instantaneous load demand
Φ_n	tax paid in current values over an n year period (€)

1. Introduction

The Greek islands of the Aegean Archipelago have insufficient electricity generation within the autonomous utility-grids of the Greek Public Power Corporation. This problem is particularly pressing during the peak consumption period in summer, with repeated black-outs of the local utility networks[1]. Moreover, the autonomous electricity production cost on these islands is extremely expensive[2], mainly due to the use of old thermal plants (mostly diesel-electric generators and gas turbines). Considering the vital impact of electricity for development, it is important that there is sufficient and affordable electricity for these island communities.

According to numerous studies[3][4], wind energy is a fiscally viable solution for the various energy-related problems of most Aegean islands, as they possess an excellent wind potential. However, one of the main obstacles to large wind energy penetration is the stochastic behaviour of wind speed, leading to significant mismatch between wind energy generation and electricity demand. Consequently there are occasions when wind power has to be rejected. Yet a properly-sized energy-storage system[5] allows variable wind-power output to be matched to a generally unsteady and unpredictable system demand[6], with potential for overall energy production-cost reduction (e.g. needing less generating capacity).

Despite technological improvement, the penetration of substantial wind power into these autonomous electrical grids is still limited, mainly due to the existing technical barriers protecting these grids from possible instability problems[7][8]. In this context, the local electricity utility (the Greek Public Power Corporation, i.e. PPC) defines an upper limit to wind power within the instantaneous electrical load demand as an attempt to control undesirable local network difficulties. This limit is usually estimated empirically from the operational characteristics of the internal combustion engines and from the time-dependent load profile. Consequently, the financial optimum for wind energy penetration is less than 10% in most autonomous island networks[9].

One of the most noteworthy cases is the island of Crete. Due to its excellent wind potential, Crete has gained a reputation among the best wind-energy-application-examples in Europe, as various wind farms have been operating there since 1993. About 180 wind turbines of 120MW rated power are in operation or under construction. Despite the relatively strong electrical system on Crete, there has been significant wind energy rejection during recent years, being equivalent to an annual financial loss of 30,000€ per MW of wind power installed. If more wind power capacity is added on the island, the wind energy rejection would be expected to increase, so reducing the revenues for both new and existing wind farms.

According to previous research[10][11][12][13][14], a reversible pumped-hydro power system may optimise the use of wind power on small-medium sized islands. Therefore, the present study considers an integrated methodology capable of maximizing the contribution of wind energy in the electricity demand problem of Crete. Thus the electrical power demand of the island is examined first, along with the main characteristics of the thermal power units. Then, the annual energy yield of the existing wind farms is investigated, in conjunction with the new wind park erection rate. Consequently, we estimate the annual profile of wind energy rejection, according to the power purchase agreement restrictions and the real data of the Crete electrical network. As a result, the impact of the proposed wind-hydro solution is examined for minimizing wind energy rejection and improving the local grid stability. Finally, we analyse the minimum trade price of wind-hydro electricity production. In this context, we compare the predicted value with the marginal operational cost of the existing thermal power units activated in peak-load periods.

The developed procedure could be applied to several other typical islands of the Aegean Archipelago (large, medium and small demand) to maximize wind power penetration and ameliorate the barriers to operation within local electricity networks. Accordingly, we predict significant reduction in air pollution, since for every 1kWh produced in Greece by wind offsetting oil, 1kg CO_2, 6g SO_2 and 4g NO_x are avoided[15].

2. The Electrical System of Crete Island

Crete has the largest autonomous electrical network in Greece, with annual energy consumption in 2004 being 2550GWh/y. In fact, there has been a substantial demand increase between 1975 (278GWh/y) and 2004, figure 1. This increase is directly related to local economic improvement, establishing Crete among the richest Greek territories. The annual peak demand shows similar growth; figure 2. The peak demand during August 2004 was 543MW, almost ten-times the corresponding value of 1975.

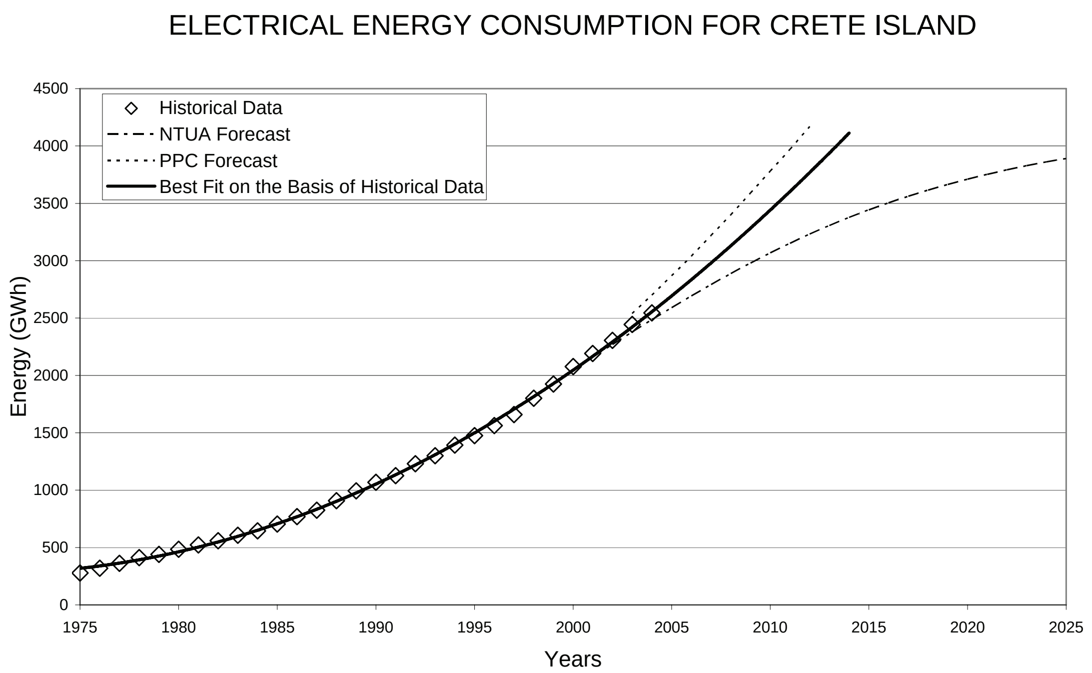

Figure1: Electrical energy demand time evolution for Crete

Previous studies include:

a. A long-term evaluation by the NTUA research team[16], predicting annual demand as 3230GWh/y by 2012 and 3890GWh/y by 2025, along with 709MW and 854MW of peak demand respectively.
b. A medium-term forecast by PPC[17], predicting 4170GWh/y and 885MW of peak load demand by 2012.

Both methods underline the need for substantial extra electrical power capacity, to facilitate the continuously increasing electricity demand. Note that the variation of the monthly electricity consumption, due to tourism, is large, with the ratio between high and low consumption periods being almost 2:1 for the last five years examined, figure 3.

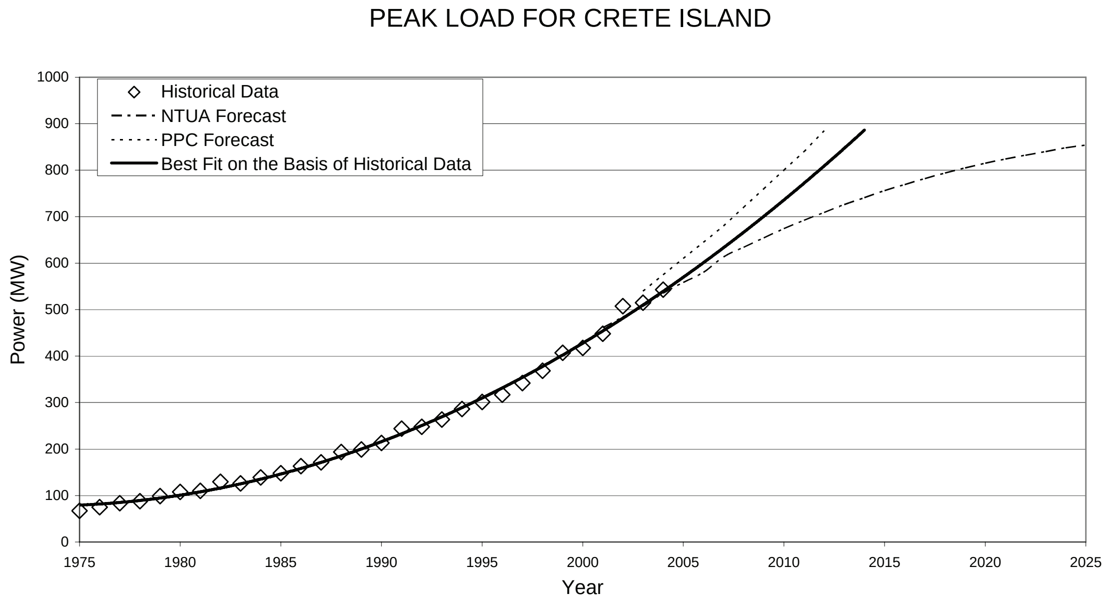

Figure 2: Peak electrical power demand time evolution for Crete

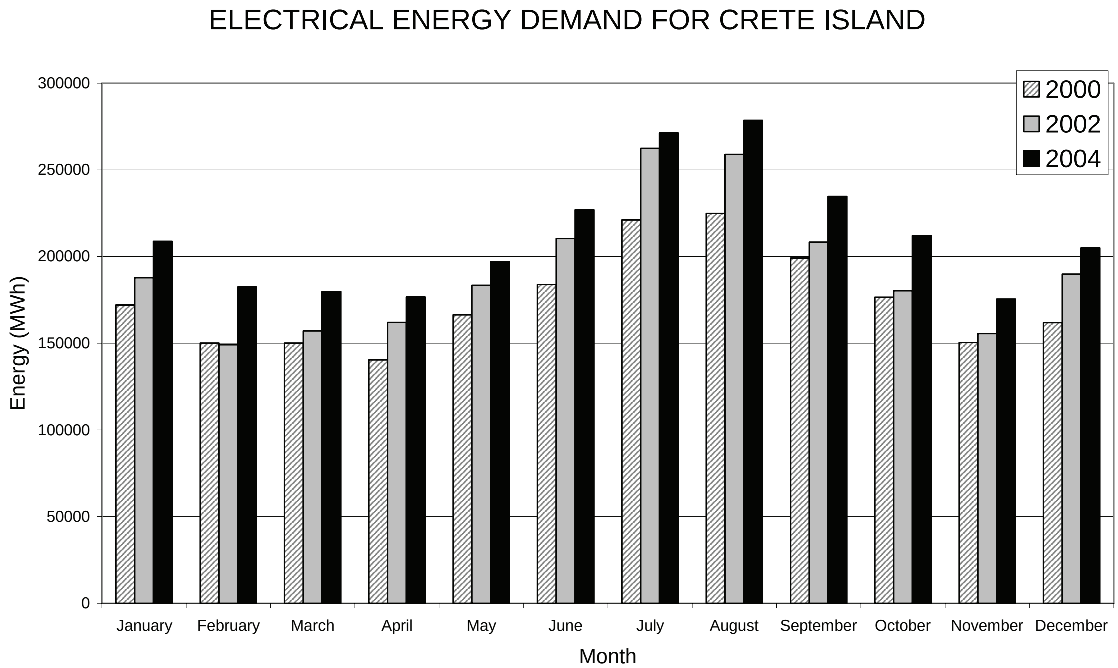

Figure 3: Monthly variation of electrical energy demand for Crete (2000-2004)

To face the above-described electricity demand profile, 26 thermal power units operate in the island, totalling a 742.9MW name-plate capacity. However, in practice, the maximum continuous power of these units is 693MW during winter and 652MW during summer, mainly due to the equipment ageing and the ambient temperature constraints. These 26 units are installed in two Cretan central thermal power stations (TPS), i.e. Linoperamata of Heraklion TPS (269.2MW) and the corresponding TPS of Chania (324MW). Recently, two internal combustion engines (2x51MW) started operating in the new

Atherinolakkos power station. Referring to Table I, 61% of the island electrical power is covered by gas-turbine generators operating at high cost and consuming imported diesel-oil. According to the PPC official scheduling, the steam turbines of 147MW (assuming combined cycle output at technical minimum) are supposed to cover the base load, while the other engines are used to meet the excess demand, starting from the small internal combustion engines[18].

Table I: Crete island electricity generation system (EGS), end 2005

	Unit Type	Location	Fuel Used	Start Up Time	Rated Power (MW)
1	Steam Turbine	Lin-Her	Mazut	1965	6.2
2	Steam Turbine	Lin-Her	Mazut	1970	15.0
3	Steam Turbine	Lin-Her	Mazut	1970	15.0
4	Steam Turbine	Lin-Her	Mazut	1977	25.0
5	Steam Turbine	Lin-Her	Mazut	1981	25.0
6	Steam Turbine	Lin-Her	Mazut	1981	25.0
7	Diesel Engine	Lin-Her	Mazut	1989	12.3
8	Diesel Engine	Lin-Her	Mazut	1989	12.3
9	Diesel Engine	Lin-Her	Mazut	1990	12.3
10	Diesel Engine	Lin-Her	Mazut	1990	12.3
11	Gas Turbine	Lin-Her	Diesel	1973	16.3
12	Gas Turbine	Lin-Her	Diesel	1974	16.3
13	Gas Turbine	Chania	Diesel	1969	16.2
14	Gas Turbine	Chania	Diesel	1979/85	24.0
15	Gas Turbine	Chania	Diesel	1979/87	36.0
16	Steam Turbine	Chania	Diesel	1993	44.4
17	Gas Turbine	Chania	Diesel	1992	45.0
18	Gas Turbine	Chania	Diesel	1992	45.0
19	Gas Turbine	Chania	Diesel	1998	59.40
20	Gas Turbine	Chania	Diesel	1998	59.40
21	Gas Turbine	Lin-Her	Diesel	1982/01	15.50
22	Gas Turbine	Lin-Her	Diesel	2002	43.30
23	Gas Turbine	Lin-Her	Diesel	2003	30.00
24	Gas Turbine	Chania	Diesel	2003	30.00
25	Diesel Engine	Atherinollakos	Diesel	2004	51.00
26	Diesel Engine	Atherinollakos	Diesel	2004	51.00

* *The Units (1 to 6 and 16 to 18) are used to cover base load*

** *The Units 16, 17 and 18 constitute a combined cycle system*

*** *Lin-Her is the Linoperamata Thermal Power Station at Heraklion*

$^{+}$ *The Engines 7 to 15 and 19 to 22 normally should not be used to cover base load*

To meet the increased electricity demand, the Greek State has been planning since 1992 to create a new TPS of 200MW in Atherinolakkos, SE of Crete. This station is based on two internal combustion engines of 2x51MW and two steam turbines of 2x50MW. However, the erection of this new station was strongly opposed by the local inhabitants on the basis of environmental impacts[19]. Consequently, the first two engines (2x51MW) entered operation during 2004, while the full operational year of the Atherinolakkos TPS was officially been transferred to 2006. Additionally, the Greek Regulatory Authority of Energy (RAE) recently called for tenders to build a new TPS of approximately 220MW near the city of Rethimno[20]. The whole procedure is just starting and the authors estimate the operation of Rethimno TPS in 2008 at the earliest.

In addition to all these TPS, in the island of Crete there operate several wind parks, total rated power 100MW (end of 2005). Note that the values used in the calculations refer to the system in 2004. More specifically, 18 wind parks of variable size exist in the island, Table II. These belong to either the PPC (1-4) or private investors (5-10, 13-18) and local municipalities (11-12). The majority of the existing wind farms are located in Lasithi prefecture, on the East side of the island, so as to exploit the excellent wind potential of the area. Seven (7) new small wind parks are under development; expected to be incorporated in the local electrical system during the next three years.

Table II: Existing and planned wind parks in Crete island (end of 2005)

	Location	**Prefecture**	**Owner**	**Start Up Time**	**Rated Power (MW)**	**Turbines Number**
1	Toplou	Lasithi	PPC	1993	5.10	17x300kW
2	Toplou	Lasithi	PPC	1993	1.00	2x500kW
3	Toplou	Lasithi	PPC	1995	0.50	1x500kW
4	Xirolimni	Lasithi	PPC	2000	10.20	17x600kW
5	Mitato	Lasithi	Private	1998	10.20	17x600kW
6	Chandras	Lasithi	Private	1999	9.90	18x550kW
7	Meg. Vrisi	Heraklio	Private	1999	4.95	9x550kW
8	Achladia	Lasithi	Private	1999	10.00	20x500kW
9	Anemoessa	Lasithi	Private	1999/2000	5.00	10x500kW
10	Krya	Lasithi	Private	1999/2000	10.00	20x500kW
11	Plativolo	Lasithi	Munic.-Priv.	2000	2.50	5x500kW
12	Mare	Lasithi	Municipality	1993	0.5	1x500kW
13	Vrouchas	Lasithi	Private	2003	7.65	9x850kW
14	Xirolimni	Lasithi	Private	2004	3.0	5x600kW
15	Plativolo	Lasithi	Private	2004	3.0	4x750kW
16	Krousona	Heraklio	Private	2004	5.95	7x850kW
17	Epanosifi	Heraklio	Private	2005	6.3	7x900kW
18	Modi	Lasithi	Private	2005	2.7	3x900kW
			Planned wind parks			
19	Xirolimni	Lasithi	PPC		3.0	
20	Ierapetra	Lasithi	Private		4.6	
21	Mires	Heraklio	Private		5.2	
22	Platanos	Chania	Private		3.3	
23	Spatha	Chania	Private		4.6	
24	Chonos	Lasithi	Private		4.5	
25	Mare	Lasithi	Municipality		1.2	

3. Analysis of the Problem

According to the data presented, the island of Crete faces a substantial deficit of energy demand fulfilment; while at the same time the excellent wind potential of the area cannot be fully exploited due to the local electrical grid stability barriers. More specifically, one of the major factors limiting the substantial wind power penetration has been the unreliability of the island’s weak autonomous electrical network. In this context, the local electricity utility (PPC) defines an upper wind energy participation limit "λ" in the instantaneous electrical power demand, to face undesirable local network problems. In addition, wind-farm operation should not violate the technical minima (N_{min}) of the conventional units. This limit is mainly empirically estimated, related to the existing thermal power units’ operational characteristics and the time dependent electricity load profile "$N_G(t)$". Thus, one may write:

$$
\begin{aligned}
N_{WT} &= 0 && \text{if } N_G(t) \le N_{\mathbf{min}} \\
N_{WT} &= N_G(t) - N_{\mathbf{min}} && \text{if } N_{\mathbf{min}} \le N_G(t) \le (1+\lambda)\cdot N_{\mathbf{min}} \\
N_{WT}(t) &\le \lambda \cdot N_G(t) && \text{if } N_G(t) > (1+\lambda)\cdot N_{\mathbf{min}}
\end{aligned}
\qquad (1)
$$

where "N_{WT}" is the permitted wind power of the system and "t" is the time.

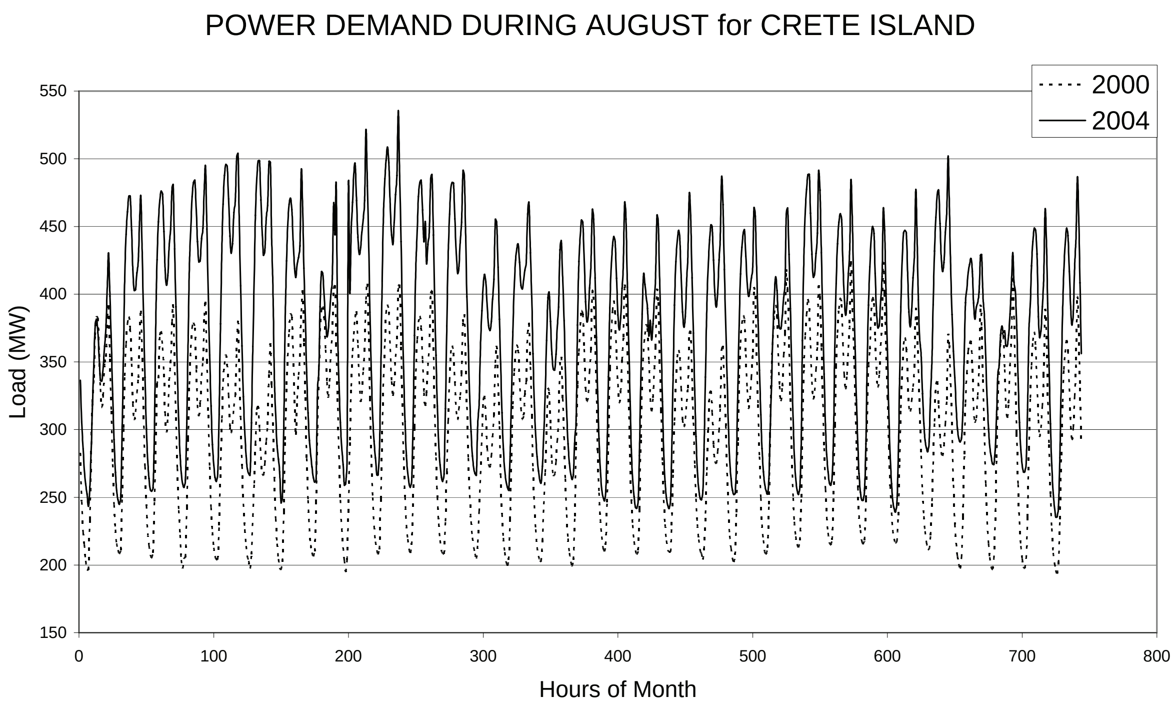

Figure 4: Electrical load variation for Crete (2000-2004); High-consumption period

Taking into account equation (1) and the island's highly variable electricity consumption profile -see for example figure 4- the maximum wind energy contribution to this consumption can be estimated. Besides, because of the stochastic wind behaviour, we cannot disregard the possibility of the available wind energy production being unable to cover the corresponding share given by equation (1).

Yet, there are numerous cases where the instantaneous wind energy production surpasses the limit of equation (1). In fact, attainment of this limit is even more possible as the installed wind power of the island is intensifying[21]. In all these cases, excess wind power has to be rejected, despite the situation in peak demand periods when the local TPS hardly cover the corresponding power demand, even using operational costly gas turbines.

Summarizing, the crucial drawback of the present situation is the use of expensive gas turbines to barely cover the island power demand; while at the same time significant wind energy production is rejected. Consequently, the excellent wind potential of the region is only partially exploited.

4. Wind Energy Rejection

A first estimate of the annual wind energy rejection is presented below, for which detailed information is essential on the following topics:

i. Time variation of the local network's annual electricity demand on an hourly basis at least, see figure 4.
ii. Time evolution of the technical minima, along with the annual maintenance plan of the existing and under-development thermal power units.
iii. Rated power and operational characteristics of the existing wind parks.
iv. Expected penetration rate of the new wind farms, along with their operational characteristics.
v. Time depending profiles (on an at least hourly basis) of wind potential parameters, regarding locations of existing or new-erected wind farms. For this, either the wind speed time-series or the corresponding wind power production of every wind park on the island is needed.

Using information of section 2 (see also Table I), with the annual maintenance plan of the existing thermal power units[16][17], the monthly technical minima of the system is presented in figure 5. Note that maintenance and upgrade of the system's TPS may be programmed during low consumption periods. In addition, future operation of the two new TPS is also included.

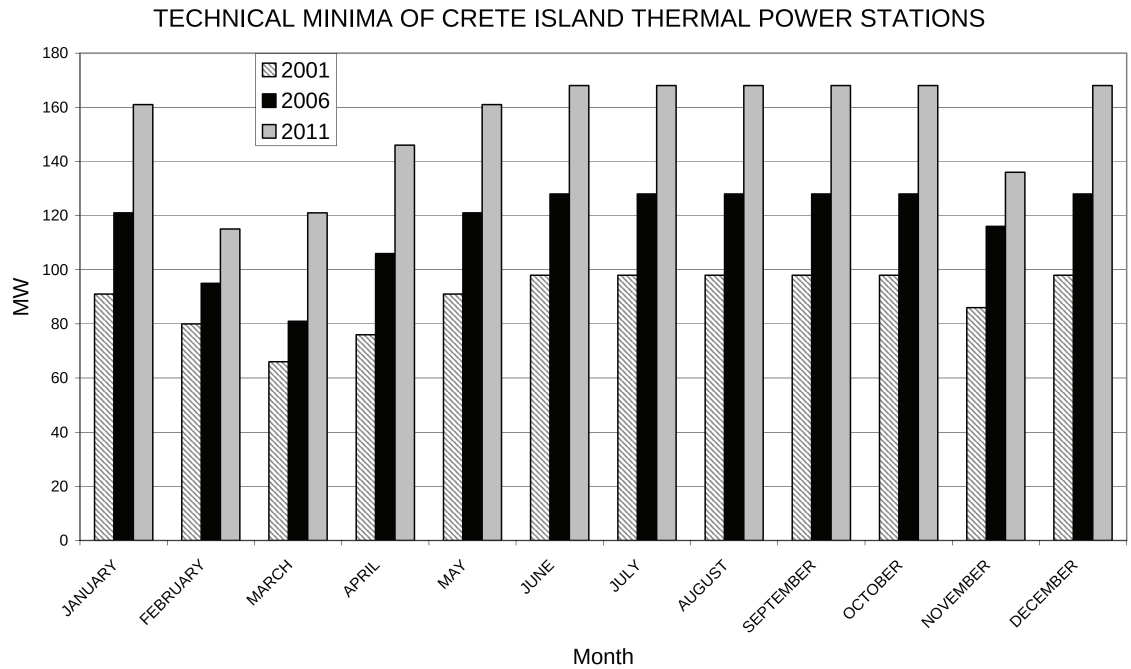

Figure 5: Estimation of the technical minima of the local system in the course time

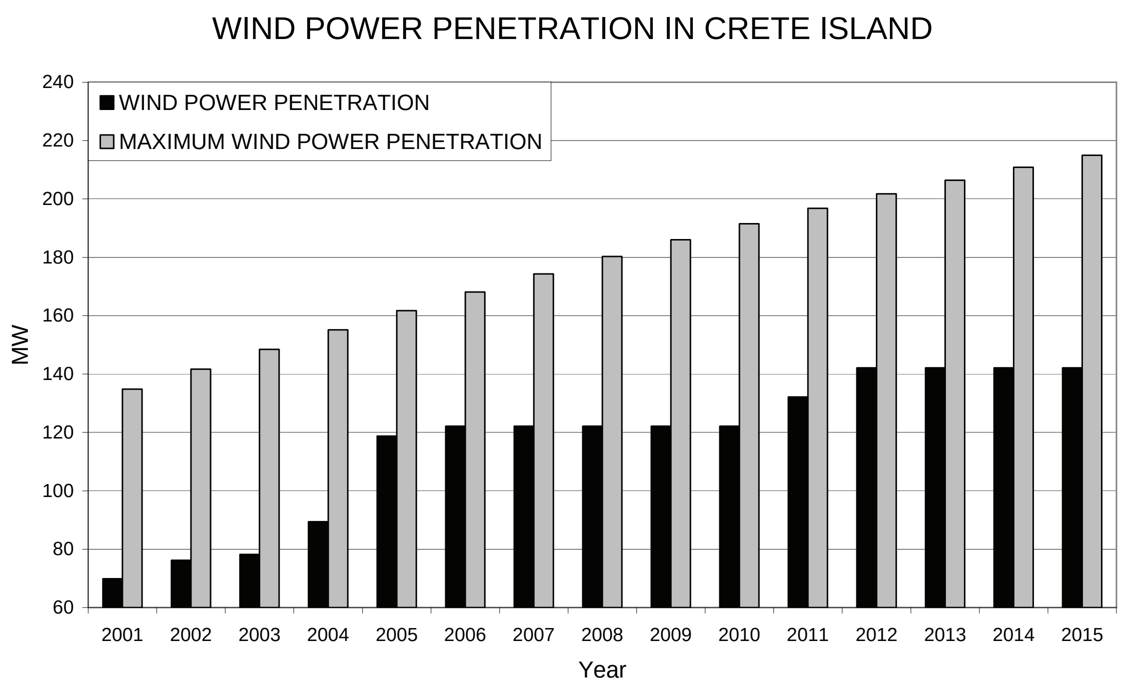

Figure 6: Wind power time evolution in Crete

In Table II, all basic operational characteristics of the existing wind parks are indicated, together with available information of the wind farms under-construction. As from Table II, thirty seven (37) wind turbines of rated power 16.8MW belong to PPC, while 6.1MW were operating on the island before the 2244/94 law applied. Also, 138 existing wind turbines of rated power 81.8MW belong to private investors and local municipalities, of which 0.5MW were installed before the law 2244/94.

Consequently, due to the excellent wind potential and the sufficient infrastructure of the area, requests for supplementary wind farms of 370MW reside in the RAE and the Ministry of Development[20]. Unfortunately, according to the existing legislative frame, the wind power penetration cannot exceed 30% of the system's peak load demand; see for example figure 2. Also, economic feasibility reasons[4][8][22] related to the amplified wind energy rejection, do not encourage new installations of rated power above 150MW up to 2015, with the exception of energy-storage-systems. Thus, considering the liberal subsidization already granted by the State authorities for several new wind parks of approximately 25MW in total, along with the usual new wind park erection rhythm in Crete, figure 6 demonstrates the expected evolution of Cretan wind power in comparison with the maximum permitted value, see also [23].

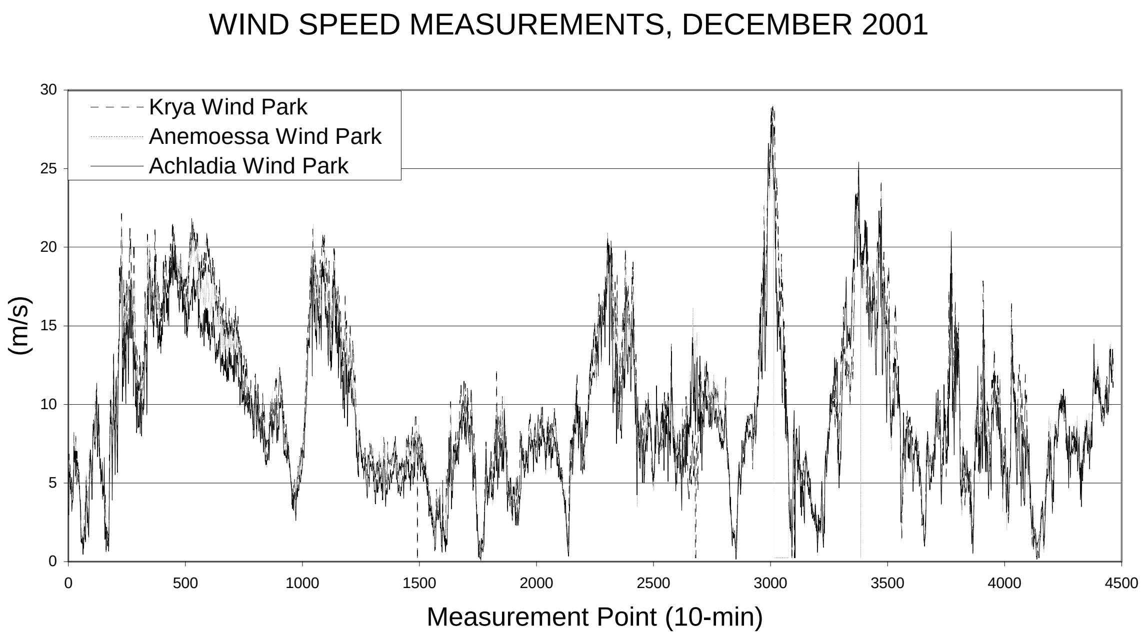

Figure 7: Wind speed measurements for December of 2001 at hub height (42m)

For the wind power time evolution in all wind-farm locations, much information is needed, in conjunction with reliable stochastic models able to reproduce wind speed time-series for the future derived from long-term wind-speed measurements. In order to improve the text clarity (given that the present work utilizes a first order estimation of the expected wind potential level) present calculations are based on the most likely annual wind speed time-dependent distributions. A parallel independent study is under preparation concerning the stochastic distribution of the wind speed in the course of time. For an introductory idea of the information used, examine in figure 7 the detailed (10 minutes average) wind speed distributions for three selected closely located wind parks (8,9,10 of Table II) at hub height (42m) for December 2001.

Finally, where there are no detailed wind speed measurements, the available values may be correlated to the existing detailed measurements in nearby regions in an attempt to reproduce the necessary data[24]. In addition, the bibliographically available numerical codes[25], properly calibrated, may also be used for the available wind speed measurements.

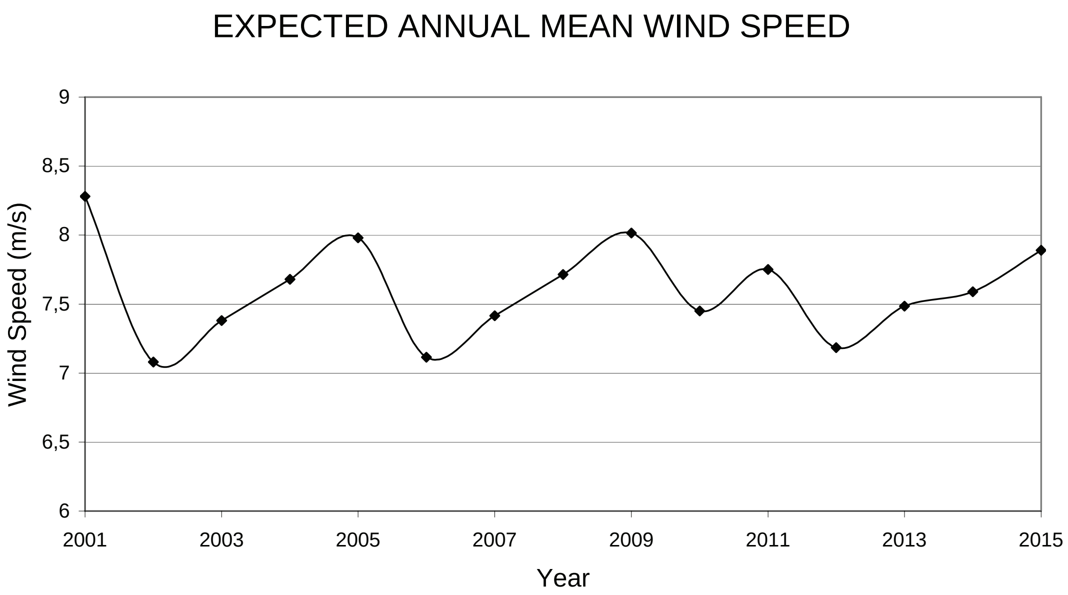

Figure 8: Expected annual mean wind speed versus time for a selected wind park

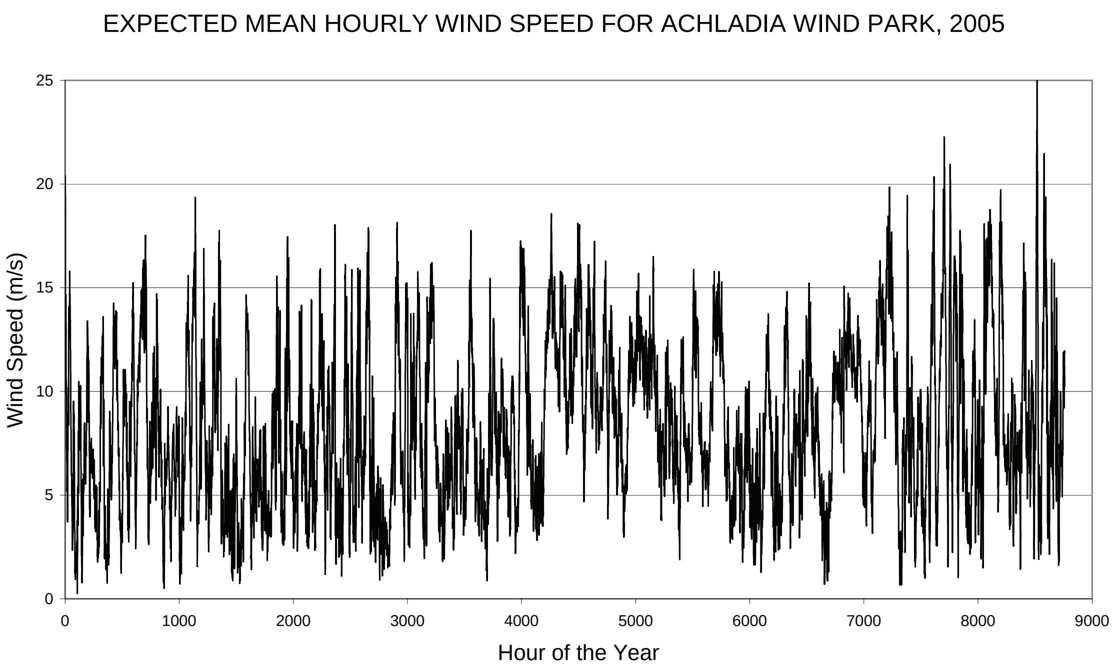

Figure 9: Expected wind speed time series for 2005, for a selected wind park

Using the above analysis, an example of the most probable annual mean-wind-speed is displayed for the 10MW wind park of Table II (line 8), for the 2001-2015 period, figure 8. Finally, the expected hourly mean-wind-speed distribution for the same installation can also be considered; see for example figure 9 for 2005.

5. Rejected Wind Energy

For wind energy rejection during a given time-period (e.g. one year) on an hourly basis, we require:

i. Estimation of the local grid load demand.
ii. Prediction of the existing wind-farm production, based on the available wind potential.
iii. Approximation of the system's current technical minima, using the analysis of section 4.
iv. Comparison of the load demand with the current technical minima of the existing thermal power units. Once the load-demand is less than the technical minima of the grid TPS, the entire wind production is rejected, equation (1).
v. If the temporary load demand is within the technical minima of the thermal power units and the technical minima of the system increased by "λ%", the excess demand (in comparison with the technical minima) is covered by the wind-farms in priority. Further wind power is rejected, equation (1). Note that wind-farms erected before the 2244/94 law (i.e. 6.6MW) enter the local grid first, during the wind power abortion procedure, while the residual wind power is divided between the other stations according to their power output.
vi. If the demand is higher than the technical minima of the system increased by "λ%", then the local network absorbs the wind energy production according to equation (1). Even in this case, wind energy surplus is rejected.

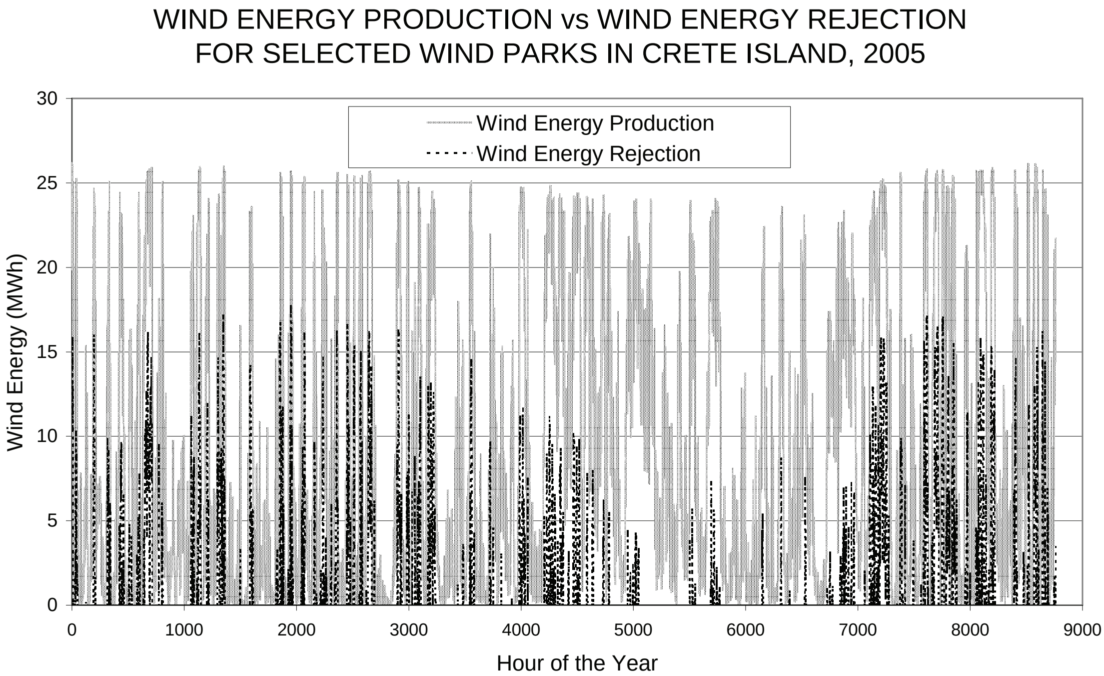

Figure 10: Estimated hourly wind energy rejection for selected wind parks during 2005

Additional wind power rejection is possible when serious problems appear in an electrical sub-grid component or even in cases of transmission lines instability or load asymmetry. Thus, the calculations based on the steps (i) to (vi) usually underestimate (by almost 15-30%) the corresponding wind energy rejection of the Crete wind farms[26].

Applying the above analysis, the hourly distribution of the wind-farms energy rejection may be estimated for every year. For example, in figure 10 we compare the time distribution of the expected wind energy production with the corresponding wind energy rejection for three selected wind parks (lines 8,9,10 of Table II, representing the 28% of the installed wind power) for the year 2005. These wind-farms employ pitch-controlled and variable-speed machines, allowing optimum integration with the local electrical network. Figure 11 shows the monthly wind energy rejection for the same wind-farms for 2001 and 2005.

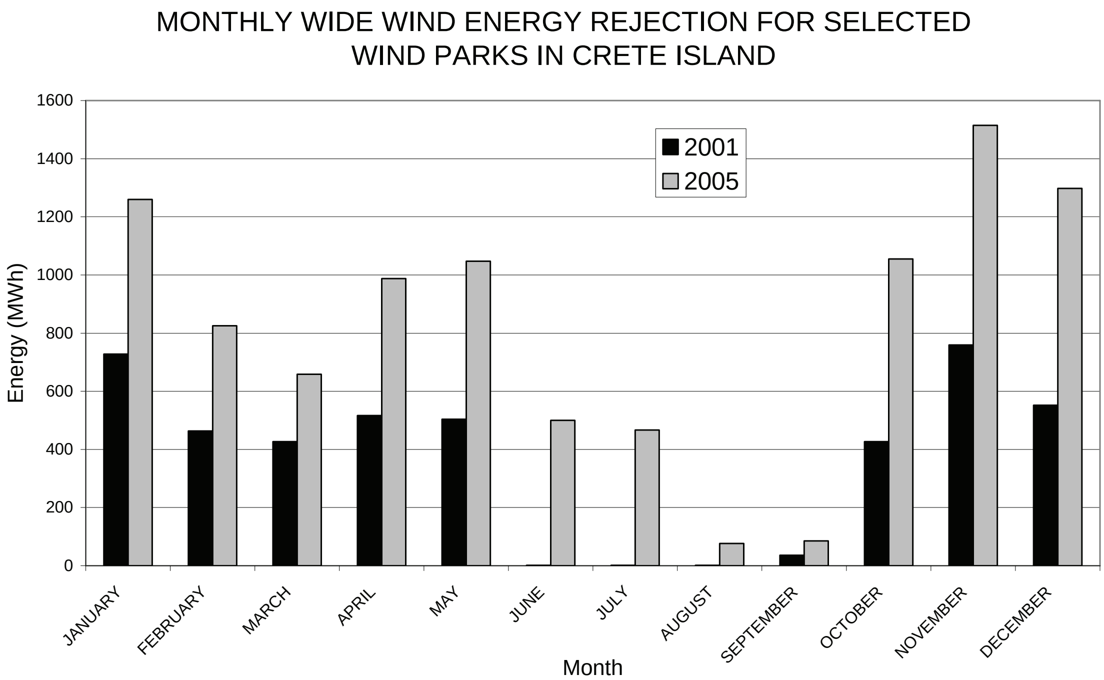

Figure 11: Comparison of monthly-wide wind energy rejection for selected wind parks between 2001 and 2005

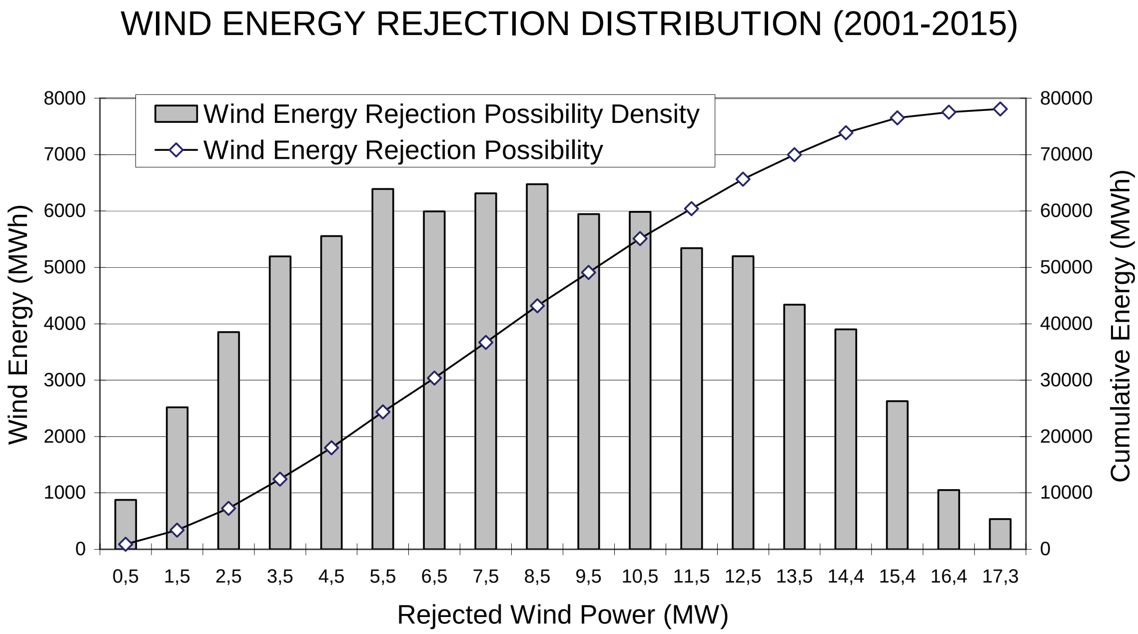

Figure 12: Wind energy rejection distribution vs. aborted wind power for the 2001-2015 period

Thus figure 12 presents the wind energy rejection distribution for the period 2001-2015, as a function of the instantaneous wind power aborted for the specific wind energy installations under investigation (rated power 25MW); lines 8-10 of Table II. From this, 76% of the potential wind energy is rejected when the set level of wind power rejection is less or equal to 12MW. Finally, for the three wind parks examined, the expected wind energy rejection equals 10,000MWh/y, being almost 10% of their annual wind energy production. This situation will deteriorate as additional wind power enters the local electrical system.

6. Proposed Solution

To avoid wind power rejection, several energy storage opportunities have been examined previously by the authors[10][11][27]. For the specific case of Crete, several combined wind-hydro stations are suggested in collaboration with grid enforcement activities and an integrate load-management plan. Moreover, the proposed solution may help water resource management[28], since the water reserves may also be used for land irrigation and water supply. This dual use of water reserves should definitely help alleviate water supply shortage, so improving the economics and benefit of the installations. More precisely, the proposed solution is based on the configuration of figure 13, i.e.:

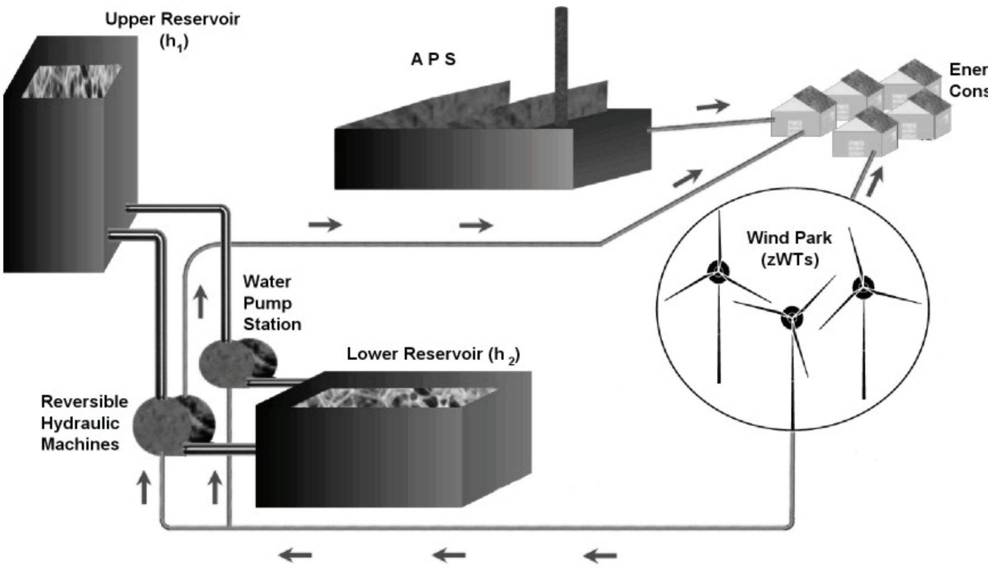

Figure 13: Proposed wind-hydro solution for Crete

a. One or more wind-farms
b. One or more small hydroelectric power plants
c. One or more water pumping stations
d. A number of water reservoirs (two minimum) at different elevations working in closed circuit and with corresponding pipelines. The area required is not prohibitive, since the entire water reservoirs volume required is less than 700,000m^3 (2x350,000m^3 for upper and lower reservoirs) at 280m height-difference to manage the wind energy surplus of the existing wind parks of the island (rated power 90MW).

The proposed solution is mainly directed at absorbing the wind energy surplus -rejected by the local electrical network due to low demand and grid instability- with rational installation-cost and minimum energy-loss. Accordingly, the energy stored could be consumed during the peak demand hours, to help the local network face the increased demand and minimizing the contribution of the high operational cost gas turbines.

The main drawback of such a solution appears to be the large capital installation-cost, basically depending on the water storage volume, the nominal power of the hydro turbines used[10][11] and the total efficiency of the entire transformation procedure, fluctuating between 50% and 70%[2][5]. Consequently, the final wind-hydro energy production cost is up to four times more than the corresponding production cost[4] of a simple wind park. Yet the wind-hydro production cost is less than the marginal operational cost of the existing gas turbine generators[1][2][17], which currently exceeds the 0.18€/kWh. For this reason, such a solution could be financially viable only when the price offered by the local network adequately compensates the prohibitively high production cost.

In order to support this costly purchase-price, the following should be noted:

a. The wind-hydro energy production should exclusively replace gas turbines of high diesel-oil consumption.
b. The wind-hydro energy production characteristics are excellent, since the hydro turbines are among the most reliable and easy-regulating electricity generators.
c. Additional electrical energy may be absorbed from the thermal power units, especially during their night operation near or below the corresponding technical minima, to be used during peak-load demand periods. In any case, such a station may contribute on improving the thermodynamic efficiency of the existing thermal power units.
d. The existence of wind-hydro installations facilitates the local network for coping peak power load periods, simultaneously increasing the system power reserves. In fact, during peak power demand periods or in the event of a system outage, water from the upper reservoirs can be released, producing electricity promptly[2][29].
e. Further wind power penetration to the Cretan electrical system becomes economically attractive because it abates polluting imported oil.

7. Minimum Acceptable Price of Wind-Hydro Electricity Generation

For the estimation of the minimum acceptable price derived from the wind-hydro electricity production, the cost-benefit model by the authors is adopted[4][30]. Prior to the model application, the numerical value of the following parameters should be defined. More precisely:

a. The average lifetime of the investment "n^*" is considered to be 15 years, a quite conservative value based on the minimum service period of wind farms and the long lifetime of hydro reservoirs.
b. The annual energy yield of the wind-hydro installation "E" results from the annual wind energy rejection per MW of operating wind power "ε" and the total energy transformation coefficient "η^*" of the entire wind-hydro system[2][10][11]. Therefore, the corresponding value "ε" in (MWh/MW or kWh/kW) may vary between 200MWh/MW and 500MWh/MW, mainly depending on wind power penetration in the local network.
c. The main parameters of local economy include the local market inflation rate "g", capital cost "i" and annual electricity price escalation rate "e". Drawing on local economic records[4], the parameters' mean values are taken as i=8%, g=3% and e=2%.

By the authors' previous work[4][30], the future value (after -n years of operation) of the investment cost of a water pumping-hydro power station is a combination of the initial installation cost and the corresponding maintenance and operation cost, both quantities given in current values. The initial investment cost "IC_o" includes the market price of the electro-mechanical equipment, the cost of the civil engineering works (including dam construction, penstock etc.) and the corresponding installation (or balance of plant) cost. Consequently, the future value of the initial investment cost can be expressed as:

$$IC_n = (1-\gamma)\cdot IC_o \cdot (1+i)^n \qquad (2)$$

where "γ" is the subsidy percentage by the Greek State, i.e. γ=30-50%.

The maintenance and operation (M&O) cost can be split into the fixed maintenance cost "FC_n" and the variable one "VC_n". Expressing the annual fixed M&O cost as a fraction "m" (m=1-2%) of the initial capital invested and assuming an annual increase of the cost equal to local market inflation ratio "g", the future value of "FC_n" is given as:

$$FC_n = m \cdot IC_o \cdot (1+g) \cdot (1+i)^n \cdot f_I \tag{3}$$

where:

$$f_I = \frac{1-\left(\frac{1+g}{1+i}\right)^n}{i-g} \tag{4}$$

The variable maintenance and operation cost mainly depends on the replacement of major parts of the installation, which have a shorter lifetime than the complete installation. For simplicity and due to the short lifetime period of the installation selected, we assume that "VC_n" is negligible in comparison with the other terms of the analysis, see for details[4][10].

Subsequently, the total savings (in current values) over an -n year period, due to the energy produced by the wind-hydro installation, are given as:

$$R_n = R_o \cdot (1+e) \cdot (1+i)^n \cdot f_{II} \tag{5}$$

where:

$$f_{II} = \frac{1-\left(\frac{1+e}{1+i}\right)^n}{i-e} \tag{6}$$

and

$$R_o = E \cdot c_o \tag{7}$$

In equation (7) "E" is the annual energy yield of the installation given as:

$$E = \varepsilon \cdot \eta^* \cdot N_w \tag{8}$$

and "c_o" is the present value of the minimum acceptable price of the wind-hydro electricity generation.

We now include the financial value of the rejected wind energy, expressed as a portion "r" of "c_o". Thus, the rejected wind energy (energy input cost) "EC_n" absorbed by the water pumping station over an -n year time period can be expressed as:

$$EC_n = \frac{r}{\eta^*} \cdot R_n \tag{9}$$

Additionally, one cannot disregard the amount paid in taxes by the water pumping-hydro power enterprise, "Φ_n" term. For simplicity and space-limit reasons, the impact of taxation, although significant, is not explicitly presented here. However, profits tax is properly included in all calculations[4][30].

Finally, the residual value "Y_n" of the investment is included[4] in the present cost-benefit analysis. The corresponding value is mainly due to amounts recoverable at the "n" year of the power station (e.g. value of land or dams or buildings, scrap or second hand value of equipment etc.) along with the experience gained and the corresponding technological know-how.

Using the above information and substituting the corresponding terms in the cost-benefit equation one gets:

$$R_n + Y_n - IC_n - FC_n - EC_n - \Phi_n = 0 \qquad \text{for } n=n^* \qquad (10)$$

or equivalently:

$$x = \frac{(1-\gamma) + m\cdot(1+g)\cdot f_I + \dfrac{\Phi_n - Y_n}{IC_o\cdot(1+i)^{n^*}}}{(1+e)\cdot f_{II}\cdot(1-\dfrac{r}{\eta^*})} \qquad (11)$$

where "x" is the ratio of annual revenues (present value) divided by the investment initial cost (viability ratio) i.e.:

$$x = \frac{R_o}{IC_o} = \frac{E\cdot c_o}{IC_o} = \frac{(\varepsilon\cdot N_w)\cdot\eta^*\cdot c_o}{IC_o} \qquad (12)$$

Using the analysis of relative works concerning the first installation cost of a hydro power station[10][11][31], the initial cost of a water pumping-hydro power station can be finally expressed as a function of the hydro turbines used rated power "N_H", see also [30]. More specifically one may use the following relation:

$$IC_o = Pr\cdot N_H \qquad (13)$$

where "Pr" is the specific (reduced) turnkey price (1500-2000€/kW) of the installation.

Substituting equation (13) in equation (12) one may estimate the "c_o" value as:

$$c_o = \frac{x\cdot Pr}{\varepsilon\cdot\eta^*}\cdot\frac{N_H}{N_W} = \frac{x\cdot Pr}{\varepsilon\cdot\eta^*}\cdot q = x\cdot Z\cdot q \qquad (14)$$

In equation (14) "N_w" is the wind power of the wind parks collaborated with the water pumping station and "q" is the ratio between the rated power of the hydro turbines used and the total wind power of the wind-hydro station.

Recapitulating, one can estimate the minimum wind-hydro electricity generation cost using equations (11) and (14) on the basis of the selected numerical values of all the problem parameters. Thus, in figure 14 we demonstrate the annual revenues ratio "x" versus the capital cost "i" variation for several typical State subsidization "γ" values. According to results of figure 14 the annual revenues of the installation should be between 7% and 13% of the total capital invested, including the State contribution, for a wide range of capital cost values (3%-23%), in order the amortization time of the investment to be 15 years. As expected, the lower the capital cost value the lower the corresponding viability ratio "x" value.

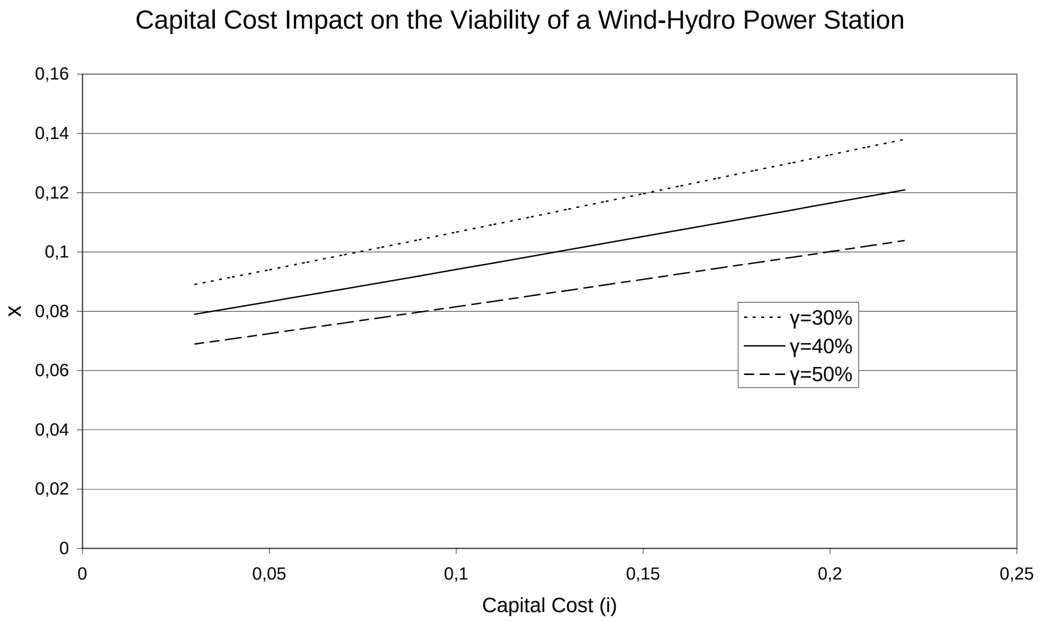

Figure 14: The impact of local economy parameters on the viability ratio of a wind-hydro power plant in Crete

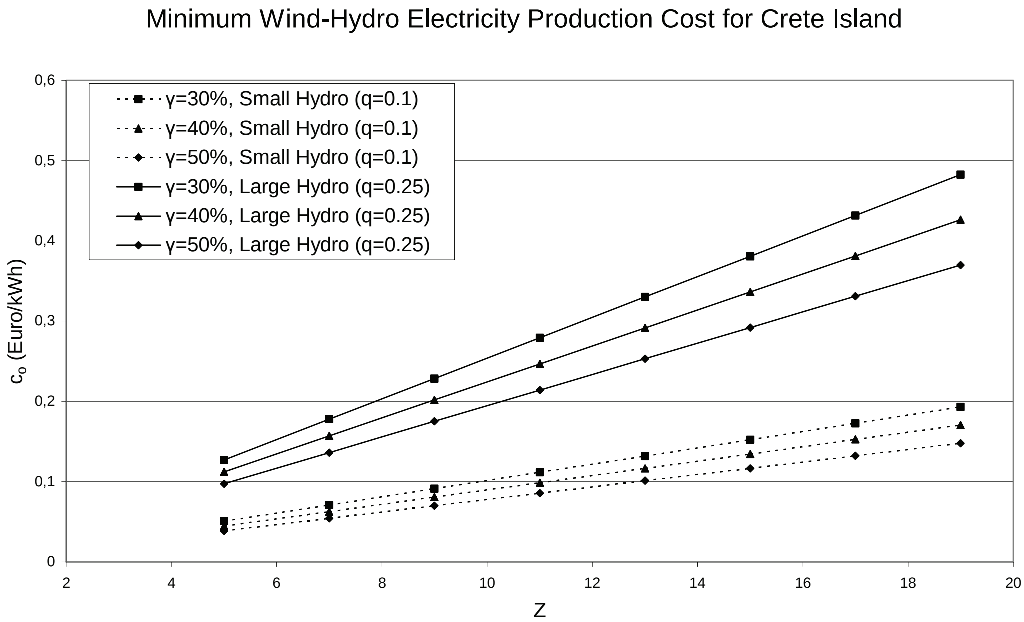

Figure 15: Wind-hydro electricity generation cost for Crete

Consequently, in figure 15 we present the corresponding minimum value of "c_o" (present value) as a function of "Z", where:

$$Z = \frac{Pr}{\varepsilon \cdot \eta^*} \left(\frac{\frac{\text{Euro}}{\text{kW}_{\text{hydro}}}}{\frac{\text{kWh}}{\text{kW}_{\text{wind}}}} \right) \tag{15}$$

This last parameter compares the water pumping and hydro power station reduced cost "Pr" with the annual energy ($\varepsilon.\eta^*$) finally given to consumption by the wind-hydro installation (otherwise rejected by the local network) per kW of rated power of wind parks investigated.

Thus the value of "c_o" increases in proportion to "Z" (i.e. as Pr increases or η^* and ε decrease). Besides, the minimum wind-hydro electricity production cost also depends on the ratio "q" of hydro turbines size divided by the wind-farms' rated capacity. More precisely, the less the value of "q" the less the production cost of the wind-hydro station. However, if the hydro turbines relative size "q" is minimal, there is no significant contribution of the proposed solution for the island's electrification problem. Thus, a higher "q" value (i.e. q=0.25) is more adequate for the present situation. In this case the minimum wind-hydro electricity production cost is definitely more than 0.074€/kWh, which is the current purchase price of wind-based electricity by the local network. In any case the most realistic values for "c_o" vary between 0.1€/kWh and 0.25€/kWh. Bear in mind that the average value of 0.175€/kWh is unquestionably less than the operational cost (currently 0.18-0.20€/kWh) of the existing old-fashioned gas turbine generators of the local system[17][23].

8. Conclusions and Proposals

Crete, like most Greek islands, actually faces an electrical power insufficiency problem especially during summer. In addition, the cost of electricity generation is extremely high due to the frequent gas turbines utilization. On the other hand, the island possesses an excellent wind potential, though partially exploited. Due to the weak local electrical network, the wind power penetration is bounded by technical and financial constraints. Therefore, one of the most promising ways to reduce large production cost, support the local electrical system reliability and avoid air pollution is to integrate properly sized wind-hydro power stations.

The present paper analyses the current electrical generation situation in view of increased wind power penetration in the local system. Special emphasis is given to estimating the annual energy yield and the corresponding wind energy rejection of the existing and under development wind parks. The wind-hydro solution is found to be technically applicable and financially attractive, provided the Greek State and the local network manager will support it. In this context, the expected marginal wind-hydro electricity production cost is predicted and compares favourably with the current operational cost of the existing thermal power units. Using available official information, the proposed solution may be applied together with considerable hydro power contribution, if the price offered by the local electrical network management is more than 0.175€/kWh. This value is clearly less than the operational cost of the local system's gas turbines.

Recapitulating, the proposed wind-hydro solution is not only financial advantageous in comparison with the existing thermal peak-power engines but it can also maximize the contribution of the wind energy to the Crete electricity supply, minimizing at the same time the wind energy rejection by the local system. The developed methodology can also be applied to several other Aegean Archipelago islands, so increasing wind power penetration and ameliorating the operational behaviour of the local electrical networks. Additional research is also necessary to optimise the dimensions of the wind-hydro system components and improve its economic competitiveness.

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TECHNO-ECONOMIC EVALUATION OF LARGE ENERGY STORAGE SYSTEMS USED IN WIND ENERGY APPLICATIONS

J.K. Kaldellis, K.A. Kavadias, A. Filios[1]
Laboratory of Soft Energy Applications & Environmental Protection
Mechanical Eng. Dept., Technological Education Institute of Piraeus
[1]Fluid Mechanics & Turbomachines Lab., School of Pedagogical & Technological Education

Abstract

Interest in employing renewable energy sources has significantly grown during the last few years, mainly as a reaction to the concern about environmental impacts from fossil and nuclear fuels, along with rate-instability in the international oil market. However, due to the periodic or even stochastic behaviour of the renewable energy sources (e.g. wind speed), the corresponding contemporary electricity generation systems cannot provide firm capacity to an electrical power system. Additionally, these fluctuations can -in some cases- cause problems to a distribution network related to stability, harmonics or flicker. Such issues present serious obstacles to the substantial penetration of wind energy, mainly into weak (medium or even large sized) power grids. On the other side, an energy storage system, when sized appropriately, can match a highly variable power production to a generally variable and hardly predictable system demand, remarkably limiting the energy production cost (e.g. generating capacity savings), taking also advantage of local wind potential overage. In the proposed study, a detailed cost-benefit analysis is carried out concerning the most widely used large scale storage systems used to cooperate with electricity power stations based on wind energy, for several representative electrical grid sizes. So therefore, an extensive parametrical study is presented taking into account the principal characteristics of the energy storage systems, like storage capacity (degree of autonomy), energy storage cost, life time duration and energy density offered. During the present work, emphasis is laid on the competitive advantages of the available storage systems, for cases of large and medium size autonomous networks. According to the results obtained, the utilization of the appropriate storage system can greatly ameliorate the economic attractiveness of any energy production installation, improving the acceleration of renewable energy applications in the autonomous island grids.

Keywords: Energy Storage, Pumped Hydro Storage, PHS, Compressed Air Energy Storage, CAES, Stand Alone Systems

1. Introduction

Interest in the use of renewable energy sources has significantly grown during the last few years, mainly as a reaction to the concern about the environmental impact from the use of fossil and nuclear fuels, along with the oil price instability and the energy supply security in the international market. On the contrary, renewable energy sources and especially wind energy have shown their independence from the economic fluctuations[1].

However, due to the stochastic behaviour of the wind, wind generation cannot provide firm capacity to an electrical power system[2]. Additionally, these fluctuations can -in some cases- cause problems to a distribution network related to stability, harmonics or flicker. Such issues present serious obstacles to the substantial penetration of wind energy primarily into weak (small) power grids[3]. On the other hand, an energy storage system, when sized appropriately, can match (see figure (1)) a highly variable wind power production to a generally variable and unpredictable system demand, remarkably limiting the energy production cost (e.g. generating capacity savings).

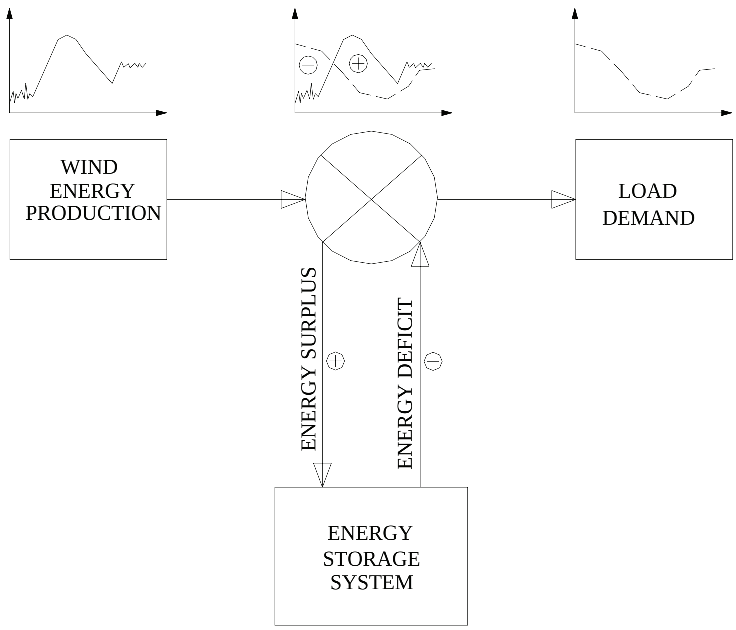

Figure 1: Typical energy storage system configuration

In the proposed analysis, medium-large scale storage systems are examined on the basis of their principal characteristics, like storage capacity (degree of autonomy), energy storage cost, life time duration and energy density offered.

More precisely, in the present work the capacity of pumped hydro storage and compressed air energy storage system to cooperate with wind parks –for typical electrical grid sizes- is investigated, including detailed cost-benefit evaluation.

2. Energy Storage Systems

The most mature energy storage technologies are:

- Pumped Hydro Storage (PHS)
- Compressed Air Energy Storage (CAES)
- Flow Batteries
- High Energy Capacitors
- Lead-Acid Batteries
- High Power Flywheels

The most widely used storage system is PHS with more than 100GW installed worldwide. Despite the lack of suitable sites for the PHS utilization, there is a continued interest in developing new systems using less land disrupting schemes, such us underground or sea based reservoirs. The most competitive to PHS energy storage system is CAES. It is important to note that CAES is not a pure energy storage system, as it stores high compressed air which requires a combustion unit and a turbine expander to provide output power.

Flow batteries[4] competes with the well-known technology of lead-acid batteries, which are characterized by low energy density, high maintenance, short lifetimes and limited discharge capability. From the three electrolyte materials that have been developed and commercialised for flow batteries the most interesting is the regenerative fuel cells (RFCs) with high depth of discharge, high cycle life and flexibility in both power and energy.

High energy capacitors[5] store electrical energy in the two series capacitors of the electric double layer which is formed between each of the electrodes and the electrolyte ions. Compared to lead-acid batteries, high energy capacitors have lower energy density but they can be cycled tens of thousands of times and are much more powerful than batteries (fast charge and discharge capability). While the small electrochemical capacitors are well developed, the larger units with energy densities over 20 kWh/m^3 are still under development.

Flywheels[6] have become commercially viable in power quality and UPS applications, and emerging for high power, high-energy applications. Their high capacity cost remains a suspending factor for their use in bulk electricity storage systems.

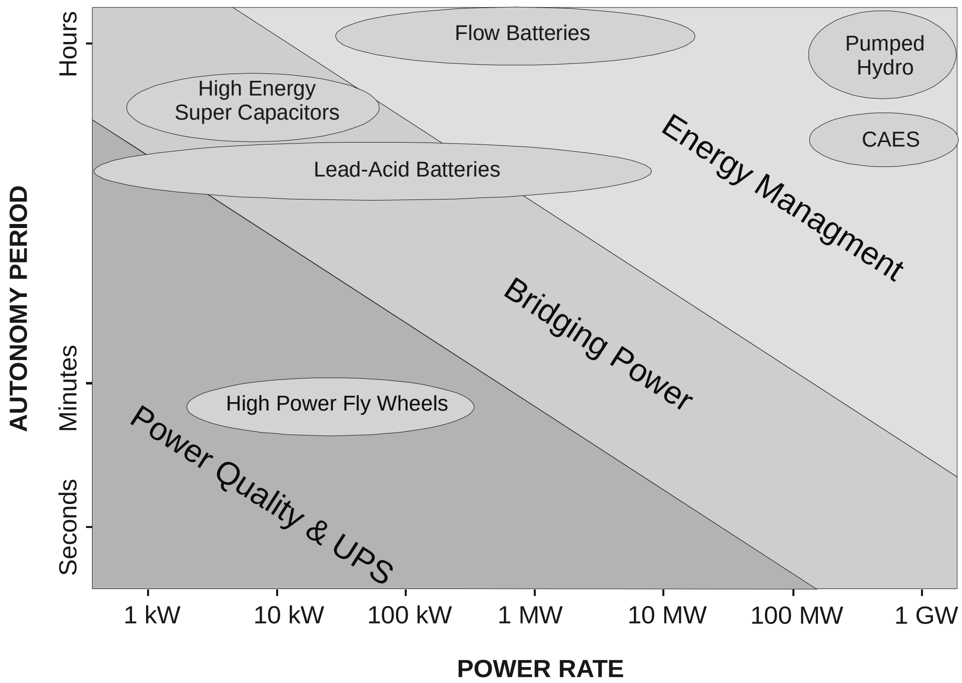

Figure 2: Uses and features of several storage systems (based on material by Electricity Storage Association)

Figure (2) demonstrates the different uses of the energy storage systems as well as their characteristics considering autonomy period and power rate. It is clear that the most mature storage technology so far for large scale systems is PHS and CAES, which combine high power rate in conjunction with high autonomy periods.

2.1. Pumped Hydro Storage

The PHS, which is a potential-energy storage system, represents the most economic artificial means presently available to store energy for stimulating electricity-generating utilities.

In a reversible wind-hydro storage system[7] the energy surplus is used to pump water into an elevated storage reservoir, figure (3). When power deficit appears the reversible hydraulic machines, working as hydro turbines, drive an electric generator in order to cover it.

The reversible wind-hydro storage systems are preferably used at regions where there are physical water reservoirs (e.g. lakes or rivers) due to their high initial cost. On the other hand, such systems may cover the load demand in a few seconds (4sec÷10sec) in addition to the high rate extracted energy.

2.2. Compressed Air Energy Storage

The basic idea of CAES[8][9] is to transfer off-peak energy produced by either conventional power units or renewable energy production systems during high demand periods, using only a fraction of the fuel that would be used by standard peaking machines, such as conventional gas turbines, figure (4). The CAES cycle is a variation of a standard gas turbine generation cycle. Therefore, when gas is combusted in a turbine, approximately two-thirds of the turbine's energy goes back into air compression. With a typical CAES system, the compression process is separated from the combustion and generation procedures.

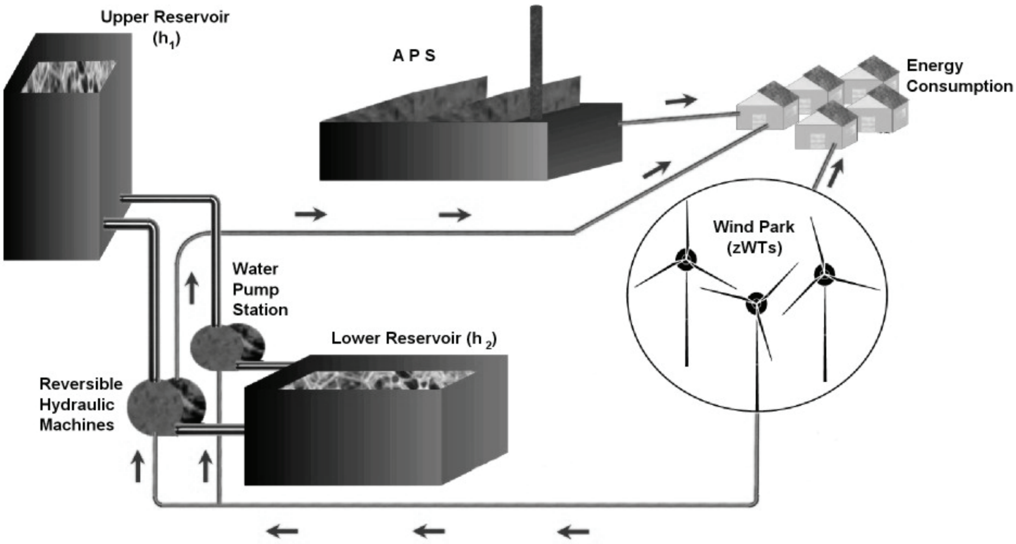

Figure 3: Integrated electricity production system based on PHS

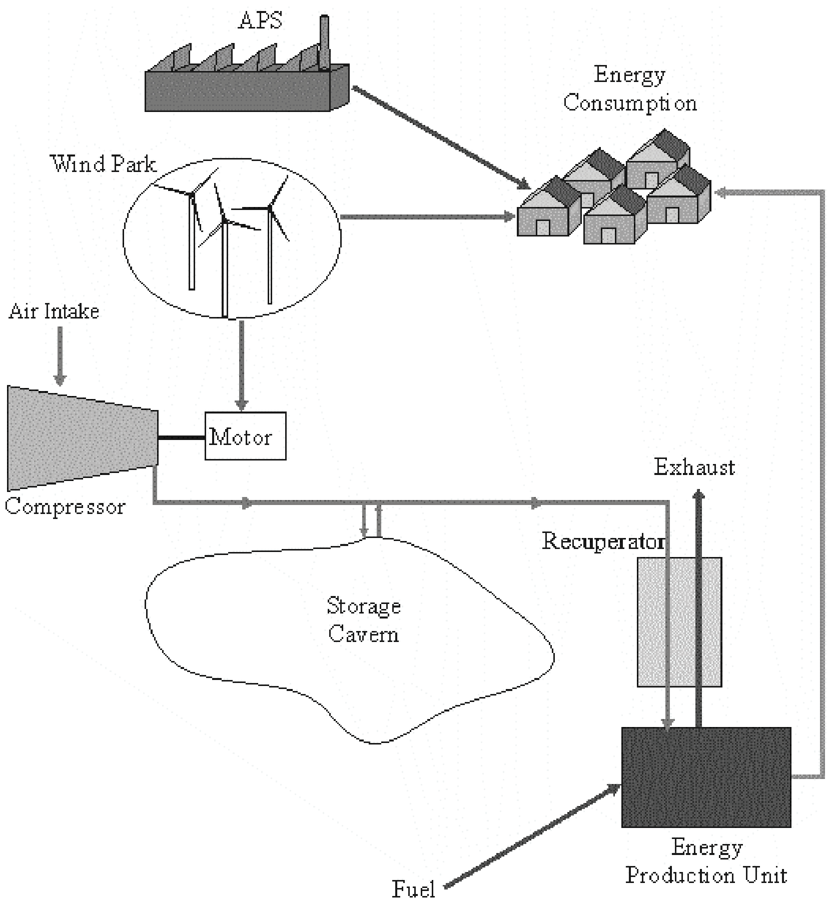

Figure 4: Integrated electricity production system based on CAES

Only two CAES facilities are in operation today[9]. The first one was constructed in Huntorf Germany in 1978 with a capacity of 290MW and 4 hour storage, while the second was built in McIntosh

Alabama in 1991 with capacity of 110MW and 26h storage. A third is being constructed in Norton Ohio with an ultimate capacity of 2700MW. The facility will be able to run at full capacity for 16h. There is also great interest in new installations worldwide, such us in Morocco and in Korea[10].

It is important to mention that the economic viability of a CAES system strongly depends on the storage media. The most commonly used are the salt caverns, the mined hard rock, the porous media and the buried pipe for small subsurface CAES units. The initial cost, depending on the storage media, can vary between 350 and 650 Euro/kW.

3. Economic Evaluation Model

The proposed evaluation model is developed for a remote island with "E_{tot}" annual energy demand and load capacity factor equal to "CF_L". In Table I we present the "E_{tot}" and "CF_L" values for selected typical Greek islands. According to the proposed evaluation model, for every island investigated the energy demand is covered by a properly sized wind park and the corresponding storage system. During the present analysis we assume that the total energy demand is covered either directly by the wind park "E_w" or via the storage system. In order to describe the contribution of the storage system to the total energy consumption we define the parameter "ε" as:

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

where "ε" takes values between zero (no storage system usage) and one (all the energy consumption is covered through the storage system).

Using the "CF_L" and "E_{tot}" values, the maximum (peak) load demand of the system is predicted as:

$$N_p = \frac{E_{tot}}{8760 \cdot CF_L} \tag{2}$$

Thus the required nominal power "N_o" of the wind park is given as:

$$\frac{N_o}{N_p} = \max\left\{1, \frac{CF_L}{CF}\left[(1-\varepsilon) + \frac{\varepsilon}{\eta_{ss}}\right]\right\} \tag{3}$$

where "CF" is the wind power station capacity factor[11] and "η_{ss}" is the energy transformation efficiency of the storage system. Generally speaking "CF_L" is greater than "CF" (see Table I) and since $\eta_{ss} \leq 1.0$ we expect $N_o > N_p$; thus:

$$N_o = \frac{E_{tot}}{8760 \cdot CF}\left[(1-\varepsilon) + \frac{\varepsilon}{\eta_{ss}}\right] \tag{3a}$$

Similarly the nominal power of the storage system "N_{ss}" is taken equal to "N_p" increased due to the power efficiency "η_p" of the system, thus:

$$N_{ss} = \frac{N_p}{\eta_p} = \frac{E_{tot}}{8760 \cdot CF_L \cdot \eta_p} \tag{4}$$

Finally, the energy storage capacity "E_{ss}" of the system also depends on the hours (days) of energy autonomy "d_o" of the remote consumer, as well as on the maximum depth of discharge "DOD_L" value of the storage system, therefore one gets:

$$E_{ss} = d_o \left(\frac{\varepsilon \cdot E_{tot}}{8760} \right) \frac{1}{\eta_{ss}} \cdot \frac{1}{DOD_L} \quad (5)$$

The initial cost of a storage system is usually expressed[12][13][14] as a function of the energy storage capacity "E_{ss}" and of the maximum power "N_{ss}" of the system, i.e.:

$$IC_{ss} = c_e \cdot E_{ss} + c_p \cdot N_{ss} \quad (6)$$

or

$$IC_{ss} = \left(c_e \cdot d_o \cdot \frac{\varepsilon}{\eta_{ss}} \cdot \frac{1}{DOD_L} + c_p \cdot \frac{1}{CF_L} \cdot \frac{1}{\eta_p} \right) \cdot \frac{E_{tot}}{8760} \quad (6a)$$

where "c_e" is a function of the type and the capacity of the storage system (Euro/kWh) and "c_p" depends on the type and the rated power of the storage system (Euro/kW). Accordingly, the initial investment cost of the wind park "IC_w" includes the market price "$P_r \cdot N_o$" of the machine (usually ex-works) and the corresponding installation-balance of the plant- cost "$f \cdot P_r \cdot N_o$". Thus we get:

$$IC_w = P_r \cdot N_o \cdot (1+f) \quad (7)$$

with "Pr"(=$P_r(N_o)$) the specific ex-works price[15] of a wind turbine, and "f"(=$f(N_o)$) expresses the installation cost as a fraction of the ex-works price of the wind turbines.

Summarizing the future value of the total energy production system (including the storage system) after –n year of operation, taking into account the fixed M&O cost of the installation, is given as:

$$C_n = IC_w \left[(1-\gamma) + m \sum_{j=1}^{j=n} \left(\frac{1+g_m}{1+i} \right)^j \right] \cdot (1+i)^n + IC_{ss} \left[m' \cdot \sum_{j=1}^{j=n} \left(\frac{1+g_{ss}}{1+i} \right)^j \right] \cdot (1+i)^n + \\ + IC_{ss} \left\{ \sum_{\ell=0}^{\ell=\ell_{ss}} \left[\frac{(1+g_k) \cdot (1-\rho_k)}{1+i} \right]^{\ell \cdot n_{ss}} \right\} \cdot (1+i)^n \quad (8)$$

with "ℓ_{ss}" the integer part of the following equation:

$$\ell_{ss} = \frac{n-1}{n_{ss}} \quad (9)$$

and "n_{ss}" is the lifetime of a storage system.

More precisely the operational life of a storage system depends on the type, on the utilization factor "ε" and on the "DOD_L" of the system. Additionally, "g_k" and "ρ_k" describe the mean annual change of the price and the corresponding level of technological improvements for every storage system analyzed. Finally "γ" is the subsidy percentage by the Greek State for wind energy applications (γ=0.4), "m" and "m'" express the annual fixed M&O cost of the wind park and the storage system respectively, given as a fraction of the initial capital invested. On top of that an annual increase of the M&O cost equal to "g_m" and "g_{ss}" is also incorporated.

Thus, for the calculation of the energy production cost present value "c_o" the following relation[16] can be used:

$$c_o = \frac{C_n}{E_{tot} \cdot (1+i)^n \cdot \sum_{j=1}^{j=n} \left(\frac{1+e}{1+i} \right)^j} \tag{10}$$

where "e" is the electricity price escalation rate.

Substituting equation (8) into equation (10) and using the appropriate values for the components of the energy production-storage system, it is possible to estimate the energy production cost "c_o" for various hours of autonomy "d_o" and size of remote consumers "E_{tot}", as well as for several degrees of utilization "ε" of the storage system.

For this purpose equation (11) reads in view of equation (8) as:

$$c_o = \frac{IC_w}{E_{tot}} \left\{ \frac{(1-\gamma) + m \cdot X \cdot \frac{X^n - 1}{X - 1}}{Z \cdot \frac{Z^n - 1}{Z - 1}} \right\} + \frac{IC_{ss}}{E_{tot}} \left\{ \frac{m' \cdot Y \cdot \frac{Y^n - 1}{Y - 1} + \sum_{\ell=0}^{\ell=\ell_k} \left[\frac{(1+g_k) \cdot (1-\rho_k)}{1+i} \right]^{\ell \cdot n_k}}{Z \cdot \frac{Z^n - 1}{Z - 1}} \right\} \tag{11}$$

where:

$$X = \frac{1+g_m}{1+i} \tag{12}$$

$$Y = \frac{1+g_s}{1+i} \tag{13}$$

and

$$Z = \frac{1+e}{1+i} \tag{14}$$

Keep in mind that "i" is the annual mean capital cost of the local market.

4. Application Results

The developed calculation frame is applied initially to a medium-size island (see Table I) with annual energy consumption equal to 1,400,000 kWh and load capacity factor 32.5% and accordingly to a large island with annual energy consumption approaching the 186,000,000 kWh (load capacity factor 52.5%). The expected capacity factor of an installed wind farm in the areas under investigation (using the wind potential parameters-wind turbine power curves) is 30%[17][18]. The operational characteristics of the storage systems analyzed are given in Table II, according to an extensive market survey. The main target of the proposed analysis is to estimate the current energy production cost of the complete energy management system for various cases of storage system contribution "ε" and for selected hours of the installation energy autonomy "d_o".

Table I: "E_{tot}" ,"CF_L" values for selected Greek Islands

Island	Total Annual Energy Consumption (kWh)	CF_L (%)
Kythnos	1,400,000	32.5
Lesvos	186,000,000	52.5

Table II: Operational characteristics of the storage systems investigated

Storage System Data	n_{ss} (years)	DOD_L (%)	η_{ss} (%)	η_p (%)	c_e (Euro/kWh)	c_p (Euro/kW)	m' (%)
Pumped Hydro Storage	>20	95	60÷70	80÷85	10÷50	1000÷2000	2.5
Compressed Air Energy System	>20	70	70÷80	80÷85	1÷5	300÷1000	2.5

Bear in mind that the proposed configuration exclusively consists of several wind parks (see equation (3)) able to cover the local energy consumption with the corporation of an energy storage system. The storage system size depends on the energy capacity required (equation (5)) and the days of energy autonomy of the specific island under investigation.

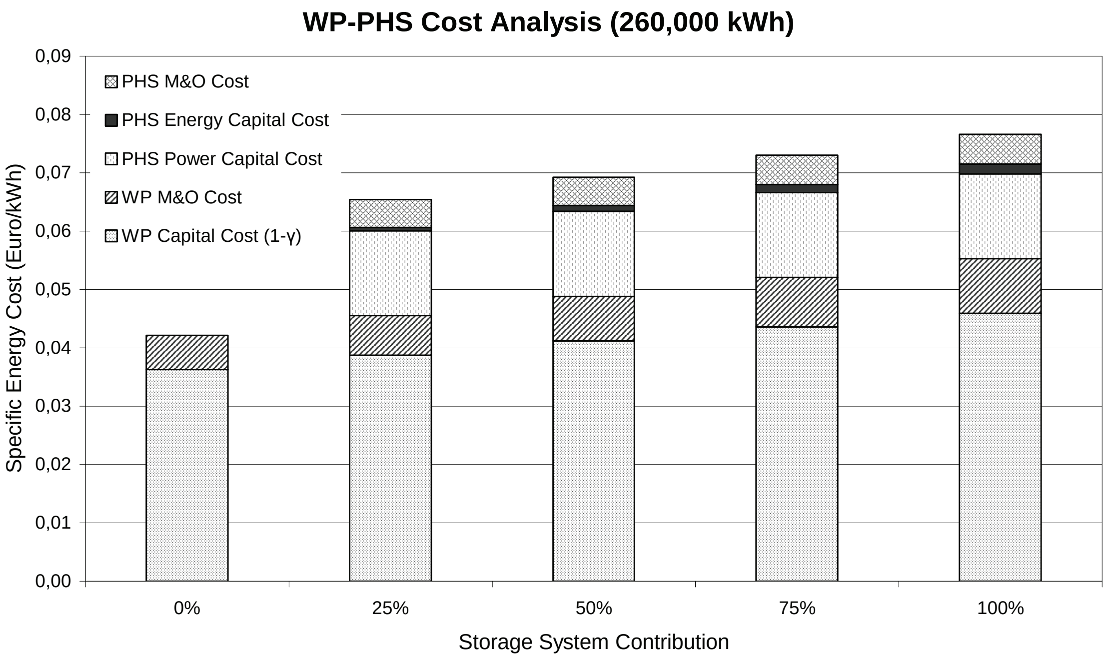

Figure 5: Cost analysis of WP-PHS system

After selecting typical values for the economic parameters of the local market (i.e. m=2%, γ=0.3, g_m=g_{ss}=3%, e=5%, i=8%) the calculation results for various "ε" values (ε=0%, 25%, 50%, 75%, 100%) are given in figures (5) to (12) for all the storage systems tested and for d_o=2, 12, 48 hours of energy autonomy for the medium and the large size islands investigated.

According to the results obtained (figures (5) and (6)) for 12 hour of energy autonomy in Lesvos Island (260,000kWh) the specific energy cost is highly affected by the storage system configuration. As it is obvious, the wind parks energy production cost is 4c€/kWh (excluding any reserve capacity cost), while by adding the PHS this value increases by 50%. Accordingly, by adding a typical CAES the energy production cost amplification exceeds the 100%. Consequently, as far as the total energy cost is concerned, the CAES is in any case more expensive than the PHS. It is also important to mention that typical CAES systems require the consumption of fuel in order to provide electrical power to the final consumer. In the present study the fuel used is natural gas.

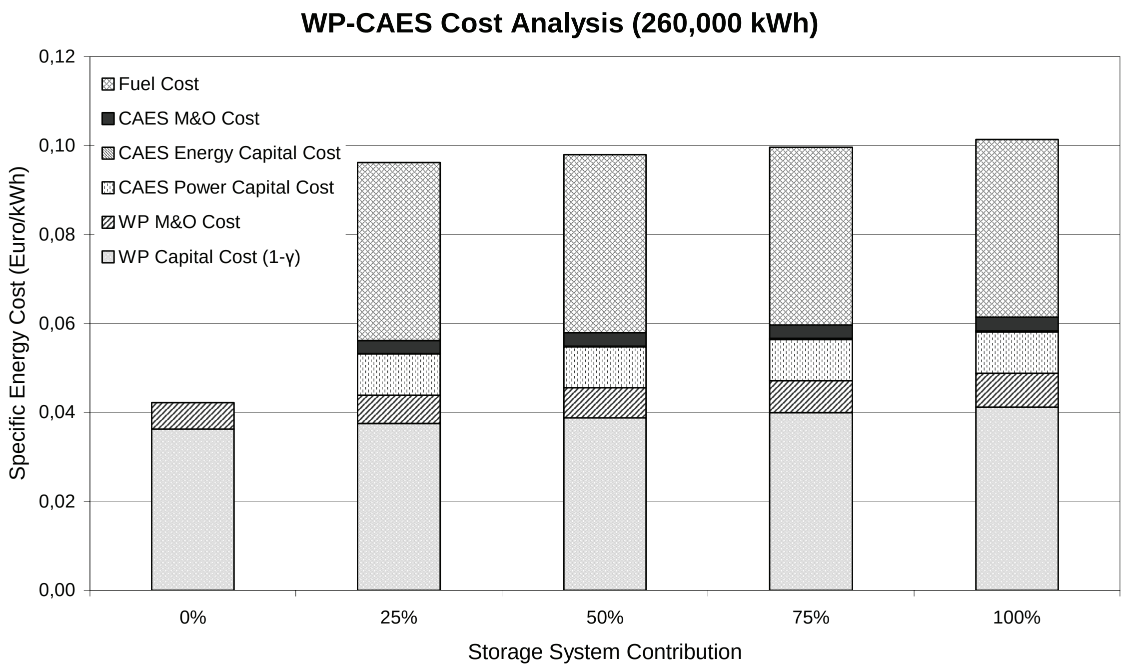

Figure 6: Cost analysis of WP-CAES system

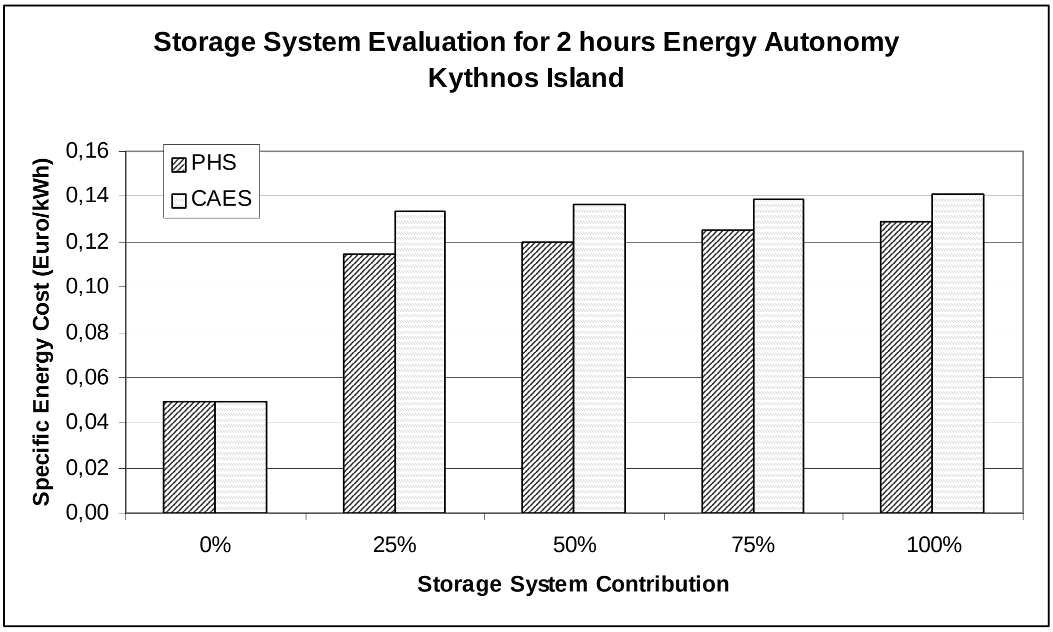

Figure 7: Storage system evaluation for medium size island (2h autonomy)

In the case that we isolate -from the CAES utility- only the compressor and the storage cavern contribution, the corresponding specific energy cost varies between 5c€/kWh and 6c€/kWh. Finally, despite the fact that the specific capital cost of the PHS is almost triple the one of the CAES, the specific energy price due to the capital cost is almost the same for both cases, which results from the different efficiency of the two systems.

Finally, according to the energy production cost analysis, the increase of the specific energy cost is mainly attributed to the wind parks cost, while the contribution of the energy storage system cost is minimal. More precisely, by increasing the storage system usage, the wind parks nominal power increases (via the energy efficiency of the storage system) in order to cover the energy consumption needs (see also equation (3a)). Provided that the total energy efficiency of the PHS is lower than the one of CAES, the cost amplification in the case of PHS is 7% while the corresponding value for CAES is 4%. It is also important to mention that storage system represents up to 30% of the PHS energy production cost and 20% for the CAES system. In the case of CAES the fuel cost contribution is up to 40%.

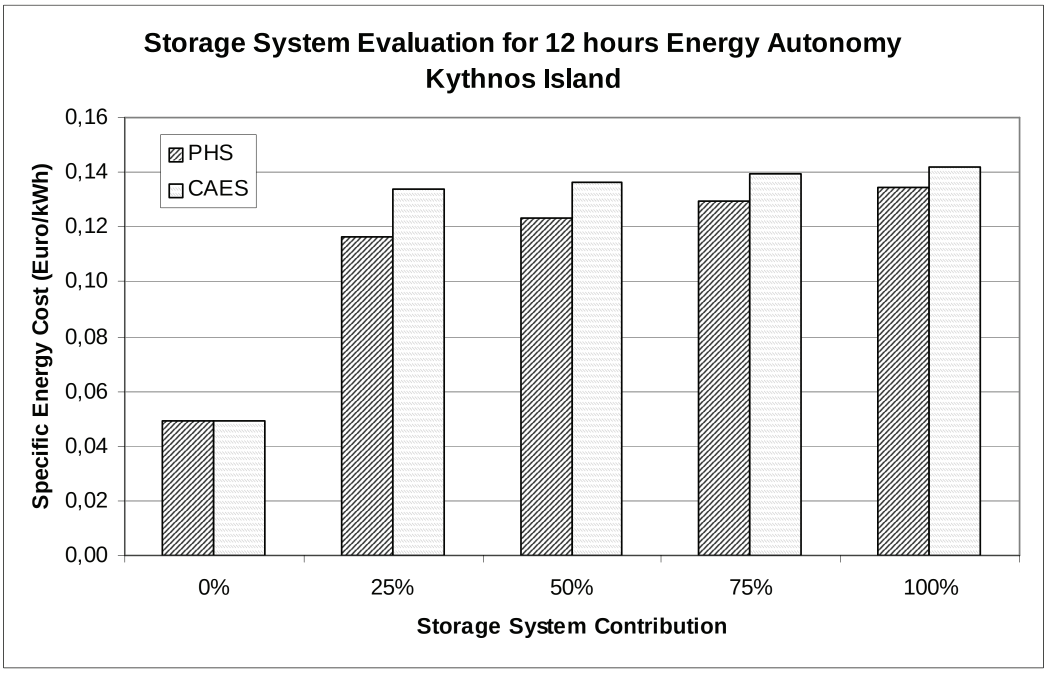

Figure 8: Storage system evaluation for medium size island (12h autonomy)

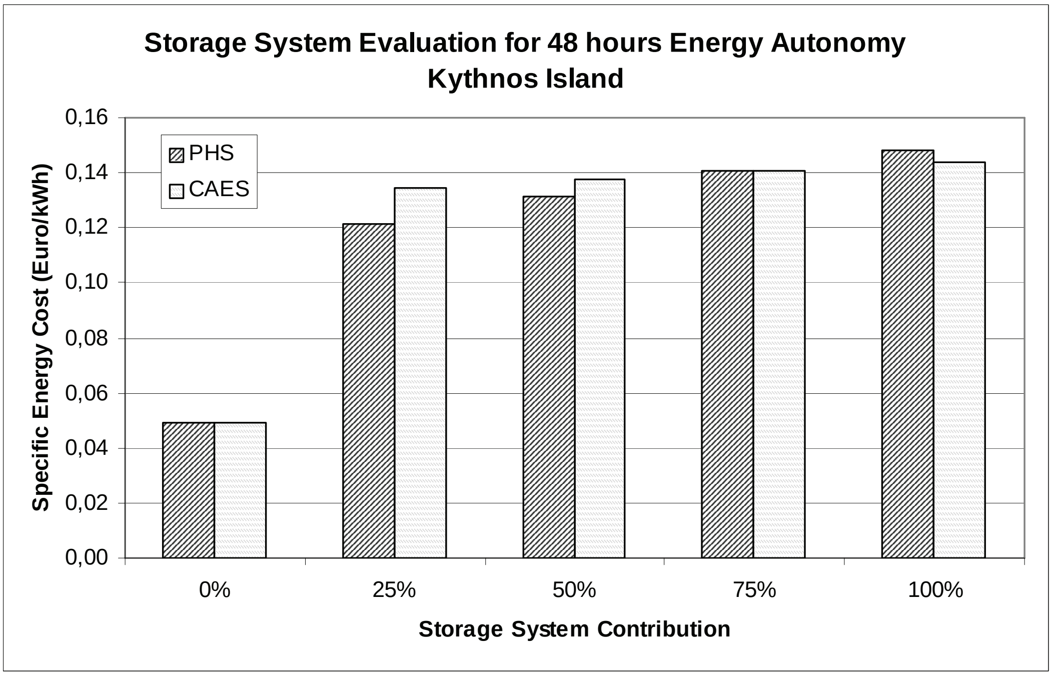

Figure 9: Storage system evaluation for medium size island (48h autonomy)

The results obtained for the case of a medium-size island (Kythnos Island) are presented in figures (7) to (9). Focusing on the different size of the storage system (2, 12 and 48 hours of autonomy), for small size configurations the total specific energy production cost of the CAES (including the fuel cost) and the PHS systems is almost the same. In the case of 48 hours of energy autonomy (7800kWh), using the storage system by 100% (the consumption is covered exclusively via the storage system), the specific energy cost of the CAES is less than the one of PHS. Due to the high installation cost of the PHS, the price of the energy is more affected by the increase of the system's size than the CAES.

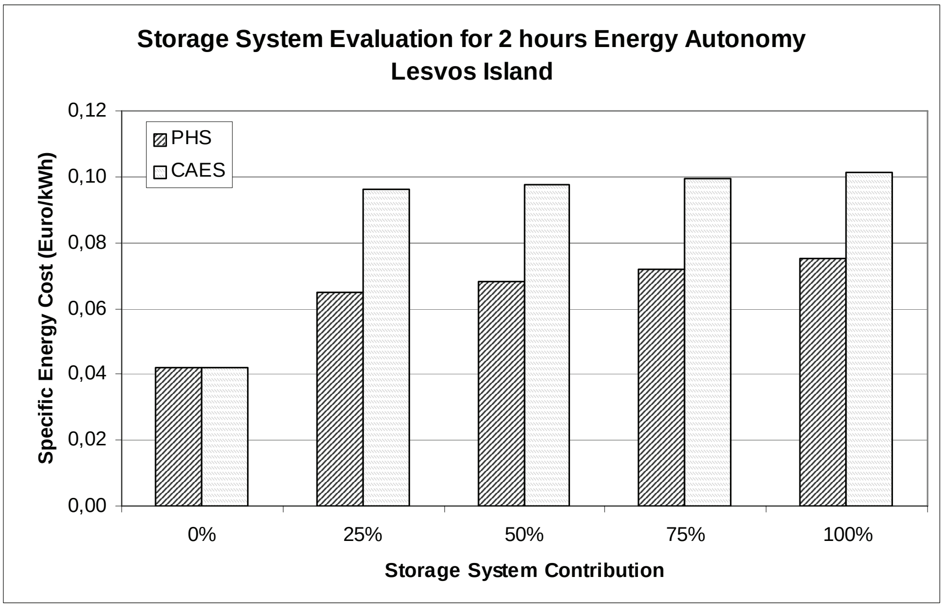

Figure 10: Storage system evaluation for large size island (2h autonomy)

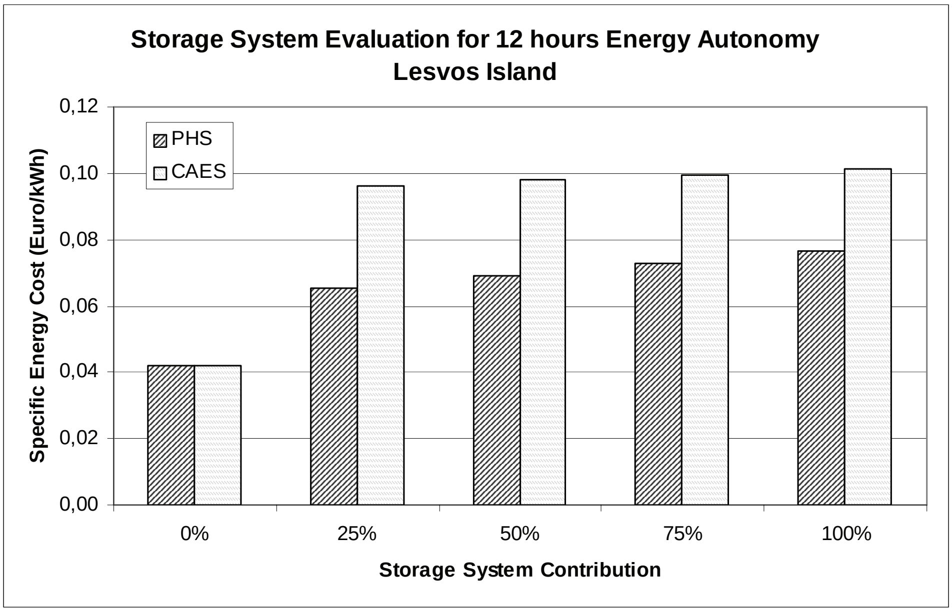

Figure 11: Storage system evaluation for large size island (12h autonomy)

In fact, the situation changes for large size systems (e.g. Lesvos Island). According to figures 10 to 12, the specific energy cost of the CAES system remains higher than the PHS one, while the absolute difference approaches the 3c€/kWh.

5. Conclusions

The present study describes an integrated evaluation model, concerning the economic behaviour of energy storage systems in collaboration with wind turbine installations for medium-large remote islands. Both energy storage alternatives demonstrate remarkable technoeconomic advantages. However, according to the results obtained, CAES cost is highly affected by the fuel consumption.

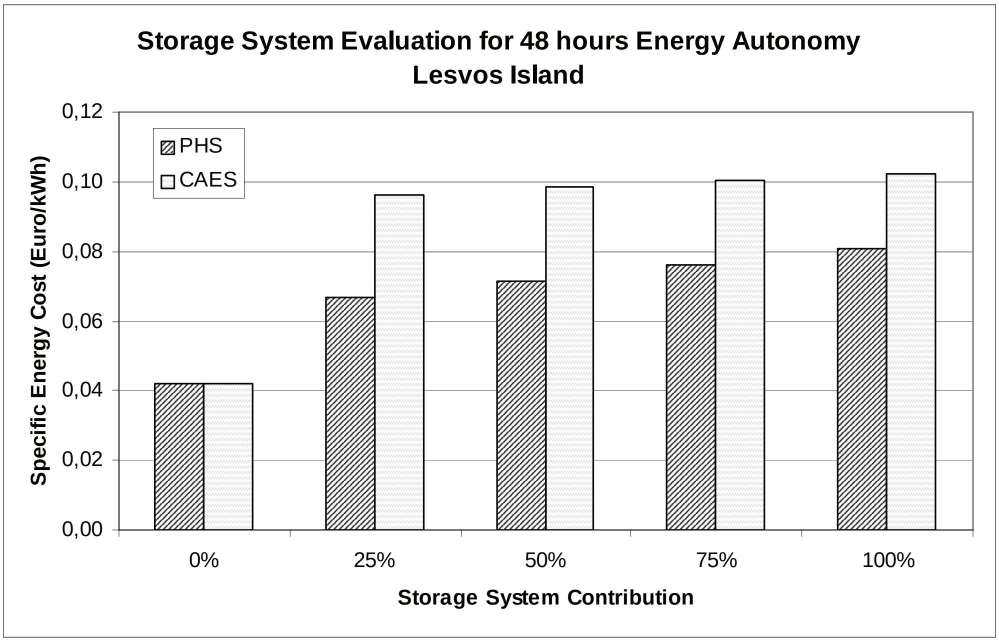

Figure 12: Storage system evaluation for large size island (48h autonomy)

A complete installation of CAES system cannot be considered as a renewable energy power plant due to the fuel consumption required. If a power plant based only in renewable energy sources is desired, the option of using biofuels instead of conventional fuels may be considered. An integrated renewable energy plant based on CAES should also include a biofuel production plant that may absorb the wind energy surplus rejected by the energy storage system.

The energy efficiency of the storage system highly contributes to the required rated power of the wind parks in order to cover the load demand. For this reason, the soft energy installations have to be accompanied by storage systems with high energy efficiency in order to achieve high renewable energy penetration values.

In the case of small configurations the specific energy cost of CAES competes with the energy cost of PHS, including the fuel cost. In all cases the specific energy cost is higher than the one of a single wind park. One should also take into consideration the increased wind power penetration in case of energy storage.

Recapitulating, the utilization of the appropriate storage system can ameliorate the economic attractiveness of any wind energy installation, improving also the acceleration of wind power applications in the autonomous island grids.

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RENEWABLE ENERGY BASED HYDROGEN PRODUCTION METHODS: AN ECONOMIC AND ENERGY EFFICIENCY COMPARISON

K.A. Kavadias, E. Kondili[1], J.K. Kaldellis
Laboratory of Soft Energy Applications & Environmental Protection
[1]Optimisation of Production Systems Lab
Mechanical Eng. Dept., Technological Education Institute of Piraeus

Abstract

The latest fluctuations in the price of conventional energy have made the use of alternative fuels for the production of energy a necessity. At the same time, the increased world community consciousness on the environmental pollution, poses an imperative need for a shift to other environmentally friendly methods of energy production. One of the most promising alternative fuels, with significant technological development, is the hydrogen. The production of hydrogen can be realised either from conventional fuels or from friendlier to the environment methods. On the other hand, the constant and continuous developments in the field of renewable energy have resulted in satisfactory levels of economic attractiveness and also technologic maturity. The design and operation of a renewable energy system that supplies part of its energy output to a hydrogen production unit, constitutes a promising solution for the energy and environmental issues of our planet. The present work reviews the reliability of the currently available hydrogen production methods. Additionally, the possibility of combining the above production methods with renewable energy systems is investigated. Finally, a detailed techno-economic evaluation of the combined systems is carried out, based on the initial investment cost, in order to determine the hydrogen production cost.

Keywords: Hydrogen Production, Alternative Fuels, Electrolysis, Renewable Energy

1. Introduction

Although hydrogen is the most abundant element in the universe, it cannot be found in its elemental form free on the Earth. It must be produced from other compounds such us water, biomass or fossil fuels. Each of the above hydrogen production methods requires some form of energy, such as heat, light, or electricity.

The nine million tons of hydrogen produced each year[1] are used mainly for chemicals, petroleum refining, metals, and electronics. For example, the gasoline and diesel fuels production processes, such as the breakdown of heavier oils and the sulphur removal process are the major users of hydrogen. The ammonia production, used in fertilizers, also consumes large amounts of hydrogen.

During the last twenty year, renewable energy and especially wind energy has been proven[2][3] to be a mature electricity production technology, constituting not only an economically attractive option for the worldwide energy demand, but also a sustainable energy solution with very limited environmental impact[4].

In many Greek regions and more precisely in the Greek islands, although their renewable potential is significantly high, there is an incapability of the local autonomous electrical networks to absorb the renewable energy produced[5]. Other barriers against renewable energy penetration are caused mainly from the significant gap between energy production and demand[6]. This is particularly observed in the case of wind energy - at present the leading renewable technology- and is due to the stochastic variability of the wind speed. As a result, significant amounts of renewable energy are rejected by the local grids[5][7]. On the other hand, hydrogen can be produced by renewable energy sources. More

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specifically, the excess energy that is rejected by the local grid could be used to produce hydrogen (e.g. via electrolysis), thus increasing the effective capacity factor of renewable energy applications.

2. Hydrogen Production Methods

2.1. Methods based on fossil fuels

Hydrogen can be produced either by conventional or by renewable energy sources (figure (1)). Steam reforming is the most energy efficient commercialized technology currently available, and it is most cost-effective when applied in large, constant loads. It is a thermal process that involves the reaction of natural gas -or other light hydrocarbons- with steam[1] and is carried out typically over a nickel-based catalyst. The product of this three-step process is a mixture of hydrogen and carbon dioxide, which then undergoes a pressure swing adsorption for the separation of pure hydrogen. In the United States, approximately 95% of hydrogen is currently produced via steam reforming[8]. Main research directions for this process are the improvement of the energy efficiency of the process and the extension of catalyst's life. The energy efficiency is improved mainly through heat integration, which would lower the temperatures required in the reformer.

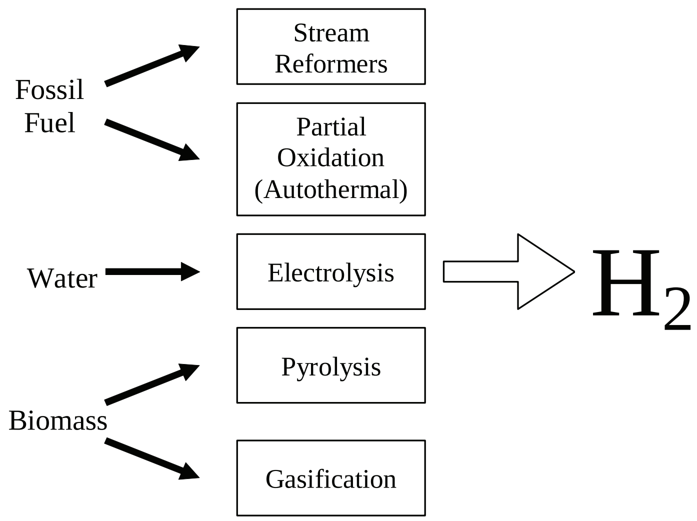

Figure 1: Hydrogen production methods

Partial oxidation of fossil fuels is another method of thermal production. It involves the reaction of the fuel with a limited supply of oxygen to produce a hydrogen mixture, which is then purified for the hydrogen production[8]. Partial oxidation can be applied to a wide range of hydrocarbon feedstock, including light hydrocarbons as well as heavy oils and solid hydrocarbons. However, it has a higher associated capital cost because it requires oxygen of very high purity, in order to minimize the volume of gas that must be treated afterwards. In order to make the partial oxidation process cost effective for the chemicals market, lower cost fossil fuels must be used. Current research is aimed at improving membranes for better separation and conversion processes, in order to increase the efficiency, and, thus, decrease the consumption of fossil fuels.

2.2. Methods based on renewable energy sources

Hydrogen is produced via electrolysis, i.e. the electricity supply in water through two electrodes. The water molecule is split to produce oxygen at the anode and hydrogen at the cathode. Three types of industrial electrolysis processes are operating today[9]. Two of them involve an aqueous solution of potassium hydroxide, being used because of its high conductivity, and are referred to as alkaline electrolysers. The third type of electrolysis process is a Solid Polymer Electrolyte electrolyser. These industrial systems are defined as Proton Exchange Membrane electrolysers. In this process, the electrolyte is a solid ion conducting membrane, as opposed to the aqueous solution in the alkaline electrolysers. The membrane allows the H^+ ion to be transferred from the anode side of the membrane to the cathode side, where it forms hydrogen. The Solid Polymer Electrolyte membrane also serves to separate the hydrogen and oxygen gasses, since oxygen is produced at the anode on one side of the membrane and hydrogen is produced on the opposite side of it.

Biomass may also be gasified using a variety of methods, primarily indirect and direct gasification[10]. Indirect gasification uses a medium, such as sand, to transfer heat from the char combustor to the gasification vessel. In direct gasification heat to the gasification vessel is supplied by the combustion of a portion of the feed biomass.

Hydrogen can also be produced via pyrolysis[10]. In this process, biomass is thermally decomposed at a high temperature in an inert atmosphere to form a bio-oil composed of about 85% oxygenated organics and 15% water. The bio-oil is then steam reformed using conventional technology to produce hydrogen. Alternatively, the phenolic components of the bio-oil can be extracted with ethyl acetate to produce an adhesive/phenolic resin co-product; the remaining components can be reformed as in the first option. The product gas from both alternatives is purified using a standard pressure swing adsorption system.

A promising long-term technology is concentrated solar energy for hydrogen production via electrolysis[11]. Two primary process configurations are used in this method. In the first, described as ambient temperature electrolysis, concentrated solar energy is used to generate alternating current (AC) electricity, which is supplied to the electrolyser. The second is the high-temperature steam electrolysis. In this system, the concentrator supplies both heat and AC electricity to convert steam to hydrogen and oxygen.

3. Proposed Solution

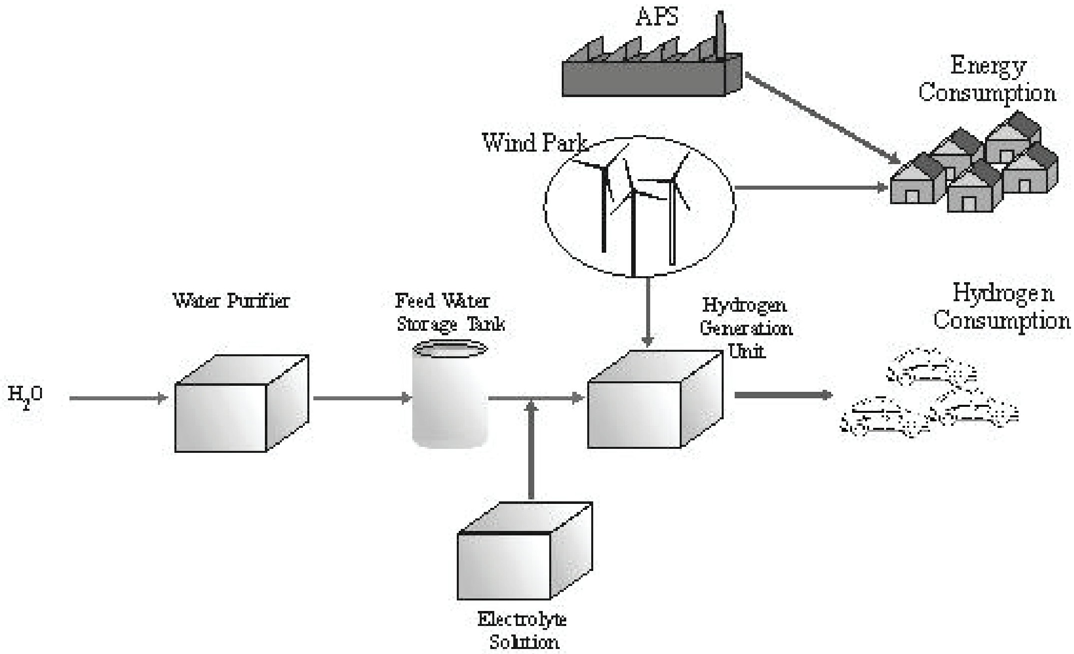

Figure 2: Integrated Wind-Hydrogen production installation

In order to minimize the problem arising by the mismatch between demand and intermittent wind energy, the possibility to produce hydrogen by the excess wind energy is investigated. According to the proposed solution, during low consumption periods excess wind energy can be used to produce hydrogen via electrolysis and sell it to the market. More precisely, the proposed configuration (figure (2)) consists of an existing wind park with total rated power 25MW, a water purification unit in order to improve its quality, a water storage tank to ensure that the process has adequate water in storage in case the water system is interrupted, the electrolyte solution (in alkaline systems) and the hydrogen generation unit. The latter consists of the electrolysis stack, the gas purification module, the dryer and the heat removal system. In the proposed analysis, hydrogen compression unit is not included as it is assumed that it is fed directly into a pipeline.

The initial investment cost of the electrolysis "IC_o" includes the market price "$Pr.N_o$" of the system and the corresponding installation -balance of the plant- cost "$f.Pr.N_o$". Thus we get:

$$IC_o = Pr.N_o.(1+f) \tag{1}$$

The future value of the initial investment cost can be estimated as:

$$IC_n = IC_o \cdot (1+i)^n \tag{2}$$

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

The annual fixed maintenance and operating (M&O) cost may be estimated as a fraction "m" of the initial capital invested, taking also into account an annual increase of the cost equal to "g_m" (i.e. the annual inflation rate). Summarizing, the fixed M&O cost of the electrolysis plant is given as:

$$FC_n = m \cdot IC_o \cdot \sum_{j=1}^{j=n} \left(\frac{1+g_m}{1+i} \right)^j \cdot (1+i)^n \tag{3}$$

The variable M&O cost mainly depends on the replacement of the electrolyser cell stack, which has a lifetime "n_k" between 5-15 years. Using the symbol "r_k" for the replacement cost coefficient, the variable M&O cost can be expressed using the following relation:

$$VC_n = r_k \cdot IC_o \cdot \sum_{l=0}^{l=l_k} \left(\frac{(1+g_k) \cdot (1-\rho)}{1+i} \right)^{l \cdot n_k} \cdot (1+i)^n \tag{4}$$

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

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

Note that "g_k" and "ρ" describe the annual change of the price and the corresponding level of technological improvements for the electrolyser cell stack.

Finally, the unit's energy supply is the electricity "E_w", produced by the wind park, with a purchase price "c_w". The cost of the input electricity is calculated as:

$$C_w = E_w \cdot c_w \cdot \sum_{j=1}^{j=n} \left(\frac{1+w}{1+i} \right)^j \cdot (1+i)^n \tag{6}$$

where "w" is the wind price escalation rate.

Summarizing, the energy production cost of hydrogen can be estimated as:

$$c_H = \frac{IC_o}{E_H}\left\{\frac{m \cdot X \cdot \frac{X^n - 1}{X - 1} + \sum_{l=0}^{l=l_k}\left(\frac{(1+g_k)\cdot(1-\rho)}{1+i}\right)^{l \cdot n_k}}{Z \cdot \frac{Z^n - 1}{Z - 1}}\right\} + \frac{E_w \cdot c_w \cdot Y \cdot \frac{Y^n - 1}{Y - 1}}{E_H \cdot Z \cdot \frac{Z^n - 1}{Z - 1}} \quad (7)$$

with:

$$X = \frac{1 + g_m}{1 + i} \quad (8)$$

$$Y = \frac{1 + w}{1 + i} \quad (9)$$

$$Z = \frac{1 + h}{1 + i} \quad (10)$$

where "h" is the hydrogen production cost annual escalation rate.

4. Application Results

The main target of the proposed analysis is to estimate the current hydrogen production cost on a techno-economic basis. The cases examined consist of different sizes of electrolysis systems and different prices of input energy. Using analytical data of wind power rejected by the local electric grid[12], the power available to the electrolysis system is calculated taking into consideration the system operation limits.

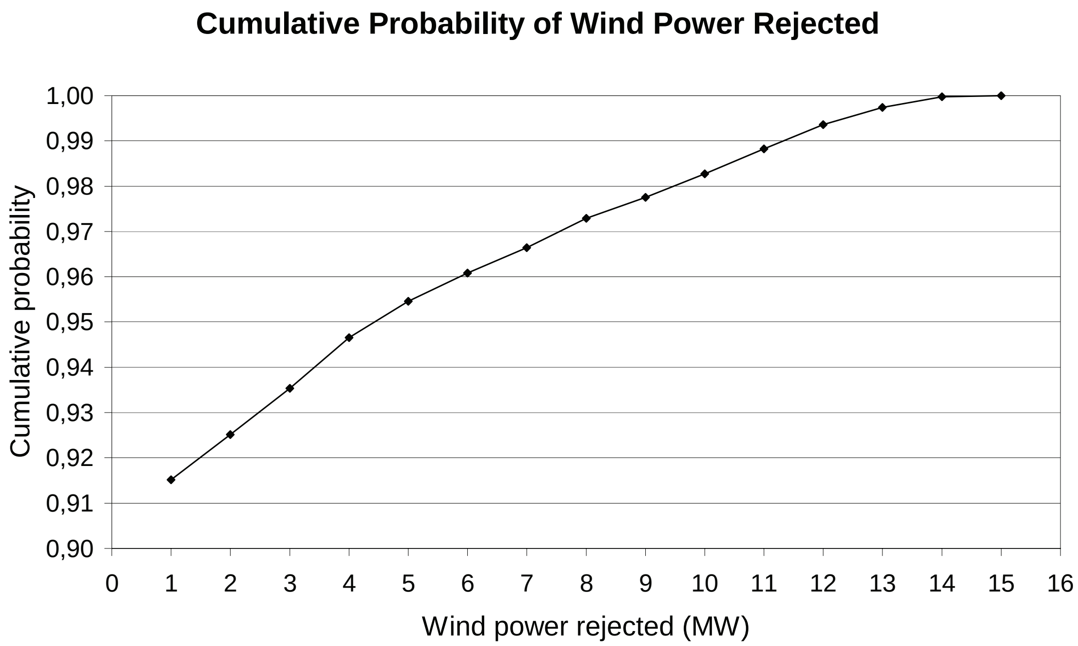

Figure 3: Cumulative probability of wind energy rejected by the local grid[12]

The sizes analyzed range between 3MW, which can absorb almost 95% of the available wind energy and 14MW, which can absorb almost 100% of the wind energy (figure (3)). For every size of the electrolysis system, the cost of the hydrogen produced has been calculated, depending on the purchase price of the wind energy. The economic parameters that have been considered refer to the Greek economy (g=2÷4%, i=10÷15%, h=w=3÷5%).

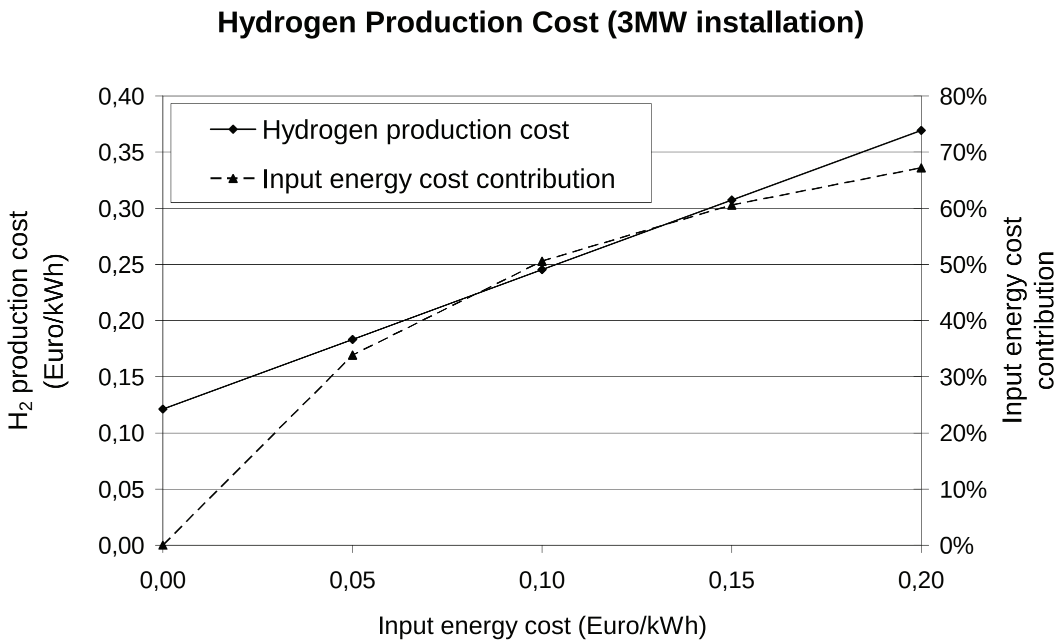

Figure 4: Hydrogen production cost for a 3MW electrolysis installation

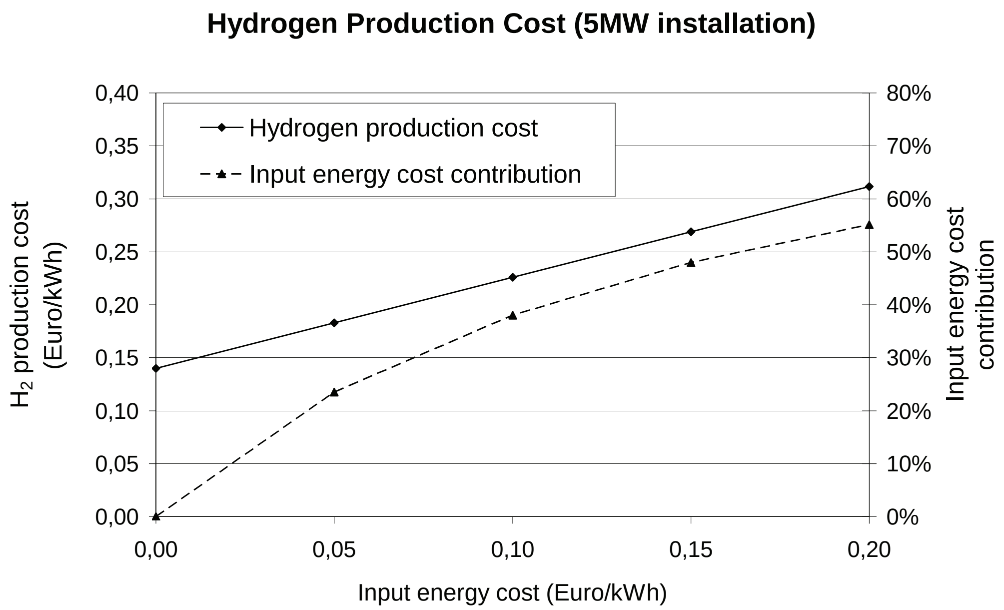

Figure 5: Hydrogen production cost for a 5MW electrolysis installation

After selecting typical values for the economic parameters of the local market, the calculation results for various prices of wind energy "c_W" (c_W=0€/kWh to 0.2€/kWh) are given in figures (4) to (7) for nominal power of the hydrogen production installation, i.e. N_o=3, 5, 10, 14 MW.

According to the results obtained, the hydrogen cost in every case increases almost linearly with the wind energy purchase price. The hydrogen price for the small system (3MW) increases by 0.25 €/kWh, whereas for the large system (14MW) increases by only 0.12 €/kWh, showing the strong influence of the energy purchase price in small systems. This conclusion is also derived by the input energy cost contribution, showing the contribution of the input energy price in the structure of the hydrogen production cost.

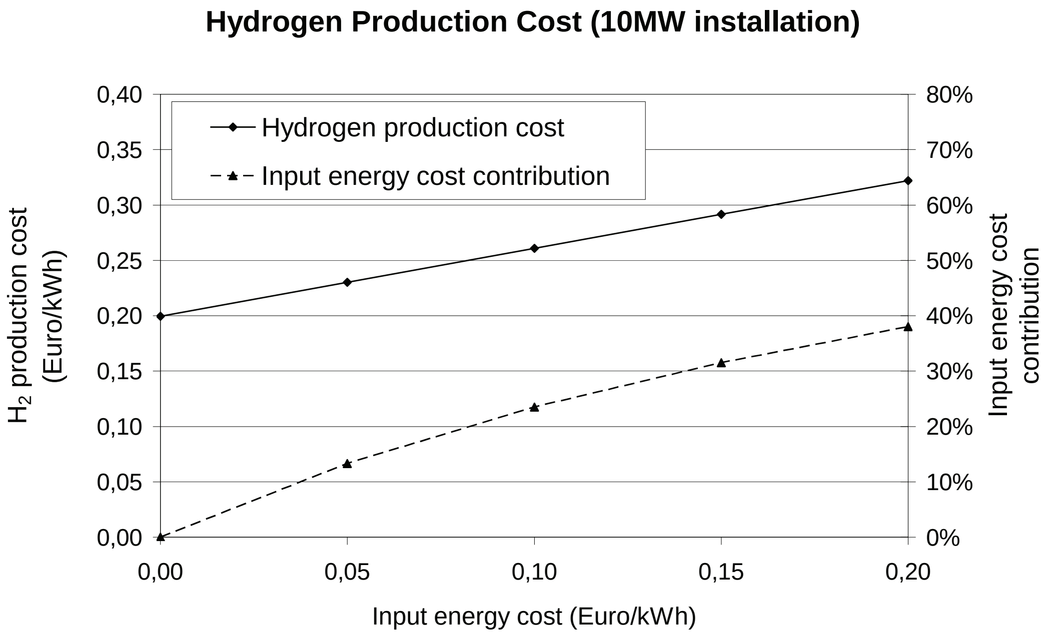

Figure 6: Hydrogen production cost for a 10MW electrolysis installation

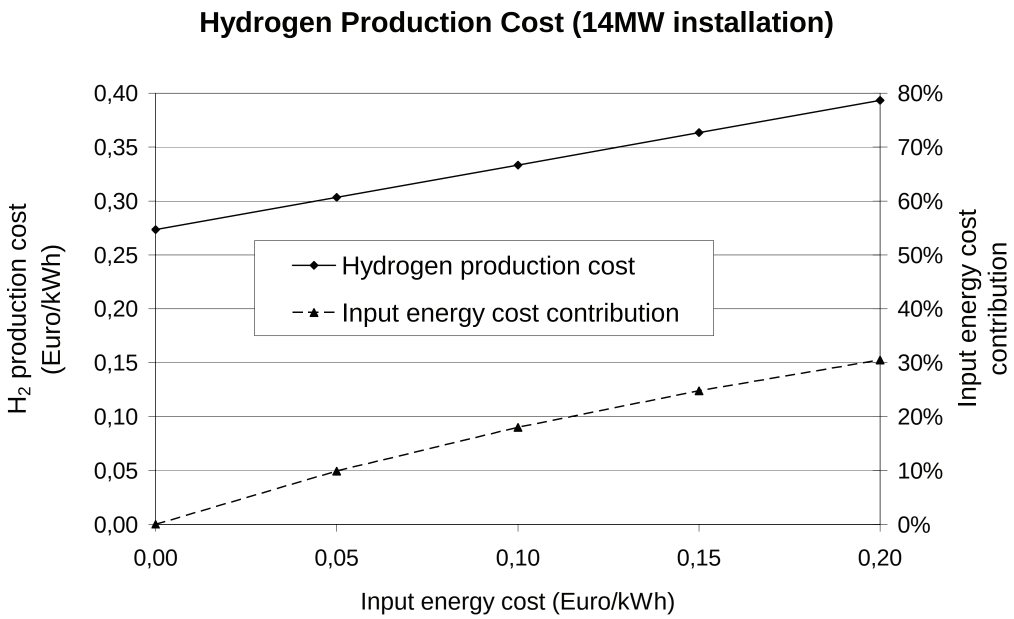

Figure 7: Hydrogen production cost for a 14MW electrolysis installation

Figure (8) presents the hydrogen production cost for three different scenarios of wind energy purchase price. According to the results obtained, for different input energy prices, there is an optimum installation size for achieving minimum production cost of the hydrogen. The higher the wind energy purchase price, the bigger the electrolysis installation should be in order to obtain the minimum production cost given the specific profile of rejected energy from the wind park.

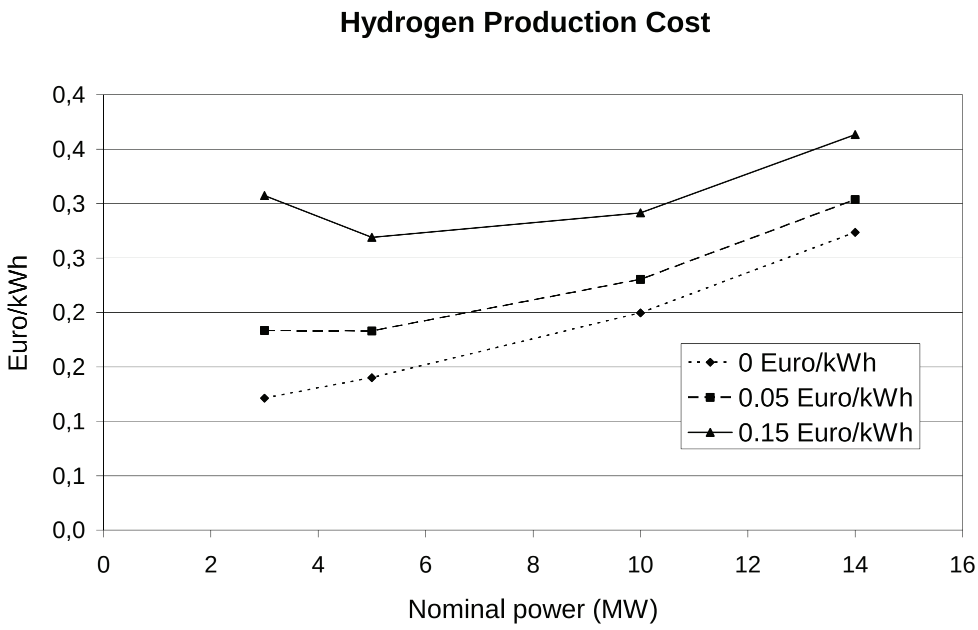

Figure 8: Hydrogen production cost for different electrolysis installation sizes

5. Conclusions

The present study reviews the current available hydrogen production methods, focusing in methods which can be combined with renewable energy sources. For the most compatible with renewable energy applications method, an integrated evaluation model is described. The techno-economic evaluation is based on a combined installation of a wind park and an electrolysis unit, using ten-minute interval analytical data of one year operation of the wind park. Based on the energy rejected by the local grid due to technical restrictions, the hydrogen production cost has been estimated for different scenarios of electrolysis unit size and different purchase price of wind energy.

According to the results obtained, the hydrogen production cost depends strongly on the input energy cost mainly for small sized systems (3MW), as in bigger systems (14MW) the first installation cost increases significantly.

It is also important to mention that, depending on the wind energy purchase price, the optimum electrolysis unit size has to be investigated. This is because larger units might have a higher investment cost but, for specific input energy profile, more wind energy can be absorbed.

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PART FOUR

RES-BASED APPLICATIONS

CRITICAL EVALUATION OF THE HYDROPOWER APPLICATIONS IN GREECE

J.K. Kaldellis
Laboratory of Soft Energy Applications & Environmental Protection
Mechanical Eng. Dept., Technological Education Institute of Piraeus

Abstract

Hydropower is a proven technology for electricity generation, contributing with almost 20% to the fulfillment of the planet electricity demand. Hydropower is also renewable because it draws its essential energy from the sun and particularly from the hydrological cycle. Greece and more precisely the west and north part of the mainland possesses significant hydro-power potential that is up to now partially exploited. In the present survey, one investigates the existing situation concerning the applications of hydro power plants in Greece, while the results obtained are compared with the corresponding international and European situation. Subsequently, emphasis is laid on estimating the electricity-generation utilization degree of the existing large hydro power stations, using 25-year long official data. The results obtained underline the fact that the electricity generation is not a priority for the national water management policy and most Greek hydro power stations are used mainly to meet the corresponding peak load demand. On the other hand, increased interest to create numerous new small hydro power plants throughout Greece has been expressed during the last five years. According to the information gathered and analyzed, one may state that the available local hydro-power potential is quite promising and can substantially contribute to the accomplishment of the national-E.U. target to cover the 21% of the corresponding electricity consumption from renewable resources. For this purpose one should first define an approved and rational water resources management plan and secondly support the increased utilization of large and small hydro power plants for electricity generation. In this case, properly designed hydro power plants should lead to considerable profits, contributing also in the country's independency from imported oil and accomplishing the Kyoto protocol obligations.

Keywords: Hydro Power; Electricity Generation; Large Hydro Power Plants; Small Hydro Power Plants; Water Potential; Capacity Factor

1. Introduction

As we move into the 21st century, global economic prosperity is driving the consumption of energy to record levels, with electricity consumption anticipated to increase[1][2][3] at rates faster than overall energy supply, see also figure (1). The vast majority of energy today is provided from carbon containing fuels, like coal, gas and oil (see for example figure (2)). However, taking into account the growing global concern regarding the lack of sustainability of these forms of energy several analysts bring into question the use of fossil fuels in a long-term time horizon. Concern over disruptive fossil fuel markets and uncertain pricing as well as the significant environmental consequences of thermal energy sources have enable sustainable energy policies that include the significant development of renewable energy supplies[4][5].

Renewable energy technology exists in many forms. From the recent point of view renewable energy is often related to the electricity from wind energy[6], solar energy[7] or geothermal energy[8]. Yet the largest source of renewable energy for electricity production comes from a proven technology[9][10][11], that of hydropower. Hydropower is renewable because it draws its essential energy from the sun and particularly from the hydrological cycle, which in its turn provides a continuous renewable supply of water. Currently hydropower represents more than nine tenth (9/10) of all renewable energy generated, and continues to stand as one of the most viable sources of the new generation into the future. It also provides an option to store energy and to optimize electricity generation[12][13]. Due to the above described characteristics and the fact that the forecasts for the energy future of our planet are not optimistic, hydropower is expected to play a very important role in the future energy balance[14].

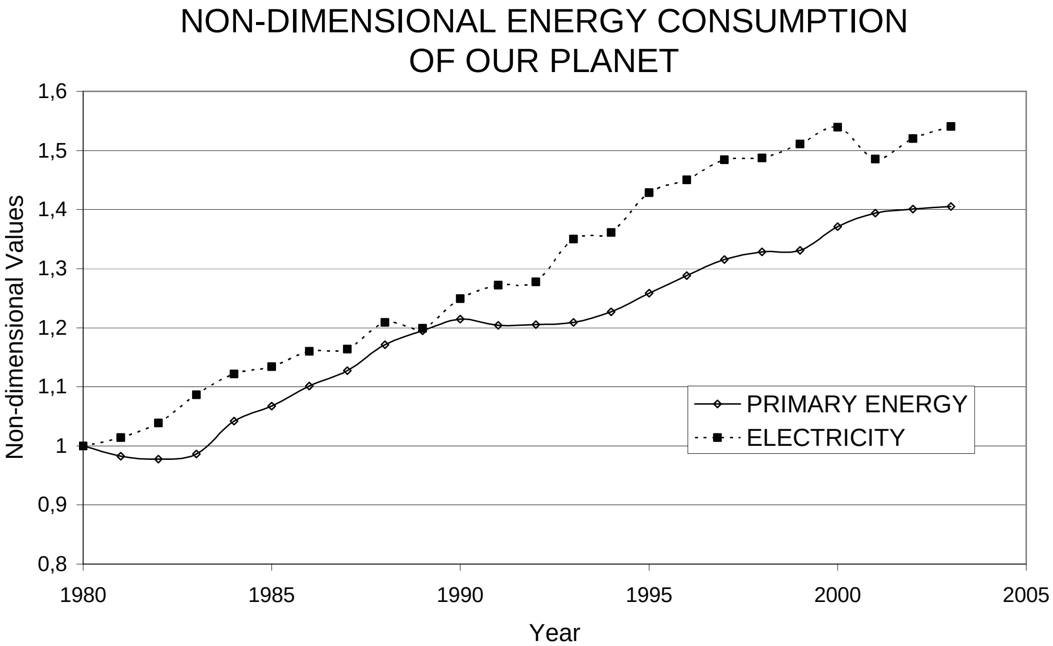

Figure 1: Worldwide primary energy and electricity consumption time-evolution

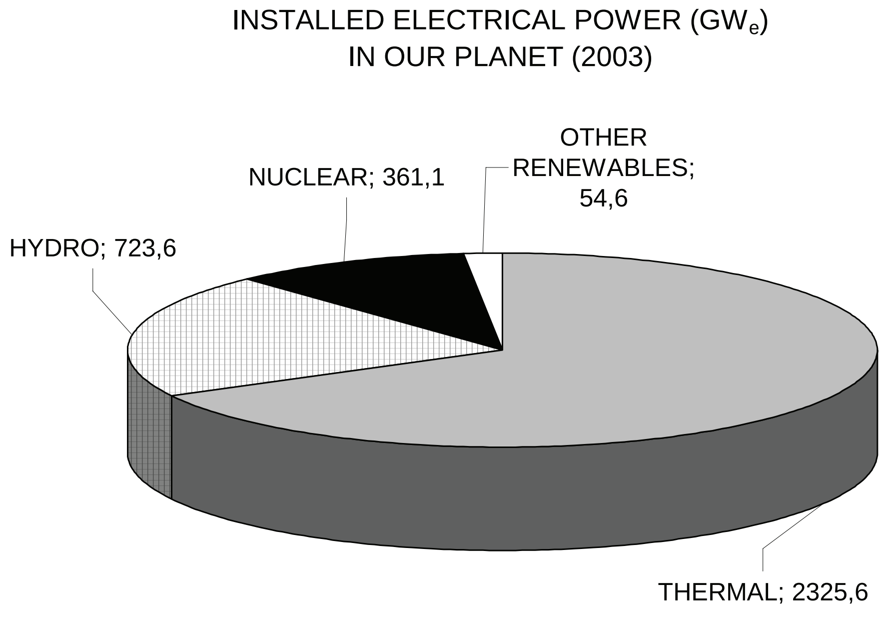

Figure 2: Hydropower contribution at the planet electrical demand

Summarizing, some of the main beneficial characteristics of hydropower are the following[15][16]:

- Its resources are widely spread around the world. Potential exists in about 150 countries and about 70 per cent of the economically feasible potential remains to be developed.
- It is a proven and well advanced technology, with a more than a century of experience, with modern power plants providing the most efficient energy conversion process (>90%) that the mankind has developed up to now.

- The production of peak load energy from hydropower allows the best use of base load power available from other less flexible electricity sources.
- It has the lowest operating costs and the longest plant life, compared with other large scale generating options.
- The fuel (water) is renewable and it is not subjected to market fluctuations up to now.

In addition to the above mentioned advantages, if one considers the fact that most of the world electric energy comes from thermal resources, which cause significant environmental impacts, hydropower can definitely contribute to a cleaner environment. For instance, the almost 2800TWh of hydro-based electricity worldwide replace either 1.2 million tons of coal or 4.5 million barrels of crude oil. In fact, more than 1300Mt of CO_2 tons emissions are avoided due to the hydropower electrical generation (2004 data).

2. Time Evolution of Hydropower Applications in Europe

The world's total technical feasible hydro potential is estimated at 14,000 TWh/year, which is slightly lower than the entire planet electricity production for the year 2005 (≈15,000TWh). According to various estimations about 8,000 TWh/year is currently considered economically feasible for development. Moreover, there is now more than 105GW[14] of new hydro-capacity under construction in comparison with the existing 720GW, worldwide. Most hydro power projects are very often part of multipurpose developments, providing also benefits such as irrigation water, industrial and drinking water supply, flood control, improved navigation etc. By far the greatest amount of current development is in Asia (84GW) and South America (14.8GW), while in Africa and Europe the corresponding new power is 2.4GW and 2.2GW respectively.

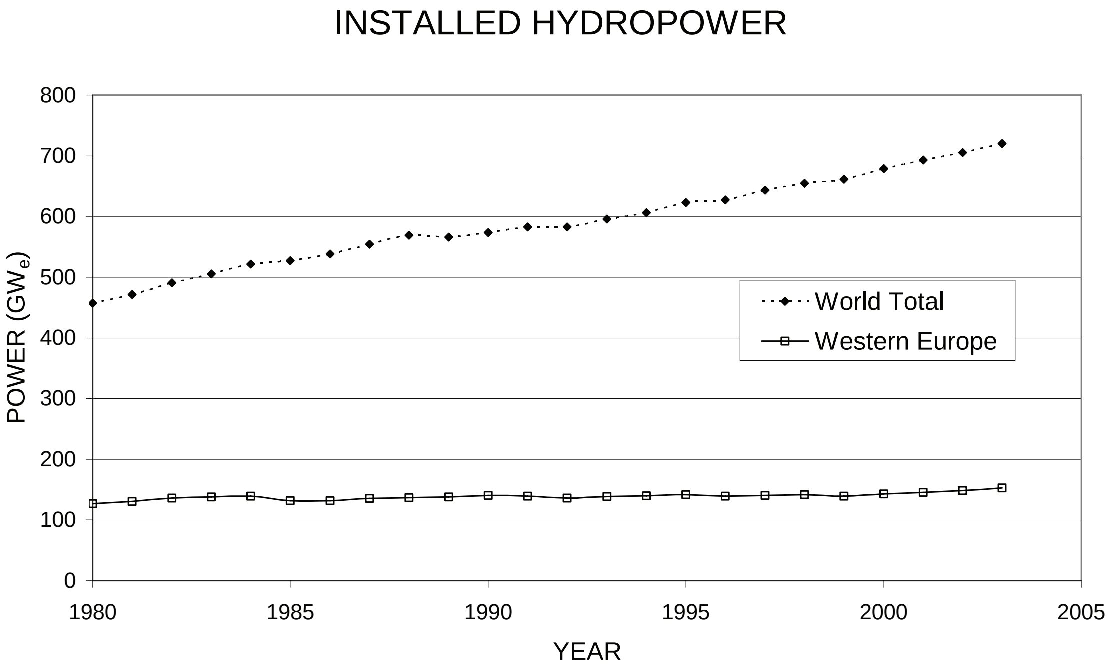

Figure 3: Time-evolution of installed hydro power

More precisely, in figure (3) one may find the "in operation" hydropower time-series since 1980 for both the Western Europe and the entire planet. According to the data available there is a constant increase of new hydro power installations worldwide, since every year approximately 10.5GW of new hydro plants come into operation. This is not the case for West Europe, since the corresponding new hydro capacity remains practically constant during the period examined, slightly exceeding the 153GW.

This situation is also supported by the annual electricity production of the existing hydro power stations in EU-15 as well as in EU-25. In fact, the corresponding electricity production in EU-15 (figure (4)) varies between 310TWh and 365TWh since 1992, while another 15TWh is the hydroelectricity generation of the ten new EU members during the same period.

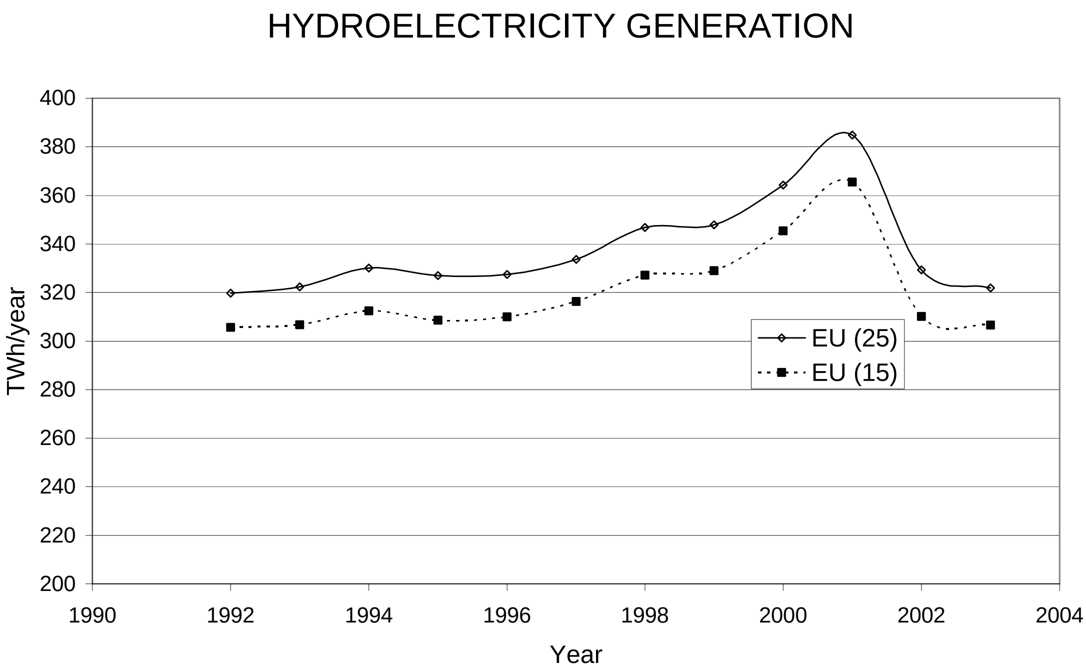

Figure 4: Energy yield of E.U. hydro power stations in the course of time

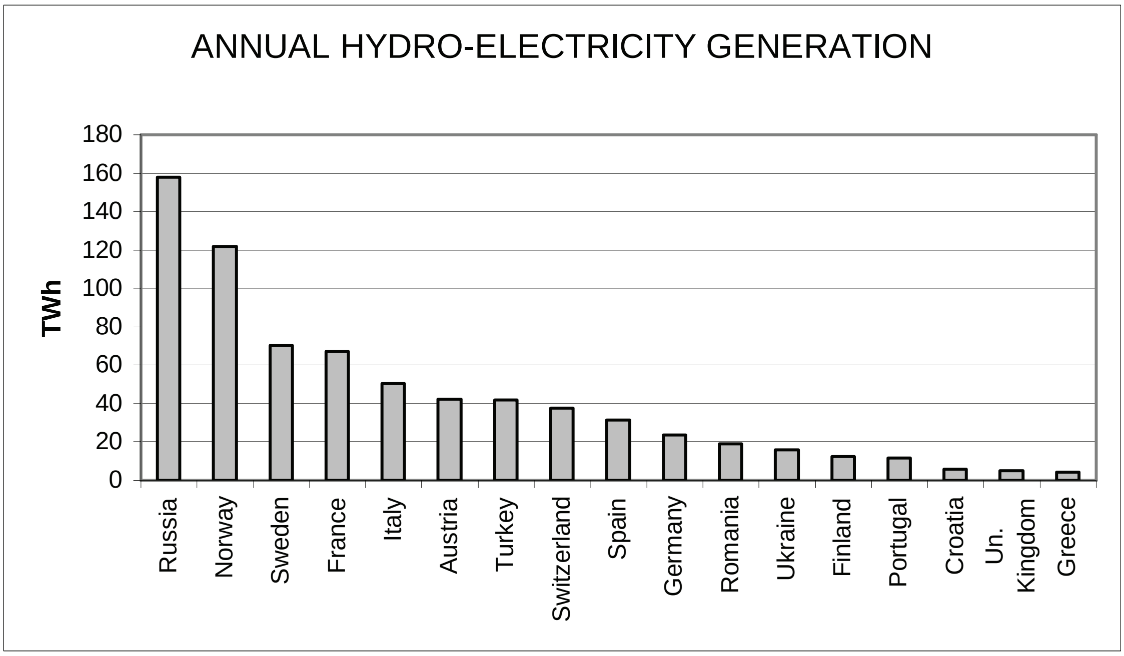

Figure 5: Hydro power contribution to national energy consumption in Europe

More specifically, hydropower contribution to the total electricity production in Europe varies considerably between countries, ranging from 0% to 99%, see figure (5). In fact, a closer inspection of the European hydropower stations map makes clear that most hydro plants are located in Western Europe (France, Italy, Spain) and in Scandinavian Peninsula. Although in many parts of Europe hydropower development has already passed its peak time, there is still considerable activity both in up rating and refurbishment projects. A total of 2210 MW of new capacity is under implementation in at least 23 countries and more than 8000 MW could be implemented in the near future. The most significant new projects are under way in Bosnia, Bulgaria, Germany, Greece, Iceland, Italy, Norway, Portugal, Romania, Slovenia, Spain and Ukraine.

3. "In Operation" Hydropower Installations in Greece

Greece is since 1980 a country member of E.U. and is located in the southeast end of Europe. Greek mainland and more precisely its west part possesses significant hydro-power potential that is up to now partially exploited. It is important to mention that the ground configuration (topography) in combination with the relative high precipitation[17], figure (6), facilitates the applications of similar power stations. In this context, one may demonstrate in figure (7) the "hydraulicity" of the major regions of the country. According to the available data, only a minor part of the local water potential is up to now exploited.

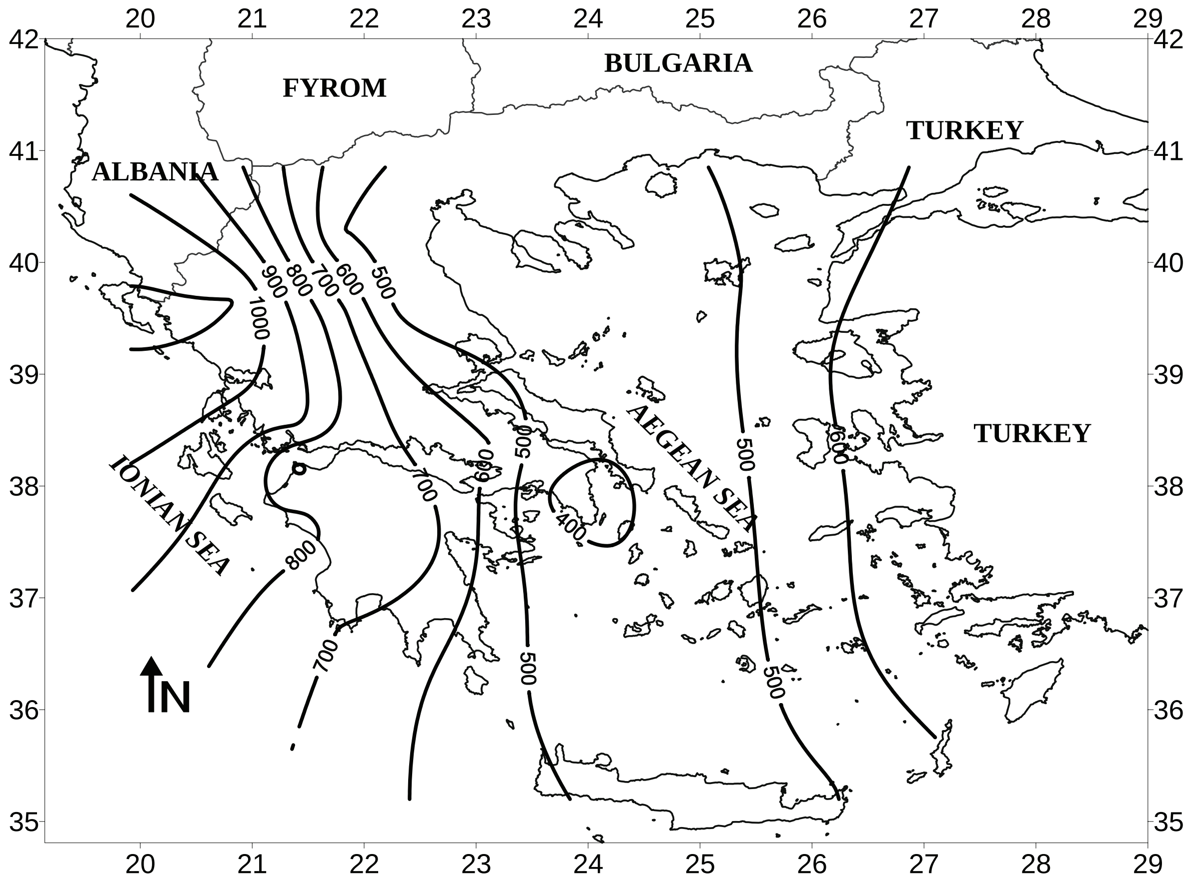

Figure 6: Annual mean precipitation values (in mmH_2O) for the 1950-2001 period

It is also important to note that several rivers go through Greece in Aegean Archipelago. The most important of them are: Evros, Nestos, Strimon, Axios, Aliakmon, Pinios, Arachtos, Acheloos, Sperchios and Alfios. From the above mentioned rivers, Acheloos has a considerable water flow of approximately 300 m^3/sec during December (see also figure (8)), while the flow rate of Axios is almost 230 m^3/sec in March. Finally, the flow rate of Evros varies between 200 and 220 m^3/sec from January to March[18]. Taking into consideration the remarkable water flow rate of all these rivers, it is quite rational that several hydro power installations have been erected in order to exploit their considerable hydro potential.

In Greece, up today, exist fifteen (15) large hydro power (LHP) stations of total capacity of 2950MW and almost fifty (50) small hydro power (SHP) stations, total rated power 70MW. The first two power stations being in operation since 1954 are the hydro power stations of Agras (I,II) and the small hydro power plant of Louros, see also Table I. Since that period, several much bigger hydro power stations have been erected, like the ones of Kremasta (440MW), and Kastraki (320MW) in west Central Greece as well as Polifito (375MW) in central Macedonia. Unfortunately, during the last ten years no other new large hydro plant has started operation. In fact, although the hydro power station of Messochora in Thessaly (rated power 170MW) is ready for operation, this is not allowed due to significant reactions of local communities, which do not accept to be removed in new locations in order to facilitate the operation of the new hydro power station.

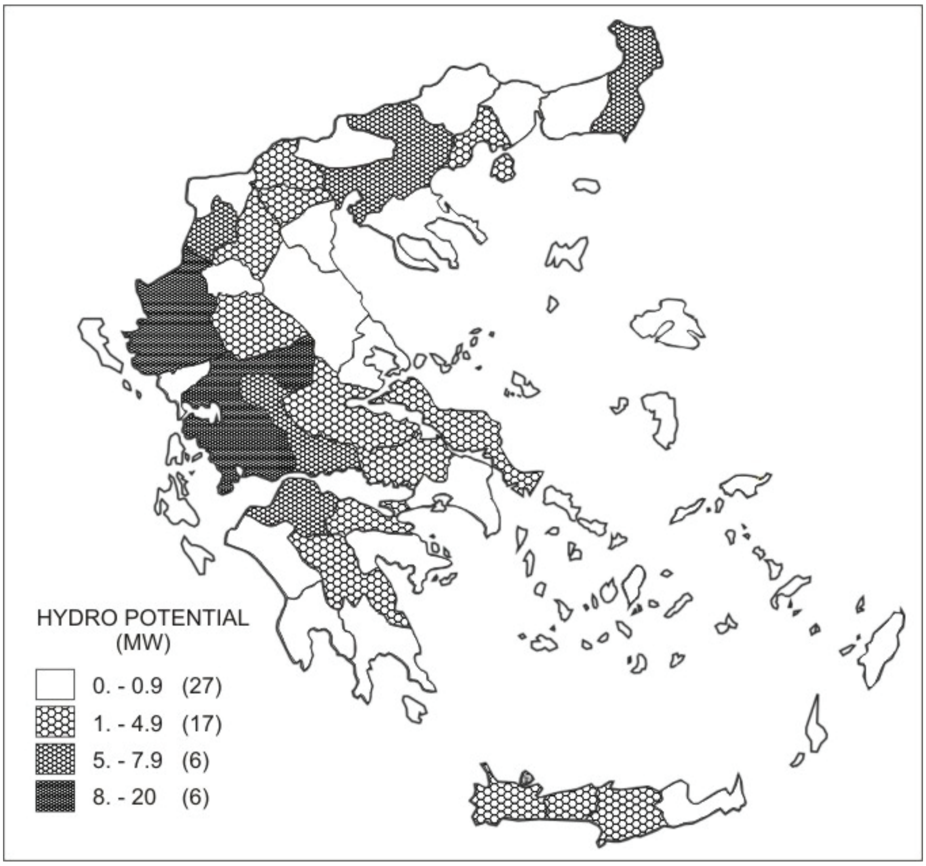

Figure 7: Greek hydro potential values

Table I: Main characteristics of existing large Hydro-plants

	Location	Start Up Time	Power MW	Turbine Number	Head mH_2O
1	AGRAS	1954	50	2	158
2	ASOMATA	1985	108	2	38.7
3	PIGES AOOU	1990	210	2	652
4	EDESEOS	1969	19	1	120
5	THISAVROS	1997	300 (rev)	3	160
6	KASTRAKI	1969	320	4	76
7	KREMASTA	1966	437.2	4	124
8	LADONAS	1955	70	2	239
9	PLASTIRAS	1960	129.9	3	577
10	PLATANOVRISI	1999	100	2	-
11	POLIFITO	1974	375	3	146.5
12	POURNARI I	1981	300	6	68
13	POURNARI II	1985	36,5	2	-

	Location	Start Up Time	Power MW	Turbine Number	Head mH_2O
14	STRATOS I	1989	150	2	36
15	SFIKIA	1985	315 (rev)	3	58.5

It is also important to note that two of the existing large hydro power stations (i.e. Sfikia and Thissauros) are operating in reversible mode, i.e. as water pumping stations during the low demand periods storing water at high elevation using cheap base load from lignite fired power stations and as hydro turbines during peak load demand periods covering the increased power demand.

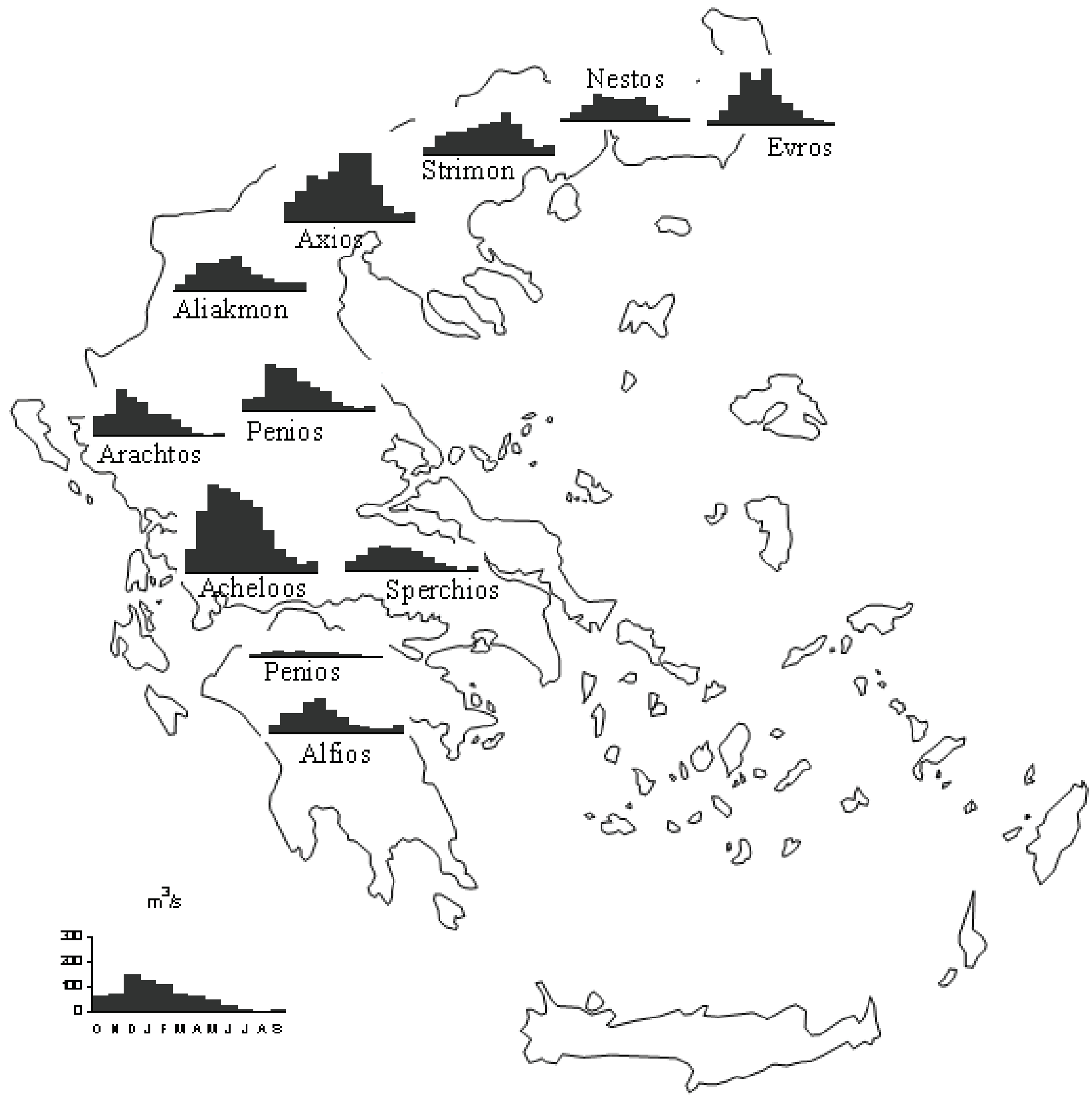

Figure 8: Mean annual flow rate of the major Greek rivers

The rated power of the hydro turbines used[19] present large variety, i.e. from 15.5MW up to 125MW. In most cases, Francis type turbines are used, excluding Plastiras (Tavropos) 3x43.3MW and Aoos (2x105MW) installation, where the high hydrodynamic head available imposes the utilization of Pelton type turbines, Table I.

In figure (9) one may find the geographical distribution of existing Greek LHP stations. In fact, the major hydro power stations are located in west Greece (Kremasta, Kastraki, Stratos, Pournari, Piges Aoou and Plastiras) as well as in central Macedonia (Polifito, Sfikia, Asomata). The two younger stations of Thissavros and Platanovrisi are located in North Greece, while only the early station of Ladonas exists in South Greece, i.e. in Peloponnesus.

Figure 9: Geographical distribution of large hydro plants in Greece, see also Table I

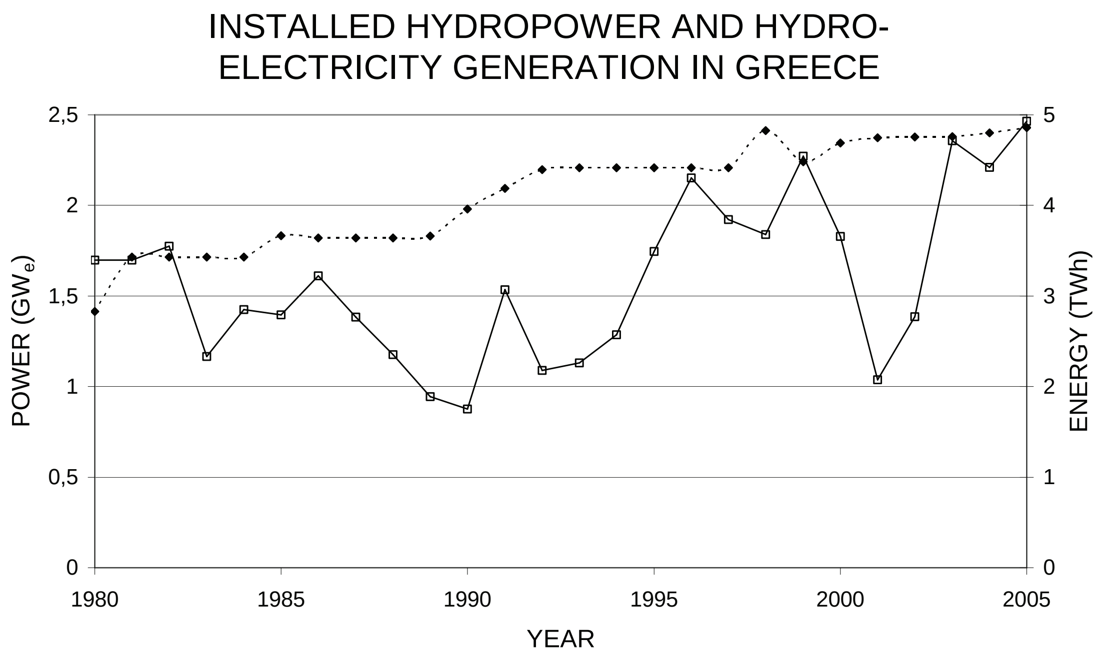

Figure 10: Installed hydro-power (excluding reversible plants) and annual energy yield

Subsequently, one may investigate, figure (10), the time-evolution of the installed hydro capacity in Greece during the last twenty years, see also Table I. As it is obvious from the data provided, there is a remarkable hydro power addition between 1980 and 1992, hence the installed capacity was 2200MW by the end of 1992. In the data presented we do not include the two reversible hydro power stations of Sfikia (315MW) and Thissavros (300MW) which started their operation in 1985 and 1997 respectively. The last LHP station which entered the Greek electricity generation system is the one of Platanovrisi in 1999. Bear in mind that during 1998 the new-erected hydro power station of Messochora was ready for operation. However, the strong and dynamic opposition of the local citizens prevents this station to come into operation.

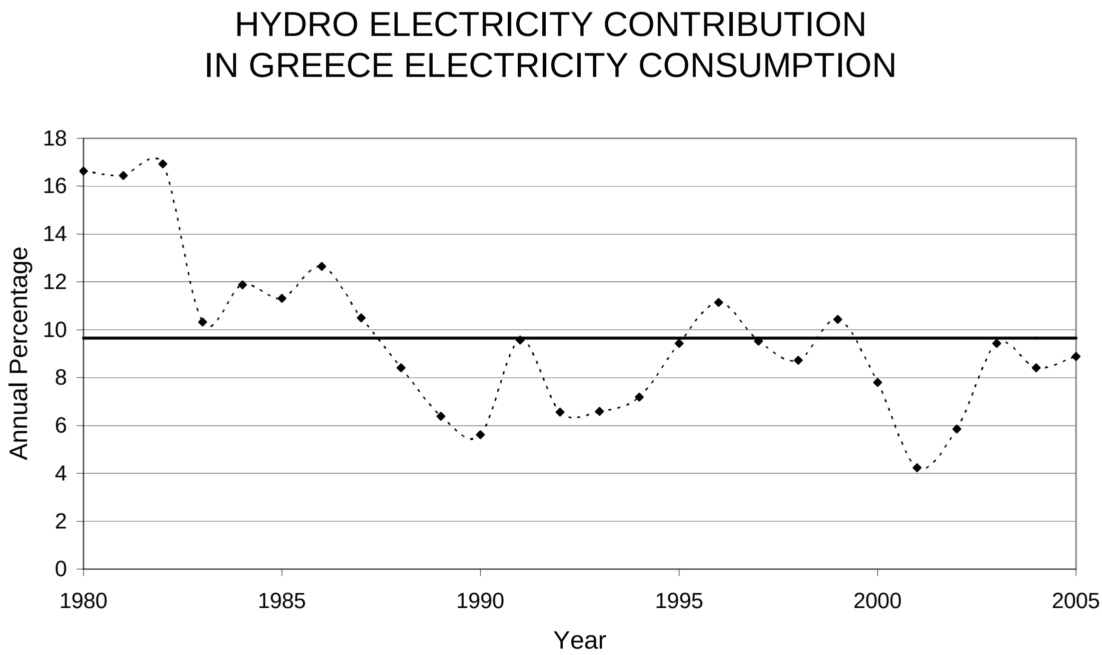

Figure 11: Hydro-electricity contribution in Greece electricity consumption

In the same figure (10) one may also find the time-variation of the annual electricity generation by the existing LHP stations. According to the official data considerable energy yield variation is encountered, since in 1990 the hydro electricity was 1.9TWh and in 2005 approached the 5TWh. Unfortunately, the hydro electricity contribution to the local electricity consumption, figure (11), is quite limited, since the 25-year average value is only 9.5%. In fact, the hydro-electricity contribution after 1990 has been always less than 11%, taking into consideration the almost constant hydro power stations capacity and the continuously increasing network electricity demand.

Finally, it is worthwhile to investigate the energy-generation utilization degree of the Greek LHP stations during the last twenty five (25) years. More specifically, the corresponding utilization degree is expressed by the appropriate annual capacity factor "CF" of the installation[20], defined as:

$$CF = \frac{E_y}{8760 \cdot N_o} \tag{1}$$

where "E_y" is the annual hydro-electricity generation and "N_o" is the corresponding rated power of the installation under discussion. Comparing the calculation results for Greece, Europe and the entire planet (figure (12)) one should state the following:

- ✓ There is a significant "CF" time variation in Greece, which is much more intense than Europe and the entire planet.

- ✓ The calculated "CF" values for Greece are considerably lower than the corresponding European and world-wide values (i.e. 17% vs. 40-44%).
- ✓ The exploitation strategy of the available hydro potential in Greece is entirely different from the one applied in the international electricity generation market. One sound explanation for this difference is the utilization of Greek LHP stations to meet primarily the corresponding peak load demand.

In the next section one is going to provide more details concerning the annual yield of each one of the existing LHP stations during the last decade (1995-2005).

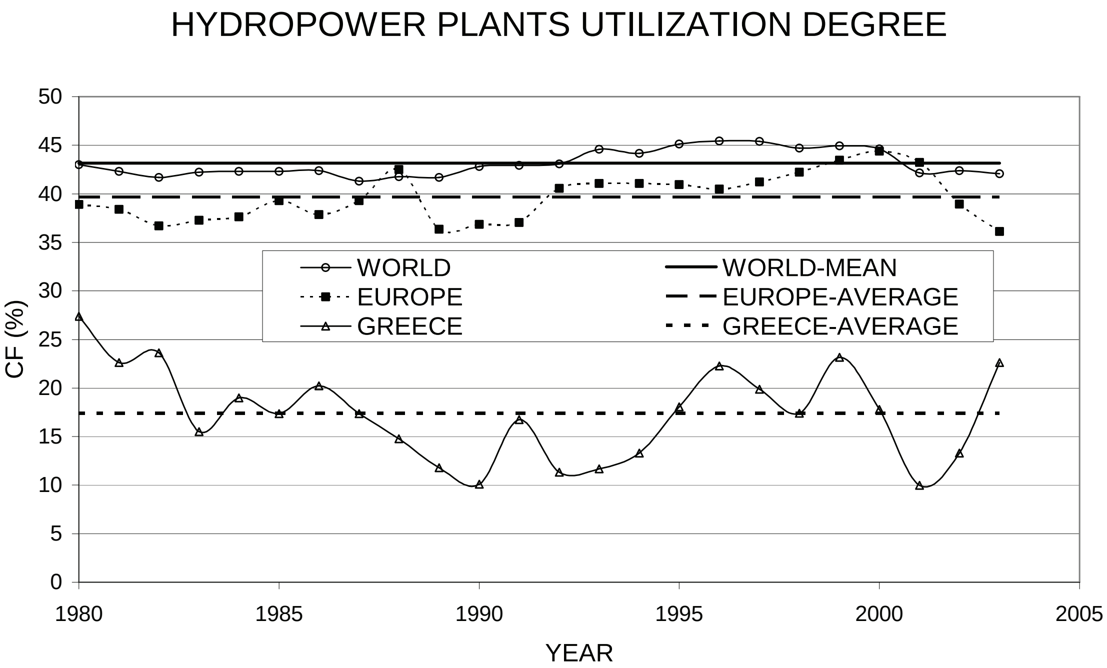

Figure 12: Existing hydropower stations utilization degree

4. Detailed Energy Production Analysis of Large Hydro Power Stations in Greece

The four biggest LHP stations in Greece (Table I) include the power stations of Kremasta (440MW), Polifito (375MW), Kastraki (320MW) and Pournari-I (300MW). All these stations were erected 25 years ago and represent more than 50% of the installed national hydro capacity. In this group one may also include the reversible power stations of Sfikia (315MW) and Thissavros (300MW). Using the long-term energy yield of all these LHP plants, figure (13), one may state that Kastraki and Kremasta power stations present considerable utilization degree (CF≈25%), producing together almost 1.5TWh per year.

On the other hand, Polifito and Pournari-I LHP stations have a considerable lower utilization degree (CF≈11%), since the available water potential is also used for several parallel activities (mainly agriculture irrigation). Finally, the two reversible LHP stations of Sfikia and Thissavros present fair capacity factor values (CF≈15%), taking also into consideration their remarkable contribution to the local network load management.

The second group contains the medium-sized hydro power stations of Asomata (108MW), Piges Aoou (210MW), Plastiras (130MW), Stratos-I (150MW) and the most recent one of Platanovrisi (100MW). According to the existing official data (figure (14)) Stratos-I (being in the same region with Kremasta and Kastraki, figure (9)) present the highest capacity factor (CF≈21%) of the group. Acceptable may be also characterized the utilization degree of Plastiras (CF≈16.5%) and Pratanovrisi (CF≈16.5%) hydro power stations. On the contrary, the capacity factor of the biggest power station of this group (i.e. Piges Aoou) is very low (CF≈8.5%) strongly questioning the financial viability[21] of the corresponding investment. Finally, the time-average capacity factor of Asomata hydro power station approaches 14%.

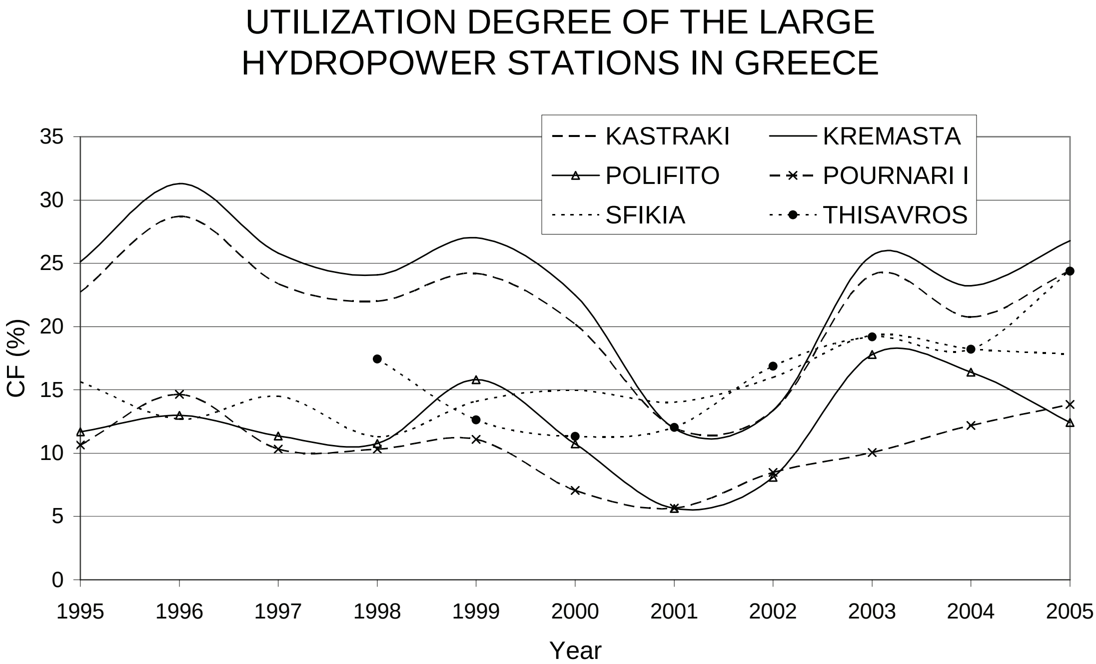

Figure 13: Existing Greek large hydropower stations utilization degree

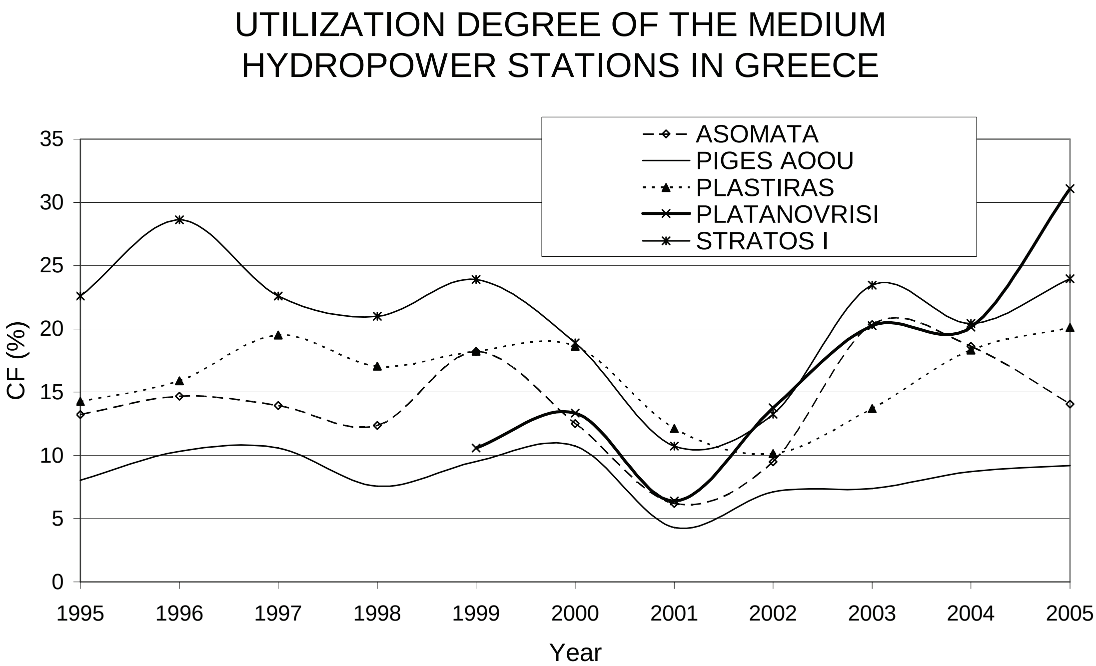

Figure 14: Existing Greek medium size hydropower stations utilization degree

The last subgroup of the existing medium-small hydro power plants include the power stations of Agras (50MW) and Edesseos (17MW), the quite recent one of Pournari-II (36.5MW) and one of the oldest Greek hydro power stations of Ladonas (70MW), being the only one located in South Greece, figure (9). Using the long-term official energy generation values, figure (15), the utilization degree of Agras is extremely low (CF≈4.5%). Similarly, the capacity factor of Edesseos (located nearby Agras) is also very low (CF≈10.5%), proving that both stations are not used by priority for energy production.

On the other hand, Ladonas power station presents the best energy utilization degree of all LHP stations in Greece, presenting long-term average CF value higher than 36%. Finally, the relatively new power station of Pournari-II presents similar capacity factor value (CF≈13%) with the biggest Pournari-I power station, which is also rather low.

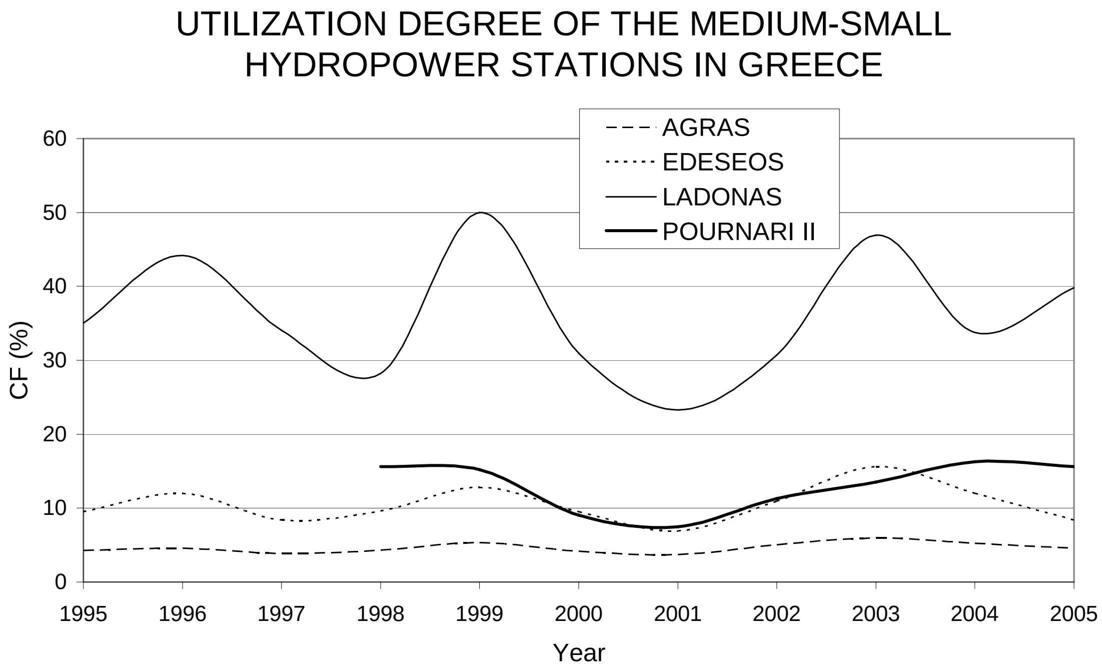

Figure 15: Existing Greek medium-small size hydropower stations utilization degree

Recapitulating and using the long-term time-series of electricity generation of existing LHP stations in Greece one may state the following:

- There is not a common energy-generation utilization degree of the existing Greek LHP stations, which present considerably variable capacity factor values, i.e. from 4.5% up to 36%.
- Only the power stations of Ladonas, Kremasta, Kastraki and Stratos-I present an acceptable energy production utilization degree, comparable with the corresponding values throughout Europe.
- The long-term annual utilization degree of Agras, Piges Aoou, Pournari-I and Edesseos is very low, strongly questioning the economic behavior of these power stations.
- All the other hydro power plants present capacity factor values between 10% and 20%, which is also quite low for the international standards.

5. Small Hydro Power Stations in Greece

According to the existing nomenclature a hydro power plant is characterized as small if its rated power is less than 10MW. The first SHP station which has been operating in Greece since 1927 is the one of Glafkos (1.6MW) located in N. Peloponnesus[22], while during almost at the same period of time (1929) the SHP station of Vermio (1.8MW) has been also erected in central Macedonia. Up to 1994, only eight SHP stations, belonging to the State controlled Greek Public Power Corporation (PPC), had been operating with total rated power equal to 42.8MW. After the application of the law 2244/94 permitting the installation of power stations based on renewable energy sources by private investors[23], an increased interest to create new SHP plants throughout Greece has been expressed.

In fact, on the basis of the available information, currently in Greece operate 32 SHP plants with rated power equal to 60MW. Eleven SHP stations (Table II) have rated power between 1MW and 10MW representing the 82% of the entire installed power. On top of this, there are additional very small (mini) hydro power stations (rated power less than 1MW) with total capacity of 10.7MW[24]. Out of the eleven SHP plants six (42.2MW) belong to PPC, while the other five were created by private investors.

Table II: Small hydro power stations in Greece

	Location/Name	Property	Power (MW)
1	VERMIO I	PPC	1.8
2	GIONA, FOKIDA	PPC	8.5
3	PATRA, GLAFKOS	PPC	4.8
4	STRATOS II	PPC	6
5	TSIVLOS, AKRATA	Private	2.82
6	AG. MARINA, LAKONIA	Private	1.0
7	KLITORIA, ACHAIA	Private	1.0
8	PLATANAKI, ILIA	Private	1.3
9	PLATANAKI ILIA	Private	1.3
10	MAKROXORI, VERIA	PPC	10.8
11	LOUROS	PPC	10.3

Figure 16: Geographical distribution of small hydro plants in Greece, see also Table II

It is also interesting to note that all the private SHP plants, along with the Glafkos power station, are located in Peloponnesus, see figure (16). Finally, one should also bear in mind that although large hydropower stations represent the vast majority of the installed hydro power, small hydro power stations constitute remarkable energy production facilities with considerable higher utilization degree of the available water potential than the LHP plants[25]. This is obvious if we compare in figure (17) the time-evolution of the corresponding capacity factor of large to the small hydro power stations of PPC, for which we have extended operational data. In fact, the average capacity factor of SHP stations is more than twofold the corresponding value of LHP plants for the last decade examined.

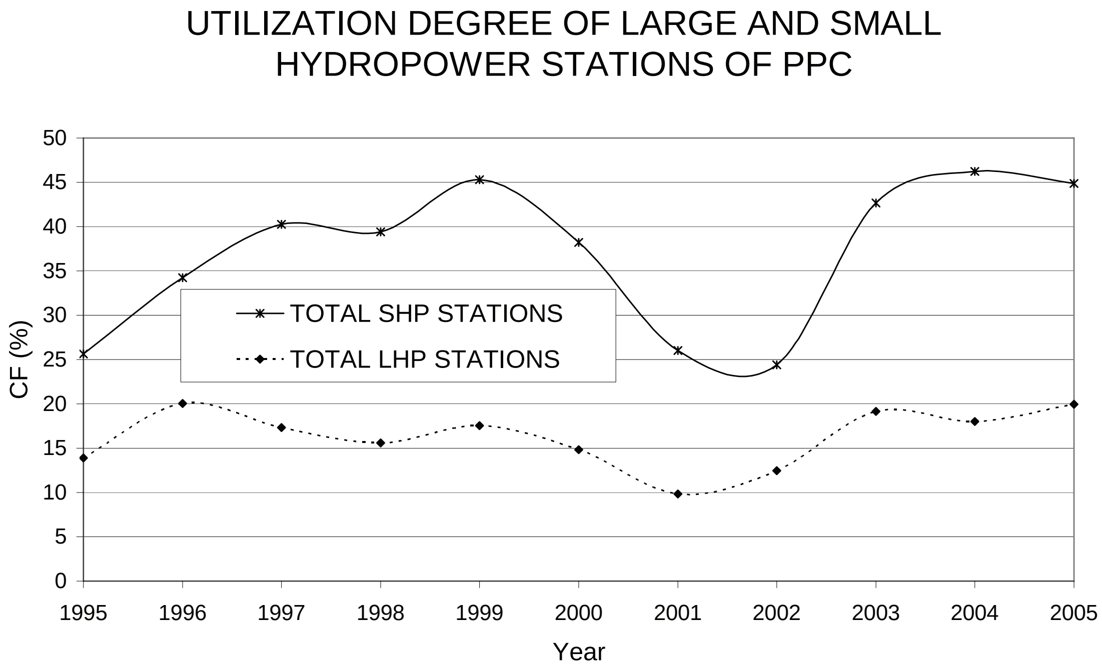

Figure 17: Comparison of the utilization degree of Greek PPC hydro power stations

6. Conclusions and Proposals

As already mentioned Greece mainland possesses a remarkable hydro potential, which can significantly contribute to covering the continuously increasing national electricity demand. However, during the last years the installed hydro power capacity stagnates, while the utilization degree of the existing LHP stations is very low. Keep in mind that all the LHP plants in Greece belong to the State controlled PPC, which after the application of the law 2244/94 lost the monopoly of the local electricity market.

More specifically, in view of the electricity market liberalization procedure PPC is no more interested in creating new LHP plants, taking also into consideration the high initial capital required and the negative attitude of the local people towards new hydro power installations in their region. This discouraging situation becomes even worst due to the entire absence of a rational national water management plant. In fact, in most cases local municipalities and agricultural cooperatives control, via their political influence, the utilization of the available water potential. Hence, the electricity production is not a priority, thus several LHP stations present, during more than a decade, extremely low capacity factor values.

On the other hand, SHP plants are characterized more attractive mainly due to their size and their negligible environmental impacts. More specifically, most SHP stations present quite higher utilization degree of the available hydro potential, while the financial opportunities offered for further exploitation of the local hydro potential in view of the existing techno-economic conditions are quite attractive. However, even for the SHP stations the proprietary problems of water resources should be solved.

Summarizing, according to the information presented and analyzed, one may state that the available local hydro-power potential is quite promising and can substantially contribute to the accomplishment of the national-E.U. target to cover the 21% of the corresponding electricity consumption from renewable resources. For this purpose one should first define an approved and rational water resources management plan and support the increased utilization of large and small hydro power plants for electricity generation. In this case, properly designed hydro power plants should lead to considerable profits, contributing also in the country's independency from imported oil accomplishing as well the Kyoto protocol obligations.

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THE CONTRIBUTION OF SMALL HYDRO POWER STATIONS TO THE ELECTRICITY GENERATION IN GREECE: TECHNICAL AND ECONOMIC CONSIDERATIONS

J.K. Kaldellis
Laboratory of Soft Energy Applications & Environmental Protection
Mechanical Eng. Dept., Technological Education Institute of Piraeus

Abstract

Hydropower is the most widely used renewable energy source worldwide, contributing almost with 18.5% to the fulfillment of the planet electricity generation. However, most locations in Europe appropriate for the installation of large hydro power stations have already been exploited. Furthermore, there is a significant local communities' opposition towards new large power stations; hence, small hydro power stations remain one of the most attractive opportunities for further utilization of the available hydro potential. Greece and more precisely the country's mainland possesses a significant hydro-power potential which is up to now only partially exploited. In parallel, a large number of private investors have officially expressed their interest in creating small hydro power stations throughout the country, encouraged by the significant Greek State subsidy opportunities for renewable energy applications. However, up to now a relatively small number of projects have been realized, mainly due to decision-making problems, like the administrative bureaucracy, the absence of a rational national water resources management plan and the over-sizing of the proposed installations. Certainly, if the above problems are suitably treated, small hydro-power plants can be proved considerably profitable investments, contributing also remarkably to the national electricity balance and replacing heavy polluting lignite and imported oil. In the context of the above interesting issues, the present study reviews in detail the existing situation of small hydropower plants in Greece and investigates their future prospects as far as the energy, economic and environmental contribution are concerned.

Keywords: Hydro Power; Electricity Generation; Small Hydro Power Plants; Water Potential; Capacity Factor; Initial Cost; Financial Behavior; Internal Rate of Return

1. Introduction

During the last 800 years watermills have been in operation all over Europe, covering the needs of local habitants for mechanical power. Later, at the beginning of the 20th century, watermills were replaced by fossil-fuel (coal, oil, nuclear, etc.) fired electricity generation plants. Recently, the depletion of world oil reserves and the significant environmental degradation have revived the interest on renewable energy sources (RES). In this context, emphasis is laid on the exploitation of wind and solar potential, with remarkable success. However, hydropower is still the most widely used renewable energy source worldwide[1][2], contributing almost with 18.5% to the fulfillment of the planet electricity generation[3][4]. Taking into consideration that the most appropriate locations in Europe for the installation of large hydro power stations have already been exploited as well as the strong opposition[5] of local communities towards new hydro power stations claiming important environmental impacts, small hydro power (SHP) stations remain an attractive opportunity for further utilization of the available hydro potential throughout Europe.

In fact, small hydro power stations constitute remarkable energy production installations with considerably less environmental impacts, since in most cases they utilize local water resources without the need of extended infrastructure facilities and the construction of huge dams. More precisely, according to the existing international nomenclature[6][7], the rated power of a SHP station is usually less than 10MW, while all stations with rated power less than 1MW are characterized as mini. For very small applications (rated power less than 50kW) one may also use the expression "micro hydro power station".

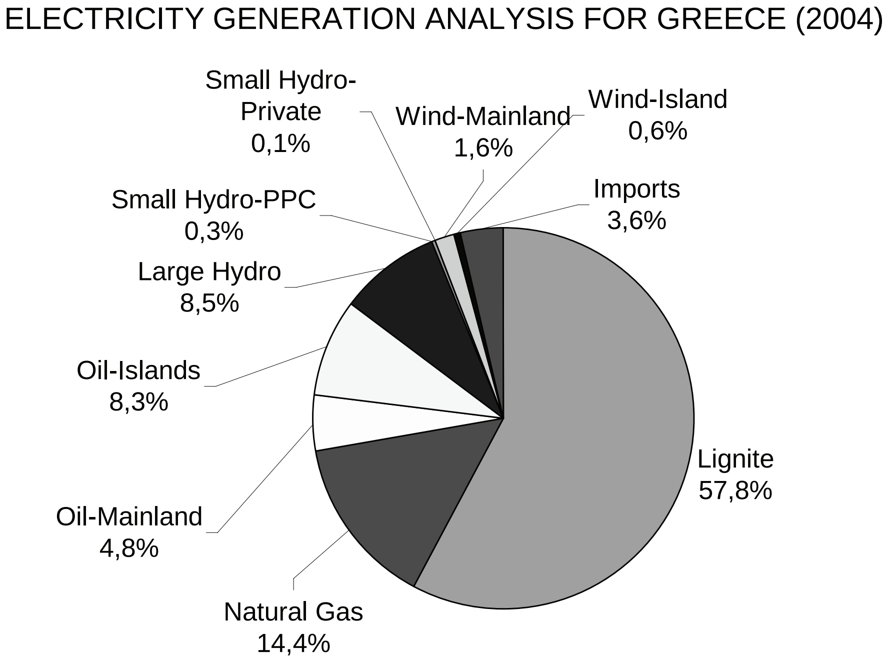

Figure 1: Electricity generation analysis for Greece, 2004

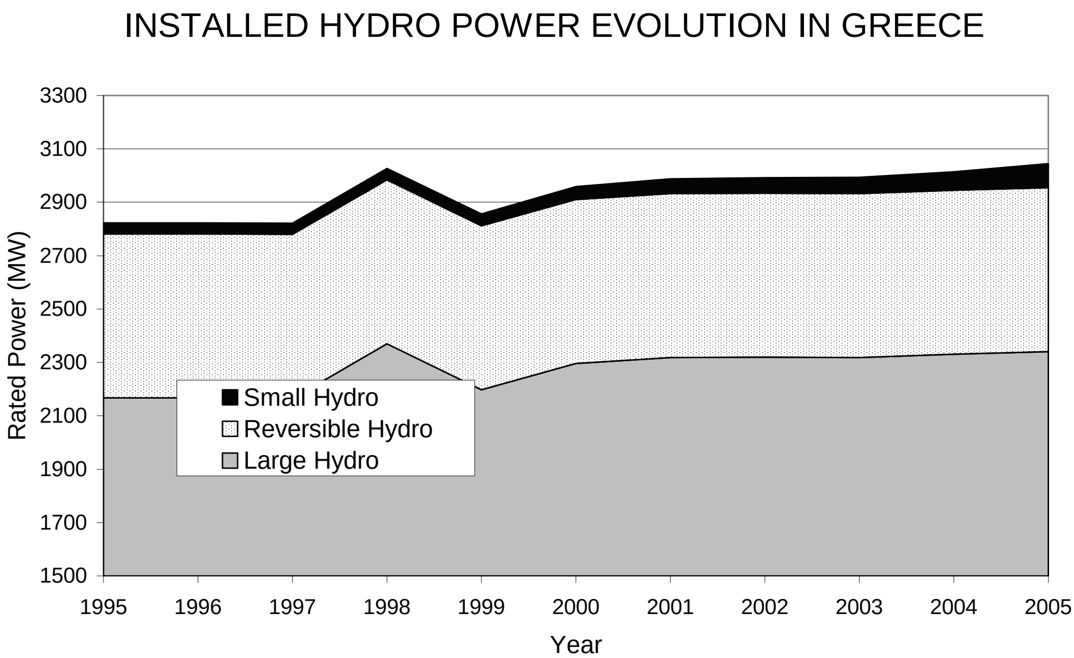

Figure 2: Time-evolution of installed hydro power in Greece

According to the EU "White Paper for the Energy"[8], Greece, being a European Union member, should cover (2001/77/EC) the 20.1% of its electricity consumption by RES up to 2010. Unfortunately, in 2005 the RES contribution has been hardly 11%, see also figure (1), mainly due to the large hydro power (LHP) plants electricity generation. Bear in mind that, currently, fifteen (15) LHP stations operate in Greece with a total rated power slightly above 3000MW[5]. Messochora LHP plant (170MW), although completed since 1998, has never operated (figure (2)) due to strong reactions and legal restrictions against Greek Public Power Corporation (PPC) caused by local habitants mainly due to disputes concerning the available water potential management.

More precisely, Greek electricity generation is based mainly on locally extracted low quality lignite as well as on imported natural gas and heavy polluting oil, used mainly in autonomous island power stations[9][10]. In this context, taking into account that the current contribution of wind energy is slightly above 2% of the national energy balance and the stagnation of large hydro power stations during the last ten-years, figure (2), SHP plants constitute one of the most realistic opportunities for approaching the national targets, dictated by the 2001/77/EC Directive.

Actually, Greece and, more precisely, the west part of the mainland, possesses a significant hydro-power potential which has been up to now only partially exploited[5][11]. It is important to mention that the ground morphology (topography) in combination with the high precipitation, especially in the Greek mainland, facilitates the application of similar power stations[12]. According to the available data, only a minor part of the local water potential is up to now exploited[12][13]. Hence, the present analysis scope is to review the existing situation and contribute to a better development of the available small hydro potential.

2. Existing Small Hydro Power Stations

The first SHP station operating in Greece since 1927 is the one of Glafkos (1.6MW) located in N. Peloponnesus[13], while the SHP station of Vermio (1.8MW) has been also erected in central Macedonia almost during the same period (1929). Up to 1994, only eight SHP stations, belonging to the State controlled Greek PPC, had been operating with a total rated power equal to 42.8MW. After the application of the 2244/94 law permitting the installation of power stations based on renewable energy sources by private investors[14], an increased interest, to create new SHP plants throughout Greece, has been expressed. In this context, a remarkable number of private SHP has been installed after 2000, i.e. almost forty (40) new plants were erected between 2000 and 2005, while the corresponding rated power has been increased by more than 120%, figure (2).

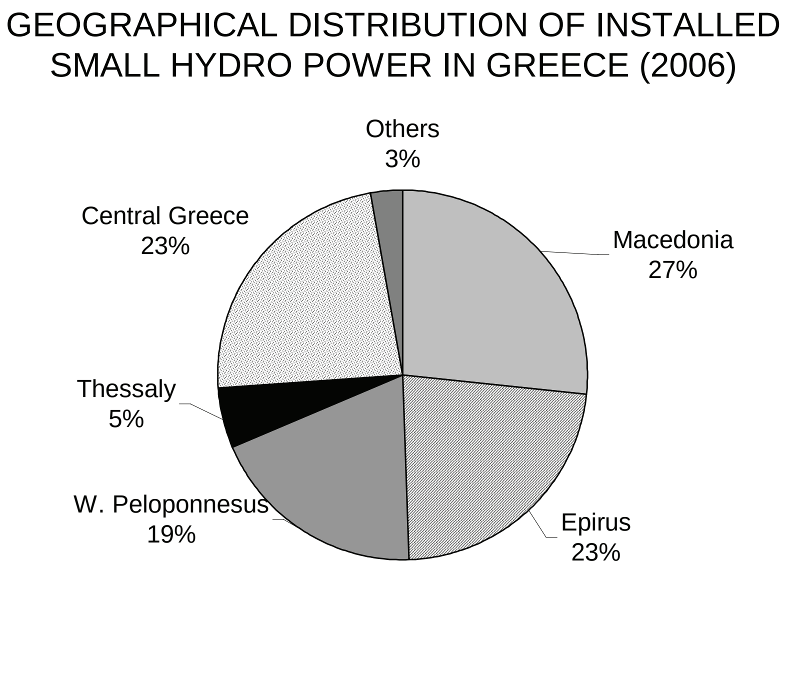

Figure 3: Geographical distribution of installed small hydro power in Greece

Figure 4: Geographical distribution of small hydro plants in Greece, Table I

Figure 5: Geographical distribution of micro hydro plants in Greece, Table II

More precisely, according to the most recent (beginning of 2006) available official information[15][16][17] currently in Greece approximately fifty (50) SHP plants are in operation with rated power equal to 93.3MW. These power stations have been almost equally distributed in Macedonia, Epirus, Central Greece and West Peloponnesus, figure (3). Using the available information, twenty one (21) SHP stations (Table I) have rated power between 1MW and 10MW representing the 82% of the entirely installed power (i.e. 75.5MW). On the other hand, the rest twenty nine stations belong to the group of mini installations (<1MW), Table II, with a total capacity of 16.75MW.

At this point it is important to note that nine out of these fifty power plants are in the possession of Greek Public Power Corporation (PPC) representing 45.7% of the installed power, four are belonging to local municipalities, while the rest are private investments. In figures (4) and (5) the geographical distribution of small and mini hydro power installations is depicted. Keep in mind that the biggest SHP plants belong to PPC, while the rated power of the largest private station is 4.5MW, see also Table I.

Table I: Small hydro power stations in Greece

	Location/Name	**Property**	**Power (MW)**
1	VERMIO I	PPC	1.8
2	GIONA, FOKIDA	PPC	8.5
3	PATRA, GLAFKOS	PPC	4.8
4	STRATOS II	PPC	6
5	TSIVLOS, AKRATA	Private	2.82
6	AG. MARINA, LAKONIA	Private	1.0
7	KLITORIA, ACHAIA	Private	1.3
8	MAKROXORI, VERIA	PPC	10.8
9	LOUROS	PPC	10.3
10	KERINITIS, ACHAIA	Private	2.6
11	LAMBIA, ILIA	Private	1.47
12	KATARRAKTIS, ARTA	Private	2.4
13	ANO GOURA, ARTA	Private	3.9
14	NEROTRIVI, IOANNINA	Private	1.94
15	KASTANIOTIKO, TRIKALA	Private	1.95
16	MERLIKA GAREFIOU, PELLA	Private	1.83
17	ROUFRAKTIS, SERRES	Private	3.0
18	MONI PANAGIAS, SERRES	Private	1.2
19	INACHOS, FTHIOTIDA	Private	4.5
20	THERMOREMA, FTHIOTIDA	Private	3.5
21	AGIORANITIKO, FOKIDA	Private	1.9

Table II: Mini hydro power stations in Greece

	Location/Name	**Property**	**Power (kW)**
1	XERIAS, KAVALA	Municipality	938
2	PIGES GOURA, IOANNINA	Private	930
3	GOURA-ANATOLIKIS, IOANNINA	Private	700
4	GOURA-MIKRO PERISTERI IOANNINA	Private	990
5	PIGES KLIFKI, IOANNINA	Municipality	100
6	VATSOUNIA-2, KARDITSA	Private	600
7	REMA GONNON, LARISSA	Private	650
8	REMA PRODROMOU, LARISSA	Private	995
9	SARAKINOS, VOLOS	Municipality	750
10	ARAPITSAS, IMATHIA	Private	625
11	SARANTOVRISSES, IMATHIA	Private	570

	Location/Name	Property	Power (kW)
12	AGIOS IOANNIS, IMATHIA	PPC	700
13	LIMNES PANAGITSAS-1, PELLA	Private	500
14	LIMNES PANAGITSAS-2, PELLA	Private	60
15	LIMNES PANAGITSAS-3, PELLA	Private	150
16	ARKOUDOREMA, PELLA	Private	350
17	TECHNITES LIMNES, PELLA	Private	560
18	MPISTRITSA, PELLA	Private	220
19	TOUPLITSA, PELLA	Private	830
20	PATINTA, PELLA	Private	560
21	KRASOCHORITIKO, SERRES	Private	650
22	AGKISTRO, SERRES	Municipality	500
23	KIRFI, VIOTIA	Private	760
24	ELIKON, VIOTIA	Private	650
25	MONASTIRAKI, EVRITANIA	Private	980
26	POUGKAKIA, FTHIOTIDA	Private	850
27	GORGOPOTAMOS, FTHIOTIDA	Private	155
28	AGIA, CRETE	PPC	300
29	ALMIROS, CRETE	PPC	300

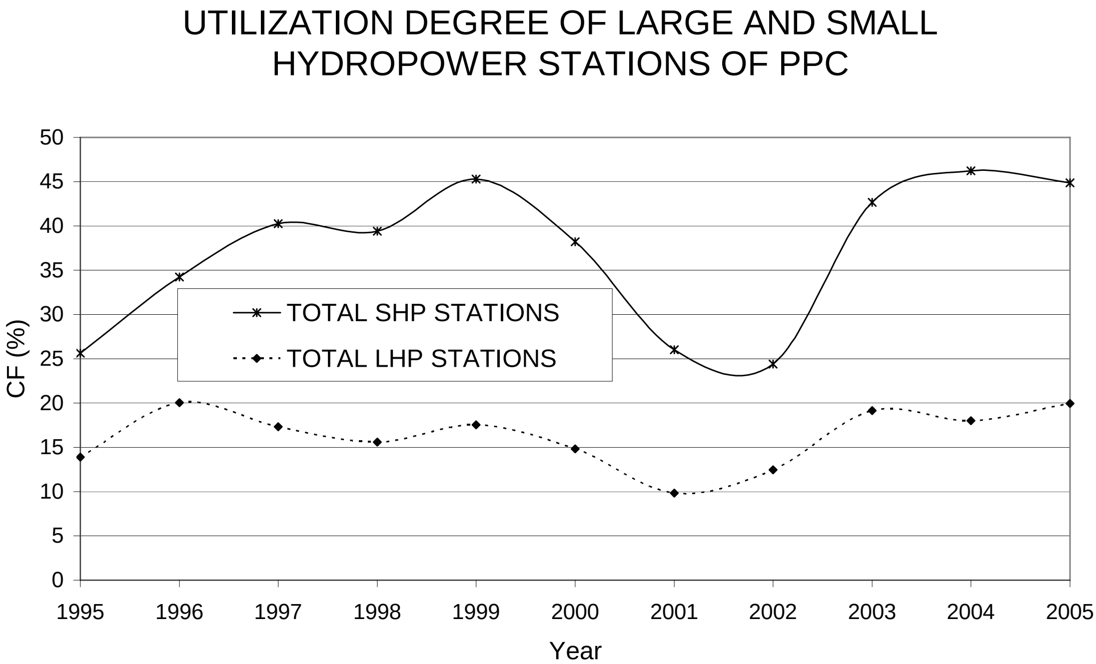

Figure 6: Comparison of the utilization degree of Greek PPC hydro power stations

In order to underline the entirely different utilization concept of small and large hydro power stations, one may compare their corresponding capacity factor for a considerably long time period. More specifically, the capacity factor "CF" of an energy production installation[18] of rated power "N_o" for a given time period "Δt" is defined as:

$$CF = \frac{E(\Delta t)}{\Delta t \cdot N_o} \tag{1}$$

where "$E(\Delta t)$" is the energy yield of the installation under investigation during the specific time period "Δt". For this purpose, the capacity factor time evolution of the large and small PPC hydro power stations is shown in figure (6), for which extended official operational data are available for more than a decade. In fact, the average capacity factor of SHP stations is more than twofold the corresponding value of

LHP plants for the last decade examined. This can easily be understood if one takes into account that most LHP stations are used mainly to meet the corresponding peak load demand of the national network, while the SHP stations are operating on the basis of the available water potential, primarily to maximize their electricity generation[19].

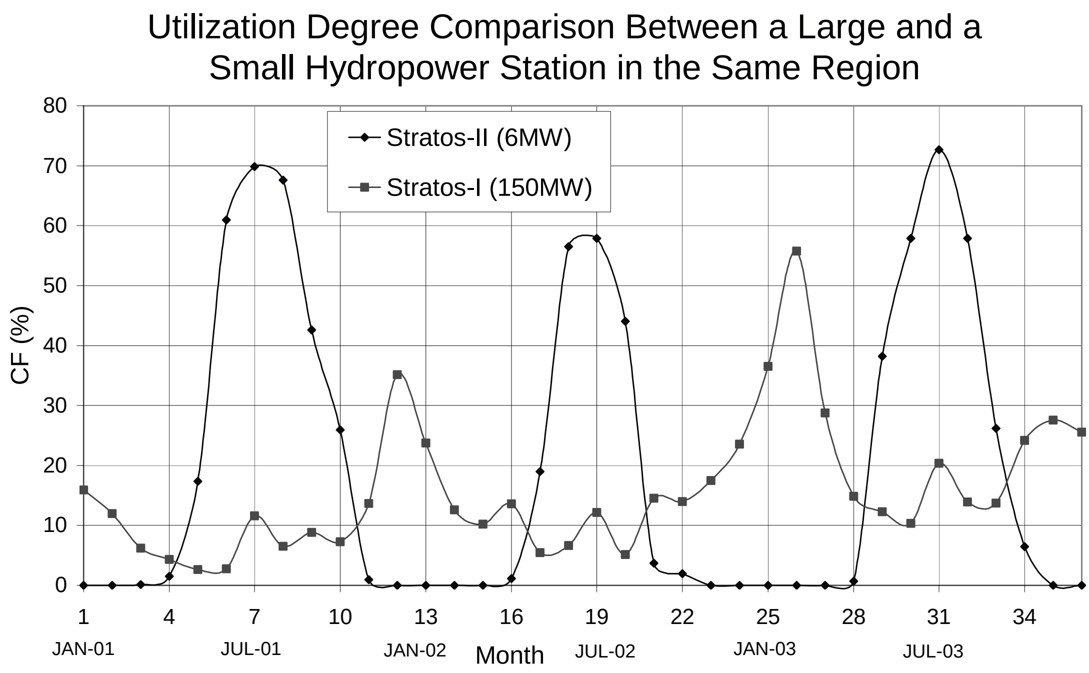

Figure 7: Comparison of the utilization degree of two nearby hydro power stations

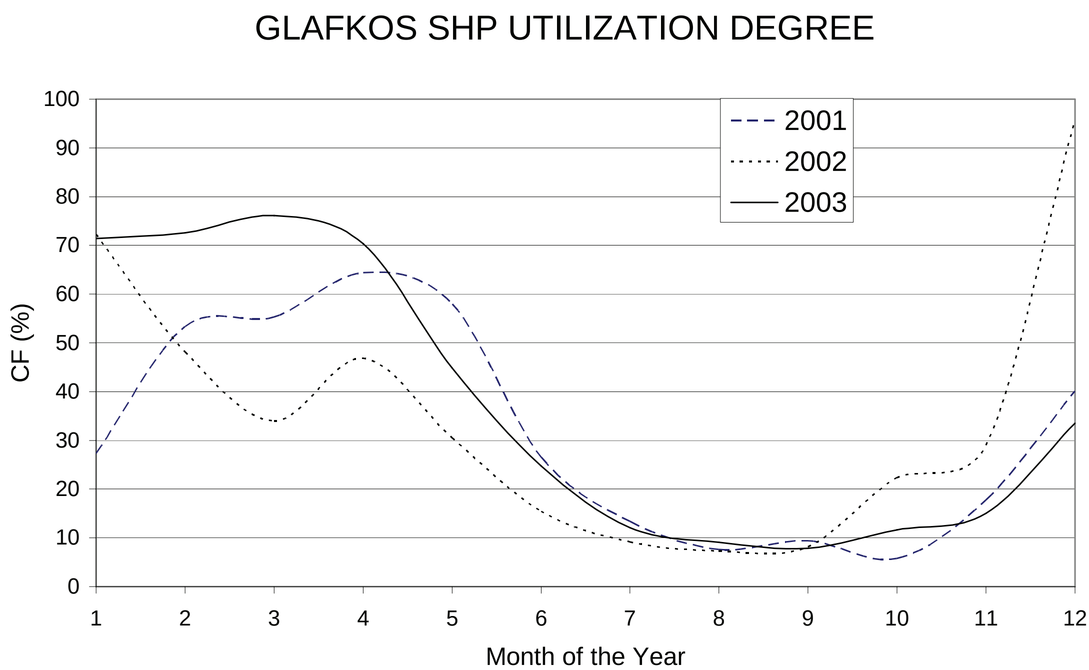

Figure 8: Energy yield of Glafkos SHP station in the course of time

In order to better perceive the different utilization strategy applied to large and small hydro power stations one may observe in figure (7) the electricity yield of two representative nearby hydro stations (i.e. Stratos-I, 150MW and Stratos-II, 6MW) located in West-Central Greece (figure (4)) throughout an entire three year period. As it is obvious from the data of figure (7) the SHP station operates with quite high capacity factor values during the May-October period every year on the basis of the available water potential. On the other hand, the LHP station operates throughout the year, using the water stored in the corresponding dam to cover increased power demand of the national network. In special cases, when excess water is stored, a spontaneous energy yield increase is encountered. The typical operation of a SHP station is also validated by the energy yield of another representative power plant located in S. Greece (Peloponnesus), i.e. Glafkos 3.6MW, figure (4). According to the capacity factor time-evolution profile, figure (8), the above mentioned station operates mainly during the wet months of the year, while the electricity generation during the dry months of the year is only the one fifth of the corresponding wet months' value. In fact, the electricity generation of most SHP stations is in accordance with the available natural water potential, see for example figure (9), where one may observe the long-term (over a twenty-year period) average monthly volume flow rate of a typical SHP plant.

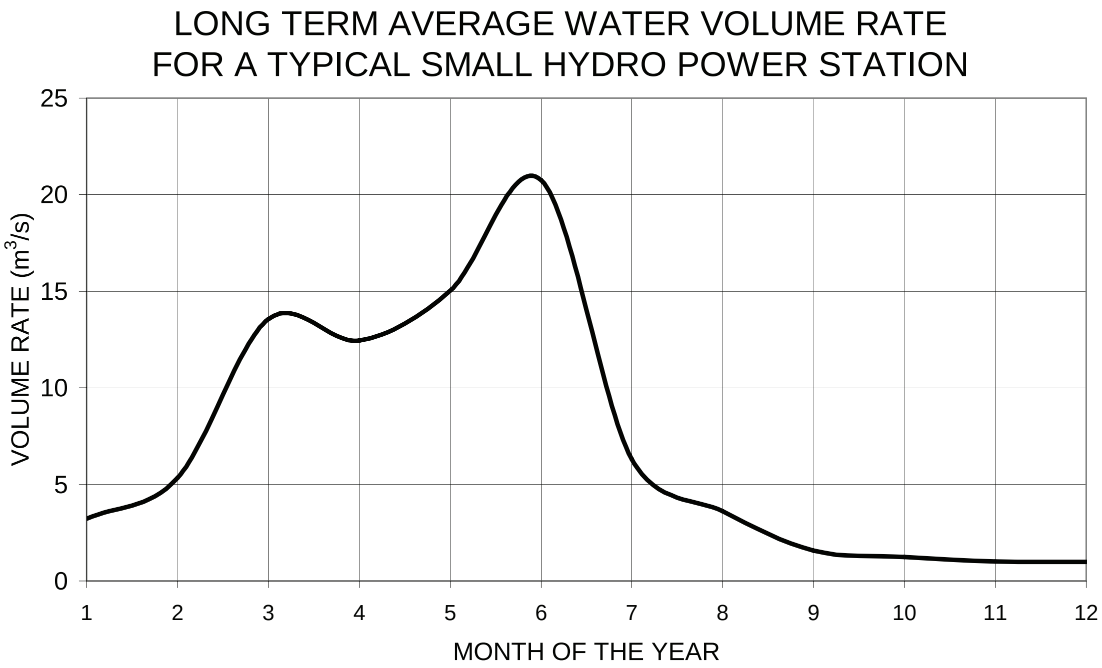

Figure 9: Twenty-year average water volume rate for a typical SHP station

3. Prospects for New Small Hydro Power Stations Erection

As already mentioned the available small hydro potential in Greece is quite high, hence there are many suitable locations for developing new stations. In this context, one may state that there is an increased investors' interest regarding the erection of small and mini hydro power plants[15][16]. Particularly, two categories of investors appear in the Greek Regulatory Authority of Energy (RAE) records[16]. The first group includes those who have already taken the permission to construct new installations. The second category concerns the investors which have already submitted their application and are waiting for the corresponding evaluation (*positive or negative*) by the Greek RAE.

Until today, more than 230 private investors have in their possession the permission to produce energy by small hydro power plants. The total rated power of all these installations exceeds the 610MW. In figure (10) one may find the major Greek areas where the new SHP stations are situated. The majority of them are to be erected in Epirus, Central Greece and Macedonia. An important rated power is also to be installed in W. Peloponnesus and in Thessaly.

On top of this, a number of proposals concerning SHP plants -submitted between 2001 and 2005- have been positively evaluated, however for various reasons they have not yet received the production permission by the Ministry of Development. Furthermore, another 533 proposals have been negatively evaluated by RAE during the same period. Finally, 125 recent proposals (rated power 341MW) have been submitted to RAE, expecting the corresponding evaluation decision. At this point it is quite impressive to note that if all these plants are to be implemented, the contribution of the SHP stations in the national electricity generation should attain the value of 5%, strongly improving the national efforts to meet the 2001/77 EU Directive target.

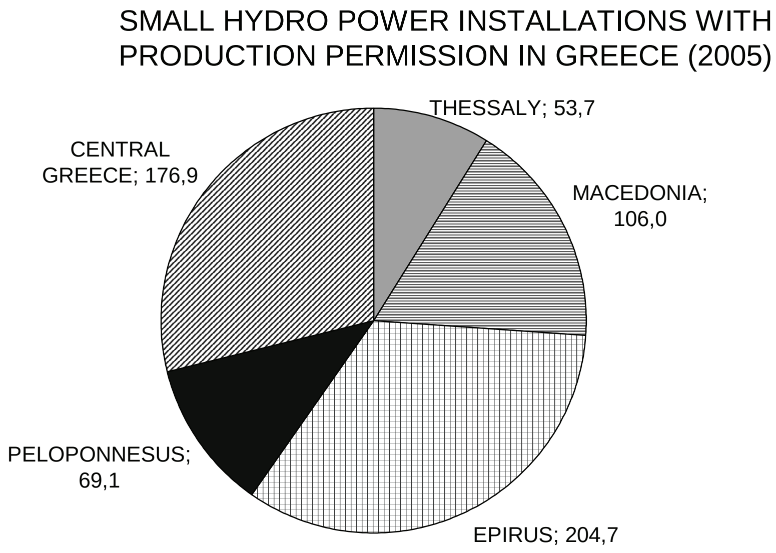

Figure 10: SHP stations with production permission in Greece (end 2005)

In view of the above mentioned target, the local electricity market liberalization started in February 2001, leading to fundamental changes in the corresponding power industry[14]. At the same time, the Greek State integrated the new Renewable's legislative frame, based on the 2244/94 law. According to this frame, the electricity produced by renewable sources (like small hydro) is sold to local utilities at a fixed percentage (70%-90%) of the corresponding retail-market price[20]. In addition, the Greek Regulatory Authority for Energy[16] along with the Ministry of Development[15] are in charge of facilitating private investments in the energy production sector. More specifically, RAE has the authority to judge all the new energy production applications making also the final proposals to the Ministry of Development about the forthcoming energy production plants (i.e. expressing *positive or negative judgment*).

The evaluation of each SHP project is carried out step by step taking initially into consideration several parameters such as:

- Environmental issues
- The location of the proposed installation and the proprietary rights of the water resources
- The installation safety and
- The integrity of typical documents required.

Accordingly, RAE examines a number of techno-economic parameters, like the installation capacity factor, the available water potential exploitation degree and the investment internal rate of return. In fact, a small hydro power plant proposal is positively evaluated if the capacity factor (see equation (1)) of the installation satisfies the following criterion:

$$CF \geq 30\% \qquad (2)$$

Subsequently, the energy exploitation degree of a SHP station expresses the annual water volume passing through the turbine, in relation with the total available water volume of the waterfall. In order a new SHP plant to obtain positive evaluation, this ratio should be at least 75%.

Finally, one of the major prerequisites of new SHP investments is to produce energy with a financially attractive efficiency[21][22]. In this case one should examine whether the investment's IRR (internal rate of return) is higher than a given limit, i.e.:

$$IRR \geq 5\% \tag{3}$$

Unfortunately, one of the basic problems that a new SHP investment faces is the bureaucracy, regarding the number of supporting documents and the public departments an investor has to apply to in order to gather the documents required. In figure (11) one may find the basic steps that an investor should follow in order to create a new SHP plant in an appropriate location. As it is obvious from this figure (11), one should apply to more than twenty public departments in order to accomplish his project, while the minimum time required is almost two years, on top of the time required in order to carry out the necessary hydro potential measurements.

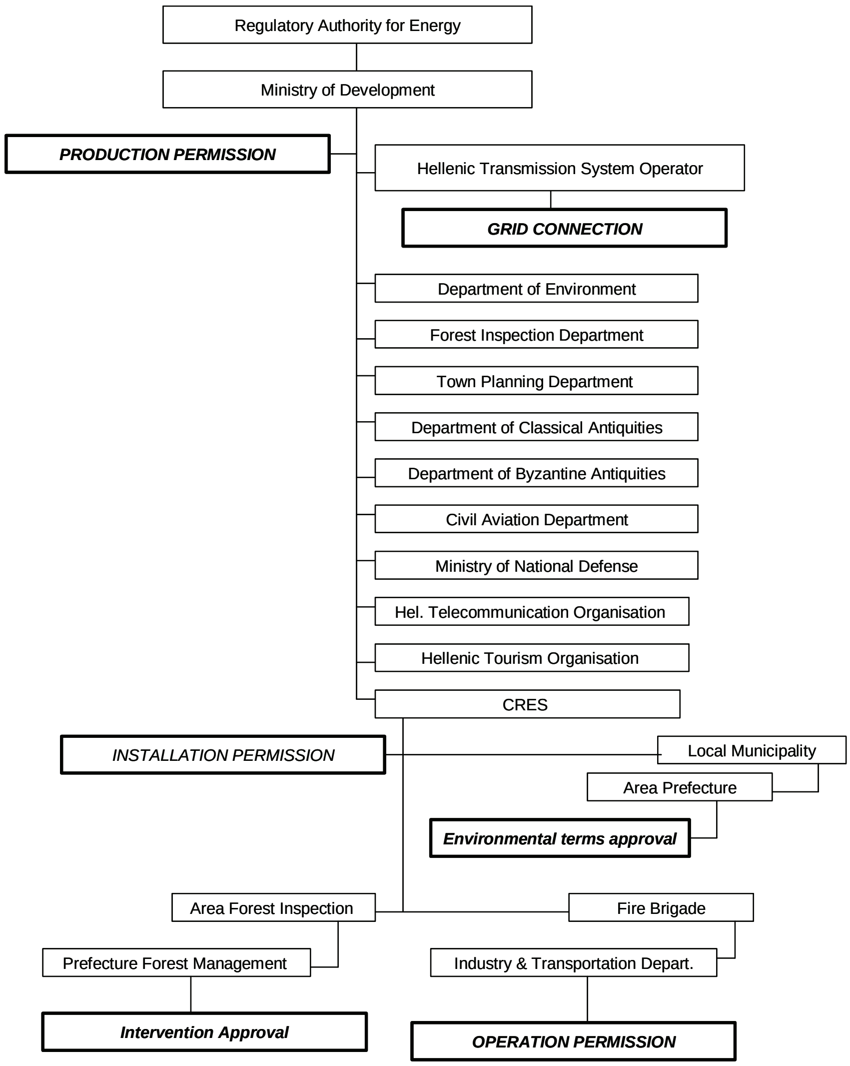

Figure 11: The officially implementation procedure of a new SHP station

4. Financial Behavior of Small Hydro Power Stations

Hydro power stations are normally characterized as capital intensive investments, since they require high initial capital for the installation of the power plant and relatively low operation and maintenance cost. Besides, SHP plants cannot take advantage of any scale economies due to their small size, however they face limited infrastructure cost, since in most cases there is no need for extended dams, if any, as in the run of the river applications.

More precisely, the initial cost of a SHP of rated power "N_o" includes the market price of the electromechanical equipment (usually ex-works), the civil engineering activities and the corresponding balance of plant cost[1][22][23]. Thus one may write:

$$IC_o = Pr \cdot N_o \cdot (1+f) \tag{4}$$

where the specific (reduced) ex-works price "Pr" (€/kW) of the SHP -at the time point where the station starts its operation (normally two-three years are needed to develop a new SHP in Greece)- is given as:

$$Pr = Pr_1 + Pr_2 \tag{5}$$

Keep in mind that "Pr_1" describes the electro-mechanical equipment reduced cost, being mainly a function of the hydro turbine nominal power "N_o" and the corresponding head "H", hence one may write for the local market:

$$Pr_1 = \frac{b_o}{N_o^{b1} \cdot H^{b2}} \tag{6}$$

with b_o=3300€, b_1=0.122 and b_2=0.107.

On the other hand, "Pr_2" expresses the specific cost of civil engineering works, including infrastructure, land purchase, dam construction (if necessary), weir and intake, water canal, forebay tank, penstock etc. Unfortunately, it is not possible to simulate the "Pr_2" value, since it depends on the local situation of every specific site. Generally speaking, according to the experience[1][11][13][18][22][23][24][25] of a remarkable number of installations, "Pr_2" can be expressed as:

$$Pr_2 = \xi \cdot Pr_1 \tag{7}$$

with "ξ" currently taking values for the local market between 0.3 and 1.0 (the exact value depends on the intangible expenses of similar installations). The higher "ξ" values appear in cases of dam construction (usually earthen) and long penstock utilization.

Finally, "f" expresses the installation and soft costs (e.g. electrical interconnection cost, access tracks, development cost etc.), which is given as a fraction (f≈5%-10%) of the "Pr" (or "Pr_1").

The maintenance and operation (M&O) cost can be split[26] into the fixed "FC" and the variable cost "VC". Actually, the annual fixed M&O cost is expressed as a fraction "m_1" of the electromechanical equipment ex-works price plus a fraction "m_2" of the civil engineering work cost, assuming also an annual increase equal to the corresponding inflation rate "g_m". In most cases the fixed M&O cost of a SHP installation is constant for the first ten to fifteen years of operation of the power station, taking values in the order of 1% of the initial capital invested, hence the present value of "FC" is given as:

$$FC_n = (m_1 \cdot Pr_1 + m_2 \cdot Pr_2) \cdot N_o \cdot \frac{(1+g_m)}{(1+i)} \cdot \left[1 + \left(\frac{1+g_m}{1+i} \right) + ... + \left(\frac{1+g_m}{1+i} \right)^{n-1} \right] \tag{8}$$

where "i" is the investment interest rate.

The variable maintenance and operation cost[22][26] mainly depends on the replacement frequency of the installation major parts (renovation), which may have a shorter lifetime than the complete power station, e.g. electrical generator, rotor blades etc. Bear in mind that this cost component becomes significant normally after ten or fifteen operational years of the SHP station.

In this context, the present value of the total investment cost "C_n" of the SHP installation after n years of operation reads:

$$C_n = (1-\gamma)\cdot IC_o + FC_n + VC_n \tag{9}$$

where "γ" is the subsidy percentage by the Greek State or the E.U.".

Subsequently, the total savings over an n-year period -resulting from the operation of a SHP station- are mainly attributed to the energy production "E" sold to the national electrical grid. In addition, there is a monthly compensation for the power added to the local network. On the other hand, according to the current legislation frame (Law 2773/99), a supplementary amount from the investment revenues (p=2%-3%) is directly transferred to the local municipalities, in order to approve the SHP installations in their location. Thus, the present value of the total SHP station income (operating for n years) is given as:

$$R_n = E\cdot c\cdot(1-p)\cdot\sum_{j=1}^{j=n}\left[\frac{1+e}{1+i}\right]^j + (\sigma\cdot\sum_{j=1}^{12} N_{max_j})\cdot c_N\cdot(1-p)\cdot\sum_{j=1}^{j=n}\left[\frac{1+e_N}{1+i}\right]^j \tag{10}$$

where "c" and "c_N" are the energy price (€/kWh) and the power reimbursement per month (€/kW/mo) respectively. Currently "c" equals to 0.07€/kWh while "c_N" equals to 1.5€/kW/mo. Also "e" and "e_N" are the corresponding electricity price and electrical power compensation annual escalation rate. Finally, "N_{max}" is the maximum output power of the station for every month of the year and "σ" is the average power contribution factor of the SHP to the local grid, defined by the 2244/94 law, i.e. σ=0.7.

Comparing the present value of the total investment cost and the corresponding total revenues, one has the ability to estimate[22][26] the net present value of the investment "NPV" after n years of operation, i.e.:

$$NPV_n = -1+\gamma-\frac{m_1\cdot Pr_1+m_2\cdot Pr_2}{(Pr_1+Pr_2)\cdot(1+f)}\frac{a_m\cdot(1-a_m{}^n)}{1-a_m}+\frac{E\cdot c\cdot(1-p)}{IC_o}\cdot\frac{a_e\cdot(1-a_e{}^n)}{1-a_e}+ (1-p)\cdot\frac{(\sigma\cdot\sum_{j=1}^{12}N_{max_j})\cdot c_N}{IC_o}\cdot\frac{a_N\cdot(1-a_N{}^n)}{1-a_N}+\frac{Y_n/IC_o}{(1+i)^{n^*}}-\sum_{j=1}^{j=n}\frac{\Phi_{(j)}/IC_o}{(1+i)^{n^*}} \tag{11}$$

where:

$$a_m = \frac{1+g_m}{1+i},\quad a_N = \frac{1+e_N}{1+i},\quad a_e = \frac{1+e}{1+i} \tag{12}$$

In equation (11) "$\Phi_{(j)}$" describes the tax paid only during the "j" year, mainly due to the revenue of the previous year. Similarly, "Y_n" represents the residual value of the investment, owing for the most part 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.) minus the decommission cost, along with the experience gained and the corresponding technological know-how. Subsequently, the internal rate of return "IRR" of the SHP investment (operating during an n-year period) is predicted by setting the "NPV" equal to zero, thus one may write:

$$IRR = i^*,\qquad \text{when}\quad NPV(i^*) = 0 \tag{13}$$

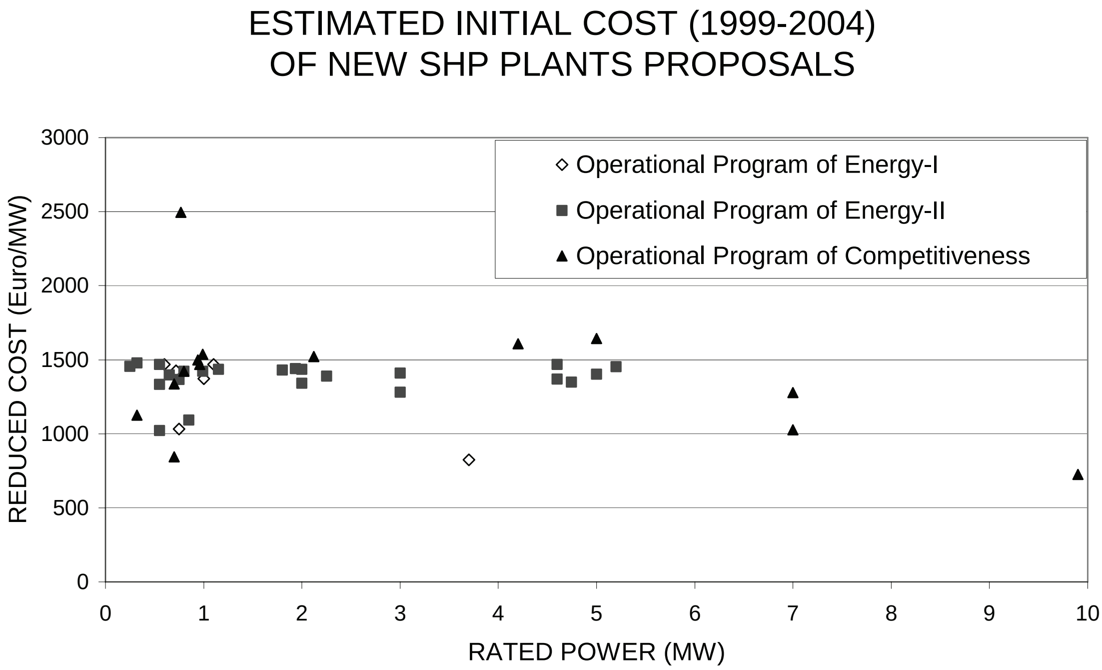

Figure 12: Estimated initial cost of proposals to the Greek Ministry of Development for new SHP plants

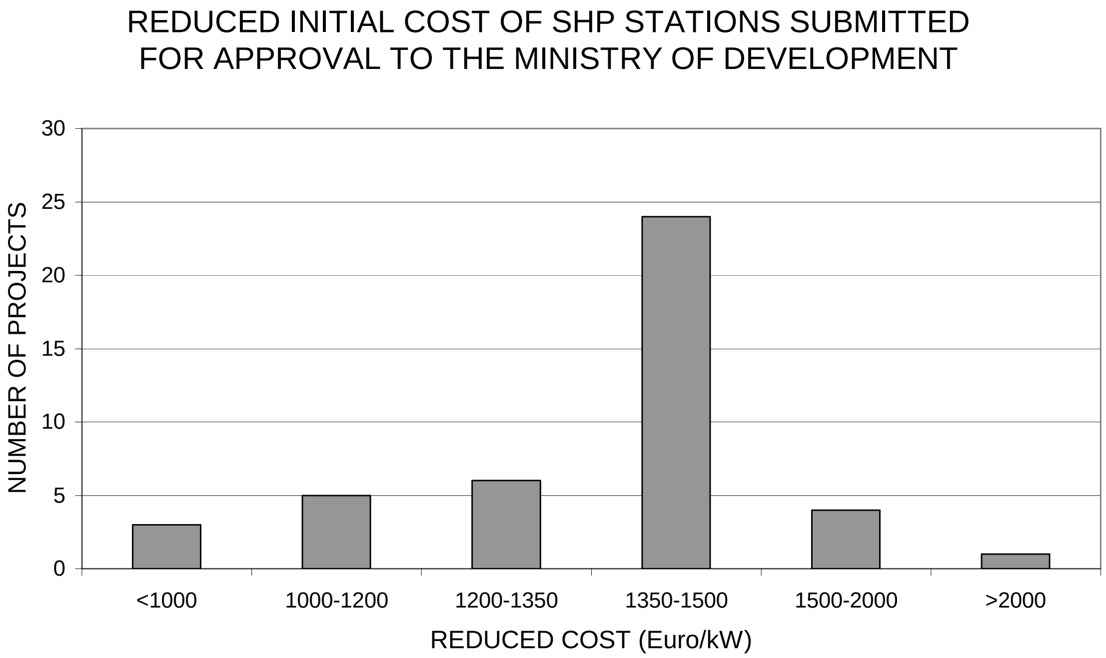

Figure 13: Variation of reduced initial cost of SHP stations submitted for approval to the Greek Ministry of Development

Using the experience of the authors resulting from the evaluation of a large number of applications[15][18] submitted to the Greek Ministry of Development in the frame of the "Operational Program of Competitiveness" and the "Operational Program of Energy", both funded mainly by the EU, one may state that the reduced turnkey cost of a SHP plant varies between 1100€/kW and

1600€/kW, see also figure (12). In fact mini hydro power stations (rated power less than 1MW) present reduced values between 1000€/kW and 1500€/kW, while the corresponding value of SHP plants (with rated power less than 5MW) is between 1350€/kW and 1600€/kW. For larger installations there is a remarkable reduced cost value decrease, however the number of available projects analyzed is quite limited in order to obtain reliable conclusions. In any case the vast majority of the SHP projects have reduced initial cost values between 1350€/kW and 1500€/kW, see also figure (13).

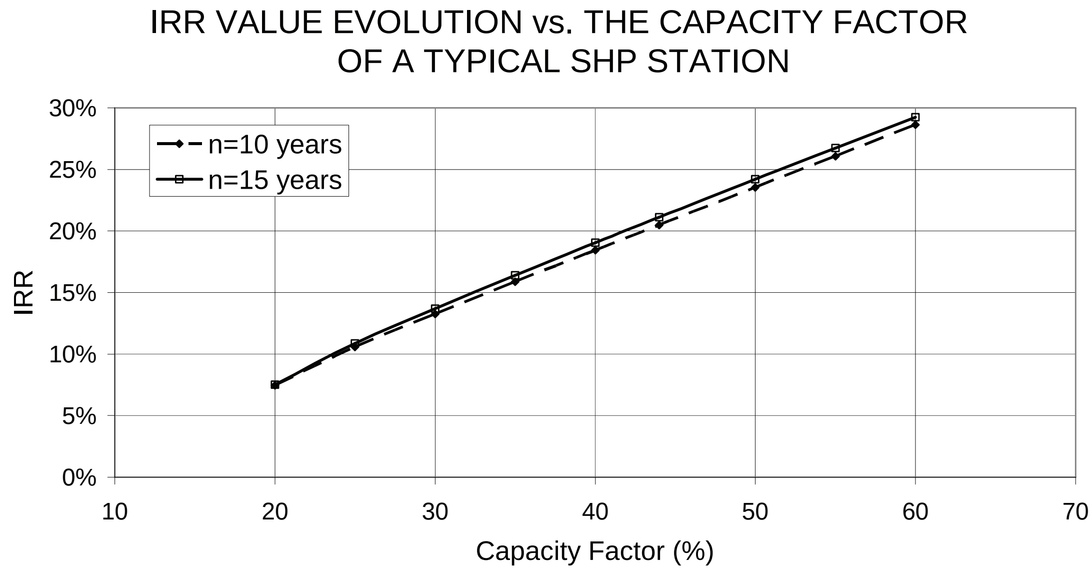

Figure 14: The impact of the capacity factor on the IRR value of SHP plants in Greece

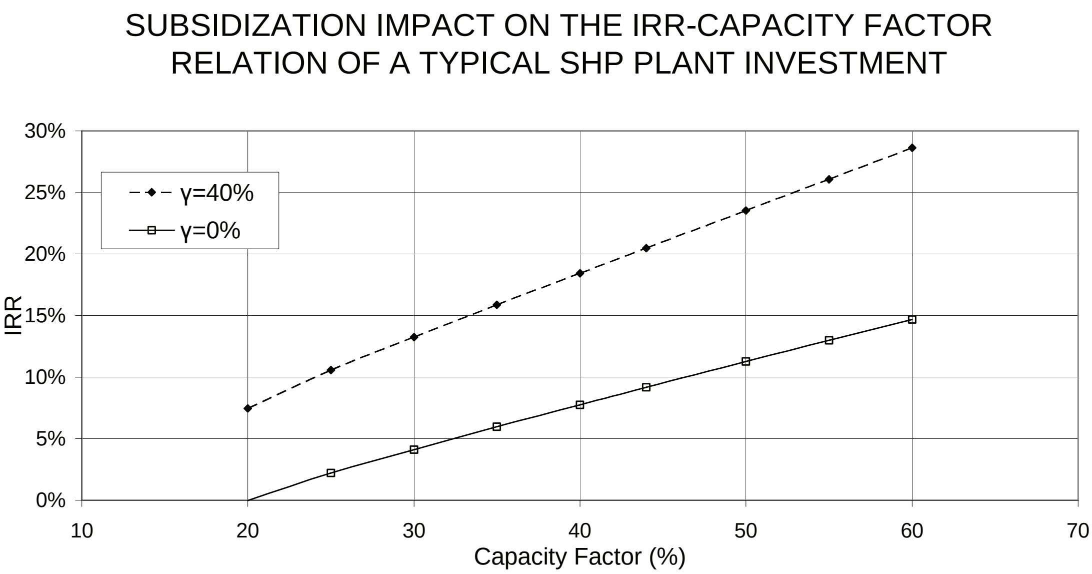

Figure 15: The influence of the subsidization on the IRR-CF relation for SHP plants in Greece

For the encouragement of similar environmental friendly energy generation applications, there is a significant subsidy for new SHP investments, making them quite attractive[15][22]. More specifically, according to the existing legislative frame one may apply for investment subsidy either to the Ministry of Economy via the current "Development Law" (e.g. 3299/2004) or to the Ministry of Development, via the "Operational Program of Competitiveness". In both cases there are specific requirements that both the investment and the investor should fulfill. The subsidy percentage is quite high, hence a 40% subsidy (i.e. γ=0.4) is offered to private investors in the area of small hydropower applications countrywide. Up to now more than forty (40) small hydro power investments have received the above mentioned financial grant, however more than one third of them are not completed yet.

Recapitulating, it is worthwhile to mention that according to the data provided and the extended techno-economic analysis made by the authors[22], it is clear that small hydroelectricity applications in Greece present a very good financial performance. More precisely, using the information of figure (14) one may note that the expected "IRR" value of similar SHP projects exceeds the 14% (even for only ten year service period of the station) if the corresponding capacity factor value is higher than 30%. Bear in mind that according to equation (2) this condition is a prerequisite in order the Greek RAE to approve the implementation of a new SHP installation. Besides, one should take into consideration that during the last decade the local market inflation rate is less than 5%, hence the corresponding capital cost is not more than 8%-10%. On the other hand, if no subsidy is provided (γ=0.0), most SHP projects become marginally profitable, figure (15), since their IRR value drops by almost 10% in case of zero subsidization. Another important aspect that local authorities should answer is the fact that the current subsidization scheme favors installations with high capacity factor, while this financial support is much more necessary to installations with medium-low capacity factor values, figure (15).

5. Problems and Prospects of Small Hydropower Plants

Using the data provided up to now, it is quite clear that small hydroelectricity applications in Greece have a very good techno-economic performance and, therefore, a promising future. However, taking into consideration the high financial efficiency of a SHP, see figures (14) and (15), one should also underline the quite slow realization degree of similar applications in view of the significant interest expressed by local investors. In this context, one should analyze the main factors delaying the installation of similar environmental friendly electricity generation plants.

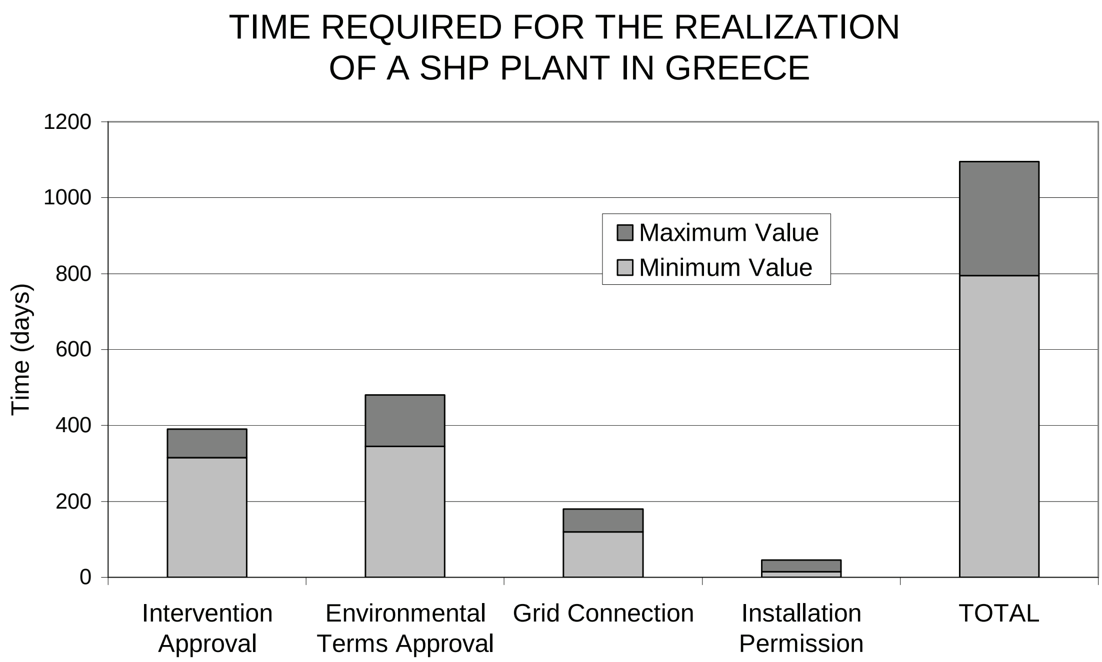

Figure 16: Average time required to create a new SHP plant in Greece

According to the experience of the authors, one of the major drawbacks decelerating SHP penetration in the local electrical market is the administrative bureaucracy. As already mentioned, despite the efforts of the Greek State there is a substantial number of documents that one should provide (figure

(11)) in order to start the construction of a new SHP station. In fact, for obtaining the final license required an investor needs to wait for a long time (usually up to three years), see for example figure (16). Hence, if the current permission procedure remains unaffected, it will be a major obstacle for the Greek small hydro plants development.

An additional serious obstacle against the creation of a considerable number of new SHP stations is the absence of an integrated national water management plan by the Greek State. This problem hinders the exploitation of the remarkable small-hydro potential locations of the country. In most cases examined, the water potential exploitation status is totally unclear, hence local municipalities and agricultural cooperatives raise exclusive or preferential proprietary rights on the existing water resources.

Essentially, in some cases local municipalities and agricultural cooperatives ask pressure, via their political influence, on the utilization planning of the available water potential. Thus in several cases the SHP plants cannot operate, see for example figures (7) and (8), since the electricity production is not a priority. However, by a careful and fair water potential management one may cover the parallel requirements of local societies/unions without zeroing the electricity generation of the SHP plants of the area.

Finally, taking into account the relatively small size of the above mentioned installations and the corresponding limited budget, most big energy-related construction companies are not very much interested in similar small-size projects. Hence, the erection of small or mini hydro power installations is realized by small private companies with limited socio-economic influence on the local and national level. On top of this, these relatively small firms have neither the necessary know-how nor the technical equipment to optimize their plants. Only in case of a number of successive SHP stations along the same river one may take advantage of scale economies. The result of this situation is the remarkable construction time required and the violation of the initial budget. Additionally, in many cases, the erected SHP stations are oversized[19], since the subsidy amount depends only on the installed power of the station and not on the corresponding energy yield. In these cases, the existing SHP stations do not operate for a considerable period of the year due to the low water volume rate available and the operational restrictions imposed by the hydro turbines of the installation, in order to avoid increased wear and maintenance of the equipment.

6. Conclusions and Proposals

Small hydro power installations are a financial attractive and an environmental friendly solution, able to contribute remarkably to the solution of the energy demand problem of Greece. In this context, the existing situation and the future prospects concerning the applications of small hydro power plants in Greece have been investigated. As already mentioned Greek mainland possesses remarkable small-hydro potential, which is partially exploited up to now. Taking also into consideration the significant subsidy opportunities by the Greek State and the EU, a large number (approx. 500) of private investors express officially their interest to create SHP stations throughout the country.

According to the available information most SHP investments present high financial efficiency if the proposed installation is properly designed in order to collaborate effectively with the existing water potential. Despite this positive situation, a relatively small number (approx. 50) of projects have been realized up to now, the biggest of them belonging to PPC and being in operation since the previous decade. This unexpected evolution can be attributed to several existing problems, like the administrative bureaucracy, the absence of a rational water resources management plan and the over-sizing of various installations encouraged by the existing subsidy scheme.

Recapitulating, one may state that in view of the numerous opportunities to build new small-hydro power stations throughout Greek mainland, if the above described problems are suitably treated, properly designed SHP plants should lead to considerable profits, contributing also by almost 5% to the national electricity consumption and replacing heavy polluting lignite and imported oil.

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BIOFUELS IMPLEMENTATION IN EAST EUROPE: CURRENT STATUS AND FUTURE PROSPECTS

E.M. Kondili[1], J.K. Kaldellis
[1]Optimisation of Production Systems Lab
Laboratory of Soft Energy Applications & Environmental Protection
Mechanical Eng. Dept., Technological Education Institute of Piraeus

Abstract

There is a continuously increasing interest concerning the biofuels implementation in Europe, mainly because of environmental protection and energy supply security reasons. In this context, EU strongly encourages the use of biofuels through a number of Directives. To that effect, EU members follow the Directives implementing various political, fiscal and technical measures and incentives. In the light of the potential created by the recently joined Eastern European countries, an increasing interest is shown in the whole biofuels supply chain within EU. In parallel, the status of the Eastern European countries domestic market, as far as biofuels are concerned, is an interesting issue, since most of these countries present a significant potential, however are still lagging in biofuels implementation. In the above context, the objective of the present work is to give a concise and up-to-date picture of the present status of biofuels implementation in East Europe. The work also aims at identifying the prospects of these countries as far as biofuels are concerned and their role in the EU framework as potential suppliers of a wider market.

Keywords: Biodiesel; Bioethanol; Eastern Europe; Biofuels Supply Chain

1. Introduction

Continuous efforts towards the solution of the energy supply security problem and the environmental impacts caused by the transportation sector have led to the development, of the so called alternative fuels, through extensive research activities. Liquid biofuels, produced from biomass such as agricultural crops, wood and food processing residues, can be used as transportation fuels in a large range of vehicles and offer the potential for development towards sustainable mobility with the involvement of the agricultural, energy and automotive sectors.

Various research works have been carried out concerning technical, political and economic issues of the production, promotion and implementation of biofuels in Europe. Critical issues that are examined by research works are the resources potential in EU[1][2], technological and economic performance and potential of various biofuels[3], evaluation of biofuel production technologies[4][5][6]. Furthermore, the enlargement of the EU by countries of Central and Eastern Europe provide some more opportunities for biodiesel and bioethanol production[7], as those countries have presently double the acreage per citizen compared to the EU-15 and have a significant potential in agro-productivity.

Various opinions have been expressed concerning the possible contribution of the Eastern European countries in the overall biofuels supply chain in EU[8][9][10]. However, there is a lack of an integrated review of their biofuels potential including quantitative information, mainly because of the lack of uniform and reliable information from these countries.

In any case, a detailed study that has recently been carried out[8] supports the idea that the potential contribution of Eastern European countries to the enlarged European production is not sufficient to cover their fair shares of the overall enlarged EU biofuel supply.

Yet, the implementation of biofuels in Eastern Europe is an interesting issue, since these countries have a significant biofuels potential, either in the raw materials or in the biofuels production[10].

Therefore, the objective of the present work is to give a concise and up-to-date picture of the current status of biofuels implementation in East Europe. The work also aims at identifying the prospects of these countries as far as biofuels are concerned and their role in the overall biofuels supply chain in EU.

2. Eastern European Countries Members of EU

The European Union is cohesion of independent countries. Out of its successive enlargements, by far the biggest happened on 1st May 2004, when ten countries joined the Union. These countries are: Czech Republic, Cyprus, Estonia, Hungary, Latvia, Lithuania, Malta, Poland, Slovakia and Slovenia. Bulgaria and Romania are likely to become members of the EU in 2007. After joining, new members must abide by the same EU laws and rules that apply to the old members.

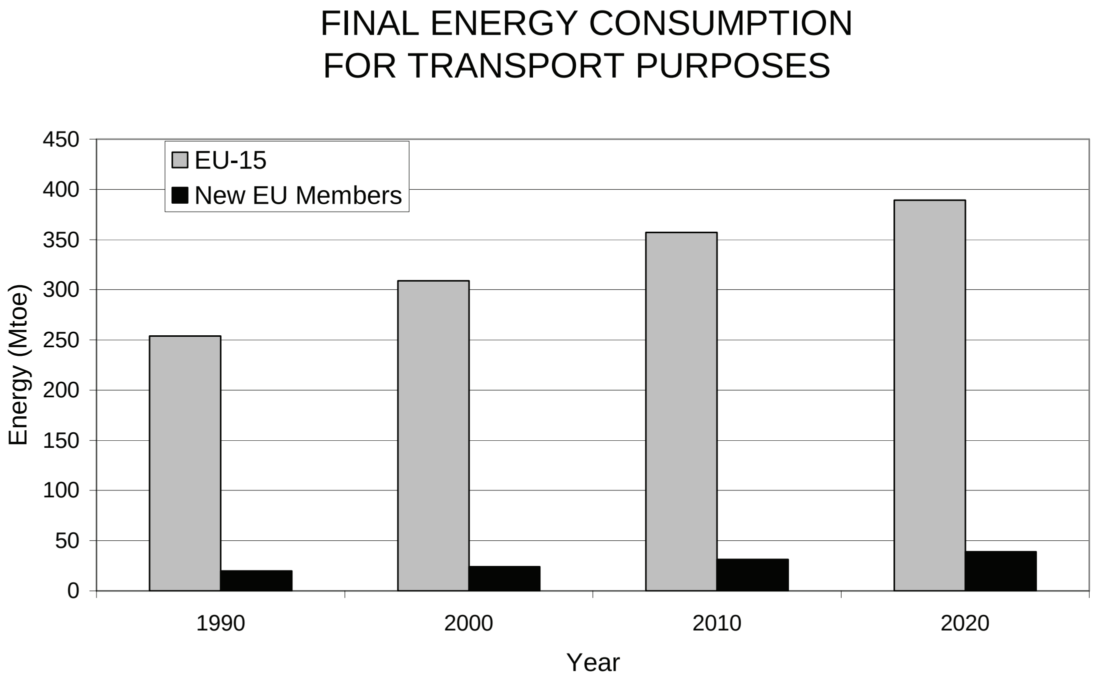

Figure 1: Final energy consumption for transport purposes in EU-15 and in the new EU members[11]

As mentioned above, the Eastern European countries that have recently joined the EU have a special interest as far as biofuels are concerned, mainly because of their land availability and agricultural and production experience and tradition. The following Table I includes the basic information concerning the ten accession and the two candidate countries[11].

Table I: Basic data concerning the new EU members

	Total Area (sq. km)	Population (2005) (million)	GDP (in 000 MEuro'00)	Energy demand in transport (Mtoe) 2005
Czech Republic	78,864	10.31	73.7	5.48
Cyprus	9,251	0.78	11.7	0.98
Estonia	45,226	1.475	7.5	0.75
Hungary	93,033	10.201	68.2	3.99
Latvia	64,61	2.52	10.5	0.85
Lithuania	65,200	3.71	16.0	1.29

	Total Area (sq. km)	Population (2005) (million)	GDP (in 000 MEuro'00)	Energy demand in transport (Mtoe) 2005
Malta	316	0.37	4.7	0.34
Poland	312,685	38.73	224.8	10.27
Slovakia	48,845	5.372	26.7	1.73
Slovenia	20,253	1.98	24.3	1.53
Bulgaria	110,912	7.78	18.4	2.19
Romania	238,391	22.67	53.6	4.69

The present work has focused in some of the above countries and more specifically in those that show a considerable progress or potential in one or more of the biofuels supply chain components. The countries that are considered in more detail in the present work are the following: Czech Republic, Hungary, Lithuania, Poland, Bulgaria and Romania.

The final energy consumption for transportation purposes actually gives an indication of the biofuels quantity that will be required in the future years. Figure (1) shows the final energy consumption for transport purposes for EU-15 and the new Eastern European EU members.

3. Biofuels Value Chain

The introduction, development and promotion of biofuels in the EU countries are interesting issues with at least two basic components and objectives:

- The primary objective pertains to the achievement of the reference targets set forth by the Directive 2003/30/EC through the substitution of the petrol and diesel consumption by biofuels and / or other renewable fuels.
- The other objective relates to the prospects that are created for the national economy of the involved countries by promoting the development of domestic feedstock and biofuel production.

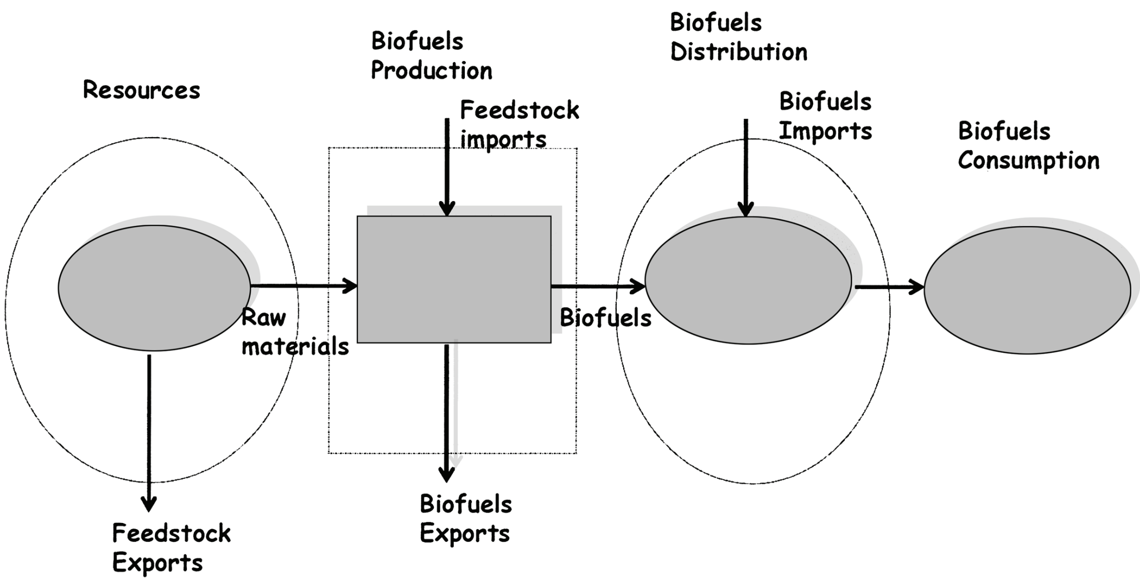

Figure 2: Biofuels supply chain structure

Certainly the first objective is an obligation and each country–EU member seeks for the most efficient and successful strategy for its achievement. The accomplishment of the primary objective does not necessarily require that feedstock or even biofuels production should be domestic. Certainly, for many countries in EU the target values will be reached only by biofuels imports.

The second objective is related to decisions concerning the development of the biofuels supply chain. Many countries consider the biofuels implementation as an important opportunity for the development of their agriculture, production infrastructure and energy supply basis and this is also an EU concern.

In the general case, the value chain for biofuels includes the following activities (figure (2)):

- Feedstock production (related to land availability and agriculture)
- Biofuel production (transformation of feedstock into biofuel)
- Blending (if biofuels are blended in fossil fuels)
- Distribution (fuel distribution chain), and finally
- Consumption

Definitely, the development of domestic biofuel production does not necessarily mean that all feedstock used should be of domestic origin. Indeed, part or whole of the feedstock or biofuels could be imported. Finally, some countries may produce feedstock and biofuels and export them, in case there is a surplus for their internal consumption.

The decision on the point of entry into the biofuels value chain raises the question of whether a country is able (technically, economically, etc.) to produce and/or import feedstock and/or biofuels. This poses questions such as whether each country intends to encourage capacity building or cover the required quantities via imports.

On the other hand, considering the EU as an integrated market, it is critical to identify the role of each member in the biofuels supply chain. Depending on the land availability and suitability, the production expertise and the domestic market development, some countries will rather serve only as raw materials producers, others as biofuels producers and others will combine a more complex role.

4. Land Availability–Feedstock Production

Biodiesel is produced from vegetable oils, which are derived from the seeds or the pulp of a range of oil-bearing crops. These oil crops can be annual (rapeseed, sunflower, groundnut, and soybean) or perennials (oil palms, coconut palms, physical nut, Chinese tallow tree). Oil from the rapeseed was the first type used for biodiesel production. Today, in Europe, rapeseed is still the main feedstock for biodiesel production. It is grown throughout Europe, while sunflower seed crops are grown in the warmer areas only.

In Europe, the main crops for the production of bioethanol are starch crops (such as common wheat) and sugar beet. Sugar beet crops are grown in most of the EU-25 countries, and yield substantially more ethanol per hectare than wheat.

The ten new member states bring with them 8% of additional total transport fuel consumption, while the additional used agricultural land is 30%. For example, Bulgaria and Romania have almost 0.7 ha per inhabitant, compared to 0.4 ha for the average of EU-25. Hence, producing required feedstock internally becomes easier. In general, feedstock availability is directly related to land availability. Therefore, land availability seems to be an important and critical factor, affecting the feedstock cost. In addition, the yield and quality problem concerning land needs to be put straight from the beginning.

The EU-25 energy consumption for transport purposes is estimated to be around 321 Mtoe. Reaching the 2003/30/EC Directive target requires to bring about 18.46 Mtoe (5.75%) on biofuels. Making the hypothesis that the share of biodiesel to bioethanol remains as 70% biodiesel - 30% bioethanol, it means that 4.7 Mha and 9.3 Mha will be required for bioethanol and biodiesel raw material respectively (wheat and rapeseed). Taking into account that bioethanol raw material is currently cultivated on 54.9 Mha in the EU-25, the estimated required 4.7 Mha represents less than 10% of this area. Hence, feedstock availability for the production of bioethanol should not be a problem.

Candidate feedstock for biodiesel production (rapeseed and sunflower) is currently cultivated on 6.4 Mha in the EU-25. The estimated required 9.3 Mha for rapeseed to biodiesel production represent nearly 150% of the current cultivated area for these crops. Although this does not mean that achieving the 2010 target is unfeasible, it will require a substantial change in production patterns and sufficient suitable land to be made available[12].

Feedstock availability for biodiesel (rapeseed and sunflower) seems much more limited than for sugar beets and wheat. In fact, in 2010 none of the EU-15 countries would be in a position to export biodiesel related fuel crop, while some of the new member states would have some surplus potential.

Table II: Feedstock availability for producing biofuels in Eastern European Countries[10]

Country	Feedstock for biodiesel		Feedstock for bioethanol			
	Rapeseed	**Sunflower**	**Wheat**	**Sugar beet**	**Maize**	**Potatoes**
Bulgaria	H	H	H	H	L	L
Czech Republic	H	L	H	L	L	L
Estonia	H	L	L	L	L	L
Hungary	H	L	H	L	L	L
Latvia	H	L	H	L	L	L
Lithuania	H	L	H	L	L	L
Poland	H	L	L	L	L	H
Romania	H	H	H	H	H	L
Slovak Republic	H	L	L	L	L	L
Slovenia	H	L	L	L	L	L

H–significant potential availability / **L**–low potential availability for biofuel production

Table III: Potential bioethanol yields from common wheat and sugar beet in Eastern European EU member states along with the land required

Country	Common wheat		Sugar beet	
	Litres/ha[13]	**% of the total area**	**Litres/ha[13]**	**% of the total area**
Czech Republic	1,568	5.66	4,982	1.78
Estonia	659	3.03	-	-
Hungary	1,365	4.24	n.a.	-
Lithuania	1,050	2.56	2,964	0.91
Latvia	908	1.92	3,036	0.57
Poland	1,215	3.57	3,555	1.22
Slovenia	1,330	6.55	4,040	2.15
Slovakia	1,360	3.41	3,486	1.34

Actually, there is feedstock availability for biodiesel and bioethanol in the Eastern European countries, as shown in Table II. The specific annual yield of each raw material per (ha) of cultivated area differs significantly from one country to the other, depending on various parameters, such as the climate, the soil, etc. Tables III and IV show the specific annual yield of each raw material for biodiesel and bioethanol production respectively, as well as the required land in order to comply with the 5.75% target, if this target is fully covered by the specific fuel.

Table IV: Potential biodiesel yields from rapeseed and sunflower in Eastern European EU member states along with the land required

Country	Rapeseed		Sunflower	
	Litres/ha[13]	**% of the total area**	**Litres/ha[13]**	**% of the total area**
Czech Republic	1,105	5.15	961	5.96
Estonia	536	2.45	-	-

Country	Rapeseed		Sunflower	
	Litres/ha[13]	% of the total area	Litres/ha[13]	% of the total area
Hungary	n.a.	-	770	4.86
Lithuania	662	2.66	-	-
Latvia	627	1.76	-	-
Poland	923	3.03	-	-
Slovenia	607	9.29	777	7.19
Slovakia	1,105	2.72	961	3.14

Among the most promising countries investigated concerning biofuels feedstock production are Poland and Romania. More specifically, in Poland the production of rapeseed increased sharply from 0.7 in 2003 to 1.25 million tonnes in 2004. Accordingly, Romania seems to have the largest currently unexplored feasible reserves of land to increase the overall biofuel output. In Romania, in 2004, almost all of 100,000 tn rapeseed, 70,000 tn of sunflower and 408,000 tn of sunflower seeds were exported.

5. Biofuels Production, Distribution and Consumption Issues

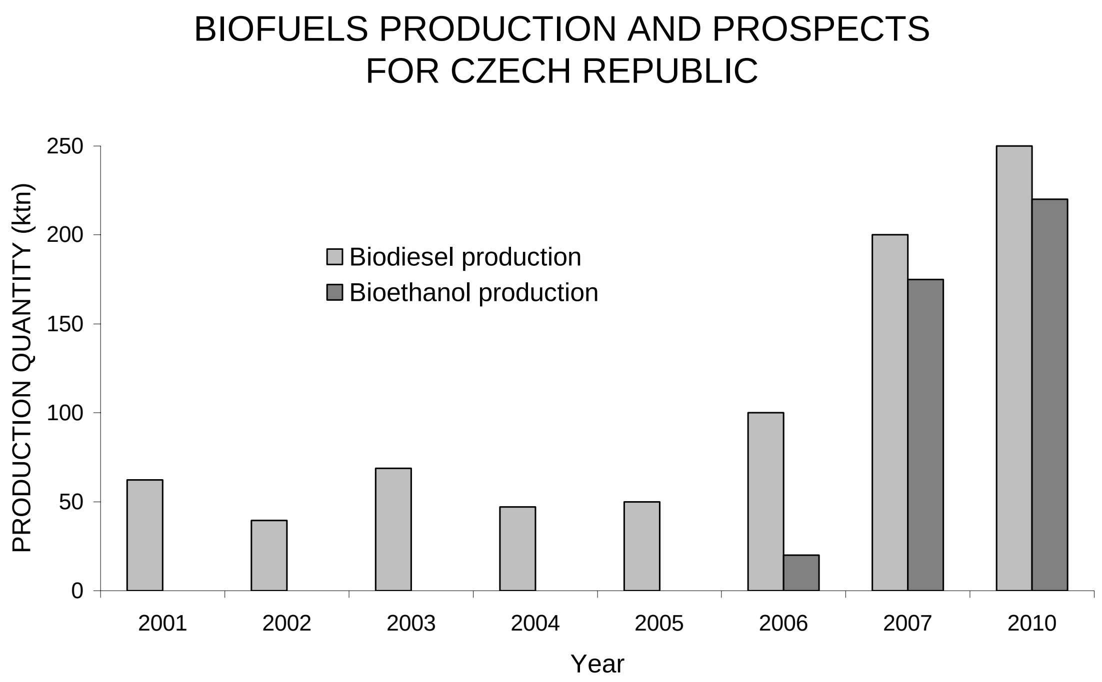

Figure 3: Czech Republic: Current biofuels production and prospects[10]

Currently, only Czech Republic (biodiesel) and Poland (bioethanol) have some experience in producing relatively large volumes of biofuels. However, many Eastern European countries have tradition and experience in the process industry, which can be exploited to produce biofuels. On the other hand, there are many investment opportunities in these countries for the implementation of small scale units for biofuels production.

Information concerning production capacity and real production quantities differs between various sources and the data are not validated. The following figures (3) and (4) provide an indication of biofuels production in selected countries.

According to available information, in many Eastern European countries distribution of biofuels is covered by companies not specialised in the biofuels transport. The main reason of this situation is that there is not an established biofuels market in these countries.

Table V: Biofuels target for Eastern European EU members for 2005[8]

Country	Biofuels 2005 target, minimum
Czech Republic	3.7% (2006)
Estonia	0%
Hungary	0.4–0.6%
Latvia	2%
Lithuania	2%
Poland	0.5%
Slovakia	2%
Slovenia	3%

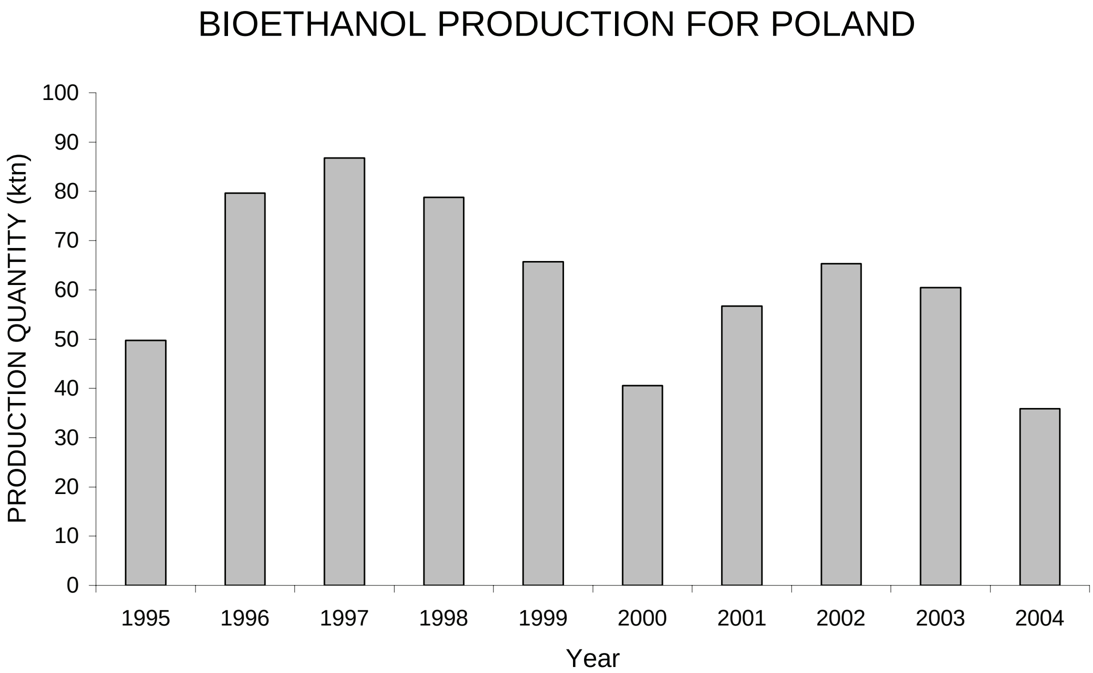

Figure 4: Poland bioethanol production[10]

In parallel, the domestic consumption of biofuels is lagging, mainly due to economic barriers, lack of legislative and regulatory framework and poor infrastructure. However, following the EU regulations a market will be formed in these countries, e.g via obligatory minimum requirements on biofuel content in all fuels. Table V shows the minimum target for biofuels in Eastern European countries, set by the government of each country.

Note also that fuels consumption in the transportation sector is expected to increase significantly during the next years. Figure (5) shows the final energy demand in the transport sector for the period 1990-2020 in Eastern European countries.

The distribution of biodiesel by delivering it to the conventional refineries -where it is blended with 5% to fossil fuels- avoids the building of a separate and costly infrastructure and big volumes can enter the market immediately. However, this has the drawback that the fuel does not become recognizable by the consumers and its advantages are applied only in a diluted way.

Promotion and use of biofuels in Eastern European countries depends on various critical factors including infrastructure, legislation and policy. In the countries under consideration this is even more difficult, mainly because -at the moment- they are lagging in technology and infrastructure in general. Country specific situation is summarised in Section 7. In general, the most important factors affecting biofuels implementation are:

- The favourable taxation (tax reduction or tax exemption on biofuels).
- The support of agriculture as well as the mentality of the farmers.
- The political, financial and legislative framework.
- Direct investment in biofuel technology and biofuel market.
- Infrastructure (roads, fuelling stations, etc.).
- The existence of major players that have invested in technology, have the resources to enter in the market and have also marketing experience.
- The ability to deploy a strategy and carry it out with continuity for a long time is a criterion of success, since most incentive actions need time to become prosperous.
- Automotive industry and cars technology play a critical role in the biofuels implementation. Most car manufacturers only allow standard grade fuel in their vehicle models, generally with maximum 5% of biofuels (e.g. EN590). This can be acceptable in the first phase to start the market, but to reach the 5.75% target of the EU in 2010, higher blends or the use of pure biofuels is necessary.
- Furthermore, the cars maintenance will also become a critical factor for the successful biofuels implementation, since proper training and infrastructure will be required.

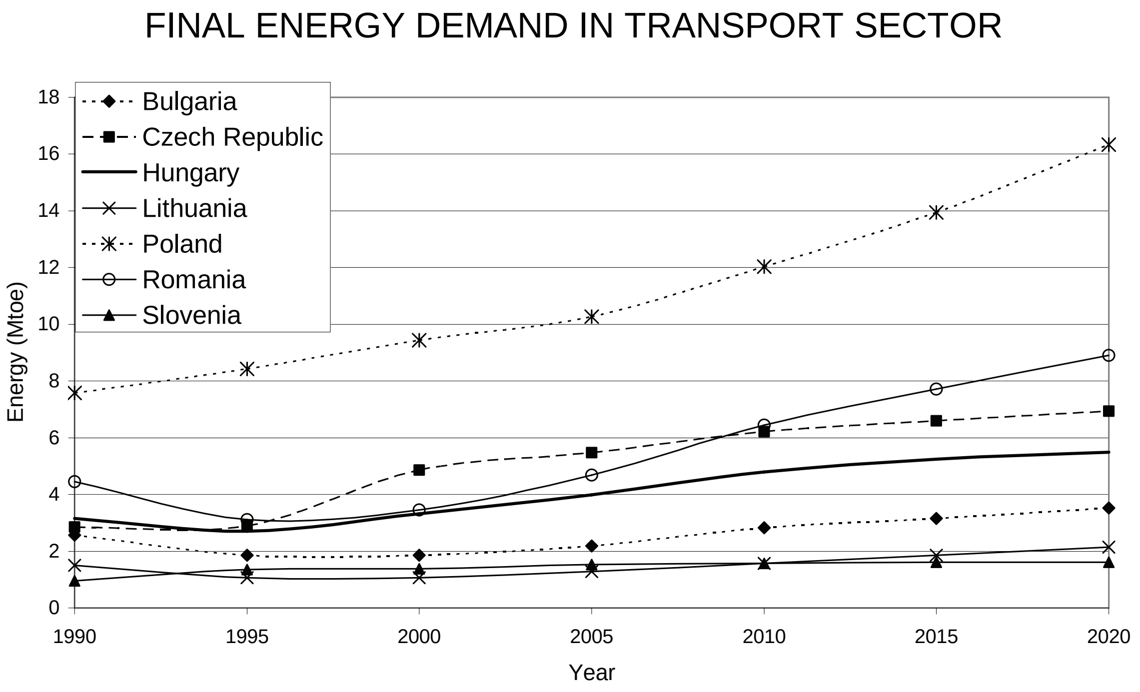

Figure 5: Final energy demand in transport sector in Eastern European Countries[11]

6. Biofuel Economics

Generally speaking, biofuels production cost is currently higher than classical fuels; sometimes the critical factor is the raw materials cost. There are also significant costs of marketing, distribution and service.

Almost 80% of the total production cost resides on the raw materials cost. As already mentioned, at the moment biofuels are more expensive than fossil fuels. Indicatively, biodiesel is about 2.3 times more expensive than fossil diesel. For bioethanol, this figure ranges between 2.6 and 2.8 as compared to petrol. However, cost comparisons are highly dependent on the fluctuations of the international market for crude oil and refined products and for biofuels feedstock. On the other hand, the continuous efforts for the increase of the raw materials yields as well as the advances in production technologies will make this cost relationship more favorable for biofuels.

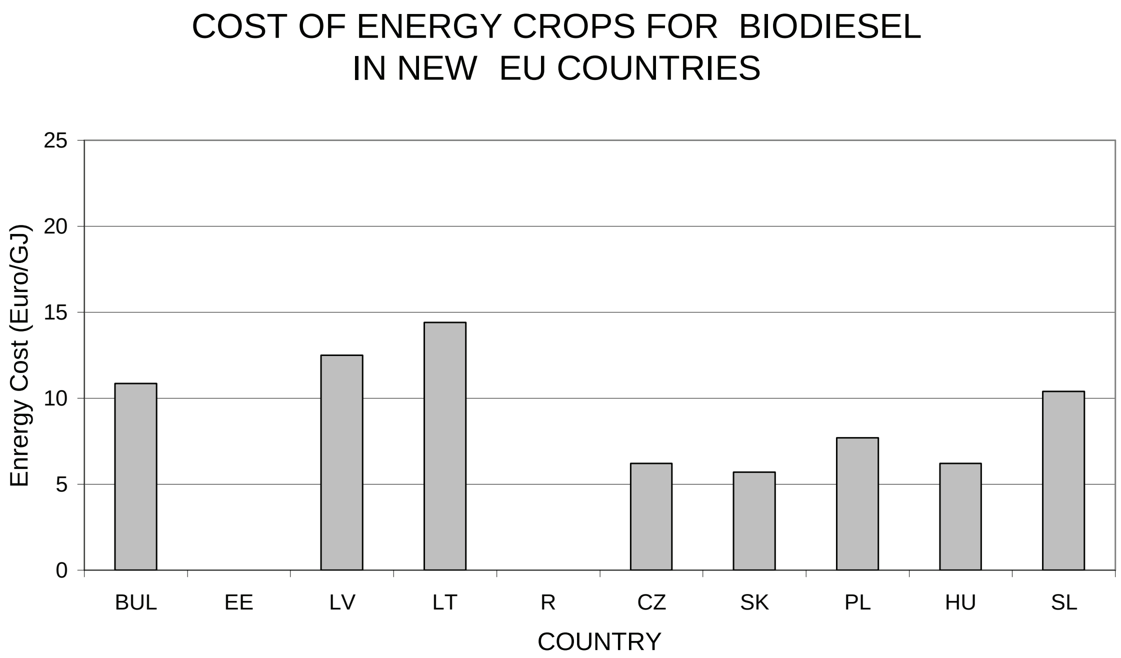

Figure 6: Cost of energy crops for biodiesel in new EU countries[8]

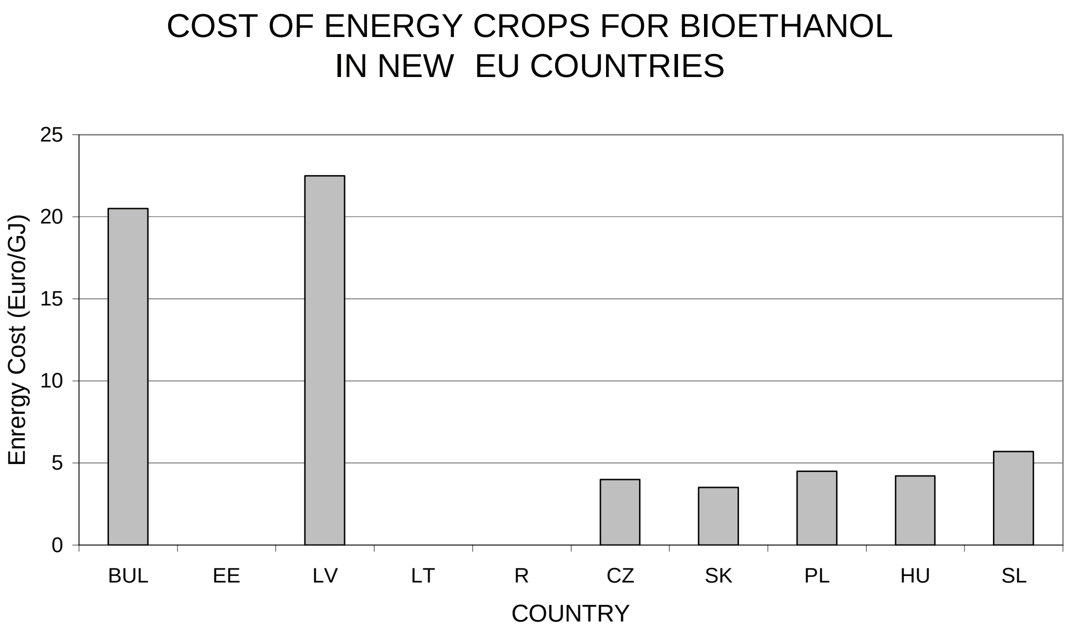

Figure 7: Cost of energy crops for bioethanol in new EU countries[8]

At the moment, only 20% of the total rapeseed grown in the EU is used for biodiesel production and this illustrates the fact that energy crops have other economical uses. Production costs of biofuels vary and are dependent on the prices of raw materials, the production method, the extent of refining undertaken and the supplementary utilization of by-products and waste. In the general case, the biofuels production cost in the Eastern European countries is not cheaper than the rest of EU. Figures (6) and (7) indicate the cost of energy crops for biodiesel and bioethanol respectively, whereas Table VI presents the current production costs of biofuels (in EUR/litre).

Table VI: Indicative production cost of biofuels (in EUR/litre) in selected Eastern European countries[8]

Country	Biodiesel	Bioethanol	Remark
Bulgaria	-	0.36	Average 1996-2000 for non-automotive purposes
Latvia	0.42	0.56	Prevailing figures
Lithuania	0.41	0.57	Prevailing figures
Hungary	0.65	-	Prevailing figure
Poland	0.75	0.60	BD – cost in 2002, BE – price in 2000
Slovakia	0.70	-	Price in 2002
EU-15	0.56	0.36-0.54	Average figures

6. Current Status in Selected Countries

In the present Section a summary of the current status concerning biofuel implementation in the countries under consideration is given. The main issues being highlighted in the description and summarized in Table VII are the feedstock availability, the production base, the use and the prospects of biofuels in the selected countries.

Table VII: Summary of the biofuels current status and future prospects

	Czech	Poland	Lithuania	Hungary	Romania	Bulgaria
Biofuels resources availability	Rapeseed availability	Extensive availability of raw materials	Long traditions and good climatic conditions for growing crops	Limited domestic biomass resources	Sweet sorghum, rape-oil & sun-flower oil	Sunflower, wheat, rapeseed
Biofuels production	Significant experience in RME production – leader in the number of production sites	Considerable biofuels manufacturing base	Limited production capacity	Small quantities	Limited	There is no significant production yet
Legislation	Subsidies for rape	Unclear-unstable legal support framework	The legal basis has been prepared	Some progress has been made	Not prepared yet	Lack of legislation
Measures – Incentives	Low excise duty on blended fuel/biodiesel	No excise tax. Major obstacles are the economic conditions	Mandatory targets have been established	Refund of excise tax on biodiesel and bioethanol	No Excise tax for biodiesel	No tax reduction. Lack of government policy

	Czech	Poland	Lithuania	Hungary	Romania	Bulgaria
Prospects for biofuels development	Very Good	Very good. Largest biodiesel manufacturer	The restructuring of a big refinery will increase production	Efforts required	Very good because of raw materials and biofuels production	Very good. Favorable climate conditions and good tradition
Prospects for biofuels exports	Very good. Domestic market will be developed	Very good. Already a net exporter	It depends on the domestic demand and the market prices	Not enough resources	Driving forces for raw materials and biofuel production development	Domestic market is unready, lack of infrastructure

As far as biofuels raw materials are concerned, Czech Republic has a significant experience, especially in the production of rapeseeds for rape methyl ester. In Poland, the key feedstock for bioethanol production is potato and cereals and it is cheaper than bioethanol from wheat and sugar beet. Lithuania has long traditions in growing crops and the climatic conditions are also favourable to the cultivation of grains. Approximately 10-15% of Lithuania's land could be used for the cultivation of corps for energy needs.
Romania has a significant potential for production of bioethanol from sweet sorghum and biodiesel from rape oil and sunflower oil. It also has very good prospects as a net exporter within EU. Bulgaria has also significant potential to produce biofuels made especially from wheat (bioethanol) and sunflower (biodiesel), being also favoured from the weather conditions.

Czech is a pioneer country in the biofuels production. It is the leader in the number of production sites with 16 biodiesel plants. Boost in biofuel production is expected for 2007 in Czech.

Poland is the only country among the new member states that already has developed the biofuels sector to a significant extent. It is a net biofuels exporter. Biofuels production in Poland is favoured by the availability of large agricultural areas, ideal for growing oil seed rape, and the good climatic conditions for rapeseeds and potato.

In Lithuania there is limited domestic production capacity for biofuels. Two pilot plants are in pilot operation, one for bioethanol and one for biodiesel. An important project in the country related to the production of biofuels is the restructuring of the Lithuanian oil refinery AB Mazeikiu Nafta.

Romania is considered to be a promising country as a clear net contributor to bioethanol availability. It also becomes the second biggest producer of biodiesel, exploiting its good expertise in research, fuels production and processing.

As far as biofuels use is concerned, in Czech, conditions for placing pure biodiesel on the motor fuel market have been created in accordance with technical measures and amendments made to legislation currently in force. The return excise tax amounts to 100 % for bioethanol used at car petrol production. There is a lower excise duty on blended fuel/biodiesel, which means that biodiesel incorporated in a fuel blend carries zero excise duty.

Currently biofuels are free from excise tax in Poland but other regulatory, legislative and economic barriers are identified. This includes the lack or the vagueness of legislation for fiscal support mechanisms and standards. Practically, the major obstacles towards the development of liquid biofuels are the economic conditions.

Lithuania has significant production base that could properly be exploited for biofuels manufacturing. The legal basis for the implementation of the biofuels Directive has been prepared. Mandatory targets have been established in the country from the end of December 2005. More specifically, two legal acts on the mandatory use of biofuel for transport (as a percentage in the conventional fuels) have been adopted.

In Romania there is a significant national market. There is no legislation or any other measure in place for biofuels promotion yet. In Bulgaria, the serious deficit of infrastructure and mentality in general for the biofuels promotion (tests, standards, investments, etc.) as well as the lack of clear Government policy and any relevant legislation make the development of the domestic market difficult.

Finally, for the two candidate countries, i.e Bulgaria and Romania, the prospects for biofuel development are very good. For Romania, the export will be the main driving force for biofuel production, while the internal market will need probably several years to be developed. Biofuels might be proved a good opportunity for the future development of the Romanian agriculture and process industry. In parallel, the lack of local investment funds and local investment support of biodiesel plants in Bulgaria create the possibility for joint ventures and consequent export. In fact, the country has very good prospects to become a significant biofuels exporter in Europe.

7. Conclusions

The accession of Eastern European countries has various positive effects as far as the biofuels implementation is concerned for the countries themselves and the EU in general. Indicatively, the effects include the following:

- The utilization of set-aside and underutilized land by the agricultural sector increase the employment potential.
- There may be small scale capital investments for the establishment of production units and, hence, the reduction of transportation costs.
- Biofuels may use the existing distribution facilities unlike any other sustainable transport fuel.

The present work has led to some interesting results concerning the prospects of biofuels in Eastern Europe. As a matter of fact, there is not a unique conclusion concerning the potential of these countries in the overall biofuels supply chain in EU. It is without doubt that these countries have significant land availability, much more than the average of the rest EU. It is also a fact that these countries possess significant production base and experience in land cultivation. Therefore, the prospects related to the feedstock and biofuels production are good. Some of these countries are in fact already leaders in biofuels production.

In parallel, the domestic consumption of biofuels is lagging, mainly due to economic barriers, lack of legislative and regulatory framework and poor infrastructure. This supports their prospects as raw materials exporters. However, following the EU regulations a market will certainly be formed in these countries, e.g via obligatory minimum requirements on biofuel content in all fuels.

In conclusion, the significance of the recently joined Eastern European countries is not only their land availability or production capacity. The most interesting issue is that the EU market is now much larger, the supply chain is more extended, the opportunities for rural development are significant and small scale production investments are more attractive.

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EXPERIMENTAL AND THEORETICAL ANALYSIS OF REMOTE MEDIUM SIZE PHOTOVOLTAIC STATIONS

E. Alasis[1], G. Spyropoulos, K.A. Kavadias, J.K. Kaldellis
[1]Heliodynami ltd
Laboratory of Soft Energy Applications & Environmental Protection
Mechanical Eng. Dept., Technological Education Institute of Piraeus

Abstract

An autonomous photovoltaic system is one of the most interesting and environmentally friendly technological solutions for the electrification of remote consumers or entire rural areas. Thus, as a contribution to the life quality amelioration of several isolated communities, an integrated solution based on a hybrid photovoltaic system has been elaborated by the authors. The primary objective of this current study is to determine the optimal dimensions of an appropriate stand-alone photovoltaic system, able to guarantee the coverage of remote consumers' energy demand. The proposed installation is based on a medium sized photovoltaic generator, peak power of 45kW, along with the appropriate battery bank and the corresponding electronic equipment (e.g. inverter, charge controller etc.), able to meet the energy demand of the local community. Accordingly, the calculation results are compared with detailed year-long experimental measurements of the installation. In fact, one has the opportunity to use the solar radiation and the ambient temperature in order to compare the theoretical prediction results with the data measured in selected points of the installation. On top of this, one has the capability to evaluate the energy behaviour of the entire installation. The results obtained are quite encouraging and the theoretical model describes satisfactorily the experimental measurements.

Keywords: Photovoltaics; Hybrid System; Energy Production; Experimental Data; Theoretical Model

1. Introduction

Energy and especially electricity is considered to be along with fresh water and clean air one of the most important elements of everyday life. However, official statistics estimate[1] that almost two billion people have no direct access to electrical networks, 500,000 of them living in European Union and more than one tenth of them in Greece[2]. Afar from decision centres and having limited political influence, isolated consumers are usually feeling abandoned, facing a quite insufficient infrastructure[2][3]. Their importance, however, is not simply based on techno-economic criteria but mainly on social or even national survival reasons.

In this context, an autonomous photovoltaic system is one of the most interesting and environmental friendly technological solutions[3][4][5][6] for the electrification of remote consumers or entire rural areas. Thus, as a contribution to the life quality amelioration of several isolated communities, an integrated solution based on a hybrid photovoltaic system has been elaborated by the authors[7][8].

More precisely, the primary objective of this current study is to determine the optimal dimensions of an appropriate stand-alone hybrid photovoltaic system, able to guarantee the coverage of remote consumers' energy demand. The proposed installation is based on a medium sized photovoltaic generator, peak power of 45kW, along with the appropriate battery bank and the corresponding electronic equipment (e.g. inverter, charge controller etc.), able to meet the energy demand of the local community[9][10].

Accordingly, the calculation results are compared with detailed year-long experimental measurements of the entire installation[11]. In fact, one has the opportunity to use the solar radiation and the ambient temperature in order to compare the theoretical prediction results with the data measured in selected points of the installation. On top of this, one has the capability to evaluate the energy behaviour of the entire installation[9].

2. Description of the Problem

The problem to be solved concerns the possibility of ones meeting the electricity requirements of a remote private consumer located in N. Greece. More specifically, the consumer under investigation is the Monastery of "Simonos Petras", one of the most well known remote monasteries of Athos State, near Thessalonica, figure (1). In fact, the annual electricity demand for the year examined is almost 130,000kWh, while in figure (2) one may find the corresponding monthly consumption, which varies between 10,000kWh and 12,000kWh per month.

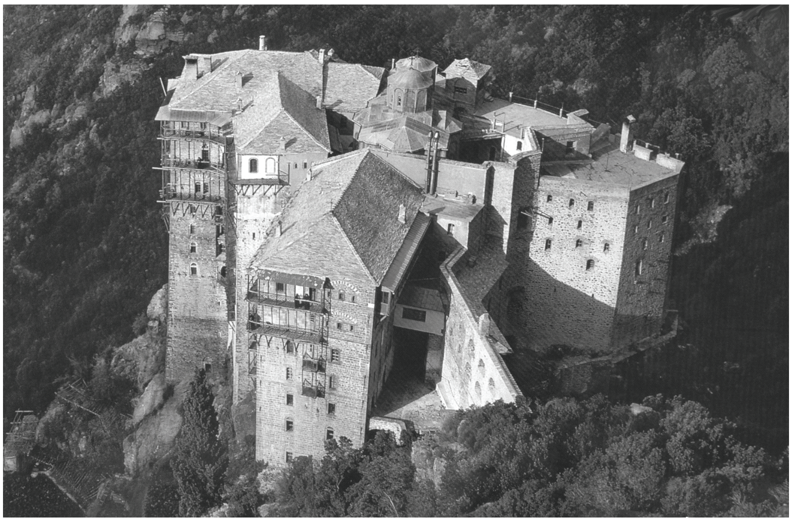

Figure 1: The Monastery of Simonos Petras

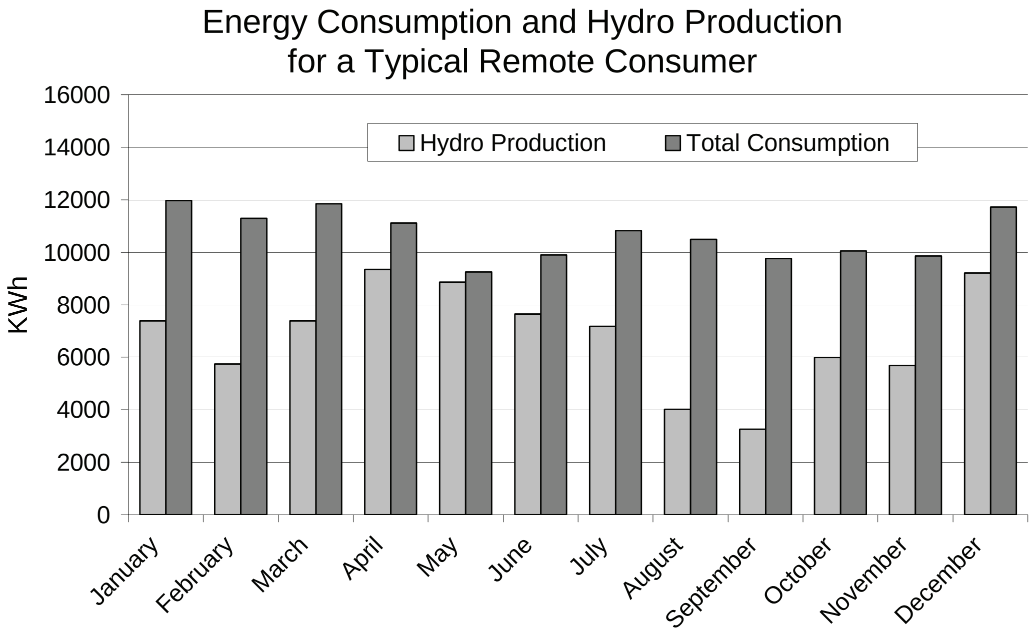

Figure 2: Remote consumer electricity demand and hydro production, 2003

The above described electricity consumption is partially covered by the existing small hydro turbine of Pelton type (nominal head of 330m), rated power equal to 33kW. The monthly hydro electricity generation is also given in figure (2). According to the available data, one may state that although the hydro turbine significantly contributes -in average (≈63%)- to cover the electricity demand, during specific dry months there is serious production lack, due to the water potential reduction, see also figures (3) and (4).

In order to face this remarkable energy deficit, the existing diesel-electric generator (rated power 50kW) should extensively be used. This engine has been included initially in the entire installation in order to be used as a back up unit. However, the gradually electricity consumption amplification and the variable electricity yield of the existing hydro turbine imposes its remarkable utilization during the entire year. On top of this, during the dry months of the year the diesel-electric generator contribution exceeds the 50%.

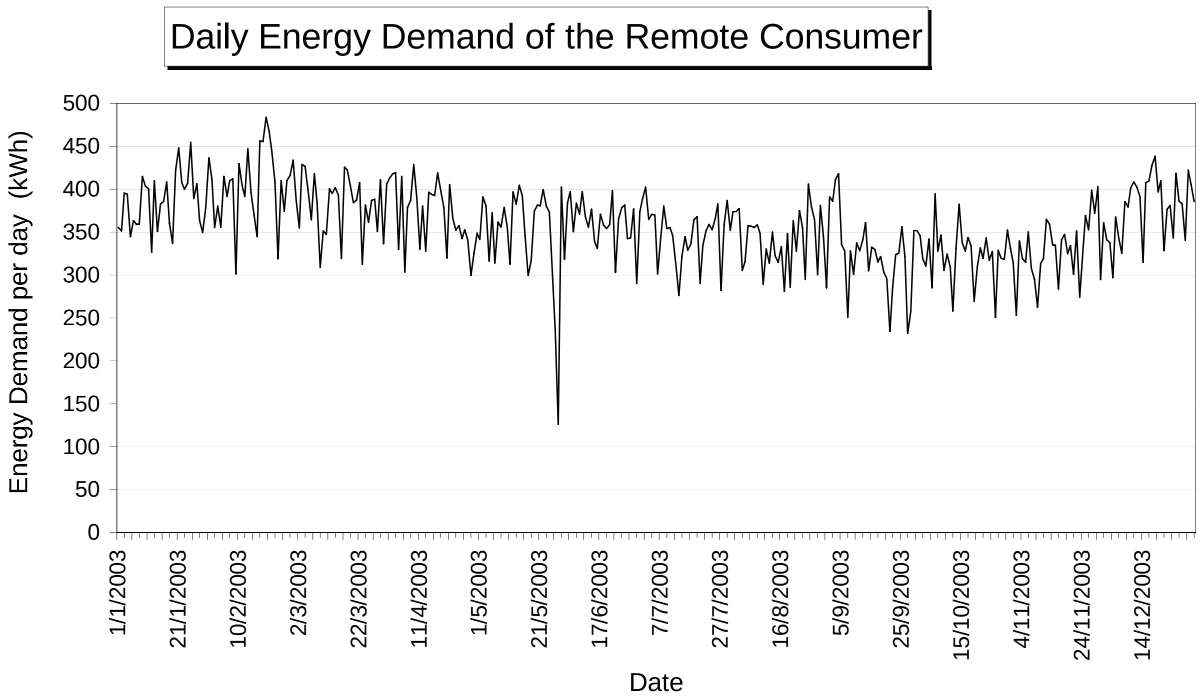

Figure 3: Daily electricity consumption of the remote consumer

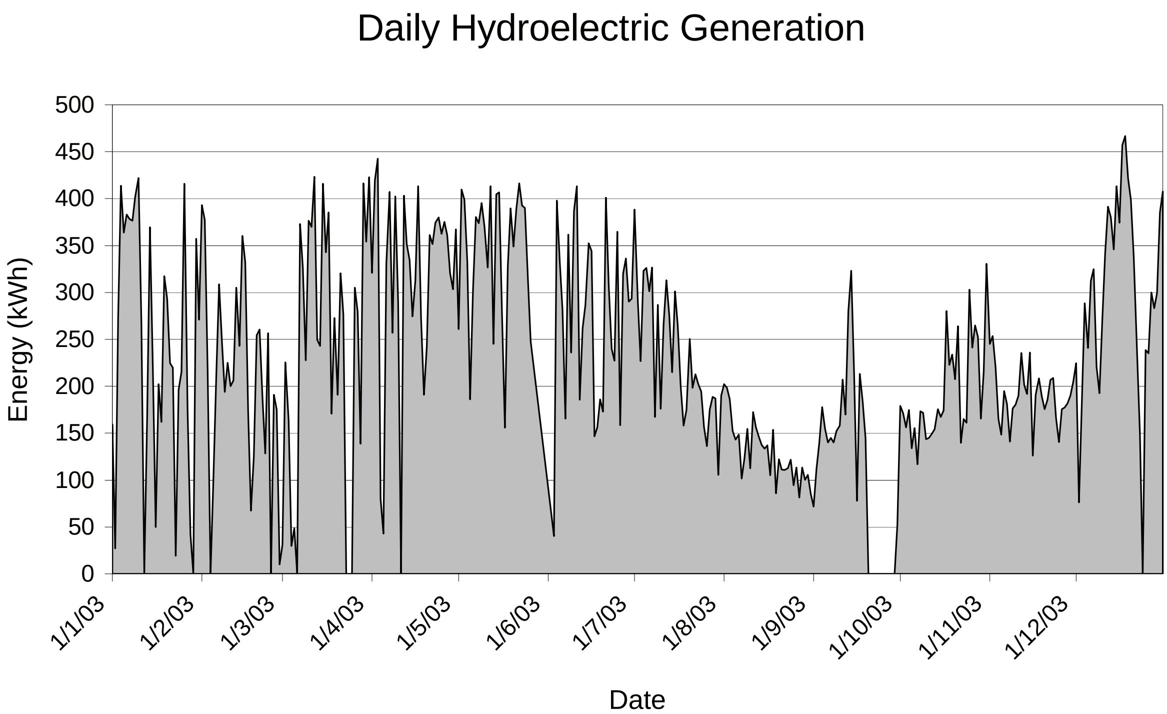

Figure 4: Daily hydroelectric generation

At the same time significant water shortage is encountered in the area either due to the Monastery activities increase or due to water related additional uses appearance. In an attempt to meet the increased electricity demand, without jeopardizing the region water reserves, one may use an appropriate photovoltaic (PV) installation. The PV installation has the ability to significantly contribute to fulfilling the increased electricity demand, limiting also the expensive and highly polluting diesel-oil consumption.

3. Proposed Solution

Using the above described analysis, one decided to install a new PV generator, which in collaboration with the existing hydro turbine can meet the entire year electricity demand of the remote consumer. Thus, according to figure (5) the proposed installation includes, besides the diesel-electric generator:

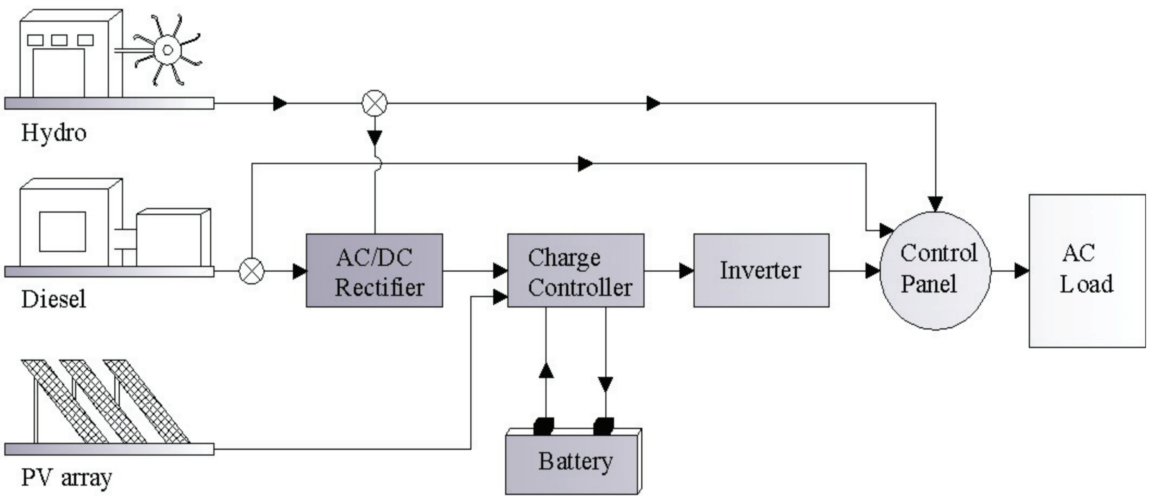

Figure 5: Proposed hybrid electricity generation installation

- One AC/DC rectifier of 220/380V and 93 kVA rating power at full load with battery charging
- One charge controller along with the system storage battery (400V, 1000Ah)
- One 60kVA inverter, max efficiency 94%.

Thus, during the long-lasting operation of the proposed hybrid electricity generation system, the following situations may appear:

i. The load demand is covered by the existing hydro turbine (figures (3) and (4)). Any energy production excess, either from the hydro power station or from the PV generator is stored up at the system batteries.

ii. The available hydro power cannot meet the corresponding load demand. In this case, the energy deficit is covered by the system batteries via the existing inverter.

iii. The load demand is higher than the output of the hydro turbine, while the system batteries are near their maximum permitted depth of discharge. In this case the energy deficit is covered by the existing diesel-electric generator.

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

4. Theoretical Model

Taking into consideration that the main scope of the Monastery community is to limit the utilization of the diesel-oil consumption in order to minimize the corresponding environmental impacts, one should estimate[11] the expected maximum energy deficit "δE_i" on monthly basis, i.e.:

$$\delta E_i = (E_L - E_H)_i \quad i = 1,12 \tag{1}$$

where "E_L" is the system load demand and "E_H" is the corresponding hydro generation. Thus, one may write:

$$\Delta E = \max(\delta E_i) \quad i = 1,12 \tag{2}$$

Hence, using the available solar potential "H_T" ($kWh/mo/m^2$), Table I, of the area[12], one may estimate the corresponding PV area required "A_t" via the expected mean energy production efficiency "η", i.e.:

$$A_t = \frac{\Delta E}{\eta \cdot H_T} \cdot (1 + \varepsilon) \tag{3}$$

where "ε" is an appropriate factor taking into account the energy transformation losses between the PV generator and the final consumption, i.e. rectifier, charge controller, battery, inverter and line loss.

Table I: Solar potential ($kWh/m^2/mo$) of the remote area under investigation

Month	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**
Solar Energy	75	87	113	142	167	171
Month	**July**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Solar Energy	192	181	151	115	83	70

Subsequently, one may calculate the number "z" of the necessary PV panels[13], using the specific area "A" of the panel to be utilized:

$$z \geq \left[\frac{A_t}{A} \right] \tag{4}$$

Finally, the peak power of the proposed PV installation is given as:

$$N_o = z \cdot N_p \tag{5}$$

where "N_p" is the peak power of each PV panel used. For the evaluation of the efficiency and the utilization degree of the above described PV generator one should compute the corresponding capacity factor of the installation according to the following relation:

$$CF_{\Delta t} = \frac{E(\Delta t)}{\Delta t \cdot N_o} \tag{6}$$

where "$E(\Delta t)$" is the energy yield for a given time-period "Δt".

Applying the proposed analysis one may select 936 PV panels of 48W each, hence the total peak power of the PV generator is 45kW. For practical reasons the PV panels are connected, figure (6), in two similar groups (A and B), while the open circuit voltage of the installation is 745 Volt.

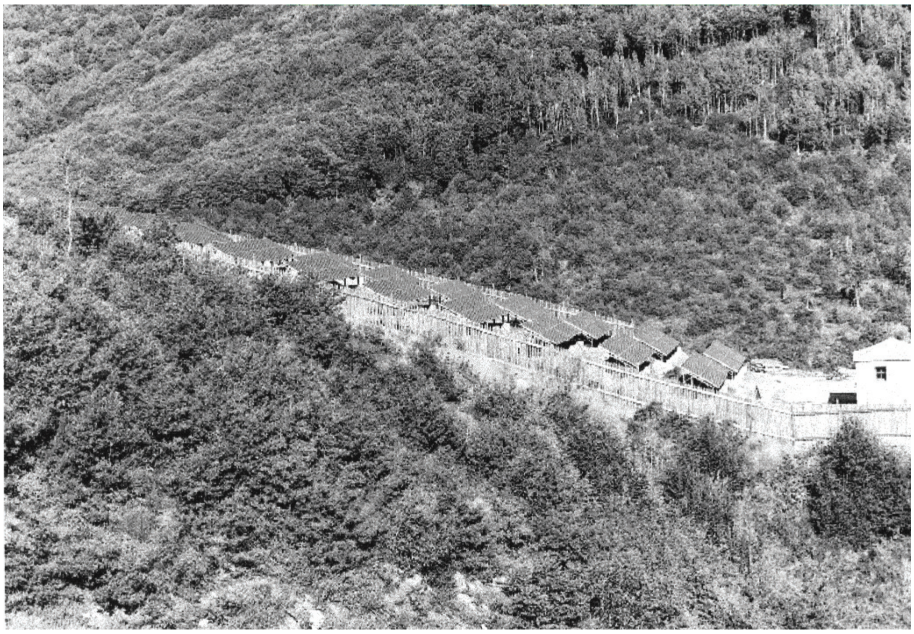

Figure 6: PV installation in Simonos Petras

5. Energy Production Evaluation on the Basis of Experimental Measurements

In the following we shall present the operational behaviour of the above described 45kW PV generator, on the basis of the existing experimental measurements for the year 2003. More specifically in figure (7) one may find the corresponding PV electricity generation for every month of the year. Keep in mind that during the wet months of the year the PV contribution is minimal, since the existing hydro turbine covers the corresponding energy demand. This is not the case from July up to November, where the PV contribution is quite important.

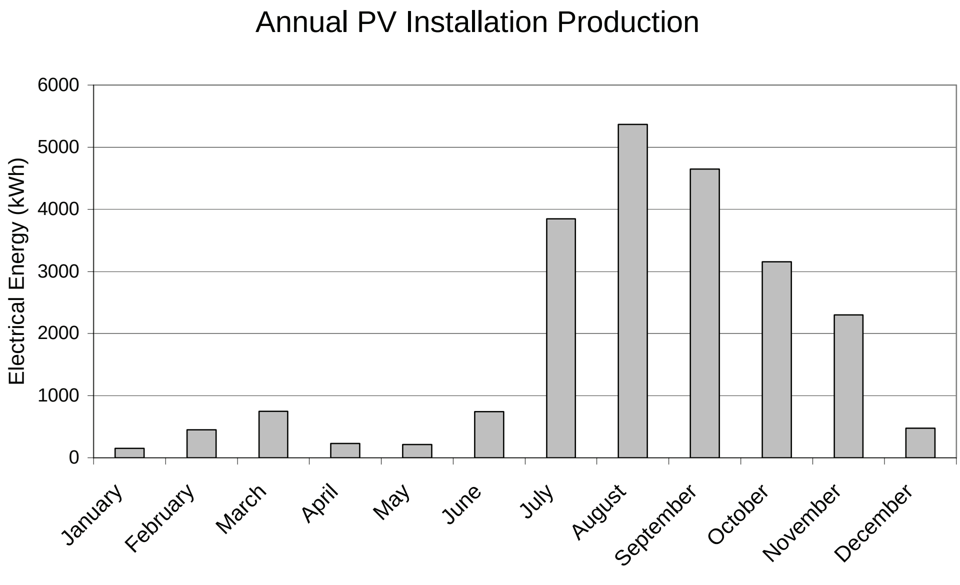

Figure 7: Proposed installation energy yield

In fact the corresponding capacity factor takes values up to 16% during August, which is a very good value for PV installations based on polycrystalline PV modules[14]. Besides, during the other dry months of the year the corresponding CF average value approaches the 12%. In this context, the proposed PV generator complements the corresponding hydro turbine generation, producing annually almost 25MWh of electricity, replacing the utilization of diesel-oil and preventing the emission of significant air pollutants quantities. On top of this, the existence of the PV generator facilitates the available water resources management, in order to improve the life quality not only of the local community but also of the numerous visitors.

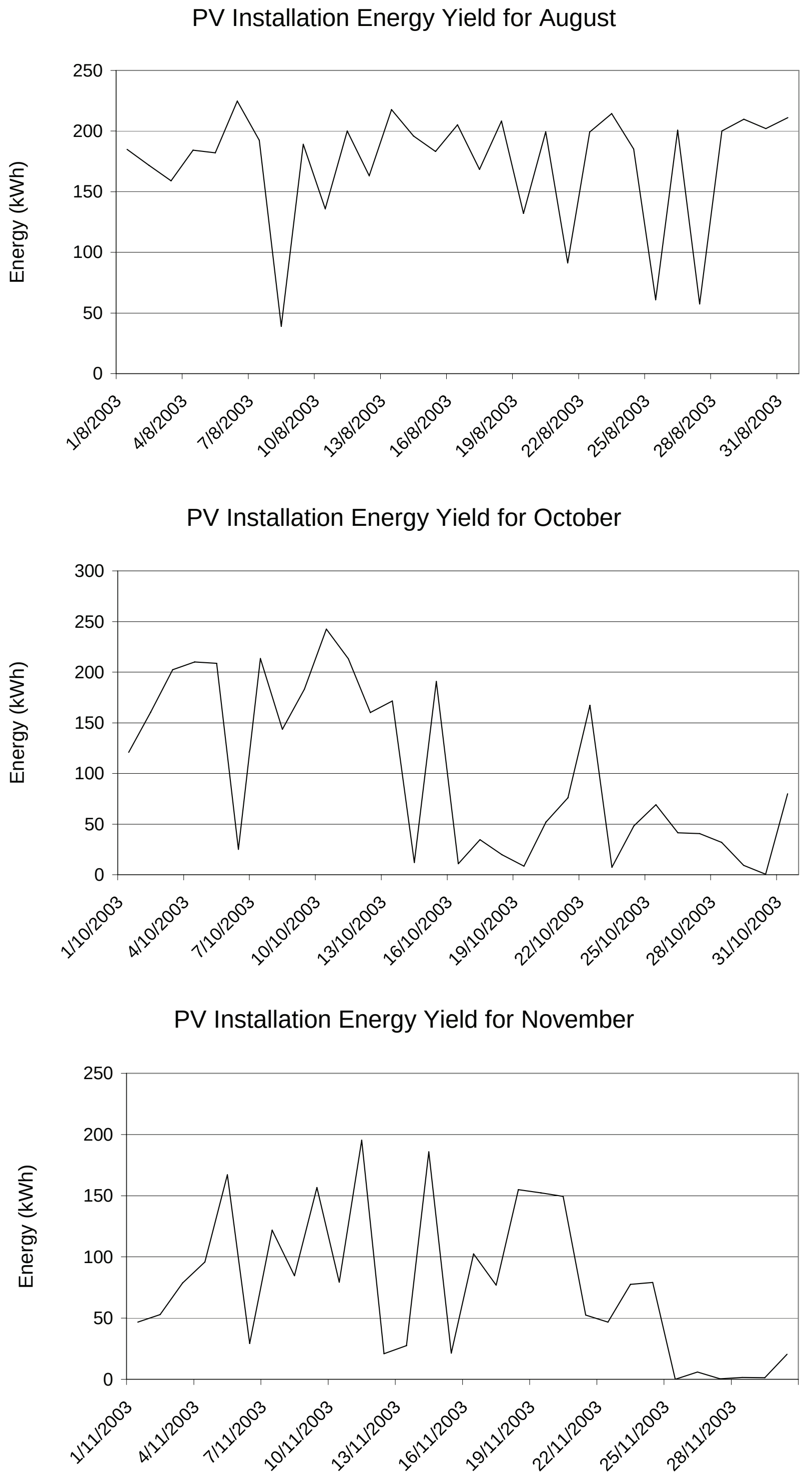

Figure 8: Daily electricity generation of the proposed PV installation

Subsequently, one may observe in figures (8a) to (8c) the electricity production of the PV installation under investigation, for selected months of the year. According to the measured data the daily energy yield of the installation exceeds the 200kWh/day during several days of the year dry period, hence the corresponding capacity factor value becomes greater than 20%, presenting its maximum value of 22.5% during the tenth of October.

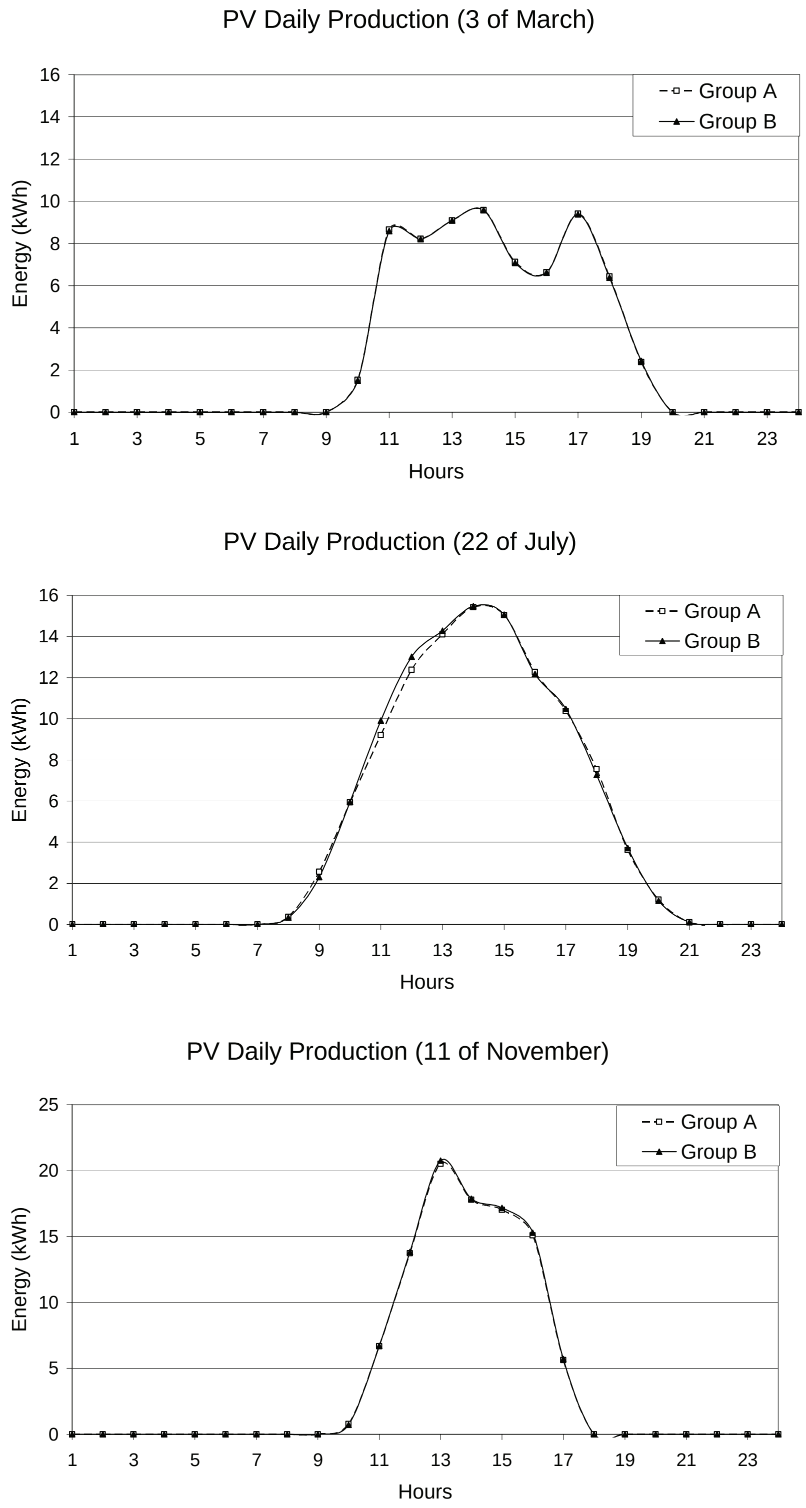

Figure 9: Hourly electricity generation of the proposed PV installation

Finally, in figures (9a) to (9c) one may observe the instantaneous PV output power measured on thirty seconds intervals for three selected days of the year, i.e. during 3rd March, 22nd of July and 11th of

November. It is important to remind that the proposed PV generator is based on two exactly similar subgroups properly connected to produce nominal voltage of 600V and peak power 22.5kW. Using the experimental data one may state that the maximum power of the system varies between 2x10kW in March and 2x21kW during November, hence the maximum output power of the installation approaches the corresponding value by the manufacturer (valid for solar radiation equal to 1000W/m^2 and module temperature equal to 25°C). On top of this, during summer, the PV power is remarkably less than the rated one provided by the manufacturer, despite the high solar radiation, mainly due to the increased temperature of the PV panels, which in special cases exceeds the 60°C.

6. Conclusions

The possibility to fulfil the electricity requirements of a remote medium-size consumer via an appropriate hybrid system, reinforced by a 45kW PV generator, is examined. According to the theoretical calculation results and the year-long detailed experimental measurements the proposed PV installation presents good performance and significantly contributes to cover the energy deficit of the consumption during the dry period of the year.

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PART FIVE

ENERGY RELATED ENVIRONMENTAL IMPACTS

EVALUATION OF GREEK WIND PARKS VISUAL IMPACT "PUBLIC ATTITUDE AND EXPERTS' OPINION"

J.K. Kaldellis
Laboratory of Soft Energy Applications & Environmental Protection
Mechanical Eng. Dept., Technological Education Institute of Piraeus

Abstract

The continuous electricity demand amplification and the retirement of aged electrical power stations emphasize the necessity for new, efficient and environmental friendly electricity generation plants. In view of this unquestionable need for electricity in Greece (mainland and island), several private and public investors have repeatedly tried to site new wind energy production facilities, an activity which has often raised serious local opposition, as it involves risk analysis and management. As a result the local wind energy market is almost stagnating favouring the imported carbon based fuels and accelerating the exploitation of the limited national lignite reserves. In previously published work extended public opinion surveys highlight a remarkable negative public attitude of local people against wind power stations, based on visual impact. In order to examine the above-mentioned problem, a complementary to the already presented public opinion surveys study is carried out. Initially the main parameters affecting the wind parks visual impact are presented, while special emphasis is laid on quantifying the corresponding impact. Accordingly, a new database is created, comprising the main characteristics along with the picture of most wind turbines operating in Greece. Finally, an evaluation process of existing wind parks is described on the basis of a selected evaluation group (experts, government officials and local society representatives), which analyzes the available information using a Delphi technique according to specific criteria. The results obtained are accordingly compared with the data of existing public opinion surveys in the vicinity of each installation investigated.

Keywords: Wind Park; Visual Impact; Experts Opinion; Delphi Method

1. Introduction

Electricity is among the main inputs for almost the entirety of human activities. Thus, access to a continuous electricity supply is considered as a human right all over Europe. However, the continuous electricity demand amplification and the retirement of aged electrical power stations emphasize the necessity for new, efficient and environmental friendly electricity generation plants. In Greece, by analyzing the existing official data of the last twenty-five years, there has been detected a remarkable electricity consumption increase from 21TWh in 1980 to almost 52.5TWh in 2004; 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 9300MW), underlining the urgent requirement for new electricity production plants in the near future[1].

Unfortunately, after a close inspection of the available information, one may conclude that the continuous increase of electrical consumption has so far been primarily covered by locally extracted low quality lignite (65%). The contribution of imported oil is 15%, while the corresponding natural gas share is 14%. Keep in mind that a continuous increase of hazardous gasses -mostly attributed to the energy production sector- like CO_2, SO_x and NO_x, is encountered by the existing air pollution-monitoring network[2]. This constant air pollution increase jeopardizes the "Greek-National Program for the Climate Change", provoking the contribution of our country in the EU effort to restrict dangerous air pollutants emissions.

The same problem seems particularly critical for the various Aegean Sea islands, including Crete, Rhodes, Lesvos and Chios. More specifically, the maximum load demand intensification in these islands has exceeded 250% during the last twenty years. The situation is even worse in the medium-small autonomous island power systems, where the corresponding escalation rate exceeds 400%[3].

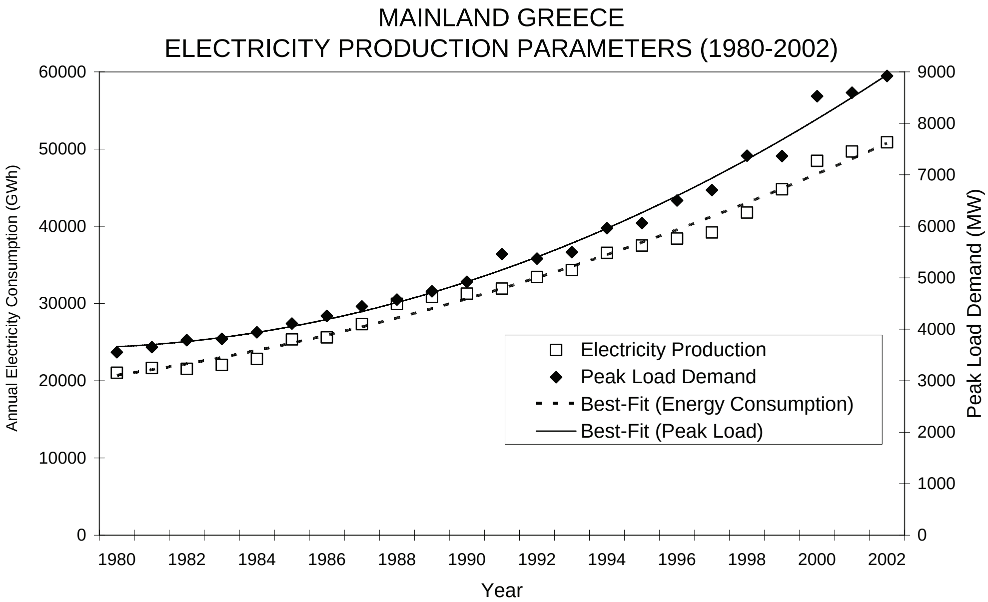

Figure 1: Greek electricity production parameters time-evolution

In view of these facts -continuous electricity demand increase and constant environmental deterioration- the use of renewable energy sources to fulfil the amplified electricity demand has been widely considered[4]. More specifically, interest in employing wind energy has significantly grown worldwide during the last years[5], mainly as a reaction to concerns about environmental impacts from fossil and nuclear fuels, along with rate-instability in the international oil market.

2. Position of the Problem

Greece and especially Aegean Sea region is a geographical area with excellent wind potential, since in several locations the annual mean wind speed approaches 8-9m/s (figure (2)). Besides, the Greek State is strongly subsidizing private investments in the area of renewable energy sources applications, either via the current development law (e.g. 3299/04) or the Operational Program "Competitiveness" of the Ministry of Development[6]. As a result, numerous requests for new wind energy production stations exist in the Ministry of Development.

In view of this unquestionable need for electricity in Greece –both in mainland and islands–several investors have repeatedly tried to site new wind energy production facilities, an activity which has often raised serious local opposition, as it involves risk analysis and management[7]. As a result the local wind energy market is almost stagnating favouring the imported carbon based fuels and accelerating the exploitation of the limited national lignite reserves. More precisely the only wind power additions during the last two years are located in Thrace, while the corresponding activity in Aegean Archipelago, Crete island, Euboea and Peloponnesus is practically zeroed, although for these specific territories there exist requests for more than 5000MW[1].

In previously published work, extended public opinion surveys[8][9] highlight the remarkably negative public attitude of local people against wind power stations, mainly based on visual impact. According to the findings of an extended survey, a considerable part of respondents declare significant visual impact of wind parks in the landscape (figure (3)). More precisely almost all individuals that do not agree with the existing wind turbines in their region find their appearance objectionable, while even a noteworthy portion of wind energy supporters claim visual impact.

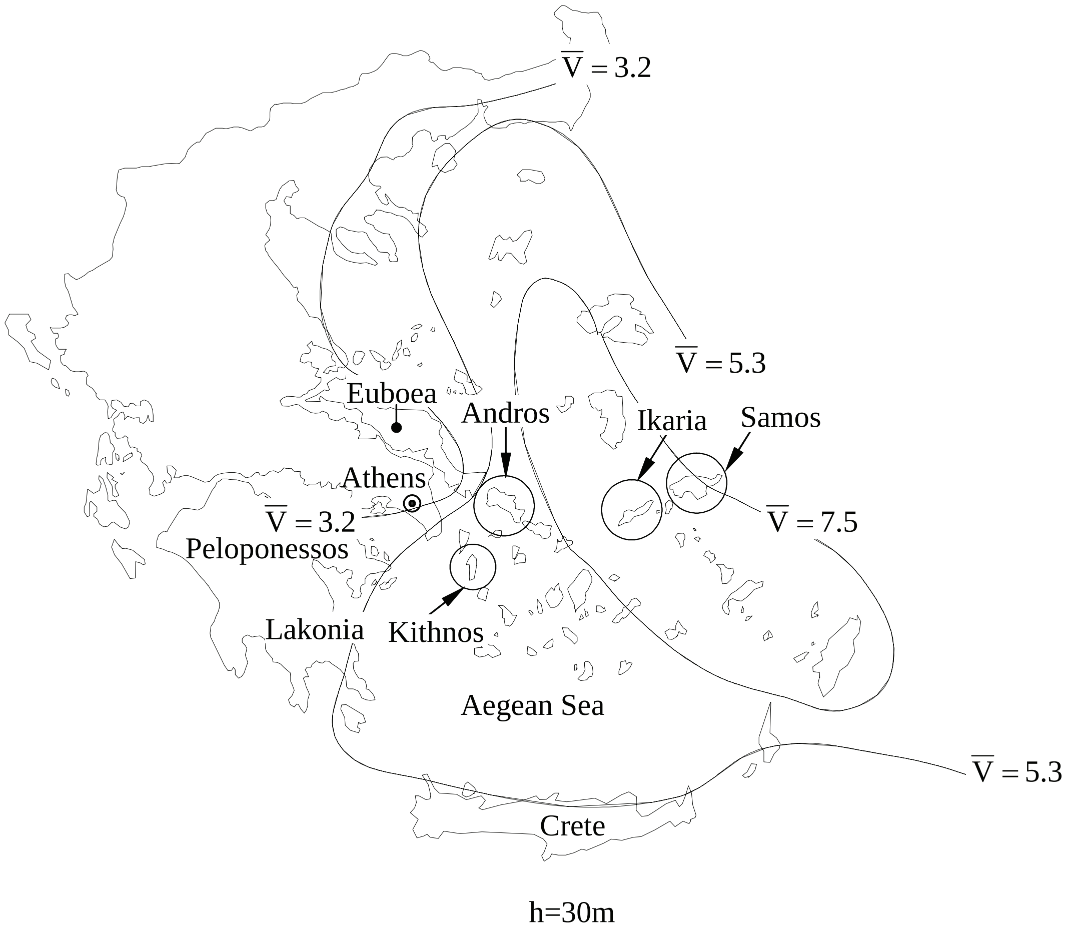

Figure 2: Selected Greek regions for the investigation of existing wind parks visual impact

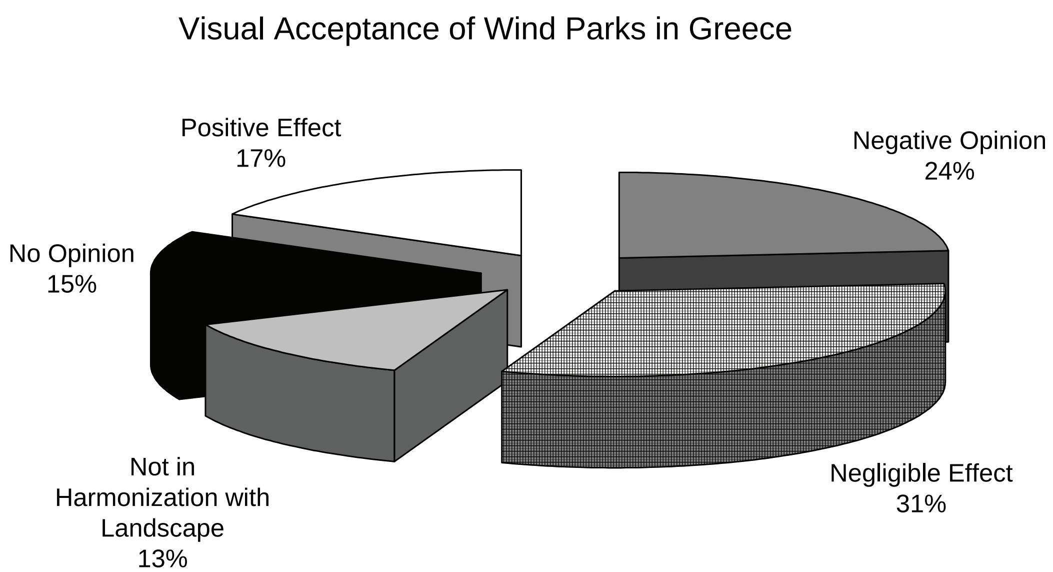

Figure 3: Public opinion survey results in selected Greek territories

In order to examine in depth the above-mentioned problem, a complementary to the already presented[8] public opinion survey study is carried out, concerning the visual impact of wind parks in Greece. This study is divided in two parts. In the first part the main parameters affecting the wind parks visual impact are presented, while special emphasis is laid on quantifying the corresponding impact. Accordingly, a new database is created, comprising the main characteristics along with the picture(s) of most wind turbines operating in Greece. Finally, an evaluation process of existing or planned wind parks is described founded on a selected evaluation group (experts, government officials and local society representatives), analyzing all available information (personal information, installation photos, computer animations or video data) according to specific criteria. The results obtained are correspondingly compared with the data of existing public opinion surveys in the vicinity of each installation investigated.

3. Main Parameters Affecting the Visual Impact of Wind Parks

The environmental benefits of wind electricity production, replacing fossil fuel powered stations, are well recognized and accepted. Recently, the intense exploitation of wind energy in several European countries and the concentration of numerous sizeable wind turbines ignite[10][11] the visual impact topic of existing or planned wind parks. Up to now in Greece, as in most European countries, there is no specific national law regarding visual impacts of new installations, although certain rules are concerned about noise intensity and environment conservation (protected animals, birds etc.).

The perception of the visual impacts of existing or new wind farms is a highly subjective topic, influenced by social factors and attitudes[12]. It is, therefore, quite difficult to set clear, objective and congruent rules in order to limit any visual impacts of new installations in their neighbourhood.

In an attempt to facilitate this procedure the Soft Energy Applications and Environmental Protection Laboratory (SEA & Envi-Pro Lab) has undertaken a long-term effort to accumulate and analyze the main factors that influence the visual impact of wind parks, see for example[8][9]. Among these factors one may include:

a. The number of wind turbines constituting the wind parks under evaluation
b. The rotor diameter (size) and the hub height of machines
c. The general aesthetics of the installation, including design, the colour of the wind turbines (mainly the tower colour) in relation with the dominant colour of the surroundings etc.
d. The distance of the wind park from the nearest (inhabited) community, expressed often as a function of the rotor diameter of the wind turbines
e. The adaptation of the wind park in the area character
f. The engines micro-sitting (layout) and uniformity

As it is obvious, the value of factors (a) to (f) actually depends on the wind park characteristics. On top of this, there is a second group of parameters that should be also included, based mainly on the receivers' specific location in relation to the wind park, i.e.

g. The houses percentage of any community affected that have optical contact with the wind park
h. The relative number of wind turbines of the installations that are visible from each house or each sector of the community
i. The viewing angle of the wind park from each community sector, since any installation could be seen frontally, diagonally or longitudinally
j. The area population
k. The relative position of the wind park axis compared with the daily sun path, considering that visual impact is strongly influenced by the sun shining

Finally, the third group that should be taken into account examines the wind park impact on the drivers of the area, including passengers and visitors. Thus one may also include:

l. The mean, minimum and maximum distance of the wind park from the area road network
m. The percentage of the area transportation network being in visual contact with the wind park
n. The average area road network load during the daylight

Rationally, every parameter has not the same impact on the public attitude towards wind energy application; however several of them can normally be quantified in order to realistically estimate the visual intrusion of a wind park. At this point it is important to mention that the main target of the present study is to compare the "objective" opinion of the sector independent experts for the visual impact of selected wind parks, with the results of an extended opinion survey[8] concerning the public attitude towards the visual impact of the above mentioned wind parks.

4. "Wind-Visual" Database Development

During the previous decade the SEA & Envi-Pro Lab started an integrated effort[9] to register all the Greek wind turbines, along with their operational characteristics and photo. Selected results of the current stage of this project are given below, emphasizing the visual impact of these machines in the neighbourhood. In this context, "WIND-VISUAL" is the third version of an integrated database originated in 1998. The current version is also developed in "Access 8.0", mainly for Windows-98 compatibility reasons. Additionally, "WIND-VISUAL" is fully collaborating with "Windbase II", containing operational characteristics[13] of commercial wind turbines since 1988.

In this "WIND-VISUAL" version, the available information for each wind turbine consists of:

a. Wind Turbine type and Rated Power
b. Engine Location
c. Engine Photo
d. Annual energy production throughout its operation
e. Major engine failures history
f. Machine arrangement in the corresponding wind park

For example, in figure (4) one may see the wind park of Marathokambos registered in "WIND-VISUAL" database, along with the nine wind converters WM-19S (9x100kW) constituting the entire station. Accordingly, for each wind turbine one may reproduce the corresponding photo; see for example figure (5) regarding the wind turbine 5 of figure (4), which stands near the ruins of an ancient windmill. Accordingly, in Table I one may get the annual energy yield of each turbine on a monthly basis. As it results from Table I, the energy output of each wind turbine fluctuated to a great extent during 2002, ranging from 255MWh/year (Capacity Factor, CF=29%) for wind turbine 2 up to 380MWh/year (CF=43%) for wind turbine 5.

Table I: Detailed energy production (MWh) of Marathokambos (9x100kW) wind park (2002)

W.T.	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Annual
1	12.0	17.1	15.3	18.9	22.8	28.5	23.3	51.8	10.0	15.0	21.0	33.8	**269.5**
2	11.4	9.2	16.2	17.9	6.3	10.1	28.1	60.3	19.9	19.6	28.1	27.9	**255.1**
3	3.3	15.1	24.1	30.7	25.3	26.9	29.2	63.9	20.6	26.8	25.8	77.0	**368.7**
4	9.2	12.5	29.5	30.3	24.7	22.5	31.9	52.4	19.9	21.4	28.8	47.8	**330.8**
5	13.7	25.5	30.2	32.3	29.2	27.5	33.0	70.6	21.0	33.6	22.8	40.8	**380.4**
6	6.2	22.8	29.8	30.4	26.4	23.0	30.3	50.1	19.6	32.4	24.9	35.4	**331.6**
7	11.9	20.9	17.3	26.6	29.0	18.1	25.1	60.4	16.3	28.0	17.1	33.2	**303.9**
8	12.1	13.6	24.2	25.1	29.7	22.3	31.6	64.1	19.6	31.1	28.2	26.6	**328.3**
9	11.0	22.0	28.5	24.8	31.1	22.0	31.4	66.1	19.0	30.6	29.0	37.8	**353.3**
Total	90.8	158.8	215.2	236.9	224.5	200.8	263.9	539.8	166.1	238.6	225.7	360.3	**2922**

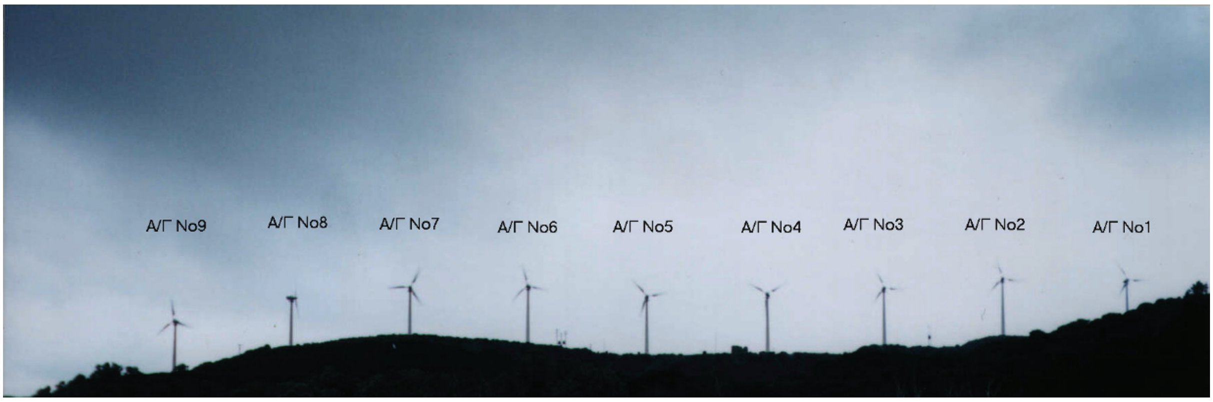

Figure 4: General view of Marathokambos (9x100kW) wind park

Up to the end of 2004, more than 460 wind converters were registered in this database, figuring up almost 250MW of rated power, out of the 450MW totally operating in Greece. However, in the present work emphasis is laid on the entire wind park appearance related to the landscape.

In this context, one has the opportunity to evaluate the visual impact of several wind parks, using the information included in "WIND-VISUAL" database. In the following typical results are presented with reference to the degree of selected wind parks integration in their surroundings.

5. Proposed Methodology

In an attempt to evaluate the potential visual impact of wind turbines, several interesting efforts are presented[14], like the "Thomas Matrix" development, which determines the visibility of a wind park in relation to the distance from the wind power installation[15]. Recently, an interesting methodology has also been presented by Hurtado et al., regarding the visual impact of wind farms in Spain[16].

Figure 5: Close view of a selected WM19S wind turbine, Marathokambos wind park

In the present work an extended Delphi technique is applied in order to estimate the visual impact of existing wind parks in the surroundings. Generally speaking, Delphi is a popular, long-range, qualitative technique for identifying and prioritizing issues for a wide variety of problems in different application domains[17]. Since the method was conceived in the early 1950s at the Rand Corporation, different variations of Delphi have evolved in an effort to develop a technique for the most reliable consensus of a group of experts[18][19]. During the current analysis the "ranking-type" Delphi variant is adopted[20] in order to develop group consensus about the relative importance of visual impact for various wind parks.

During this procedure, several parameters (belonging at the present analysis to the first subgroup of Section 3) are selected in order to quantify the visual intrusion of wind turbines upon the local environment. More precisely, one should take into account the parameters (a) to (f) depending mainly on the wind park technical characteristics.

During the evaluation process of each existing wind park, a number of evaluators (qualified experts, government-local communities officials and local society representatives) analyze the available information (personal information, installation photos, computer animations or video data resulting from "WIND-VISUAL") according to the above-mentioned criteria; see also Table II. One of the most important aspects of the Delphi method is the selection of the appropriate experts. Following recommendations from Delphi literature, it is decided to divide experts into three panels in order to obtain a reasonable degree of consensus. Also the international literature recommends 10-18 experts on a Delphi panel. In the present analysis each panel includes 15 members. More precisely the first group contains qualified experts, i.e. academics and experienced professionals working in the wind park design and erection. The second group includes members of the regional and national administration, while the third group is based on selected members of the local society, like politicians, representatives of ecological groups, members of local development agencies etc.

Table II: Information about wind parks analyzed

Location	**Rated Power (kW)**	**Production (MWh/year)**	**Diameter (m)**	**Hub Height**	**Mean Altitude (m)**	**Permanent Population**	
						in 500m	**in 5km**
Marathokambos Samos	9x100	1800-3000	19	≈25m	450	2	15
Pithagorion Samos	9x225	6000	27	≈30m	530	5	10
Marmari Euboea	17x300	10000-13000	27	≈30m	580	0	10
Karystos-Antia A Euboea	40x600	73000	44	≈50m	500-900	5	180
Andros	7x225	4000-5000	27	≈30m	400	15	20
Ikaria	7x55	1200	15	≈18m	520	0	2

During the application of Delphi technique one should rank the wind parks under investigation from "0" prohibitive impact to "5" (negligible or no impact), while "1" is used for dominant impact, "2" for serious impact, "3" for fair impact and "4" for light impact. The wind power installation attaining the maximum mark is assumed as the one inducing the minimum visual impact on the landscape.

The proposed technique is going to be applied at six wind parks existing in specific areas, where extensive public opinion surveys have taken place; see figure (2). The results of these surveys were presented in recent publications by the authors[8][9][21] and will be used as the basis for comparison purposes. Keep in mind that during the evaluation process by the group of the experts, the public opinion survey results have not been widely announced, while all the experts were asked to express their own "professional" opinion minimizing the impact of any external information occasionally appearing in the mass media.

6. Experts Evaluation Results-Comparison With Public Surveys

Considering the public opinion surveys presented in previous publications by the authors, various wind parks located in S. Euboea and Samos Island are embraced in this analysis. On top of that, two

PPC (Greek Public Power Corporation) wind parks located in the islands of Andros and Ikaria are also included.

More specifically, the first wind park investigated (figure (4)) is the one located near Marathokambos, a small town at the center of Samos Island. This is one of the oldest wind parks in Greece (erected in 1990-91), based on nine small wind converters (of the 1st generation), i.e. 9 Windmatic 19S (or Aiolos-100) machines, rated power 9x100kW. As it results from the available photos, figure (4), all nine-wind converters are sited along a hillcrest, distant from houses and public areas. Additionally, first generation machines are quite small (see also Table II), although their rotor blades are unusually large in comparison to the contemporary blades.

Figure 6: General view of Pithagorion wind park 9x225kW

Accordingly, the next wind park examined is the PPC wind park located near Pithagorion, a historic small town at the south of Samos Island. This wind park belongs to PPC and consists of nine Vestas wind converters (of the 2nd generation), i.e. nine V-27 wind turbines (rated power 225kW), installed since 1993, approximately producing 6000MWh/year, Table II. As it is clear from the available photos, e.g. figure (6), all wind converters are sited on a plateau near the sea, far from houses and public areas. V-27 machines belong to the most popular type of the 2nd generation wind turbines, operating with a fair annual energy production under the unfavourable conditions of a remote island.

Figure 7: General view of Marmari-Euboea wind park (17x300kW)

The third wind park presented concerns the "famous" wind park of PPC in central Euboea, erected since 1993 in Marmari region. More precisely (see Table II), the wind park analyzed comprises 17

Windmaster converters of 300kW each, while -when created- it was the biggest wind park of the Mediterranean area. Unfortunately, major blade failures obliged PPC to replace all the rotors, thus the normal operation of the park started only during 1999. As it is obvious from the available photos, figure (7), Marmari wind farm is built in a remote plateau, near the sea and it is almost perfectly adjusted to the scenery.

Figure 8: Antia-A wind park (40x600kW) at Karystos of S. Euboea

Figure 9: Ikaria wind park of 7x55kW

The next wind park investigated (figure (8)) is also located in S. Euboea (Karystos-Antia A) and it is one of the biggest wind parks ever erected in Greece. It consists of 40 large-medium sized Bonus wind turbines (MkIV-600) while its rated power is equal to 24MW. Although all wind turbines are properly sited to maximize their annual energy yield, the numerous and relatively big wind turbines dominate in the nearby scenery. One should not disregard that this specific wind park may cover the electricity needs of almost 12000 families.

Subsequently, the Ikaria wind park -erected by PPC in 1991- is examined. Ikaria is a medium-sized island of East Aegean Sea, situated 240km from Athens, nearby Samos (figure (2)). The mean annual wind speed exceeds 9m/s. The Ikaria wind park is one of the smallest Greek parks, consisting of seven old-fashioned (1^{st} generation) wind converters, i.e. 7 Windmatic 15S (or Aiolos-55) machines, rated power 7x55kW. According to the photos collected (figure (9)), this wind park is sited on a plateau, at a large distance from public areas. The engines used are rather tiny, compared with the wind turbines applied nowadays.

Figure 10: General view of Andros wind park (7x225kW)

The last station analyzed here is a PPC owned wind park in the Andros island, figure (10).This station consists of seven V-27 wind turbines (rated power 225kW), installed since 1993, producing approximately 5000MWh/year, Table II. This specific wind farm is located in an open area, far from any village. The main problem of these machines has been their limited maintenance; hence some corrosion results appear in almost all the towers of the park. As it is clearly stated by the available photos, the machines are smoothly incorporated in the landscape, while the wind park major area is also used by cattle-breeders.

The results obtained are typical examples of the information included in "WIND-VISUAL" database. Considering the collected visual material and information of Table II, one may demonstrate the expert's attitude concerning these wind power stations visual impact; see Table III. In this context, the small or medium scale wind converters (Ikaria, Marathokambos) and the minimum number of wind turbines constituting a wind park (Ikaria, Marathokambos and Pithagorion) induce the lightest visual impact. However, one should also keep in mind the energy yield of each installation, expressed as the number of households (approximate annual consumption ≈6MWh/year) being electrified.

Table III: Visual impact evaluation of existing wind parks according to Delphi technique

Criterion	Ikaria	Andros	Marathok	Pithagor	Marmari	Karystos
(a)	4.2±0.3	4.0±0.4	3.9±0.4	3.8±0.3	3.1±0.4	1.4±0.4
(b)	4.4±0.3	3.6±0.4	4.2±0.4	3.6±0.5	3.5±0.3	2.5±0.3
(c)	3.6±0.4	2.7±0.5	3.8±0.7	3.9±0.8	4.0±0.7	1.3±0.6
(d)	4.2±0.4	3.0±0.4	4.3±0.4	3.9±0.4	3.9±0.4	3.2±0.5
(e)	4.0±0.5	2.5±0.6	3.7±0.6	4.1±0.6	4.1±0.5	1.8±0.6
(f)	4.2±0.4	3.5±0.4	3.5±0.5	3.5±0.5	3.6±0.4	2.8±0.5
Average	4.1	3.2	3.9	3.8	3.7	2.2
Visual Impact	Light	Fair	Light	Light	Light-Fair	Serious
Families Served	200	700-850	300-500	1000	1500-2000	12000

Several towers of Andros wind parks have corroded, as a result of their limited maintenance, inducing a negative image of these installations. On the other hand, Marmari wind park presents the best general aesthetic, while Karystos wind park report the worst aesthetic presentation. Similarly, the fair adaptation of this wind park in the installation area underlines its dominant impact on the surrounding area.

Using the available information, Andros wind park adjoins habited regions, while most other wind parks are more than 5km afar from existing communities. This is also the case for Karystos wind park, which however is easily distinguished by sea.

Finally, Ikaria wind park seems to obtain the best micrositing in the installation area, while other wind parks mostly lack micrositing problems. On the other hand, Karystos wind park presents the worst micrositing impact, as a result of the extent and distribution of individual wind turbines in various subgroups; figure (8).

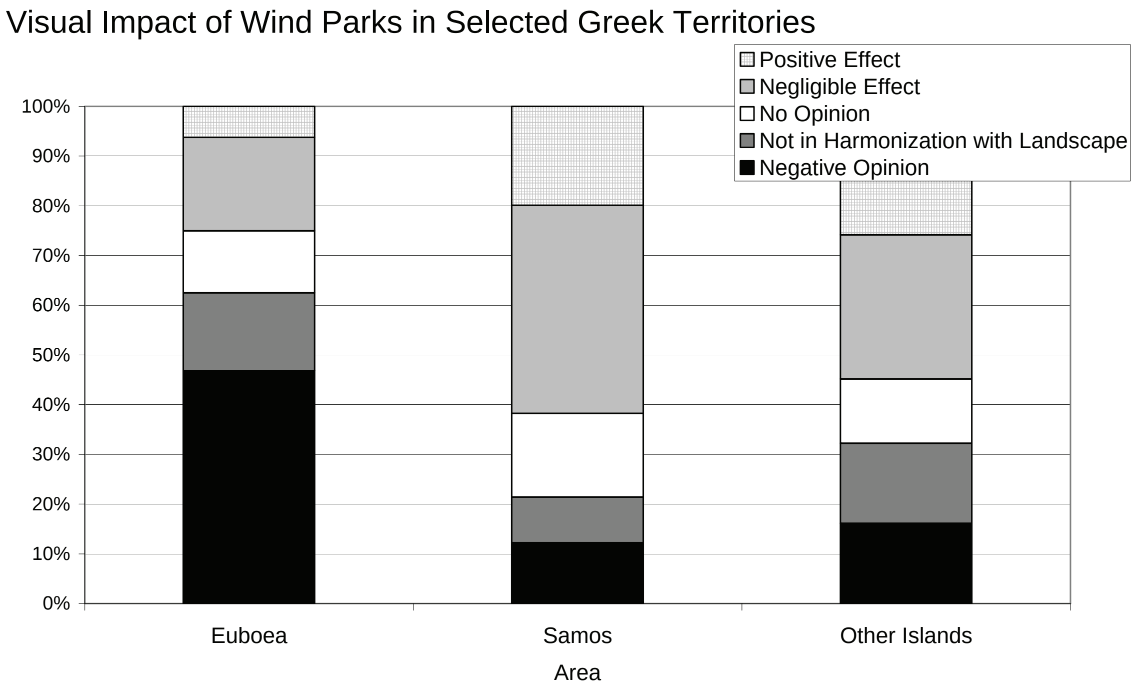

Figure 11: Public opinion survey concerning the visual impact of wind parks in Greek territories

Recapitulating, the visual impact of central Aegean wind parks on the nearby communities is rather fair, mainly due to the appearance of their irregularly maintained machines. This conclusion is in accordance with the recently published[8] opinion survey results (figure (11)), where 16% of the local population has formed negative opinion regarding the visual impact of the existing wind parks, while another 16% mentioned that these machines are not in harmony with the landscape.

Accordingly, using the Delphi technique, both Samos wind parks are expected to induce light visual impact on the surroundings, a fact also validated by the public opinion survey in the area; figure (11). On the contrary, the visual impact of the relatively huge private wind park of S. Euboea is characterized as almost serious in the landscape. This is not the case for the Marmari wind park. Considering the existence of another ten sizeable wind parks in the same major area, one may justify the strong negative attitude of local habitants against wind parks, figure (11), claiming dominant visual impact of these installations on their territory.

7. Conclusions

Visual impact is one of the major factors creating negative public attitude towards wind energy applications. In an attempt to clarify the visual intrusion of the existing wind parks in the surroundings, the present study initially registers the main parameters affecting this incident.

Accordingly, the information of a new "WIND-VISUAL" database -created to comprise the main characteristics of the existing wind power stations including photos and videos of the installations- is taken into consideration. Hence, on the basis of a Delphi technique, a selected evaluation-experts group analyzes the available information and ranks the wind parks under investigation according to the degree of their visual impact. The experts' evaluation results are also compared with the corresponding public opinion results conducted in the same area.

According to the data presented, no wind park is imposing dominant or prohibitive visual impact on the nearby communities, while the impact of their vast majority is characterized as light or fairly light. Another interesting finding of the present work is that in most cases the experts evaluation coincides with the results of the public opinion surveys in the same area. In this context, relatively sizeable wind parks (rated power higher than 10MW) practically influence the aesthetic of the region. However, these power stations fulfil the electricity requirements of a considerable (5000-12000) number of families, avoiding at the same time the environmental deterioration resulting from thermal power stations. On the other hand, negative attitude is also induced by the irregular maintenance of several aged wind turbines, giving thus the impression of abandoned installations.

Considering that both public and experts agree upon the visual impact of existing wind parks, this experience should contribute to the upgrading of new wind parks appearance, limiting the negative attitude against wind energy. Finally, the idea of creating a numerical coefficient able to objectively determine the degree of visual impact of a wind park should be among the targets of a forthcoming research effort.

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OPTIMIZING THE ENVIRONMENTAL PERFORMANCE OF THE GREEK ELECTRICITY SECTOR CONCERNING THE NO_X EMISSIONS

G.C. Spyropoulos, K.J. Chalvatzis, J.K. Kaldellis
Laboratory of Soft Energy Applications & Environmental Protection
Mechanical Eng. Dept., Technological Education Institute of Piraeus

Abstract

The energy production process is found guilty of significant air pollution, including the annual emission of more than 70000tons of nitrogen oxides in Greece. Separate NO_x emissions factors are used in order to classify the existing large combustion power plants. In the present study we calculate the NO_X emissions resulting by using in priority the most environmental friendly power stations to face the electricity load requirement of the Greek mainland. The proposed methodology may offer the opportunity to quantify one major component of the environmental degradation, considering the significant air pollution impact on everyday life.

Keywords: Electricity Sector; Nitrogen Oxides; Power Stations; Lignite Emission Factors

1. Introduction

The continuous technological development is closely associated with increased energy consumption. One of the most user-friendly energy resources used by contemporary human societies is electricity and the leading part of energy in everyday life activities is well recognized[8]. The energy production process, however, is found guilty of significant air pollution, including the annual emission of more than 70000tons of nitrogen oxides in Greece, contributing to local environmental degradation[6] as well as to long distance, even transboundary, effects to manmade and natural ecosystems.

The electricity production process is assumed by this time responsible for more than 25% of the national nitrogen oxides emissions. Based on an extensive analysis that was carried out by the authors[8] and the available long-term official measurements, separate NO_X emissions factors are used for each Greek large power station.

Nitrogen oxides production in Greece as well as in the vast majority of the developed countries is driven by the transport sector. Despite the massive renewal of the private vehicles fleet that took place in the early 90's the sector's contribution is growing in an increasing trend[4]. Focusing on the reasons of this trend we should notice the continuing enlargement of the amount of vehicles used in Greece as well as the inadequate control of their proper operation. As a result transport holds the 60% of the total share while electricity and industry are following[12].

2. Brief Presentation of Greek Electricity Power Stations

Greek electricity generation network is almost exclusively based - from its foundation in the early 60's - on fossil fuels, using lignite and heavy-oil fired stations to meet base and peak load demand respectively[9]. Only in the past years a remarkable natural gas penetration in the Greek energy market tends to change the fuel mix of the electricity sector. On the other hand, although the hydroelectric power stations amount a rather high installed capacity, they contribute relatively low, basically due to water reserves deficit and applied electrical load management plan[11]. Finally, despite the high wind potential of the country, due to the ideal geographical position that Greece possess, the contribution of the wind parks to the Greek electricity production is still limited[7]. Only recently a modest number of wind parks started their operation in some areas such as Euboea and Crete.

***Spyropoulos G.C., Chalvatzis K.J., Kaldellis J.K., 2006,** "Optimizing the Environmental Performance of the Greek Electricity Sector Concerning the NO_x Emissions", International Conference of Protection and Restoration of the Environment VIII, Chania-Crete, Greece.*

Based on official data[3][13] from the Greek Regulatory Authority of Energy (RAE) and the Greek Public Power Corporation (PPC), the local electricity generation system (as of the beginning of 2005) is divided in two branches. The first part contains the mainland electricity production network based on thermal power stations (TPS) with rated capacity of 7619 MW and over 3000MW of large and small hydropower installations. The second part includes medium-small autonomous thermal power stations (APS) in the island network[14]. More precisely, the Greek thermal power stations can also be categorized according to the fuel used, as shown in Table I that follows:

Table I: Categorization of Greek Mainland Thermal Power Stations

Fuel	**Installed Capacity (MW)**	**Region**
Lignite	4438 MW	North Greece
Lignite	850 MW	South Greece
Natural Gas	1581 MW	Mainland
Heavy-oil (Mazut)	750 MW	Mainland

In addition, the lignite-fired power 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 specified 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 proportionally different. In the current study only official data[1] will be utilized, hence the lignite-fired stations nominal power is taken equal to 4088 MW for North Greece and 850 MW for South Greece ones.

The present work is focused on investigating in detail the nitrogen oxides emissions. Nitrogen oxides are produced in high temperature when nitrogen molecules of the atmospheric air and the fuel are oxidized. Inside the burner the produced oxides divide into 95% NO and 5% NO_2. While the nitrogen monoxide is the major nitrogen component inside the burner, the vast majority of it is further oxidized to nitrogen dioxide. The factors contributing to the production of nitrogen oxides are related to the oxygen content inside the burner, along with the burner’s temperature together with the time period that the nitrogen molecules are exposed to that environment. Nitrogen dioxide is a very toxic air pollutant, which according to its concentration and the exposure time it may cause from breathing difficulties to death. Moreover the nitrogen oxide reacts with the atmospheric humidity creating nitrogen acid with very corrosive characteristics.

The Public Power Corporation has established during the last decade a program emphasizing on the control of environmental impact of the electricity generation procedure and the air pollution, in particular. Among others the technologies implemented include electrostatic precipitators for the control of the ash and desulphurization units. Regarding the nitrogen oxides most of the investments are focusing on the installation of (superior) NOx control technology burners together with the use of gas combined cycle turbines in order to maximize the efficiency factor[14]. More precisely the Florina power station features a burner of low NOx technology while the Lavrio, Agios Georgios (Keratsini) and Komotini power stations feature low NOx and combined cycle technologies.

3. NOx Emission Factors of Greek Thermal Power Stations

Taking into consideration the significant role of electricity generation on the national nitrogen oxides production, the present work is focused on investigating, in detail, the nitrogen oxides emissions for each power unit. Using previous work by the authors[9][10], considering the quantity of air pollutants production and annual energy yield one may define the NO_X emission factor "e_j" for the "j-th" thermal power station, i.e:

$$e_j = \frac{m_{NO_X}}{E_j} \quad (1)$$

where "m_{NO_X}" is the annual NO_x mass production and "E_j" is the annual energy yield of the "j" thermal power station.

For the calculation of the results, official data have been used[15]. Accordingly, one may classify the power stations, bearing in mind their environmental impact per electricity generated. For a representative year, where official data exist, the results are presented in Table II. In this context, a detailed classification has taken place by sorting the power stations starting from the one with the lowest emission factor to the one with the highest. The analysis has been carried out separately for each unit of the power stations and the presented differences are a result of the age and the operational characteristics of each one of them.

More precisely, the NO_x emission factors rise from approximately 1.2gr/kWh to 3.8gr/kWh. It is interesting to note that although each unit of every power station is consuming lignite of the same characteristics, however the corresponding NO_x emission factor may differ in a certain degree. It is imperative at this point to observe the low but not unnoticed differences in the emission factors of South and North Greece power stations. Taking into consideration the results of Table II, along with additional data concerning the rest energy consumption sectors, one may observe the corresponding emission factors. The highest NO_x values characterize the North Greece thermal power station of Liptol, being equal to 3.8 kg/MWh, lacking any integrated anti-pollution measures. It's important to mention that the above station is the oldest in Greek electricity generation network, as the unit Liptol I started its operation in 1959 and Liptol II in 1965. Furthermore, both units are relatively small.

Table II: NO_x emissions factors for Greek thermal power stations (2001)

Power Station	**Power Unit**	**Rated Power (MW)**	**Emission Factor (kg/MWh)**
Megalopolis-A	III	300	1.2
Megalopolis-A	II	125	1.2
Aminteo	I	300	1.3
Megalopolis-A	I	125	1.3
Aminteo	II	300	1.5
Megalopolis-B	IV	300	1.6
Agios Dimitrios	V	366.5	1.7
Ptolemaida	III	300	1.8
Agios Dimitrios	IV	310	1.8
Ptolemaida	II	125	1.9
Ptolemaida	IV	300	1.9
Agios Dimitrios	III	310	1.9
Ptolemaida	I	125	1.9
Agios Dimitrios	I	300	1.9
Agios Dimitrios	II	300	2.0
Kardia	III	300	2.0
Kardia	IV	300	2.1
Kardia	II	300	2.1
Kardia	I	300	2.1
Liptol	I&II	43	3.8

The environmental criteria used for the assessment of the power stations are referring only to their NO_x emission factors. It is crucial, therefore, to mention that different criteria e.g. for a variety of air pollutants, would result in a different classification, taking under consideration the weighted environmental impact of each air pollutant, along with the contribution of the electricity generation sector to the national releases of the pollutants in question.

The data used in the current study are extracted from the time-series curve of the electrical power demand, for the year 2001. The energy and power demand are given on an hour by hour basis and concern only the lignite-fired power stations. The peak demand is a phenomenon noticed to be occurring at the noon and late evening hours. Moreover the lignite-fired power stations in Greece are introduced in the operational plan as base load units and subsequently the peak load demand is met using the hydropower and heavy oil fired stations. Therefore the power demand curve presents a narrow ranging.

In the procedure adapted one disregards, during the selection process among the available Greek power plants, any operational, grid-stability, system efficiency and cost-effectiveness criteria. Hence, the calculation methodology takes under consideration only the electricity generation capacity during the year. Taking into consideration the maintenance plan, the ideal annual operational plan for each station can be drawn. In any case the contribution to the grid for each power station is limited up to the 90% of its maximum nominal capacity. Therefore "shut down" and "break down" incidents are almost completely excluded.

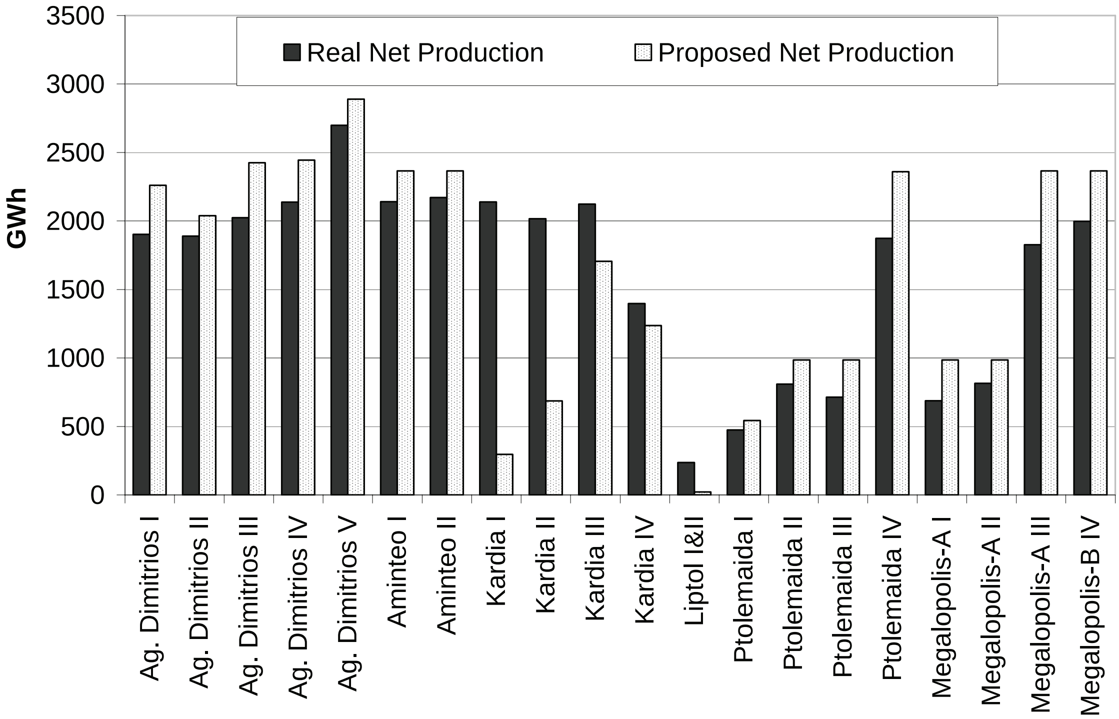

Figure 1: Real and proposed environmental friendly net electricity production for the year 2001

Additionally, an important parameter to be considered is the lowest operational level of an electricity generation unit. Technically, for a lignite-fired power station, this cannot be lower than 60% of its nominal capacity, due to the steam turbine cycle characteristics. The methodology developed for the present study seeks to meet the hourly power demand, making use of the most environmental friendly power stations. As a result of the knowledge and characteristics for each station it occurs that eight of them are used for all year round on a defined capacity. Only Agios Dimitrios IV is used on 72% of its normal installed capacity, while all the rest power stations are used on the maximum available capacity. The power demand, when exceeding the capacity of the aforementioned eight stations, is covered by the next power stations as listed in Table II.

More precisely, the energy production by every power unit separately is presented in figure (1). In the dark color one may notice the real net production for the year investigated as it is known from the official data[15], while in light color the estimated net production is shown, if the proposed model would be applied.

The base load power stations are utilized in a higher extend, which is on average 1.2%. However, for the Megalopolis station the above mentioned increase reaches the 1.3%, mainly due to the low emission factor of nitrogen oxides. The Liptol and Kardia power stations –being the most polluting ones– are minimizing their contribution to the electricity grid. Especially the Liptol power station, having in the year 2001 an actual energy production of 237 GWh, supports in the proposed model the domestic electrical network with only 22.1 GWh.

4. Nitrogen Oxides Annual Production Calculation

Making use of the proposed model to meet the actual energy demand of the grid, the network supervisor should know the diurnal operational time of each power station, the power contributed to the network as well as the NO_x emissions for each unit of the power stations. In figure (2) one may notice the NO_x production for two cases, the real one as well as the corresponding one on the basis of the proposed model. More precisely, the NO_x production for each unit of Greek thermal power stations is presented.

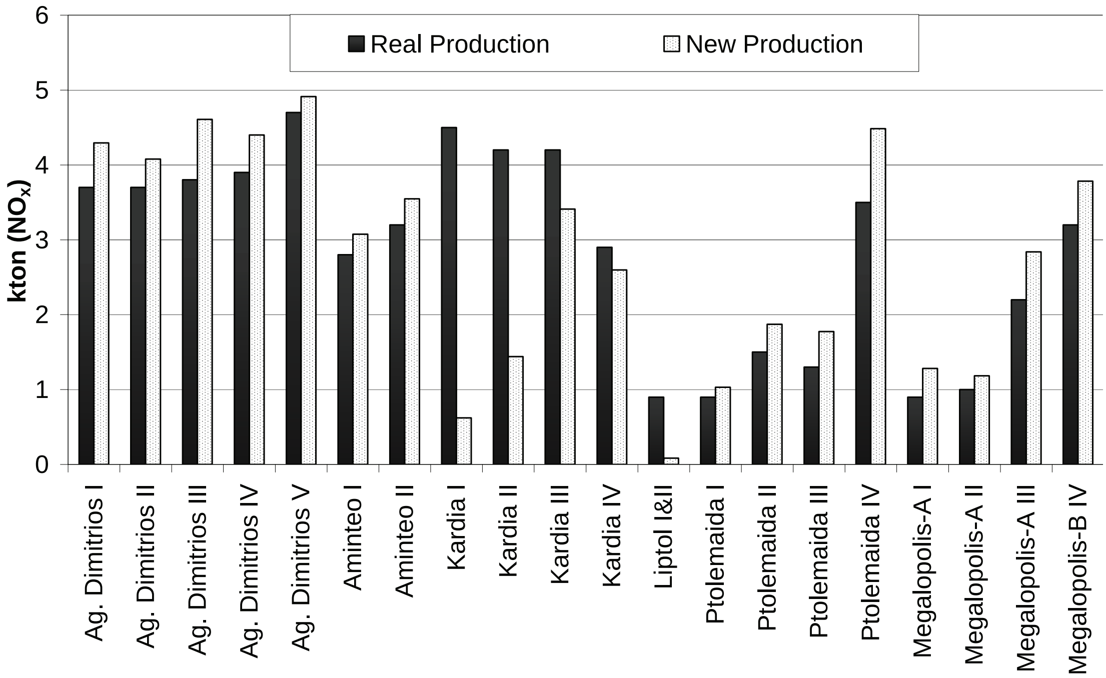

Figure 2: Total NO_x releases by the Greek thermal power units

According to the methodology in use, most of North Greece power units are utilized in a higher than their usual extend and therefore their NO_x releases are increased from 30,000 to 38,000 ton. Only Kardia and Litpol are an exception as they are found to be the most polluting units of this group. Therefore their contribution to the electricity grid is reduced with proportional results to the NO_x emissions decreased by 8,500 ton. On the other hand the NO_x production of South Greece units, meaning Megalopolis station, is increased by almost 1,800 ton.

In figure (3) one may observe the proposed diurnal electricity generation of Liptol power station. Being the oldest and most polluting power station of the Greek electricity network this station is used only to cover peak load as and if it occurs. While the total contribution of Liptol power plant for the year 2001 is suggested to be eliminated at 22 GWh, the rate of its actual production to its nominal capacity falls to 9%.

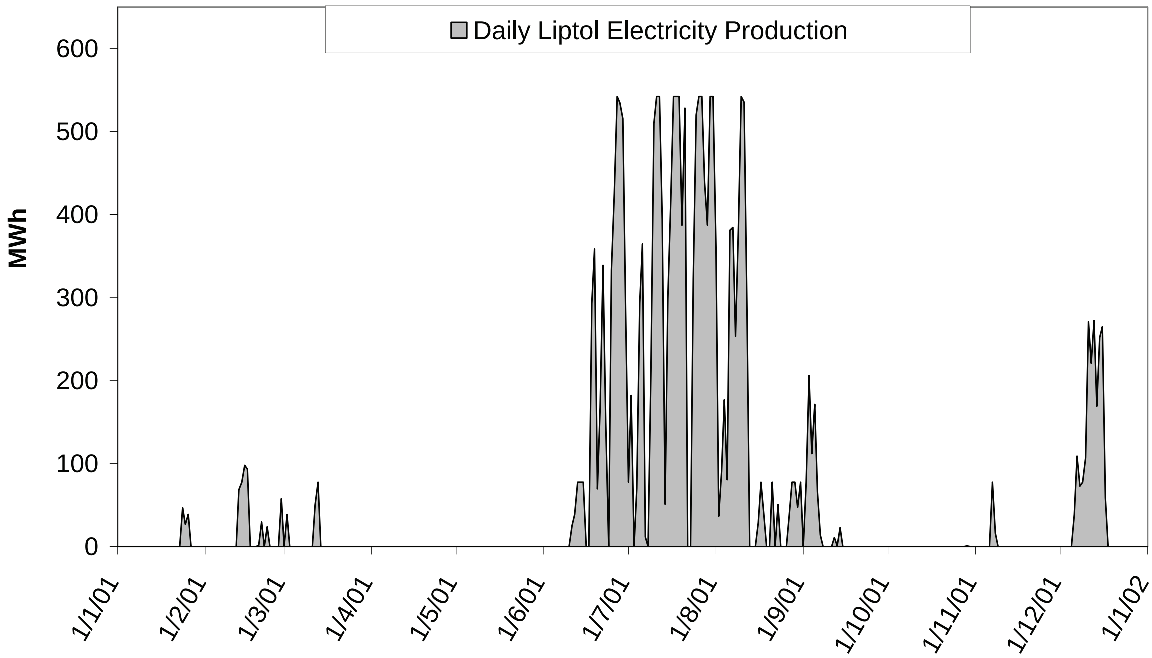

Figure 3: Total daily electricity production of Liptol power station

At this point it is important to mention the significant insecurity in forecasting the power demand in Greece. While the energy demand forecast is in general successfully projected, the peak loads curve how a correlation to natural parameters like the temperature, the cloudiness etc. In several cases forecasting the peak demand curve in Greece is depended on temperature projection models and this correlation is getting stronger every year, mostly due to the increasing number of air conditioning installations[5].

According to UCTE[16] the reserved capacity demanded to cover random accidents and operational disorders can be secured by hydropower stations. At the same time the aforementioned institute, in a study entitled "Load Management", suggests bilateral contracts of the network supervisor and the industries in order to spread out the peak power demand in a diurnal basis. The industrial sector could be attracted in such a step through subsidies and price discounting policies. In this way the peak demand can be met directly without any impacts in the domestic sector.

5. Conclusions

Evaluating the final result of the nitrogen oxides emissions one may notice that it is not overwhelming. This is mostly due to the relatively narrow ranging (1.8 ± 0.54 kg/MWh) of the NO_x emission factors of the power stations examined. Moreover, despite the suggestion to shut down Liptol, the outcome is not of major importance as the installed capacity of the power station in question is the lowest one in the current network. With the heavy polluting units set in limited or no use, according to the operational plan of the proposed model, the total decrement of nitrogen oxides production is approximately 2000 ton. On top of this, the authors believe that the electricity sector in Greece needs vital pollution control investments. Therefore, the overall environmental benefit is considered to be crucial and the suggested methodology could contribute into classifying the most environmental friendly power stations by taking into consideration the weighted environmental impact of the most important air pollutants, like NO_x.

The status quo in the electricity power sector is almost proven to be leading in a remarkable air pollution rise during the next decade, a fact that is also validated by previous studies. In this context, the proposed methodology may offer the opportunity to quantify one major component of the environmental degradation and assist Greek society in taking vital decisions regarding the local electricity production sector for the next few years, considering the significant air pollution impact on everyday life.

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EUROPEAN INTEGRATION AND TRANSBOUNDARY TRANSFER OF AIR POLLUTION: ANALYZING THE CASE OF NITROGEN OXIDES

K.J. Chalvatzis, G.C. Spyropoulos, J.K. Kaldellis
Laboratory of Soft Energy Applications & Environmental Protection
Mechanical Eng. Dept., Technological Education Institute of Piraeus

Abstract

The recent expansion of the EU, in May 2004, included ten new members eight of which used to belong to the so-called "former eastern block". The post WWII environmental policy followed in this region has been radically different from the tendencies followed in Western Europe. While in both regions the industrial development has been the main goal, the lack of conservation regulations at the Eastern European countries has resulted in a rather harmful industrialization, regarding natural resources and environmental quality. In the meanwhile, Europe experienced the severe consequences of the transboundary transfer of air pollution with sensitive ecosystems of the continent being devastated. The European Monitoring and Evaluation Program has published data regarding the transboundary transfer of nitrogen oxides throughout the European continent in the course of over 15 years. The present study utilises these data, focusing on the contribution of the new member-states to the environmental pressure faced by the older member states and vice versa, in order to analyse the situation and discuss the present and future environmental policy concerning air pollution.

Keywords: Transboundary, Air Pollution, Nitrogen Oxides, Europe, Integration, EMEP

1. Introduction

Since May 2004, ten more countries have joined the European Union, in its greatest expansion historically. Eight out of the ten new members used to belong to the so called “former eastern block”, with a post WWII history significantly different than that of the Central and Western Europe. These countries, being politically and financially isolated during the last decades, have been left behind in the implementation of any environmental protection policies.

While during the post WWII period the struggle to improve the economic indicator was rising, Europe experienced the threatening consequences of the transboundary transfer of dangerous air pollutants. Up to that time problems caused by the rising production of acidifying and eutrophying gaseous pollutants have been identified but it has been thought that their effects were only local around the area into which they were produced. In contradiction to that belief numerous lakes and hectares of forests in Scandinavia were found to be exposed in very high acidity, which was not produced in the nearby area[1][2]. Acid compounds that have been emitted in central Europe degradated forest and aquatic ecosystems of the Scandinavian Peninsula[3].

The recognition of the problem of transboundary transfer of certain air pollutants throughout the European continent led in 1979 to the initiation of "The Convention of Long-Range Transboundary Air Pollution" (CLRTAP)[4] which had set a clear framework not only for the environmental and health consequences but also for the internationally cooperative approach needed for their abatement. The Convention was signed by the European Community, while 34 governments established the European Monitoring and Evaluating Programme (EMEP)[5][6] for the promotion of scientific research and intensive monitoring of the Transboundary Air Pollution Transfer (TAPT) effect, funded by the Organization for Economic Cooperation and Development (OECD)[7].

Although the first actions taken for the control of the TAPT effect were focused on the mitigation of the sulphur dioxide emissions, the increase of road transport as well as the lack of any abatement

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measures resulted also in the dangerous increase of the nitrogen oxides production. While in Western Europe it was mostly the extensive growth of the private vehicles fleet that was causing the problem[8][9], in the centrally planned economies it was the extreme industrial specialization, which heavily demanded cargo overland transfer for raw materials and products. The United Nations Economic Commission for Europe (UNECE) implemented the 1st Nitrogen Protocol in year 1988, asking the signatory parties to keep their nitrogen oxide emissions below the 1987 levels until the year 1994.

Although the "first generation" protocols contributed a lot in the emissions control, still the monitoring procedures were reporting high acidity in several ecosystems. This fact put forward the need for a different approach, as scientific research should answer the question of how much acidity were the ecosystems able to receive and still maintain their balance[10]. Data from all the participating countries were collected in order to sort out solutions for minimizing the environmental damage with the lowest economic cost[11]. Taking into account the transboundary transport of air pollution as well as the ecosystems limits, each country was examined individually and advised to lower its emissions at an adequate level. The latest evolution of the legal and policy framework for the abatement of acidification and eutrophication is set in the EU by the emission ceiling directives (e.g. Directive 2001/80/EC).

2. A Brief Spatial Analysis of the Integrated EU Area

The integrated European area consists of the old EU members as well as the new countries, eight of which are located in the central and north-east Europe. The present study is based on defining a hypothetical border line between the old and the new member states. In this way we are examining the air pollutants exchanged towards each direction.

Figure 1: Map of Europe

Beginning with a north towards south analysis one may notice (figure (1)) that the neighbouring countries in the Baltic sea region are Estonia, Latvia, Lithuania and Poland from the new member states and Finland, Sweden and Germany from the old member states. It is obvious that while Finland is closer to Estonia and Latvia, Sweden interacts mostly with Lithuania and Poland. The latter is also heavily influenced from Germany. However, SW Poland together with the SE part of Germany (former German Democratic Republic – GDR) and the Czech Republic (western part of the former Czechoslovakia) were forming the area which was well known as the “Black Triangle”. The heavy industrialisation of this region in combination with the early exploitation of its high quality brown coal resulted in the utilisation of poor quality fuels with a high sulphur content. Serious damages have been reported in the ecosystems of this region[12] and these were directly correlated to the high concentrations and deposition of airborne sulphur compounds and acidity[13]. It has been the aftermath of the dramatic increase of the sulphur dioxide emissions in this region by a factor of ten in the 1960-1985 period[14]. Moving to the South, the former Czechoslovakia, Hungary and Slovenia are surrounding the eastern Austria. Finally northern Italy neighbours with Slovenia.

One may notice that from the present study are excluded several countries along Western Europe as well as countries which are at the East of the new member states. As regards to the western European countries like United Kingdom, Netherlands, Belgium, Luxembourg, France, Spain and Portugal, the distance from the hypothetical border line is significantly large resulting in minor air pollution transfer to the new members and vice versa.

Same as above is the situation considering the eastern European countries of Belarus, Moldova, Ukraine and the western part of Russian Federation. Moreover these countries are not member states of the EU therefore there is little interest in complying with EU-wide environmental policies. While Romania and Bulgaria are not EU members either, they are in the final stage of completing the entry process so there is a particularly increased interest for their interaction with Greece as the closer neighbouring old member state at the southern Balkan Peninsula. However, this issue has been extensively studied in a previous work of the authors[15].

3. Transfer of Oxidised Nitrogen Air Pollutants

Oxidised nitrogen air pollutants are mostly produced by the transport sector from the internal combustion engines. Therefore the emitting sources are mainly non-stationary and are found spread throughout the urban areas as well as in the national road networks[16][17][18]. Bearing in mind the results presented for the oxidized sulphur exported by the new EU members one may realize that the situation is not similar regarding the nitrogen oxides exports (figure (2)). Poland is obviously playing the key role on the oxidized nitrogen emissions, transferred to the old EU members and only the contribution of the Czech Republic may be considered as comparable. Although the available data begin from 1997, the heavy industrialization together with the close neighboring to Germany and Austria are the major reasons for the high significance of the Czech emissions, despite its relatively small size. The rest of the new member states present only a minor contribution and only Slovenia exceeds in 1997 the 5kt of NO_X exported.

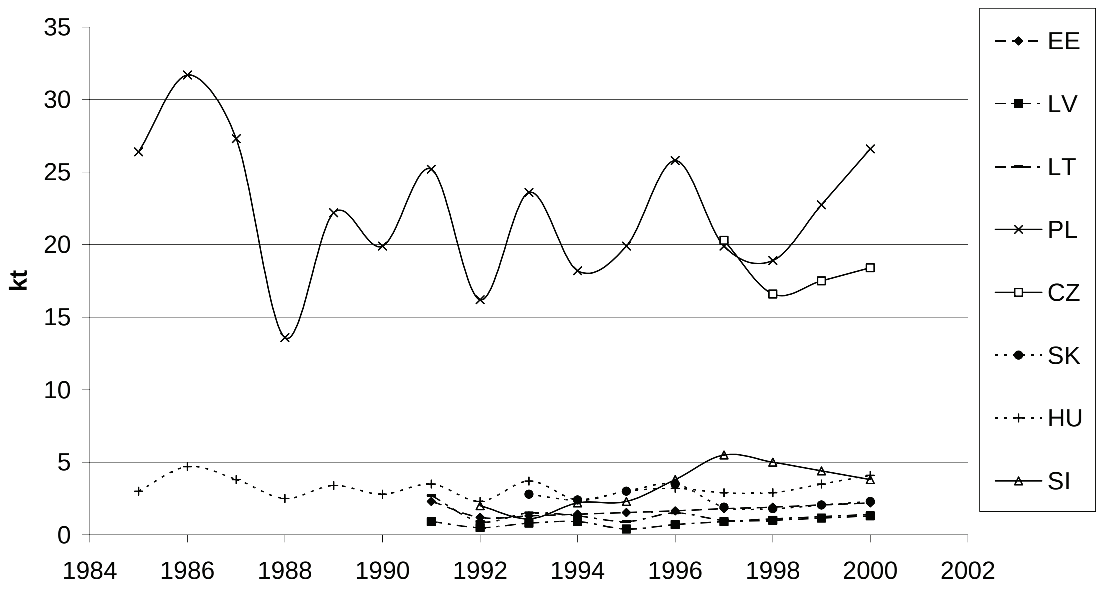

Figure 2: Nitrogen oxides exports from new EE States

In the light of the data presented concerning the oxidized nitrogen exports from the new EU states, an attempt to study their allocation to the old EU members follows. Hence, one may observe (figure (3)) that despite the fact that Germany is the main nitrogen oxides importer from the eastern EU members, other countries like Sweden and Finland are receiving considerably high quantities, presenting an increasing trend in the last examined years. The situation for Austria and Italy is not the same since those two countries, together with Germany, show a declining tension.

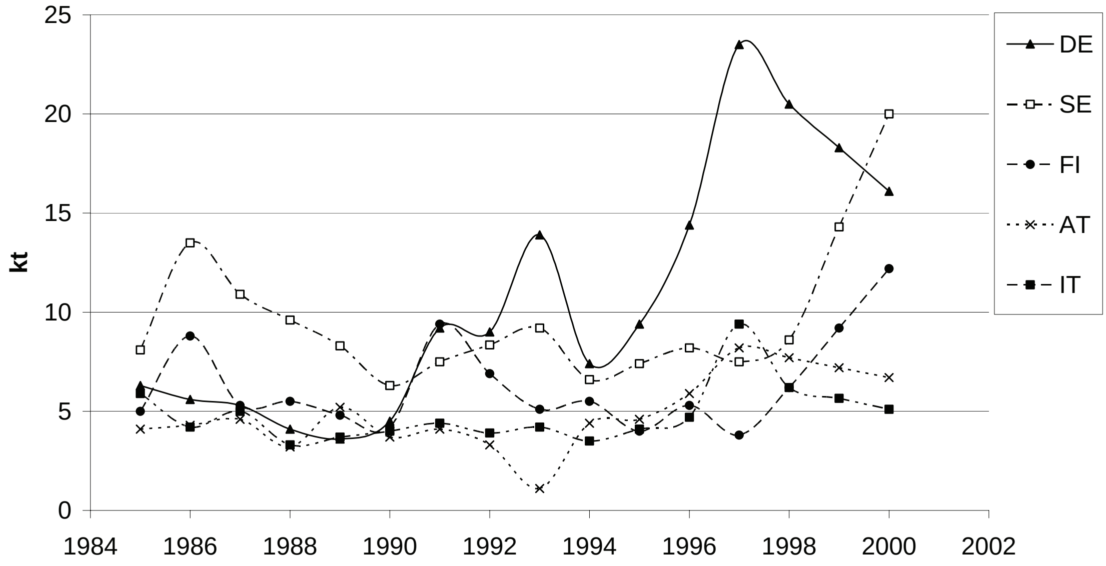

Figure 3: Nitrogen oxides imports to old EE States

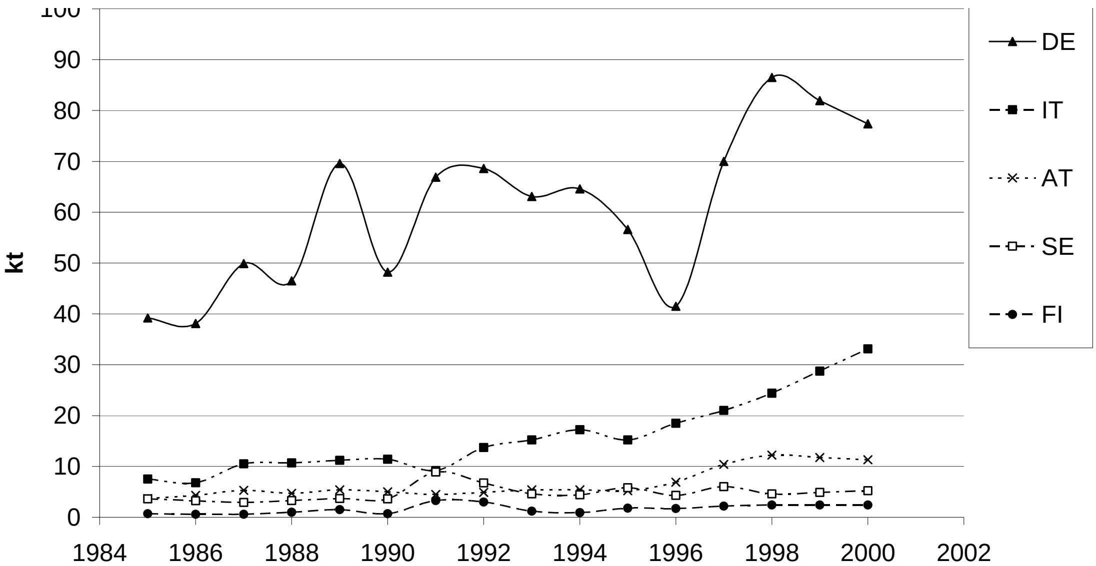

Figure 4: Nitrogen oxides exports from old EE States

As the transboundary transfer of the nitrogen oxides from the new member states to the old ones has been presented this part of the study focuses on the vice versa route of the air pollutants in question. In figure (4), the evolution of the exported oxidised nitrogen quantities from the old EU members is presented. In this context one may realise that Germany is the major exporter not only of sulphur, but also of nitrogen oxides. Moreover, the increasing trend of the Italian emissions can be considered as remarkable, resulting in year 2000 in a percentage of 25% of the total western oxidised nitrogen exported. The Scandinavian countries of Sweden and Finland present no significant changes during the examined time period, and never exceed the 9% of the total emissions. Finally, Austria exporting to the new EU members more than 10kt of nitrogen oxides presents a noteworthy contribution.

Studying the allocation of the West Europe originated nitrogen oxides air pollutants one may refer to figure (5) out of which becomes obvious that Poland is without any doubts the major receiver of oxidised nitrogen among all the new members. Czech Republic, being in the "Black Triangle" region is also receiving a considerably high amount of the NO_X emitted by the old EU members, while similar is the situation for Hungary, which neighbours to Austria. The rest of the countries under study receive individually quantities lower than 10kt without any considerable variation in the period examined.

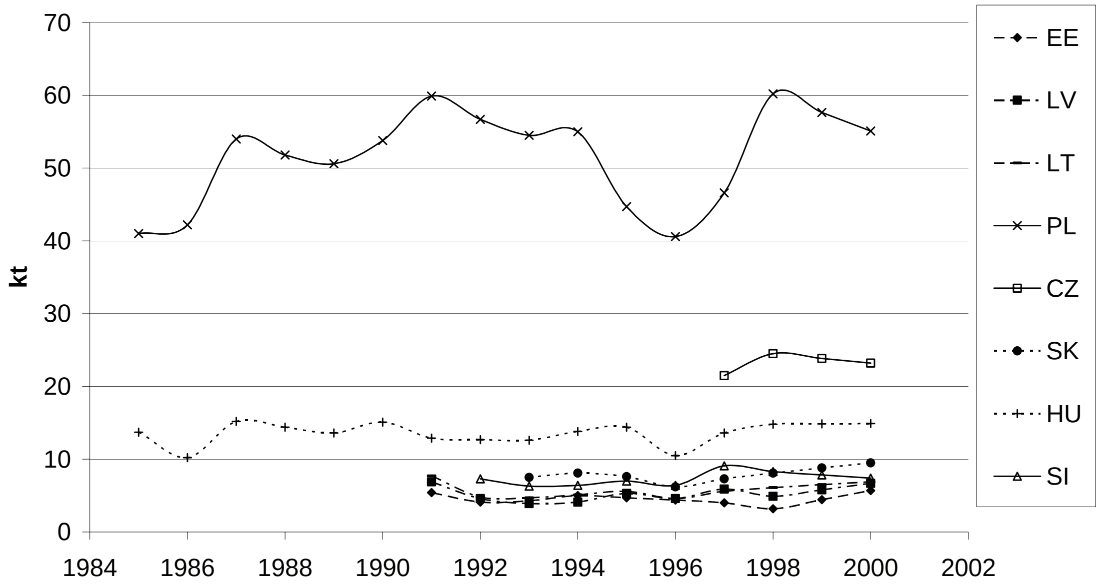

Figure 5: Nitrogen oxides imports to new EE States

4. Discussion of the Results

While having already examined the evolution of the air pollutant quantities which have been exchanged between the old and the new EU members, one may try to assess whether the transboundary transfer of the oxidised nitrogen is beneficial or not for every individual country.

Regarding the transboundary transfer of the oxidised nitrogen for the new EU members, it appears that all of them have received bigger NO_X quantities than those exported. Among the least harmed countries one may find Estonia, Latvia and Lithuania together with the Czech Republic, Slovakia and Slovenia. While none of the aforementioned states has received more than 45kt of NO_X in comparison with their exports, Poland and Hungary are by far exceeding that limit. In fact, Poland is the country harmed in major, receiving in the period examined 466kt more emissions than those exported, while Hungary is following with 165kt.

As regards to the status of the old EU states towards the transboundary transfer of oxidised nitrogen, the study shows that only the Scandinavian countries of Sweden and Finland are harmed in average by not more than 5kt per year each. Austria is slightly benefited exporting less than 2kt of NO_X more than its imports, while the relevant quantity for Italy is barely exceeding the 11kt. Finally, Germany is in this case the major benefited country exporting 50kt more oxidised nitrogen emissions than its imports.

5. Conclusion

Recapitulating one may notice that the TAPT effect is harmful for most of the countries included in the present paper. While Germany is the only country benefited by large scale exports of oxidised nitrogen, some of the other countries are benefited too, but in a lower extend. As such may be considered Estonia, Hungary, Slovakia, Austria and Italy. However, all the rest of the countries under study have been harmed severely from major nitrogen oxides imports.

Transboundary transfer of pollution is a phenomenon not strictly bound to air pollutants but also relevant to cases of water contamination when neighbouring countries share the same rivers or lakes.

The air pollutants in question are considered to be responsible for various environmental hazards such as the eutrophication of aquatic ecosystems, the acidification of forests, the historical monuments degradation and the significant deterioration of the urban air quality[19][20].

The analysis presented in the current paper refers to data until year 2000 and therefore one may consider it as outdated. However, the authors believe that there is a certain reasoning supporting the usefulness of this study. Out of the parameters resulting in the TAPT effect, the climatic phenomena together with the land surface characteristics are not changing significantly in the course of time. Therefore the only factor which can be considered as variable in the short term examination is the air pollution emissions of every country. Thus, this paper, making use of the analytical data of EMEP for over 15 years can provide for a comprehensive outlook of the tendencies of the TAPT effect on either sides of the hypothetical border line of the integrated European continent.

While the environmental problems caused are severe, the TAPT effect seriously questions the applicability and adequacy of the “Polluter Pays” principle. Thus the need for a framework providing for a steady ground which will better improve the environmental quality by allocating the funds and efforts more efficiently is emerging. The authors believe that the Integrated Europe with the old, new and forthcoming member states can meet these needs sufficiently.

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Contact Address

Laboratory of Soft Energy Applications & Environmental Protection

TEI of Piraeus

P.O. Box 41046, Athens 12201, Greece

Tel. +30-210-5381237

FAX +30-210-5381467

e-mail: sealab@gdias.teipir.gr

www.sealab.gr