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STAMOULIS
PUBLICATIONS

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

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

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

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

Educational Activities

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

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

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

Research Areas

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

Published Results:

- **Kaldellis J.K., Zafirakis D., 2007,** "Present Situation and Future Prospects of Electricity Generation in Aegean Archipelago Islands", *Energy Policy Journal*, Vol.35(9), pp.4623-4639.
- **Kaldellis J.K., 2006**, "An Integrated Model for Performance Simulation of Hybrid Wind-Diesel Systems", *Renewable Energy Journal*, Vol.32(9), pp.1544-1564.
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2. "Estimation of Social - Environmental Cost in the Energy Production Sector"

Published Results:

- **Kaldellis J.K., Kondili E.M, Paliatsos A.G., 2007,** "The Contribution of Renewable Energy Sources on Reducing the Air Pollution of Greek Electricity Generation Sector", *Fresenius Environmental Bulletin*, Vol.17, No 7/8/9.
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3. "Technological Progress in Wind Energy Market"

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4. "Technological Progress in Solar Energy Market"

Published Results:

- **Kaldellis J.K., Zafirakis D., Kaldelli El., Kondili E., 2007,** "Combined Photovoltaic and Energy Storage Systems. An Integrated Electrification Solution for Small Islands", accepted for publication in the *International Journal of Technology & Management*.
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5. "Flow Field Prediction for High Speed Turbomachines"

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

Published Results:

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

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Research Projects under Development

Participation in Research Programs (2002-2007)

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

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

TABLE OF CONTENTS

PART ONE

PART TWO

PART THREE

PART FOUR

PART FIVE

PART ONE

ENERGY STORAGE

TECHNO-ECONOMIC COMPARISON OF ENERGY STORAGE SYSTEMS FOR ISLAND AUTONOMOUS ELECTRICAL NETWORKS

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Abstract

The oil dependent electricity generation situation met in the Aegean Archipelago Islands is in great deal determined by increased rates of fuel consumption and analogous electricity production costs, this being also the case for other island autonomous electrical networks worldwide. Meanwhile, the contribution of renewable energy sources (RES) in the constant increase recorded in both the Aegean islands' annual electricity generation and the corresponding peak load demand is very limited. To compensate the unfavourable situation encountered, the implementation of energy storage systems (ESS) that can both utilize the excess/rejected energy produced from RES plants and improve the operation of existing thermal power units is recommended. In the present study, a techno-economic comparison of various RES-ESS configurations supported by the supplementary or back-up use of existing thermal units is undertaken. From the results obtained, the shift of direction from the existing oil-dependent status to a RES-based alternative in collaboration with certain storage technologies entails -apart from the clear environmental benefits- financial advantages as well.

Keywords: Techno-Economic Comparison; Electricity Generation; Energy Storage; Autonomous Electrical Network; Renewable Energy Sources

Nomenclature

c_1	Specific input energy cost (€/kWh)
c_e	Specific energy storage system's capacity cost (€/kWh)
CF	Capacity factor of the under study electrical network
c_f	Specific energy cost of fuel used (€/kWh)
CF_{ss}	Capacity factor of the energy storage system
c_o	Present electricity generation cost of the energy storage system (€/kWh)
c_p	Specific energy storage system's power cost (€/kW)
C_{ss}	Total cost of the energy storage system (in present values)
d_o	Energy autonomy period of the energy storage system (hours)
DOD_L	Maximum permitted depth of discharge of the energy storage system
EC	Cost of input energy utilized to charge the energy storage system (€)
E_{dir}	Energy demand covered directly by the existing power stations (kWh)
E_h	Average hourly load of the electrical network under study per annum (kW)
E_{ss}	Energy storage capacity of the energy storage system (kWh)
E_{stor}	Energy demand covered directly by the energy storage system (kWh)
E_{tot}	Annual energy demand of the local electricity network (kWh)
FC_{ss}	Fixed M&O cost of the energy storage system (€)
g_k	Mean annual change of cost for major parts to be replaced
i	Capital cost of the local market
IC_{ss}	Initial investment cost of the energy storage system (€)
k_o	Major parts to be replaced during the system's service period
k-th	Major components of the energy storage system
l_k	Times of replacement for major parts being replaced (integer number)
m	Fraction of annual M&O cost to the total initial investment
n	Years of operation for the proposed configuration (years)

***Kaldellis J.K., Zafirakis D., Kavadias K.A., 2007,** "Techno-Economic Comparison of Energy Storage Systems of Island Autonomous Electrical Networks", Renewable and Sustainable Energy Reviews, on-line available (03/12/2007) in www.sciencedirect.com.*

N_{in} Maximum input power of the energy storage system (kW)
n_k Lifetime of energy storage system's major parts to be replaced
N_o Rated power of the existing power stations (kW)
N_p Annual peak load demand of the local electricity network (kW)
N_{ss} Nominal output power of the energy storage system (kW)
n_{ss} Service period of the energy storage system (years)
r_k Replacement cost coefficient for major parts to be replaced
SF Safety factor for the under study electrical network
vc_{ss} Non dimensional variable maintenance cost of the energy storage system
VC_{ss} Variable maintenance cost of the energy storage system (€)
x_1 Mean annual escalation rate of the input energy price
x_2 Mean annual M&O cost inflation rate
x_3 Mean annual escalation rate of fuel input price
x_4 Mean annual escalation rate of electricity price

Greek Letters

γ Ratio of State subsidy to the total investment cost
Δt_{ch} Charge time for the energy storage system (hours)
ε Energy demand ratio covered directly by the energy storage system
ζ Peak load demand ratio covered by the energy storage system
η_p Power efficiency of the energy storage system
η_{ss} Energy transformation efficiency of the energy storage system (round-trip)
ρ_k Mean annual change of technological improvement for major components
$\tilde{\upsilon}_n$ Non-dimensional residual value of the energy storage system (in present values)
Yn Residual value of the energy storage system (€)

1. Introduction

The several scattered Aegean Archipelago islands being favored by rather appreciable wind and solar potential[1] encouraging the implementation of RES-based electrification solutions, are in great deal described by heavy oil and diesel electricity generation features that determine the former electricity supply status. More specifically, the increased fuel consumption leading to analogous electricity production costs and environmental pollution[2] along with the special characteristics attributed to such small autonomous electrical grids, i.e. serious barriers set to a respectable RES penetration[3], well demonstrate the situation existing in the specific area. Meanwhile, energy storage systems (ESS) are predominantly determined by their suitability in cases of significant energy demand variation in the course of time as well as in cases that the energy generation cannot be thoroughly controlled, e.g. in the wind energy production and the photovoltaic electricity generation. The phenomenon of a variable electricity load demand is more intense in small autonomous electrical networks, such as those encountered in thirty-six (36) of the Greek Aegean islands comprising autonomous electrical grids, figure (1). As already mentioned, the electricity generation cost in these specific islands is remarkably high[4], figure (2), therefore allowing for a competitive advantage to appear in respect of the wind and solar energy exploitation.

As a matter of fact, if also considering the respectable wind and solar potential of the area, (figure (3)) the installation of wind farms and photovoltaic power stations, both implying an appreciable energy yield, becomes techno-economically feasible. However, the instability of the existing electrical grids and the requirement for complete control over the quality of the electrical energy provision, set some serious obstacles in the dynamic exploitation of RES in autonomous electrical networks, this leading to the introduction of an upper limit of instantaneous RES contribution equal to a pre-described percentage (e.g. 30%) of the corresponding electricity demand. The specific constraints along with the intense seasonal electricity demand variation encountered in the islands have up to now resulted in a maximum 10% of RES annual participation in the local electrical energy balance[4], thus bounding further RES utilization and also insisting on the imported oil-dependent thermal power stations solution for the security of supply with significant macroeconomic and environmental costs entailed.

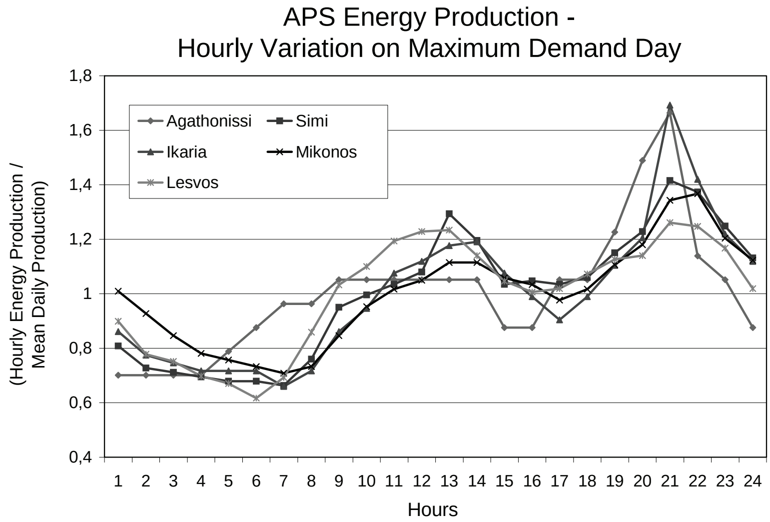

Figure 1: Daily electricity consumption variation in representative Aegean Archipelago islands

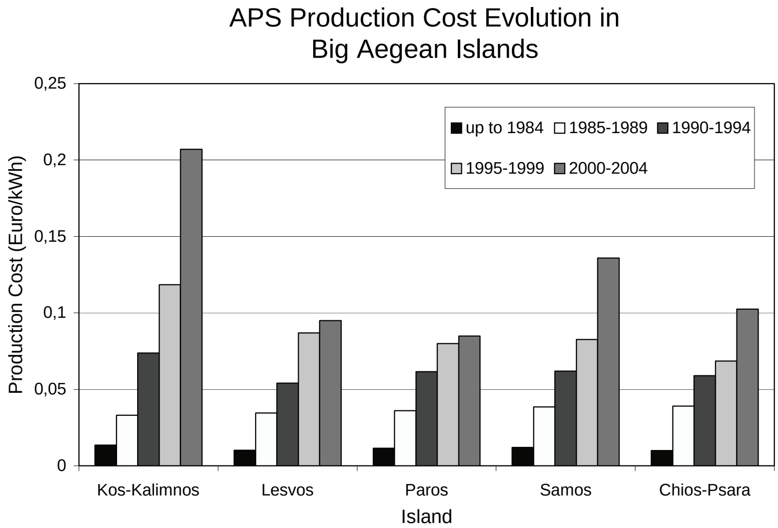

Figure 2: Time-evolution of electricity production cost of selected big Aegean Archipelago islands

To confront the problem described, several authors have every so often proposed alternative supply concepts such as water-pumping solutions, hydrogen storage, battery schemes and hybrid systems[5][6][7][8]. In the present study, an effort is realized to systematically investigate the possibility of utilizing appropriate energy storage systems leading to both increased RES power stations presence and optimum operation of existing thermal power stations. As a result, reduced electricity generation costs and abundant high quality provision of electrical energy with minimum environmental impacts are to be expected.

In this context, an integrated methodology of techno-economical evaluation for the existing commercially-established and potentially applicable to the Greek islands electrical networks ESS is presented. Accordingly, the proposed methodology is applied to representative case studies in order for the results obtained to be compared with the already existing solutions.

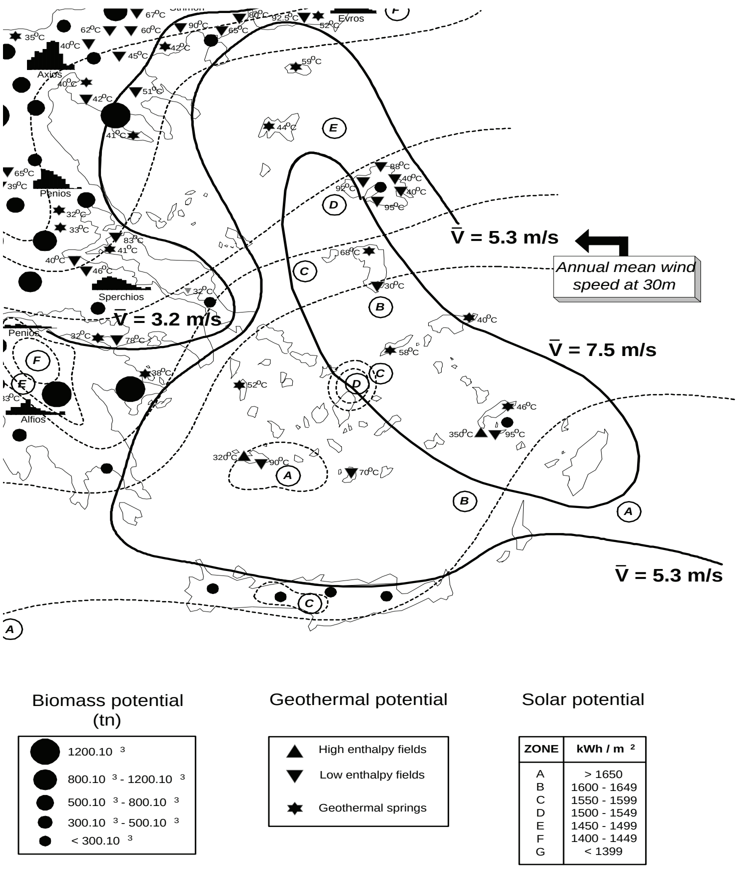

Figure 3: RES potential in the Aegean Archipelago region

2. Problem Presentation-Proposed Solution

Currently, the electricity balance status is determined by the operation of oil-based thermal power stations -most of them being outmoded- and by minimum or even zero RES contribution, mostly deriving from wind farms. Considering the above, the increase of RES contribution, the installation of one or more energy storage systems, and the use of thermal power stations only as supplementary or back-up units, are strongly recommended (e.g. the island of Kythnos[9]). For this purpose, a demarcation between the islands featured by appreciable wind potential and the islands favored by respectable solar potential suggests the maximum possible exploitation of wind energy in the first case (and PV stations as the case may be) and the corresponding solar in the second, with the latter mainly encountered in the smaller-scale islands.

The proposed operation principle of a respective electrical scheme (figure (4)) supports the prior exploitation of RES in collaboration with state of the art internal combustion engines set to operate in the range of minimum specific fuel consumption (maximum efficiency), while the ESS adopted is used to meet the satisfaction of power quality issues. In case of energy surplus, the excess amounts of energy are used to charge the ESS. When increased load demand and low RES production rates appear, the energy content of the ESS is used and if necessary, the programmed control of the thermal power stations calls for the back-up engines to set out.

The main points configuring the proposed solution are following:

- The extent of the thermal power units' utilization is principally dependent on the rated power of the existing RES stations and secondarily on the dynamics (capacity, input and output power) of the ESS employed.

- The existing thermal units being used for much less time leads to the extension of their service period and the reduction of maintenance needs, therefore prolonging the replacement requirements and constraining the environmental and macroeconomic effects.
- When asked to set out, the existing thermal power units should operate with regards to their operational characteristics and remain at all times close to the optimum point of operation (reduced cost and wear).
- The increased and prioritized contribution of RES combined with the respectable wind and solar potential of the area, further ameliorates the already (scale economies-no cut-outs) high economic efficiency of the specific technologies.
- The relatively high procurement cost of energy storage systems, thoroughly compensated if also considering the extremely high operational cost of the existing autonomous power stations (APS) (figure (2)), eventually turns out to considerable pay offs and gains.

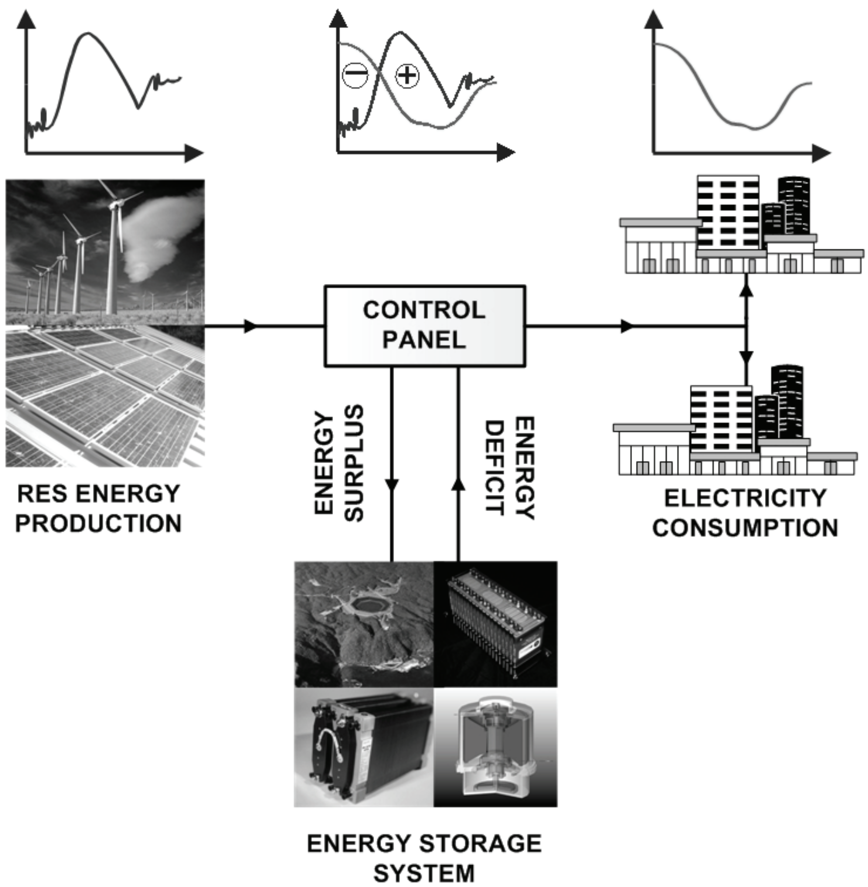

Figure 4: Typical Energy Storage System Configuration

3. Analysis of Existing Situation-Selection of ESS

From the analysis of recently published (2005) official energy consumption data (figure (5)), it becomes clear that the operational area of existing APS ranges between 300MWh and 300,000MWh per year. Correspondingly, the peak load demand ranges from 100kW to 100MW. More explicitly, the existing electricity networks may be classified into four main groups based on the annual energy consumption and the corresponding peak load demand (see also Table I).

Table I: Aegean islands classification in terms of peak load demand[4]

Category (Scale)	Peak Load Demand (MW)	Electricity Production (MWh)	Islands
Very Small	<1 MW	<2 MWh	Agathonissi, Agios Efstratios, Anafi, Antikithira, Donoussa, Erikousses, Megisti, Othoni
Small	<5 MW	<15 MWh	Amorgos, Astipalea, Kithnos, Samothrace, Serifos, Simi, Skiros
Medium	<35 MW	<100 MWh	Andros, Ikaria, Ios, Karpathos, Milos, Patmos, Andros, Lemnos, Mikonos, Santorini, Siros, Sifnos, Samos
Big	> 40 MW	>100 MWh	Chios, Kos-Kalimnos, Lesvos, Paros, Rhodes

- The first of the groups (Group I) includes 8 tiny islands with a population of less than 200 habitants, peak load demand up to 600kW (in any case less than 1MW) and annual energy production up to 2MWh.

- The second group (Group II) comprises of 7 relatively small scale islands with an annual energy production up to 15MWh (class of 10MWh=10x1MWh) and peak load demand up to 5MW (10x500kW).

- The third group (Group III) includes 13 medium sized islands with an annual energy production up to 100MWh (100x1MWh) and a corresponding load demand up to 35MW.

- Finally, the last group (Group IV) involves all the big scale islands of the Aegean Archipelagos (apart from Crete) with an installed electrical power over 40MW and an energy production that exceeds 100MWh per year.

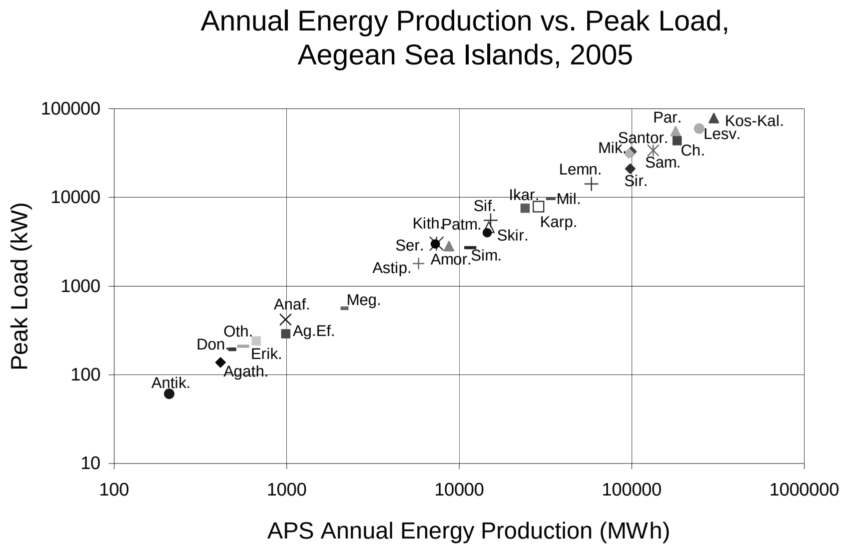

Figure 5: Main operational characteristics of Greek Islands APS (2005)

Moreover, since the presence of thermal power stations should be considered as de facto even in the case of an increased RES contribution, a rationalized upper limit regarding the autonomy of the ESS is set equal to 24hours. Consequently, the requirements of an ESS may be determined by a maximum autonomy of 24 hours (likely time periods of 6-12hours) and load demand from 0.1MW to 100MW maximum. Given the presence of the APS, the load demand share to be covered by the ESS should not lead to the purchase of a system greater than 10MW rated power (maximum 20MW), this irrationalizing the system's utilization.

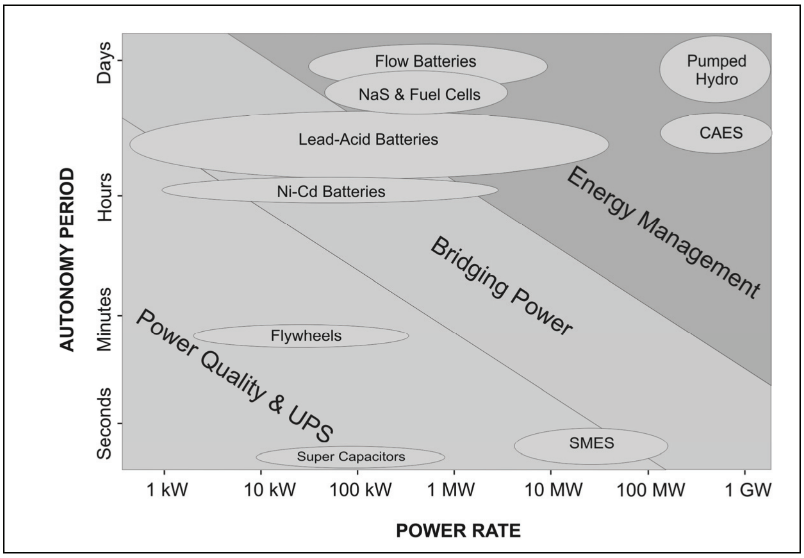

Figure 6: Energy Storage Systems Applications' Range (based on material by ESA), Presenting the Autonomy Period and the Power Covered by Each Specific Energy Storage System

In figure (6) one may encounter the application ranges of the currently established ESS, based on the available literature data. Regarding the area of interest (power demands from 100kW to 20MW and autonomy periods from 2h to 24h) the proposed systems currently investigated are the following:

- Lead-Acid Batteries (100kW-10MW)
- Na-S Batteries (100kW-10MW)
- Fuel Cells (100kW-10MW)
- Flow Batteries (100kW-10MW)
- Li-ion Batteries (100kW-1MW)
- Pumped Hydro (1MW-100MW)
- CAES (1MW-100MW)
- Flywheels (≈100kW)

From the present energy analysis the systems of Super Capacitors (SC) and Superconducting Magnetic Energy Storage (SMES), both referring to power quality applications mostly[10][11], are excluded. Moreover, although efforts to face the serious environmental impacts caused by the use of Ni-Cd batteries (owed to the cadmium deposition) have been encountered[12], an established method is not yet developed, hence the latter will not be considered as well. Accordingly, the main features for each of the technologies examined are pointed out with emphasis laid on their application range.

4. Brief Description of Energy Storage Systems

As already mentioned, several ESS may be used to cover the electricity demand problems of numerous remote islands of Aegean Archipelago in collaboration with the existing APS and RES-based power stations (mainly wind parks and photovoltaic generators). For application purposes one should, for every ESS, define several operational parameters of every system, like the corresponding service period "n_{ss}", the maximum permitted depth of discharge "DOD_L" for long-term operation, the total (round-trip) energy efficiency "η_{ss}", the efficiency of the power output branch "η_p", the initial cost "IC_o", the annual maintenance and operation coefficient "m" and the power range in which every system can be utilized.

4.1 Pumped Hydro Storage (PHS)

In a pumped hydro storage system, the energy surplus appearing in times of low demand and increased production (e.g. from existing wind parks or PV stations) is exploited to pump water into an elevated (upper) storage reservoir, figure (7). Accordingly, during peak demand periods, water is released from the upper reservoir and the hydro turbines of the installation operate to "feed" the connected electrical generators. Thus, the system is able to cover the existing power deficit by using the appropriate amount of energy previously stored. Moreover, PHS systems are able of taking up load in few seconds and are well defined by high rates of extracted energy.

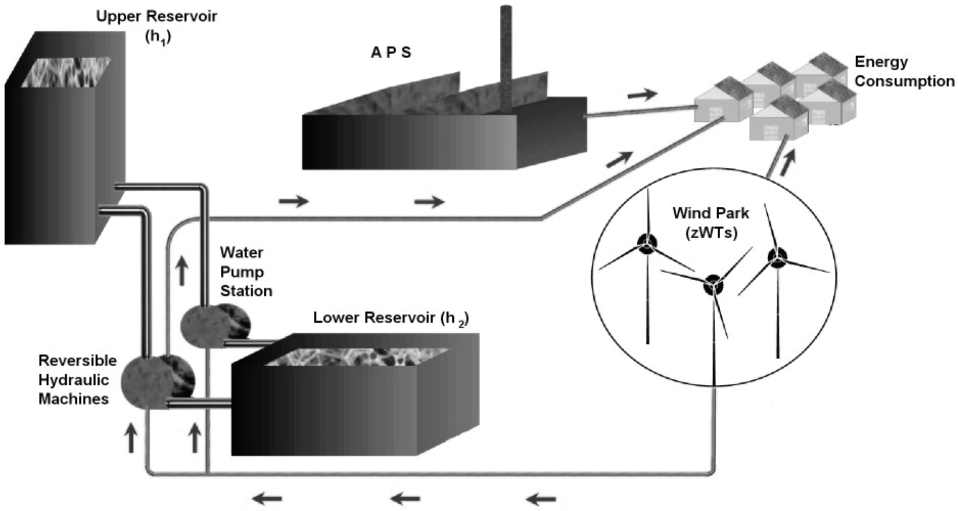

Figure 7: Pumped Hydro Storage

The typical overall efficiency of such systems mostly ranges between 65% and 77%[13], while their maximum depth of discharge is up to 95% without affecting their considerable (up to 50 years) service period. Since the lack of suitable sites is a fact, the main drawback for the creation of a new PHS system is the high capital cost, directly related to the need for the creation of two reservoirs with a respectable elevation difference. Towards this direction, open sea[14] along with underground caverns[15] may also serve as lower reservoirs as well. The environmental impact caused during the construction works and operation on the surroundings is also a matter to concern[16]. Finally, in terms of specific investment cost, a larger project seems more attractive[17], hence installations of rated power less than 1MW (Island Group-I) will not be analyzed here.

4.2 Compressed Air Energy Storage (CAES)

The CAES cycle is a variation of a standard gas turbine generation cycle. Hence, in a compressed air energy storage system, figure (8), off-peak or excess power from RES-based applications is used to pressurize air into an appropriate air storage facility (e.g. underground cavern) via a compressor. During times of peak demand, the required amount of air to cover the consumers’ load is released from the cavern and supplied to a gas turbine where expansion takes place. Electricity is then generated from the directly connected electric generator. Before being expanded, the amount of preheated air (in the recuperator) is sufficiently heated in the combustion chamber of the installation, figure (8). CAES, like PHS, demands favourable sites and geological formations suitable for underground storage. The storage media most commonly used are rock caverns, depleted gas fields, saline aquifers and salt caverns[18][19].

The benefit arising from the operation of a CAES system lies on the fact that the stages of compression and generation are separated from one another. Consequently, what seems to be as much as 60% to 70% of fuel consumption for the compressor to be driven in a typical gas turbine generation cycle is not the case for a CAES cycle. In conclusion, in a CAES system, the entire power of the gas turbine is available to the consumption, however important fuel consumption is necessary. In fact, during a charging/discharging cycle, approximately one kWh of generated electricity requires about 0.75 kWh of compression energy and 4,500 kJ of fuel[16]. This required amount of fuel is the main subject of controversy over the unconditional acceptance of such systems.

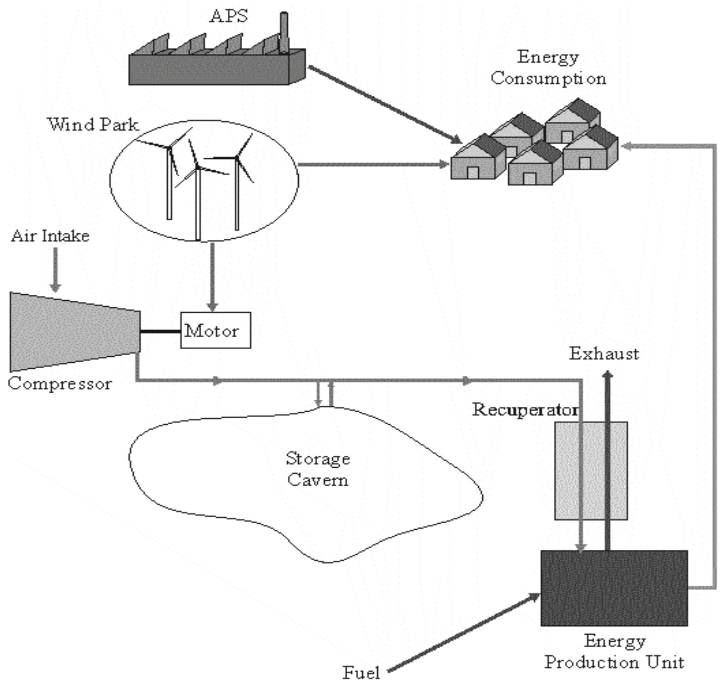

Figure 8: Compressed Air Energy Storage

Due to the distinctive features given by the use of gas in a conventional CAES, the efficiency rate of the system can be expressed in different ways. Excluding the gas role and based only on the efficiency of expansion and compression, an overall electricity efficiency rate that can be directly compared to other storage technologies is around 70%[20]. It is important to consider that the viability of such systems is well dependent on the storage media. Assuming an already existing cavern is utilized, additional benefits concerning environmental impacts should also be appreciated[21]. In terms of capacity range, if taking into consideration that the rated power of the existing CAES installations are higher than 100MW, CAES is thought to be the only, up to now, reliable alternative option for PHS. In this context, CAES are not thought as an appropriate solution for small scale applications like the ones corresponding to the Island Group-I of Table I.

4.3 Flywheels Energy Storage (FES)

In a flywheel energy storage system[22][23], figure (9), kinetic energy is stored by causing a disk or rotor to spin on its axis. The amount of energy stored in a flywheel is directly proportional to the rotor’s mass moment of inertia and the square of its rotational speed. When short-term back-up power is required the flywheel takes advantage of the rotor's inertia and the kinetic energy previously stored is converted into electricity. A modern flywheel consists of a rotating mass (a rim attached to a shaft) supported by bearings and connected to a motor/generator. During the motor operation, electrical energy is provided to the stator and the produced torque increases the kinetic energy of the rotor. During discharge, the system operates in the opposite way.

To minimize air drag and bearing losses, the flywheel along with the motor/generator must be placed inside a vacuum chamber so as to avoid deceleration effects caused by air. Concerning the friction losses, the bearings currently suggested to use for the latter minimization are the active magnetic, the passive magnetic, and the superconducting magnetic bearings[22][24].

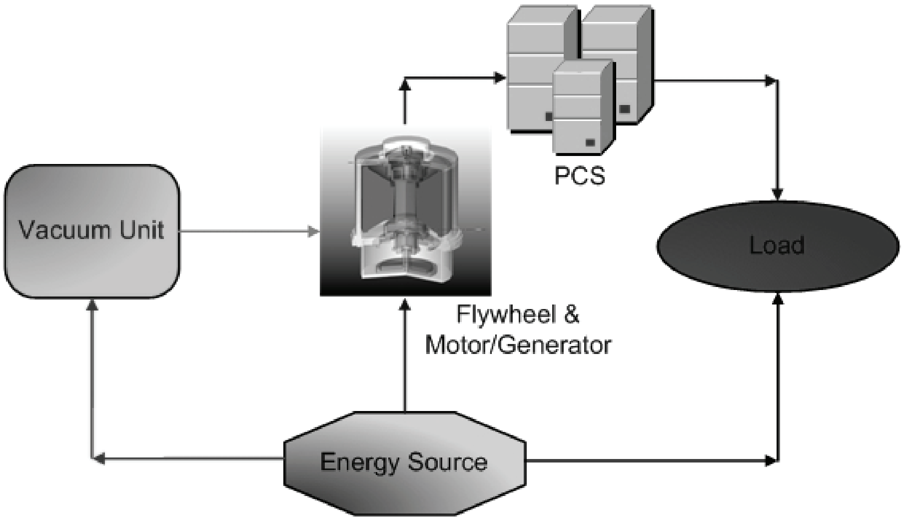

Figure 9: Flywheel Storage System

Some of the key features describing the flywheels' nature[23] are the high power and energy density, the relatively low maintenance needs (consider that a flywheel consists of kinetic components), the rather short recharging time, the friendly characteristics towards environment, the deep discharges and the high overall efficiency value (~85%). The losses during standby operation are not higher than 2% of the flywheel's rated power. In any case, one cannot find flywheels applications for rated power higher than some hundreds of kW, while their potential operational period is kept within a maximum of few hours. For this reason flywheel system should used only for the very small islands of Group-I.

4.4 Battery Energy Storage (BES)

Batteries are the most popular storage system. As far as their application range is concerned, battery energy storage systems show almost no restrictions. The technologies currently examined are the "mature" lead-acid along with the advanced sodium-sulphur and lithium-ion batteries, lately beginning to commercialize. In fact Li-ion systems may be used only for the very small islands of Group-I, i.e. maximum power rate less than 500kW.

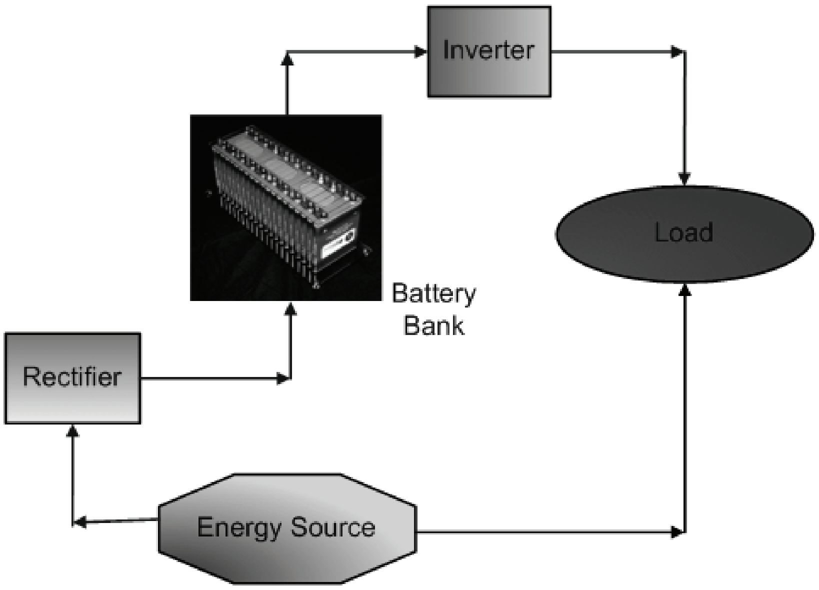

Figure 10: Battery Storage System

The components of a BES system (figure (10)) are the string of batteries, the power conversion system and the control system. The factors that mostly affect the operation of a battery system are the depth of discharge, the temperature of operation, the number of cells in series, the discharge-charge control and the periodic maintenance. The main advantage of the technology is the absence of kinetic parts, implying the reduction of the operation and maintenance cost.

In brief, lead-acid batteries are defined as a mature technology with known performance characteristics and a reliable market background[25][26][27]. The low self discharge value, the proven standby capability and the low maintenance requirements are some of the main advantages. On the other hand, the low energy density, the limited service period, the environmentally unfriendly content and the recommended low depth of discharge are the drawbacks of the particular technology[28].

Subsequently, Na-S batteries demonstrate increased energy densities, both gravimetric and volumetric in comparison with the lead-acid ones[28]. Due to the existence of beta alumina (it has zero electron conductivity) there is no self discharge phenomenon. In addition, the energy efficiency of such batteries is kept quite high and may reach a value of 85%. At the same time the cost is thought to be low, the maintenance needs appear insignificant, and the service period is very satisfying. However, the use of Na-S may not be able to satisfy certain systems' requirements as the need to maintain the temperature high levels (320-360 ^{o}C) sets a serious obstacle.

Finally, the main advantages of lithium-ion technology are the high energy density with a potential for yet higher capacities, the high efficiency value (~95%), and the respectable lifetime combined with deep discharges[29]. Additional advantages include the low self discharge rate, the low maintenance needed, and the ability for the provision of very high currents[30]. The limitations set at present are the required protection circuits to maintain voltage and current within safety limits, the technology not yet sufficiently developed and the high cost for the batteries' manufacture.

4.5 Flow Batteries (FB)

Flow batteries, also known as redox flow cells, constitute a relatively new technology. The energy is stored and released by means of a reversible chemical reaction. The charging and discharging stages introduce the conversion from electrical to chemical energy, and vice versa. The main characteristic of these systems is that the energy and power ratings are independent from one another. The storage capacity exclusively depends on the quantity of the electrolytes used, while the power rating is determined by the active area of the cell stack.

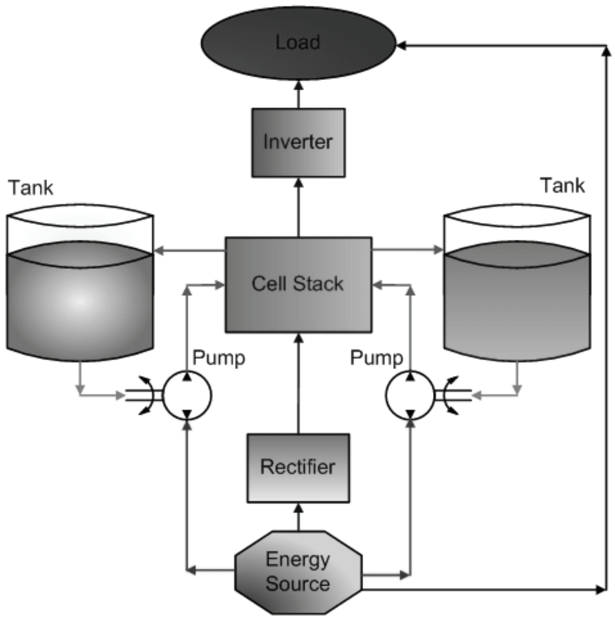

Figure 11: Flow Battery Storage System

The flow battery system, depicted in figure (11), is formed by a number of electrochemical cells, each one having two compartments (one for each electrolyte) being separated by an ion-exchange membrane. The two electrolytes are pumped from the tanks, through the cell stack and across a membrane. When passing through the membrane, the one electrolyte is oxidized and the other is reduced, producing current available to the external circuit. The employed pumps, necessary to circulate the electrolytes, bring some parasitic losses but at the same time contribute in keeping the system temperature at desired level. An extra concern is the use of aggressive chemical solutions.

As already mentioned, the energy capacity of these systems depends on the size of the electrolytic tanks. Apparently, by increasing the quantities of electrolytes used, may lead to the service of large energy storage applications, in a scale where only PHS and CAES are occupied. The present technologies, presented in Table II[31], are principally defined by the electrolyte couples currently used.

Table II: Capacity range of the three flow batteries technologies[31]

Technology	**Representative Systems**	**Projected Capacity**
Vanadium Redox	250 kW,520 kWh 1.5 MW, 1.5 MWh	50 kW, 500 kWh to 5 MW, 20MWh 50-100 MW upper range, 500 MW feasible
Na polysulphide/ Na Bromide	12-15 MW, 120 MWh	5-50 MW, 100-250 MWh, 500 MW feasible
Zinc/Bromine	50 kW, 500 kWh module 200 kW, 400 kWh trailer	300-600 kW, 300-1,000 kWh modular arrays 4-5 MW, 4-10 MWh upper range (no practical limit)

4.6 Fuel Cells (FC)

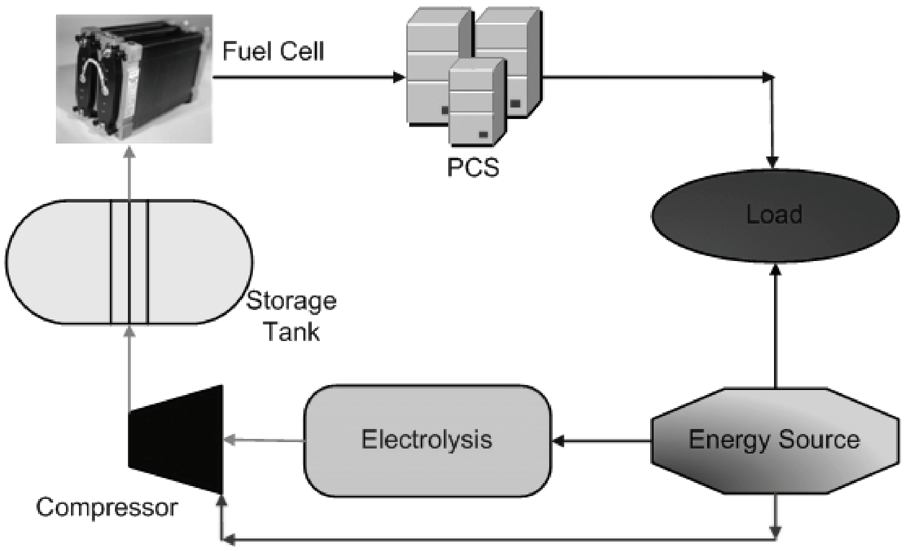

Figure 12: Hydrogen Storage System

Fuel cells consist (figure (12)) of two electrodes surrounding an electrolyte. Oxygen passes over one electrode and hydrogen over the other, generating electricity, water and heat. In principle, a fuel cell operates like a battery. However, a fuel cell does not require recharging; as long as fuel is supplied to the cell, electricity is produced. Thus, the restrictions opposed on the storage capacity are only determined by the fuel tank size. The energy that a fuel cell produces is directly depended on the fuel cell type, the operation temperature, and the catalyst used to improve the chemical reaction’s performance. There are several types of fuel cells that are commonly used. The main disadvantage of this technology is the overall efficiency rate, which by including the hydrogen storage procedure is estimated to be around 30-40%. The losses are detected during the electrolysis for the hydrogen to be produced, during the phase of storage, and finally during the generation procedure via the fuel cell.

The different types of fuel cells are able of covering a broad range of applications[32]. For example, for stationary applications where higher power demand along with high efficiency values are required the most suitable types are the MCFC and the SOFC. Additional beneficial characteristics of hydrogen based storage systems are the high energy density of hydrogen (33 kWh/kg) and the well separated stages of storage and production.

5. Energy Storage System Sizing

The problem to be solved concerns an autonomous electrical network, which for a given time period (e.g. one year) presents total electricity consumption "E_{tot}", peak load demand equal to "N_p", while the rated power of the existing power stations is "N_o". For safety reasons:

$$N_o \geq N_p \tag{1}$$

or introducing an appropriate safety factor "SF" one may write:

$$N_o = N_p \cdot (1+SF) \tag{2}$$

In this context the capacity factor "CF" of the autonomous electrical system is defined as:

$$CF = \frac{E_{tot}}{8760 \cdot N_o} = \frac{E_{tot}}{8760 \cdot N_p \cdot (1+SF)} = \frac{E_h}{N_p \cdot (1+SF)} \tag{3}$$

where:

$$E_h = \frac{E_{tot}}{8760} \tag{4}$$

is the average hourly load of the electrical network under investigation.

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

$$\varepsilon = \frac{E_{stor}}{E_{tot}} = 1 - \frac{E_{dir}}{E_{tot}} \tag{5}$$

since:

$$E_{tot} = E_{dir} + E_{stor} \tag{6}$$

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

In any case the ESS under evaluation is characterized by the energy storage capacity "E_{ss}", the maximum input power "N_{in}" and the nominal output power "N_{ss}" of the entire energy storage subsystem. More precisely, the energy storage capacity may be estimated by the following relation:

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

where one should take into account the desired hours of energy autonomy "d_o", the maximum depth of discharge "DOD_L" and the energy transformation (round-trip) efficiency of the ESS "η_{ss}".

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

$$N_{ss} = \zeta \cdot \frac{N_p}{\eta_p} = \zeta \cdot \frac{E_h}{CF} \cdot \frac{1}{\eta_p} \cdot \frac{1}{1+SF} \tag{8}$$

where "ζ" is the peak power percentage of the local network that the energy storage branch should cover, see also equation (3).

Accordingly, the input power "N_{in}" of the ESS depends on the available power excess of the existing electricity generation units and the desired charge time "Δt_{ch}" of the installation, since the following relation may be used as a first estimation:

$$\Delta t_{ch} \approx \frac{E_{ss}}{N_{in}} \tag{9}$$

Finally, the utilization (or capacity) factor "CF_{ss}" of the ESS is given as:

$$CF_{ss} = \frac{E_{stor}}{8760 \cdot N_{ss}} = \frac{\varepsilon \cdot E_{tot}}{8760 \cdot N_{ss}} = \frac{\varepsilon}{\zeta} \cdot CF \cdot \eta_p \cdot (1+SF) \tag{10}$$

6. Electricity Generation Cost

The total investment cost (after -n years of operation) of an energy storage installation[33][34] is a combination of the initial installation cost and the corresponding maintenance and operation cost, both quantities expressed in present values. In this context, the initial cost "IC_{ss}" of an ESS can be expressed as a function of two coefficients. The first "c_e" (€/kWh) related to the storage capacity and the type of the system, and the second "c_p" (€/kW) referring to the power conversion system's nominal power (i.e. inverter, hydro-turbine, gas-turbine etc.) and the type of the storage system. In this analysis one implicitly assumes that the input power of the system is of the same order to the corresponding output power of the ESS (or the charge and the discharge time period are comparable), hence one may use the following relation:

$$\mathrm{IC_{ss}} = \mathrm{c_e} \cdot \mathrm{E_{ss}} + \mathrm{c_p} \cdot \mathrm{N_{ss}} = E_h \cdot \left[\frac{\mathrm{c_e} \cdot \mathrm{d_o} \cdot \varepsilon}{\eta_{ss} \cdot \mathrm{DOD_L}} + \frac{\mathrm{c_p} \cdot \zeta}{CF \cdot \eta_p} \cdot \frac{1}{1+SF} \right] \tag{11}$$

In order to obtain a first idea of the numerical values of the above mentioned parameters (i.e. DOD_L, η_{ss}, η_p, c_e, c_p) one may use the data of Table III, based on the available information in the international literature[35][36][37][38]. In the same Table III, the service period "n_{ss}" and the corresponding annual M&O factor "m" are also included. As it is obvious from Table III, a wide range of values have been found for most energy storage systems under investigation.

Table III: Major Characteristics of the Energy Storage Systems Examined[35][36][37][38]

Storage System	Service Period n_{ss} (years)	DoD (%)	Power Efficiency η_p (%)	Energy Efficiency η_{ss} (%)	Specific Energy Cost c_e (€/kWh)	Specific Power Cost c_p (€/kW)	M&O m(%)
P.H.S.	30÷50	95	85	65÷75	10÷20	500÷1500	0.25÷0.5
C.A.E.S.	20÷40	55÷70	80÷85	70÷80	3÷5	300÷600	0.3÷1
Regenesys	10÷15	100	75÷85	60÷70	125÷150	250÷300	0.7÷1.3
F.C.	10÷20	90	40÷70	35÷45	2÷15	300÷1000	0.5÷1
Lead Acid	5÷8	60÷70	85	75÷80	210÷270	140÷200	0.5÷1
Na-S	10÷15	60÷80	86÷90	75÷85	210÷250	125÷150	0.5÷1

Subsequently, in addition to the initial investment cost one should also take into consideration the input energy cost "EC", i.e. the cost of energy supplied to the storage system in order to be able to provide the amount of energy expected ($\varepsilon \cdot E_{total}$). Since the amount of energy needed to charge the storage system is expressed as ($\varepsilon \cdot E_{total}/\eta_{ss}$), the corresponding input energy cost for a time period of "n" years (in present values) can be expressed as:

$$EC_{ss} = \frac{E_{stor}}{\eta_{ss}} \cdot c_1 \cdot \sum_{j=1}^{j=n} \left(\frac{(1+x_1)}{(1+i)} \right)^j = \varepsilon \cdot \frac{E_{total}}{\eta_{ss}} \cdot c_1 \cdot \sum_{j=1}^{j=n} \left(\frac{(1+x_1)}{(1+i)} \right)^j = \varepsilon \cdot \frac{E_{total}}{\eta_{ss}} \cdot c_1 \cdot X_1 \quad (12)$$

where "c_1" is the specific input energy cost value and "x_1" is the mean annual escalation rate of the input energy price, while "i" is the capital cost of the local market.

Accordingly, the M&O cost can be split into the fixed maintenance cost "FC_{ss}" and the variable one "VC_{ss}". Expressing the annual fixed M&O cost as a fraction "m" (see Table III) of the initial capital invested and assuming an annual increase of this cost equal to "x_2", the present value of "FC_{ss}" is given as:

$$FC_{ss} = IC_{ss} \cdot m \cdot \sum_{j=1}^{j=n} \left(\frac{(1+x_2)}{(1+i)} \right)^j = IC_{ss} \cdot m \cdot X_2 \quad (13)$$

The distinctive nature of a CAES principle operation imposes the need for the fuel factor to be also included[39]. In fact, a typical CAES requires a considerable fuel input in the combustion chamber of the installation[40], see also section 4.2. In this context, equation (13) is rewritten in order to include the fuel input contribution as following:

$$FC_{ss} = IC_{ss} \cdot m \cdot \sum_{j=1}^{j=n} \left(\frac{(1+x_2)}{(1+i)} \right)^j + c_f \cdot (E_{stor}) \cdot \sum_{j=1}^{j=n} \left(\frac{(1+x_3)}{(1+i)} \right)^j = IC_{ss} \cdot m \cdot X_2 + c_f \cdot (\varepsilon \cdot E_{total}) \cdot X_3 \quad (14)$$

The "c_f" coefficient derives by combining the specific energy cost of the fuel used with the amount of fuel needed per kWh produced via the gas turbine incorporated (e.g. 4500kJ/kWh). Besides, "x_3" expresses the mean annual escalation rate of fuel input price in case of CAES.

The variable maintenance and operation cost mainly depends on the replacement of "k_o" major parts of the installation, which have a shorter lifetime "n_k" than the complete installation "n_{ss}". Using the symbol "r_k" for the replacement cost coefficient of each one of the "k_o" major parts of the installation, the "VC_{ss}" term can be expressed as:

$$VC_{ss} = IC_{ss} \cdot \sum_{k=1}^{k=ko} r_k \cdot \left\{ \sum_{l=0}^{l=l_k} \left(\frac{(1+g_k)(1-\rho_k)}{(1+i)} \right)^{l \cdot n_k} \right\} = IC_{ss} \cdot vc_{ss} \qquad (15)$$

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

$$l_k = \left[\frac{n-1}{n_k} \right] \qquad (16)$$

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

Recapitulating, the total cost ascribed to the storage system installation and operation after "n" years (in present values) may be estimated using equation (17).

$$C_{ss} = IC_{ss} \cdot (1-\gamma) + EC_{ss} + FC_{ss} + VC_{ss} \Rightarrow$$
$$C_{ss} = IC_{ss} \cdot \{(1-\gamma) + m \cdot X_2 + vc_{nn}\} + (\varepsilon \cdot E_{total}) \cdot \left\{ \frac{c_1}{\eta_{ss}} \cdot X_1 + c_f \cdot X_3 \right\} - \frac{Y_n}{(1+i)^n} \qquad (17)$$

where "γ" is the subsidy percentage by the Greek State and "Y_n" is the residual value of the ESS after n-years of operation in current values. For simplicity reasons one may define as "$\tilde{\upsilon}_n$" the non-dimensional value of "Y_n" in present values, i.e.:

$$\tilde{\upsilon}_n = \frac{Y_n / IC_{ss}}{(1+i)^n} \qquad (18)$$

Finally, one may express the present value of the electricity generation (€/kWh) of the ESS by dividing the total cost of the installation during the n-year service period with the total energy generation during the same period, taking into consideration the expected produced electricity price escalation rate "x_4". Therefore the corresponding electricity generation cost is given as:

$$c_o = \frac{C_{ss}}{E_{stor} \cdot \sum_{j=1}^{j=n} \left(\frac{(1+x_4)}{(1+i)} \right)^j} = \frac{C_{ss}}{\varepsilon \cdot E_{tot} \cdot X_4} \qquad (19)$$

Substituting equations (12), (14), (15), (17) and (18) into equation (19) we get that:

$$c_o = \frac{IC_{ss}}{\varepsilon \cdot E_{tot}} \left(\frac{1-\gamma}{X_4} + m \cdot \frac{X_2}{X_4} + \frac{vc_{ss}}{X_4} - \frac{\tilde{\upsilon}_n}{X_4} \right) + \frac{c_1}{\eta_{ss}} \cdot \frac{X_1}{X_4} + c_f \cdot \frac{X_3}{X_4} \qquad (20)$$

Using equations (4) and (11) one may estimate the ratio "$IC_{ss}/(\varepsilon \cdot E_{tot})$" as follows:

$$\frac{IC_{ss}}{\varepsilon \cdot E_{tot}} = \frac{1}{8760} \cdot \left[\frac{c_e \cdot d_o}{\eta_{ss} \cdot DOD_L} + \frac{c_p}{CF \cdot \eta_p} \cdot \frac{\zeta}{\varepsilon} \cdot \frac{1}{1+SF} \right] \qquad (21)$$

At this point it is important to define the terms "X_i" appearing in the above equations. Note that all these parameters are depending exclusively on the corresponding economic parameters of the local market, thus one may write:

$$X_i = \sum_{j=1}^{j=n} \left(\frac{(1+x_i)}{(1+i)} \right)^j \qquad i = 1,4 \tag{22}$$

Recapitulating, one may state that an energy storage investment is financially attractive if the energy production cost value of equation (20) is less than the energy production cost of the existing autonomous (thermal) power stations, see for example figure (2). Furthermore, one should also take into consideration the additional benefits related to the energy storage system operation, due to the increased reliability of the entire electrical network and the improved quality of the electricity offered.

7. Application Results

The above mentioned analysis is going to be applied to representative autonomous island networks existing in the Aegean Archipelago, figure (3). In order to facilitate the in depth analysis of the electricity generation opportunities for the available ESS, as already mentioned, one may divide the existing power stations in four subgroups on the basis of their peak load demand, see also Table I. More precisely, the first group includes very small islands, with rated power less than 1MW. In this category one may find the tiny islands of Agios Efstratios, Donoussa, Megisti etc. On the other hand, the last group includes the existing big APS, with rated power higher than 40MW, like the ones of Rhodes, Lesvos, Kos-Kalimnos etc.

Accordingly, one should also define representative long-term average values concerning the parameters "x_i" and "i" for the local market. More precisely, the capital cost "i" depends mainly on the investment opportunities, the timing of repayment and the risk of the investment. Subsequently, the term "electricity price escalation rate", describing the terms "x_1" and "x_4" takes into consideration the annual rate of change of the input and the produced electricity respectively. In general, the exact value of these parameter depends on various factors (e.g. euro-dollar exchange rate, nature of the conventional energy to be replaced, the policy of the electrical utilities towards RES-ESS configurations). Next, the M&O cost inflation rate "x_2" describes the annual change (increase) of the M&O cost, taking into accounts the annual changes of labor cost and the corresponding spare parts. Finally, the term "x_3" expresses the mean annual escalation rate of fuel input price and is valid only for CAES. In fact, taking into consideration the long-term records and the expected prospects of the local market[33] we assume that $x_1=x_4=3\%$, $x_2=3\%$, $x_3=5\%$ and i=8%.

7.1 Very Small Electrical Networks

As mentioned above the first group examined consists of eight very small islands, which can be represented by a typical electrical network with average annual electricity consumption equal to 900MWh, and corresponding peak load demand equal to 300kW. Note that the current electricity production cost on the basis of the existing small thermal power stations is almost 0.65€/kWh with an average annual increase rate of over 10%. Using equation (4) the average hourly load of these islands is approximately 100kWh/h, hence for every hour of energy autonomy provided by the ESS the energy amount required is equal to $(100 \cdot \varepsilon)$ kWh. In figure (1) one may see the typical hourly load demand of several islands, on annual basis.

Due to the small size of the islands examined some ESS may not be appropriate, e.g. PHS, CAES, to be adopted in similar situations. On the other hand, ESS used mainly for power quality purposes or for short term applications like flywheels and Li-ion batteries have been included mainly for comparison purposes. Assuming 50% annual contribution of the ESS (ε=50%) and 12 hours of energy autonomy of the system (d_o=12h) and ζ=1.0 the electricity generation cost of the system (c_1=0.1€/kWh) is less than 0.22€/kWh, excluding the fuel cells solution, figure (13). In fact, for several ESS systems the life cycle

(LC) cost is less than 0.20€/kWh, in comparison to the current electricity generation cost of 0.65€/kWh. According to the calculation results Na-S batteries and the Flywheel option present the minimum LC cost, i.e. 0.175€/kWh, while even the lead-acid batteries utilization shows an acceptable value of 0.222€/kWh. By doubling the desired energy autonomy of the system (i.e. d_o=24h) a remarkable production cost increase is encountered, hence the minimum LC value (0.215€/kWh) is achieved by the utilization either Na-S batteries or Flow Batteries (Regenesys). All the other ESS present a significant cost increase, while the Flywheels cannot technically support such high energy autonomy values.

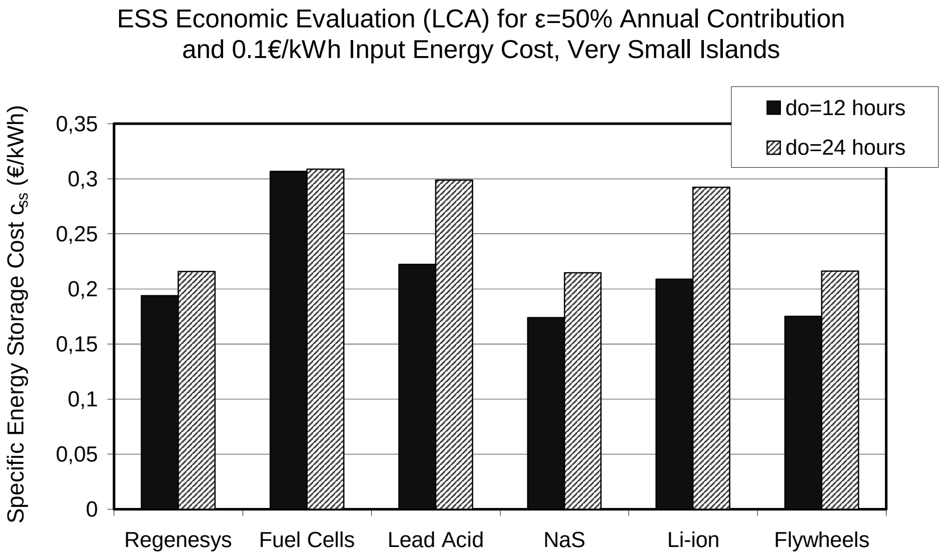

Figure 13: Electricity Production Cost for Very Small Islands

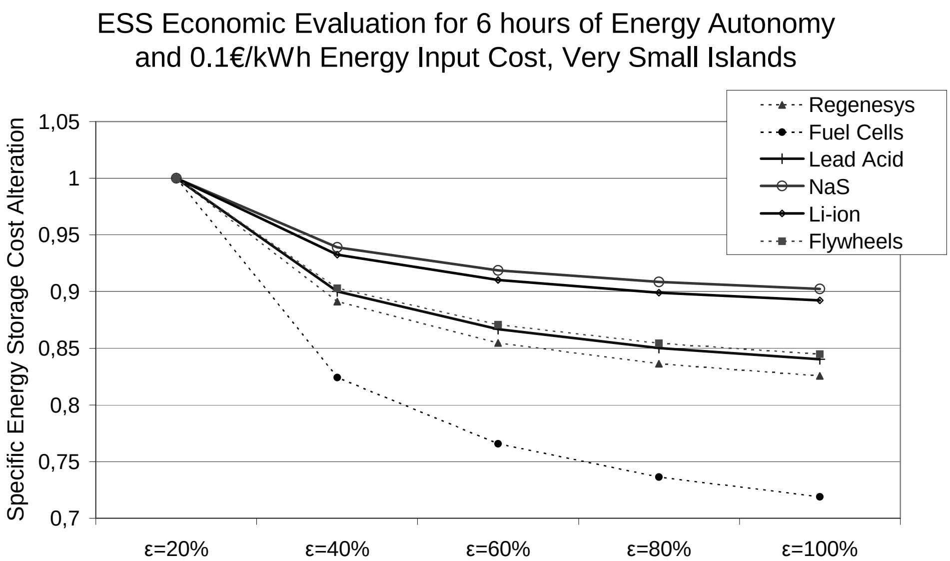

Figure 14: Relative Electricity Production Cost variation for Very Small Islands

Besides the relative electricity production cost values are remarkably decreased (figure (14)) as the ESS participation increases from 20% to 60%. The faster cost reduction is observed for the fuel cells, while the Na-S system shows that is slightly affected by the "ε" increase. As it is easy to understand values of "ε" higher than 60% are not realistic and are included here only for theoretical comparison purposes.

7.2 Small Electrical Networks

The second group includes another seven islands with average annual electricity consumption of approximately 10,000MWh and peak load demand equal to 3300kW. The corresponding current electricity production cost is 0.27€/kWh with an annual average increase rate of 8%. Most islands possess high wind potential and abundant solar irradiance, hence one may encourage the RES exploitation in order to cover the local societies electricity demand. At this point one should mention that the average hourly load of the islands under investigation is approximately 1.2MWh/h, thus for every hour of energy autonomy the corresponding ESS should provide (1200·ε) kWh. In figure (1) the annual mean typical hourly load demand is depicted. According to the official data there are two peak load demand values, one during noontime and the other at night.

Due to the size of the islands examined some ESS -previously used- may not be appropriate, e.g. Li-ion batteries and Flywheels, while other systems like PHS and CAES may be applied in similar situations. Assuming 50% annual contribution of the ESS (ε=50%) and 12 hours of energy autonomy of the system (d_o=12h) and ζ=1.0 the energy production cost of the system (c_1=0.1€/kWh) is less than 0.19€/kWh, excluding the lead-acid and fuel cells solution, figure (15).

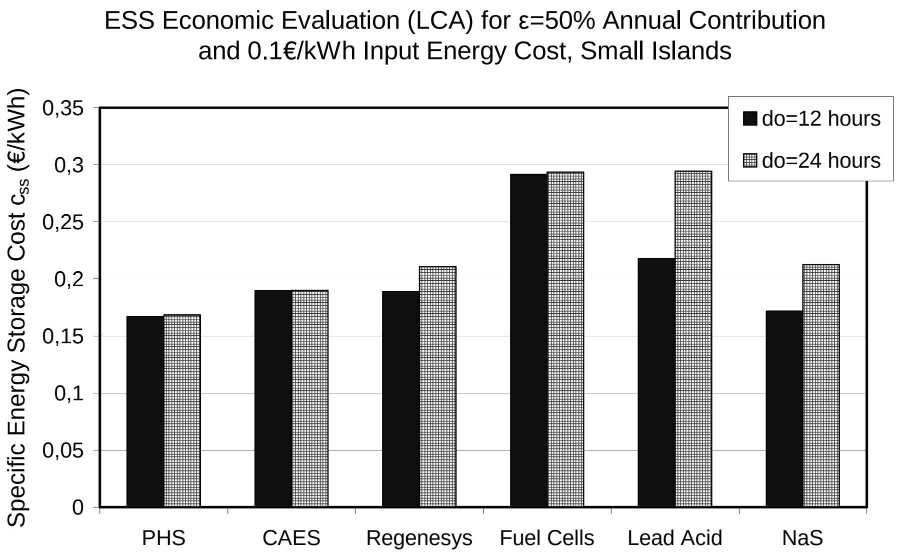

Figure 15: Electricity Production Cost for Small Islands

In fact, the minimum life cycle electricity generation cost is expected for PHS (i.e. 0.167€/kWh). In islands where this solution is not possible due to topographical restrictions the Na-S batteries and the Flow Batteries (Regeneys) option present also a low cost alternative, i.e. 0.172€/kWh and 0.189€/kWh respectively. By doubling the desired energy autonomy of the system (i.e. d_o=24h) a remarkable production cost increase is encountered, for most ESS, excluding PHS and CAES. In this scenario the minimum LC value (0.168€/kWh) is achieved by the PHS, while the second alternative should be based on CAES (0.190€/kWh). Note that the CAES cost is strongly influenced by the input fuel cost, hence any change in this value (c_f=0.034€/kWh) is going to affect the calculated electricity cost value. Finally, one should underline the fact that the energy production cost value on the basis of ESS is quite lower than the marginal production cost of the existing thermal power stations.

7.3 Medium Size Electrical Networks

The third island group contains another thirteen medium size islands with average annual consumption of 50,000MWh and peak load demand equal to 10MW. The corresponding current electricity production cost is 0.195€/kWh with an annual average increase rate of 6%. Due to their geographical location most islands possess high wind potential (wind parks exist in all these islands) and abundant solar irradiance. In this context, the average hourly load of the islands under investigation is approximately 6.0MWh/h, thus for every hour of energy autonomy the corresponding ESS should provide (6000·ε) kWh.

Assuming 50% annual contribution of the ESS (ε=50%) and 12 hours of energy autonomy of the system (d_o=12h) and ζ=1.0 the energy production cost of the system (c_1=0.1€/kWh) is less than 0.19€/kWh, excluding the lead-acid and fuel cells solution, figure (16).

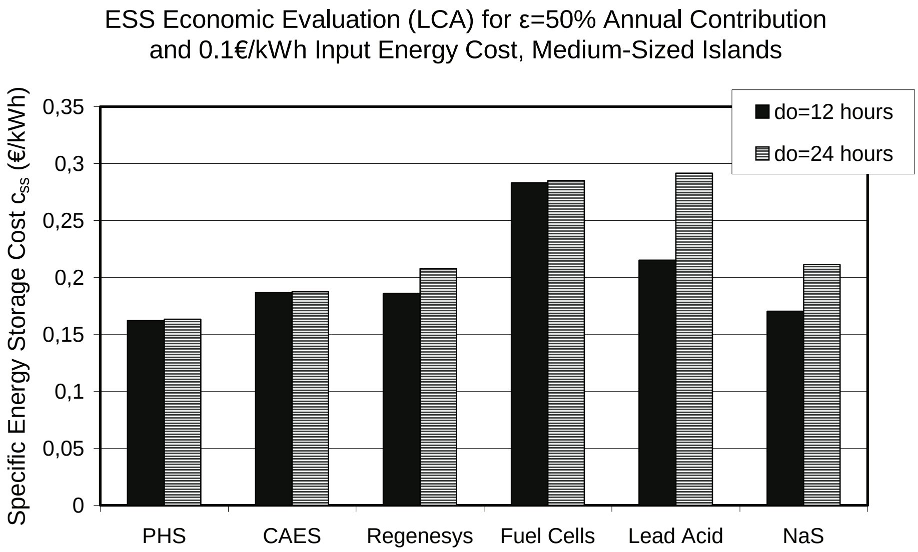

Figure 16: Electricity Production Cost for Medium-Sized Islands

In fact, the minimum life cycle electricity generation cost is expected for PHS (i.e. 0.162€/kWh). In islands where this solution is not possible due to topographical restrictions the Na-S batteries, CAES and the Flow Batteries (Regeneys) option present also a low cost alternative, i.e. 0.170€/kWh, 0.187€/kWh and 0.186€/kWh respectively. By doubling the desired energy autonomy period of the system (i.e. d_o=24h) a remarkable production cost increase is encountered, for most ESS, excluding PHS and CAES. In this scenario the minimum LC value (0.163€/kWh) is achieved by the PHS, while the second alternative should be based on CAES (0.187€/kWh). Note that CAES and PHS seem almost unaffected by the energy autonomy increase of the system, while the ESS based on any type of batteries is significantly increased. Fuel cells also are not influenced by the energy autonomy increase of the local network, however their electricity generation cost remains high at the present.

7.4 Big Island Electrical Networks

The last case analyzed concerns the five biggest islands of Aegean Archipelago with annual electricity consumption of approximately 200,000MWh and peak load demand in the proximity of 50MW. The corresponding current electricity production cost is approximately 0.10€/kWh with an annual average increase rate of 5%. Due to their size all the islands possess locations with high wind speed (wind parks exist in all these islands), while the corresponding solar irradiance is also considerable. In this context, the average hourly load of the islands under investigation is approximately 22.0MWh/h, thus for every hour of energy autonomy the corresponding ESS should provide (22,000·ε) kWh. In this context, ESS based on batteries may not be technically feasible, however the corresponding calculation results are included here for theoretical comparison purposes.

Assuming 40% annual contribution for the ESS (ε=40%) and 12 hours of energy autonomy for the system (d_o=12h) and ζ=1.0 the energy production cost of the system (c_1=0.05€/kWh) is less than 0.10€/kWh, excluding the CAES and fuel cells solution, figure (17). In fact, the minimum life cycle electricity generation cost is expected for Flow Batteries and PHS (i.e. 0.095€/kWh). Both Na-S and Lead-acid batteries present lower cost values, however one has not used similar systems for so large applications.

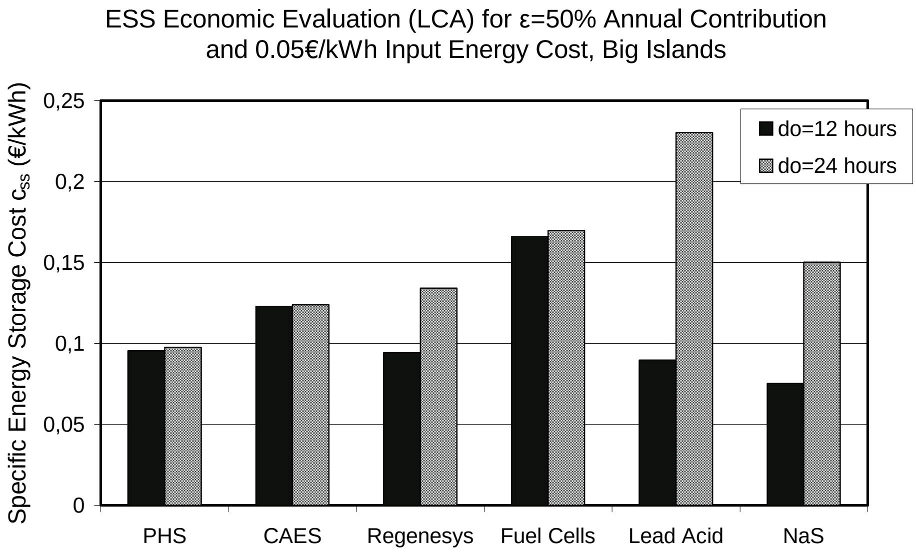

Figure 17: Electricity Production Cost for Big Islands

By doubling the desired energy autonomy of the system (i.e. d_o=24h) a remarkable production cost increase is encountered, for most ESS, excluding PHS and CAES. In this scenario the minimum LC value (0.098€/kWh) is achieved by the PHS, while the second alternative should be based on CAES (0.124€/kWh). All other systems present electricity generation values definitely higher than the marginal production cost of the existing thermal power stations. As already mentioned the CAES production cost value strongly depends on the fuel cost value.

8. Conclusions

In the present study, an integrated methodology developed is able to estimate the electricity generation cost ascribed to the implementation of various RES-ESS configurations on the basis of minimum energy dependence on local thermal power stations. For this purpose, one should take into account the corresponding schemes' sizing parameters as well as the electricity features of the network each time examined. In order to designate optimum combinations between the electricity network magnitude and ESS technologies, the proposed methodology is applied to four Aegean island-groups resulting from the variation in the rates of peak load demand and electricity consumption.

From the results obtained, it becomes evident that for the majority of RES-ESS configurations the resulting electricity generation cost is lower than the corresponding of the local APS, especially in the case of small and very small size islands. More specifically, it is the Na-S batteries that may be thought as suitable for very small island cases, while PHS comprise the optimum solution for big size islands. Lead acid batteries' mature technology may also be considered as an option for big scale islands, however suitable only for moderate autonomy periods.

Regarding the small and medium sized islands PHS appear to be slightly better than Na-S batteries for a given autonomy period of 12 hours, while they present a clear advantage in the case of 24 hours. Concerning CAES -largely dependent on the fuel cost factor- the specific system's adoption may be thought as an alternative only in medium and big scale islands and for large autonomy periods required.

Finally, fuel cells and flow batteries, positively influenced by the increased ESS participation in the local island network, may suggest promising future solutions since the corresponding technologies' costs are up to now higher than of other, more traditional systems investigated.

From the analysis undertaken it results that the proposed RES-ESS configuration comprises a financially viable electrification solution, also contributing to the production of reliable and high quality electricity. Hence, one may conclude that the prospect of further RES exploitation in the local island networks using an appropriate ESS along with the parallel reduction of the electricity generation cost and the abatement of environmental impacts is a realizable scenario, not jeopardizing the quality of energy provided.

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OPTIMUM ENERGY STORAGE TECHNIQUES FOR THE IMPROVEMENT OF RES-BASED ELECTRICITY GENERATION ECONOMIC EFFICIENCY

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Abstract

The high wind and solar potential along with the extremely high electricity production cost met in the majority of Greek Aegean islands comprising autonomous electrical networks, imply the urgency for new renewable energy sources (RES) investments. To by-pass the electrical grid stability constraints arising from an extensive RES utilization, the adaptation of an appropriate energy storage system is essential. In the present analysis, the cost effect of introducing selected storage technologies in a large variety of autonomous electrical grids so as to ensure higher levels of RES penetration, in particular wind and solar, is examined in detail. A systematic parametrical analysis concerning the effect of the energy storage systems' main parameters on the economic behaviour of the entire installation is also included. According to the results obtained, a properly sized RES-based electricity generation station in collaboration with the appropriate energy storage equipment is a promising solution for the energy demand problems of numerous autonomous electrical networks existing worldwide, at the same time suggesting a clean energy generation alternative and contributing to the diminution of the important environmental problems resulting from the operation of thermal power stations.

Keywords: Electricity Generation; Energy Storage; Autonomous Electrical Network; Renewable Energy Sources; Electricity Production Cost

Nomenclature

c_e	Specific energy storage system's capacity cost (€/kWh)
c_f	Specific equivalent energy cost of fuel used (€/kWh)
c_p	Specific energy storage system's power cost (€/kW)
c_w	Specific input energy cost (€/kWh)
d_o	Energy autonomy of the energy storage system (hours)
e	Electricity price escalation rate
DOD_L	Maximum permitted depth of discharge of the energy storage system
EC_w	Cost of input energy utilized to charge the energy storage devices (€)
E_{dir}	Energy demand covered directly by the existing power stations (kWh)
e_f	Mean annual escalation rate of fuel price
E_{ss}	Energy storage capacity of the energy storage system (kWh)
E_{tot}	Annual energy demand of the local electricity network (kWh)
FC_{ss}	Fixed M&O cost of the energy storage system (€)
g_k	Mean annual change of cost for major parts to be replaced
g_{ss}	Annual fixed M&O cost inflation rate
i	Capital cost of the local market
IC_n	Future value of the initial investment cost (€)
IC_{ss}	Initial investment cost of the energy storage system (€)
k_o	Major parts to be replaced during the system's service period
l_k	Times of replacement for major parts being replaced (integer number)
m	M&O cost coefficient
n	Years of operation for the proposed configuration (years)
n_k	Lifetime of energy storage system's major components

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N_p Annual peak load demand of the local electrical network (kW)
N_{ss} Nominal power of the energy storage system (kW)
n_{ss} Service period of the energy storage system (years)
r_k Replacement cost coefficient for the major parts to be replaced
VC_{ss} Variable maintenance cost of the energy storage system (€)
w Mean annual escalation rate of the input energy price

Greek Letters

γ State subsidy percentage to the total investment cost
ε Energy demand ratio covered directly by the energy storage system
ζ Peak load demand ratio covered by the energy storage system
η_p Power efficiency of the energy storage system
η_{ss} Energy transformation efficiency (round-trip) of the energy storage system
ρ_k Mean annual change of technological improvement for the major system components

1. Introduction

The ongoing electricity consumption increase to be satisfied along with the environmental protection to be considered, have long since imposed the need for the renewable energy sources (RES) application[1]. In this context, the compliance with the targets set by the EU[2][3] and adopted by each member state, also calls for further RES technologies' promotion. Besides, strong incentives supported by attractive pricing regarding the purchase cost of certain RES technologies' energy yield by the local grid -such as in the case of the recent law enactment in Greece[4]- suggest the revival of the investing interest. If also taking into account the high wind and solar potential met in the majority of Greek Aegean islands along with the extremely high electricity production cost of the existing thermal power stations[5], additional reasons for the RES substantial adoption are evident.

On the other hand, the variable or even stochastic wind energy production causing side-effects that affect the smooth operation of an electrical network[6][7] -especially in the case of isolated grids such as autonomous island networks- presents some inability to thoroughly conform to the local electricity demand. Similarly, the "de facto" restricted generation of a photovoltaic unit, depending on the solar irradiance during daytime, also underlines the necessity for the treatment of the current electricity production status. A number of studies addressing the importance of further RES exploitation in the particular featured island grids are encountered[8-14]. However, wind energy (and most RES) applications have been treated for a long time period as simple fossil fuel saving installations. This strategy not only underestimates the capabilities of RES-based hybrid power stations (e.g. to provide firm capacity) but also limits their contribution in the weak autonomous (island) networks to single digit figures. In fact, there are several examples where a remarkable wind energy production cannot be absorbed by the local autonomous network due to the mismatch between the electricity production and the corresponding load demand. The outcome of this incapability is the significant financial loss of the wind parks owners, hindering the further exploitation of the local renewable potential.

In order to confront the variable or even stochastic behaviour of the renewable energy sources often not being able to meet the electricity grid's needs, the adaptation of an appropriate energy storage system (ESS) is thought to be essential, figure (1). The beneficial character describing the energy storage systems' implementation as ancillary units is further supported by the improvement of already existing power units' operational features and the avoidance of new ones' installation. On the other hand, storage technologies are faced with controversies mainly referring to the high initial cost rates, the additional transformation losses and the noteworthy environmental impacts, largely depending on the correlation between the type of technology used and the site selected[15].

Generally speaking, an energy storage system, when sized properly, can match a highly variable power production to a generally variable and hardly predictable system demand, remarkably limiting the energy production cost and improving the operational behaviour of the local system thermal power units[16].

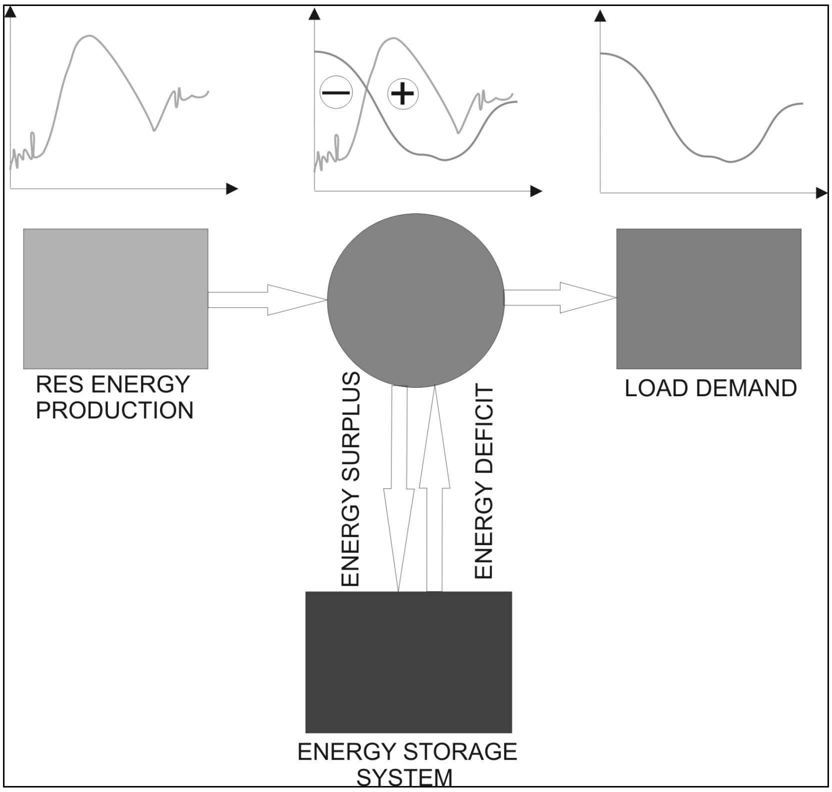

Figure 1: Typical Energy Storage System Configuration

In the present analysis, the cost effect of introducing certain storage techniques for the greater penetration of renewable energy technologies (specifically wind and solar) in either a small or a large scale autonomous electrical grid, is comprehensively examined. On top of this, a systematic parametrical analysis concerning the impact of the main energy storage system parameters on the economic behaviour of the entire installation is also included.

Closing, one should not disregard the alternative solution recently revived and regarding either the islands' connection to the mainland's electricity network[17] or the option of internal interconnection among certain Aegean islands. In this way, a gradual retirement of the local autonomous power stations joined by high rates of RES absorption by the national electricity network and the integrated group-island grids may be ensured.

On the other hand, such an electricity production strategy has to face the significant technological problems related to the undersea electricity transportation, the rather high first installation cost (approx. 3 million Euros per km of transportation grid) and the strong opposition of local societies claiming important impacts on the marine fauna. Additionally, the "sacrifice" of particular islands - either being close to the mainland (e.g. Skyros island) or being favored by remarkable RES potential (e.g. geothermal fields in Milos)- in order for big scale RES projects to be installed, jeopardizes the tourist character of the islands in the name of bulk power production units.

On the contrary, the distributed generation provided by RES-ESS configurations ensures greater levels of energy autonomy based on rational project-scale requirements, thus allowing for the implementation of compatible to the local environment energy production configurations.

2. Energy Storage Systems Basic Parameters

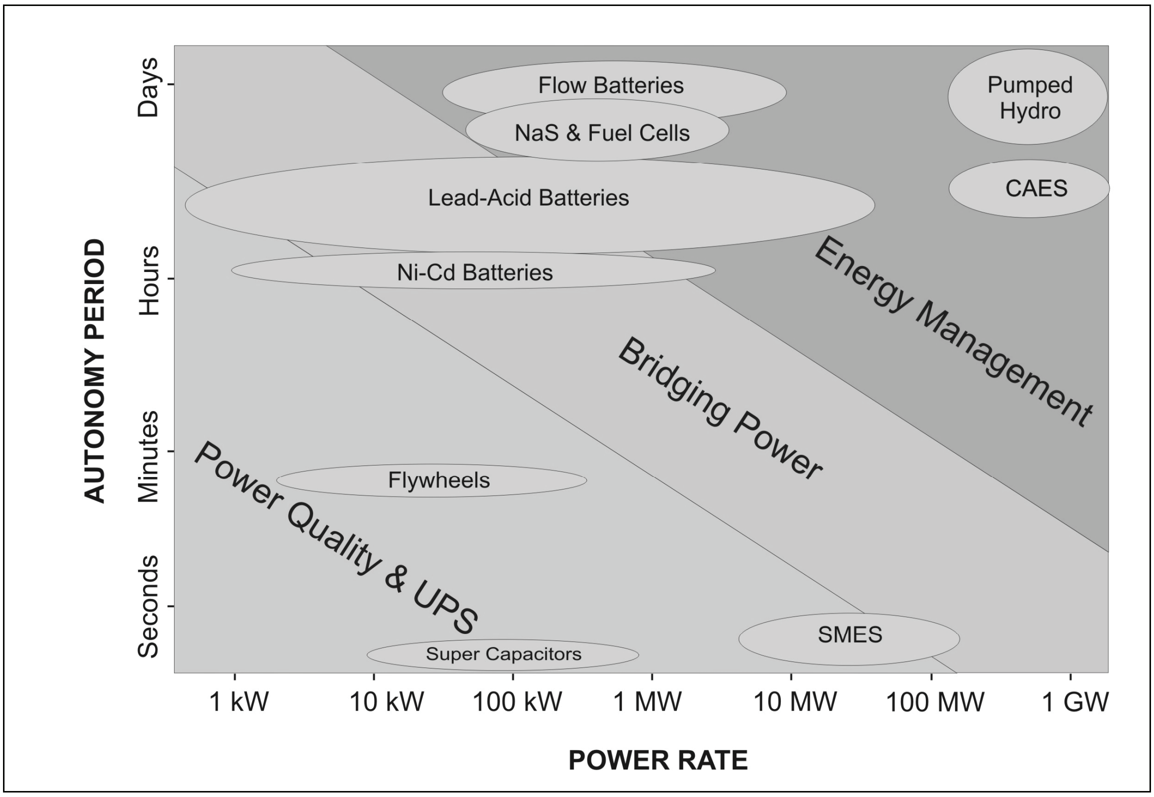

Figure 2: Energy Storage Systems Applications' Range (based on material by ESA), Presenting the Autonomy Period and the Power Covered by Each Specific Energy Storage System

A widely accepted demarcation (see figure (2)) divides the storage systems in those described by high power provision and being able to confront the power quality issues (flywheels, super-capacitors, superconducting magnetic energy storage, etc.), and in those presenting high energy capacity rates and being able to deal with the energy management applications, i.e. Pumped Hydro Storage (PHS), Compressed Air Energy Storage (CAES), Hydrogen Storage coupled with fuel cells (HS-FC), most of the batteries and flow batteries. The energy storage systems under study have been selected with respect to the scope of managing the load loss probability deriving from the extensive exploitation of renewable energy sources. Since the power quality provision is not to examine, the systems serving the specific purpose will not be currently evaluated.

In the present analysis, the evaluation model developed is applied to autonomous electrical networks (e.g. remote islands) described by the given values of annual energy demand "E_{tot}" and maximum (peak) load demand of the system "N_p". Since we assume the installation of an ancillary storage unit to support the electricity grid status incorporating RES-based applications, the contribution of the former must be determined. Hence, during the present analysis we assume that the total energy demand is covered either directly by the existing power stations "E_{dir}" 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:

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

where "ε" takes values between zero (no storage system usage) and one (all the energy consumption is covered through the storage system). Between these two extreme values, a contribution range determined by the existing power units' principle features (including photovoltaics and wind turbines) dictates the potential use of the system on an annual basis.

In the following, one should define the energy storage capacity "E_{ss}" and the nominal power "N_{ss}" of the entire energy storage subsystem. Concerning the energy capacity required, the typical hours of energy autonomy "d_o", the maximum depth of discharge "DOD_L" and the energy transformation (round-trip) efficiency of the energy storage system "η_{ss}" should also be taken into account. Hence, one may write:

$$E_{ss} = d_o \left(\frac{\varepsilon \cdot E_{tot}}{8760} \right) \frac{1}{\eta_{ss}} \cdot \frac{1}{DOD_L} \tag{2}$$

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

$$N_{ss} = \zeta \cdot \frac{N_p}{\eta_p} \tag{3}$$

where "ζ" is the peak power percentage of the local network that the energy storage branch should cover.

Having specified the storage capacity and the nominal power of a typical energy storage system, an effort to express the initial cost "IC_{ss}" as a function of the two previous parameters entails the introduction of two new coefficients. The first "c_e" (Euros/kWh) related to the storage capacity and type of the system, and the second "c_p" (Euros/kW) referring to the nominal power and type of the storage system. Thus one may use the following relation:

$$\mathrm{IC_{ss}} = \mathrm{c_e} \cdot \mathrm{E_{ss}} + \mathrm{c_p} \cdot \mathrm{N_{ss}} = \mathrm{c_e} \cdot \mathrm{d_o} \cdot \left(\frac{\varepsilon \cdot \mathrm{E_{total}}}{8760} \right) \cdot \frac{1}{\eta_{ss}} \cdot \frac{1}{\mathrm{DOD_L}} + \mathrm{c_p} \cdot \zeta \cdot \frac{\mathrm{N_p}}{\eta_p} \tag{4}$$

In order to obtain a first idea of the numerical values of the above mentioned parameters (i.e. DOD_L, η_{ss}, η_p, c_e, c_p) one may use the data of Table I, based on the available information in the international literature[18][19][20][21]. In the same Table I, the service period "n_{ss}" and the corresponding annual M&O factor "m" are also included. As it becomes obvious from Table I, a wide range of values have been obtained for most energy storage systems under investigation, since their exact values are usually site dependent. In the present analysis mean values have been adopted, while in a forthcoming study the entire values' range may be analyzed.

Table I: Major Characteristics of the Energy Storage Systems Examined[18][19][20][21]

Storage System	Service Period n_{ss} (years)	DOD (%)	Power Efficiency η_p (%)	Energy Efficiency η_{ss} (%)	Specific Energy Cost c_e (€/kWh)	Specific Power Cost c_p (€/kW)	M&O m (%)
P.H.S.	30÷50	95	85	65÷75	10÷20	500÷1500	0.25÷0.5
C.A.E.S.	20÷40	55÷70	80÷85	70÷80	3÷5	300÷600	0.3÷1
Regenesys	10÷15	100	75÷85	60÷70	125÷150	250÷300	0.7÷1.3
H.S.-F.C.	10÷20	90	40÷70	35÷45	2÷15	300÷1000	0.5÷1
Lead Acid	5÷8	60÷70	85	75÷80	210÷270	140÷200	0.5÷1
Na-S	10÷15	60÷80	86÷90	75÷85	210÷250	125÷150	0.5÷1

3. Energy Production Cost Evaluation Model

The future value (after -n years of operation) of the total investment cost of an energy storage installation[22] is a combination of the initial installation cost and the corresponding maintenance and operation cost, both quantities expressed in current values. Taking into consideration the analysis of section 2, the future value of the initial investment cost can be expressed as:

$$IC_n = IC_{ss} \cdot (1-\gamma) \cdot (1+i)^n \tag{5}$$

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

In addition to the initial investment cost one should also take into consideration the input energy cost "EC_w", i.e. the cost of energy supplied to the storage system in order to be able to provide the amount of energy expected ($\varepsilon \cdot E_{total}$). Since the amount of energy needed to charge the storage system is expressed as ($\varepsilon . E_{total}/\eta_{ss}$), the corresponding input energy cost for a time period of "n" years can be expressed as:

$$EC_w = \varepsilon \cdot \frac{E_{total}}{\eta_{ss}} \cdot c_w \cdot \sum_{j=1}^{j=n} \left(\frac{(1+w)}{(1+i)} \right)^j \cdot (1+i)^n \tag{6}$$

where "c_w" is the specific input energy cost value and "w" is the mean annual escalation rate of the input energy price. In most cases the typical values of "c_w" range from zero Euros/kWh (i.e. in the case when the provider of the energy input is also the owner of the storage configuration and uses the excess electricity production of an existing power station) to 0.2Euros/kWh.

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

$$FC_{ss} = IC_{ss} \cdot m \cdot \sum_{j=1}^{j=n} \left(\frac{(1+g_{ss})}{(1+i)} \right)^j \cdot (1+i)^n \tag{7}$$

The distinctive nature of a CAES principle operation imposes the need for a fuel factor to be included[23]. In fact, a typical CAES requires a considerable fuel input in the combustion chamber of the installation[24]. This required amount of fuel is the main subject of controversy over the unconditional acceptance of such systems. In an effort to disengage the CAES from the fossil fuel (e.g. natural gas) dependency, one proposal supports the use of biofuel[25]. In any case, equation (7) is rewritten in order to include the fuel input contribution as following:

$$FC_{ss} = IC_{ss} \cdot m \cdot \sum_{j=1}^{j=n} \left(\frac{(1+g_{ss})}{(1+i)} \right)^j \cdot (1+i)^n + c_f \cdot (\varepsilon \cdot E_{total}) \cdot \sum_{j=1}^{j=n} \left(\frac{(1+e_f)}{(1+i)} \right)^j \cdot (1+i)^n \tag{7a}$$

The "c_f" coefficient derives by combining the specific energy cost of the fuel used with the amount of fuel needed per kWh produced via the gas turbine incorporated. Besides, "e_f" expresses the mean annual escalation rate of fuel input price in case of CAES.

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

Using the symbol "r_k" for the replacement cost coefficient of each one of the "k_o" major parts of the installation, the "VC_{ss}" term can be expressed as:

$$VC_{ss} = IC_{ss} \cdot \sum_{k=1}^{k=ko} r_k \cdot \left\{ \sum_{l=0}^{l=l_k} \left(\frac{(1+g_k)(1-\rho_k)}{(1+i)} \right)^{l \cdot n_k} \right\} \cdot (1+i)^n \tag{8}$$

with "l_k" being the integer part of the following equation (9), i.e.

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

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

Recapitulating, the future cost ascribed to the storage system installation and operation after "n" years may be estimated using equation (10).

$$\begin{aligned} C_{ss} = IC_{ss} \left\{ (1-\gamma) + m \cdot \sum_{j=1}^{j=n} \left(\frac{(1+g_{ss})}{(1+i)} \right)^j + \sum_{k=1}^{k=ko} r_k \cdot \left[\sum_{l=0}^{l=l_k} \left(\frac{(1+g_k)(1-\rho_k)}{(1+i)} \right)^{l \cdot n_k} \right] \right\} \cdot (1+i)^n + \\ + (\varepsilon \cdot E_{total}) \cdot \left\{ \frac{c_w}{\eta_{ss}} \cdot \sum_{j=1}^{j=n} \left(\frac{(1+w)}{(1+i)} \right)^j + c_f \cdot \sum_{j=1}^{j=n} \left(\frac{(1+e_f)}{(1+i)} \right)^j \right\} \cdot (1+i)^n \end{aligned} \tag{10}$$

For the estimation of the energy production cost (€/kWh, in present values) of the entire energy storage installation one should divide the total cost of the installation (eq.(10)) with the corresponding total energy production, i.e.:

$$c_{ss} = \frac{C_{ss}}{\varepsilon \cdot E_{tot} \cdot \sum_{j=1}^{j=n} \left(\frac{(1+e)}{(1+i)} \right)^j \cdot (1+i)^n} \tag{11}$$

where the electricity price escalation rate "e" should also be included. Note that an energy storage investment is financially attractive if the energy production cost value of equation (11) is less than the energy production cost of the existing thermal power stations. One should also take into account the additional benefits related to the energy storage system operation, due to the increased reliability of the entire electrical network and the improved quality of the electricity offered.

4. Application Results

The developed evaluation model aims to determine the cost-effectiveness of incorporating a storage unit in an existing electrical network. In the current analysis the evaluation model is applied to two electrical systems differing in terms of scale, however described by similar master characteristics. To be more precise, the case studies investigated refer to two Aegean Sea islands, i.e. Donoussa and Lesbos (figure (3)) islands, comprising a very small and a large-scale isolated electrical grid respectively. In Table II one may find the main parameters of the local networks to consider.

Table II: Main Parameters of the Donoussa and Lesbos Electricity Systems

Island	Peak Power Demand kW-2005)	Total Annual Energy Consumption (MWh-2005)	RES-Based Power Unit	Population (2001 census)	Area (km^2)
Donoussa	194	460	PV	166	14
Lesbos	60,000	246,000	Wind Turbines	90,643	1,630

Both islands' electrical networks present similar operational characteristics, like the intense demand fluctuations on an annual basis, the quite narrow power security margin and the extremely high production cost[5] (especially the small island of Donoussa), mainly owed to the corresponding fuel consumption rates and the existing outmoded APS maintenance needs. If also considering the favourable wind and solar potential met in the specific areas, an additional reason for the investigation of adopting energy storage systems in collaboration with appropriate renewable based power stations appears.

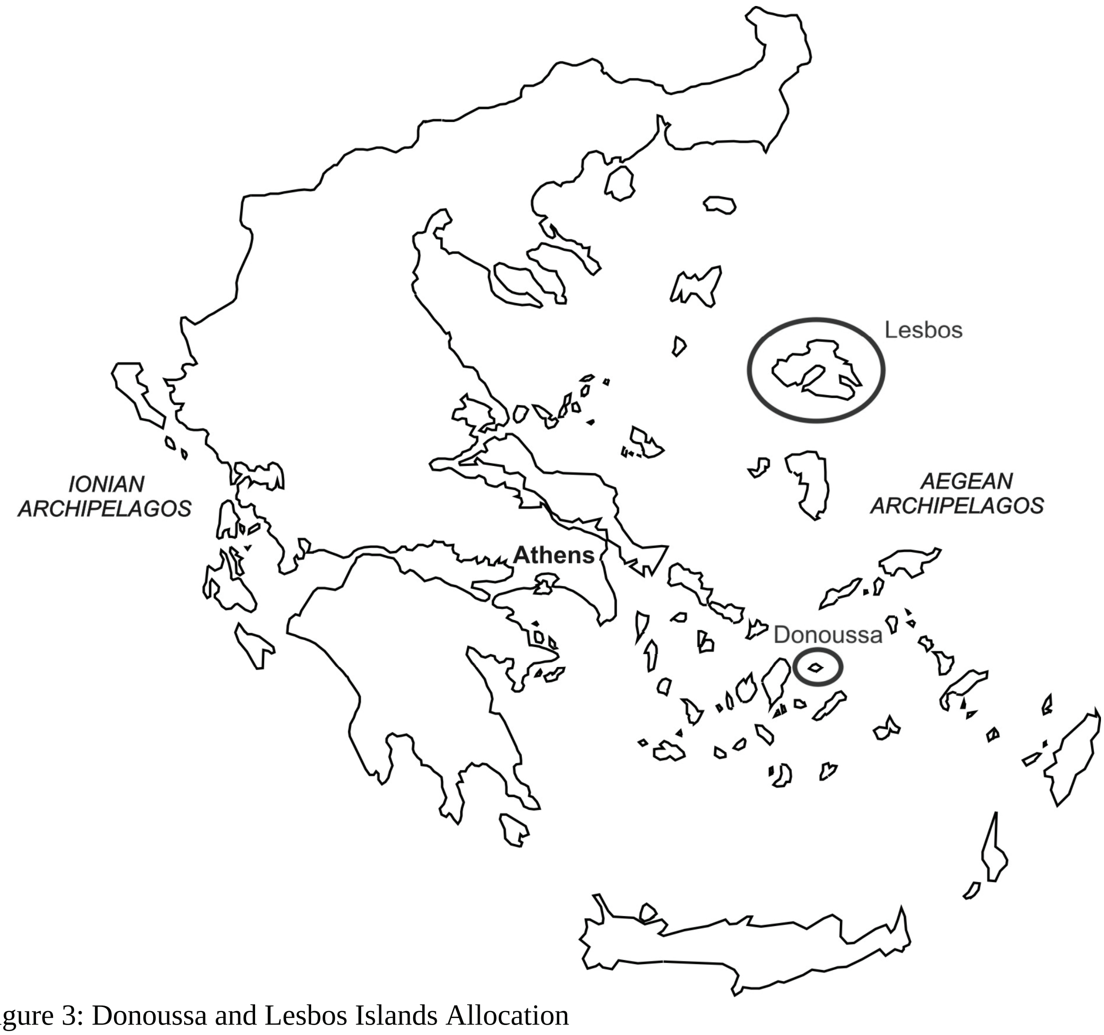

Figure 3: Donoussa and Lesbos Islands Allocation

Finally, by taking into account the potential installation of several energy storage systems and by examining various scenarios of the latter contribution (impact of "ε" parameter), also involving the levels of autonomy (impact of "d_o" parameter) supported by the selected storage units, the electricity production cost in a given electrical grid on the basis of the existing storage system may be calculated. To get a broader view of the systems' cost effectiveness against alternative productive methods however, one should also consider the input energy (necessary for the systems' charging) cost value

"c_w" on the total electricity production cost of the entire installation. More precisely, in cases of high wind potential the input electricity cost is set equal to the corresponding wind park marginal production cost (0.05€/kWh)[26], while for locations of excellent solar potential one may use the photovoltaic power stations marginal production cost (0.1€/kWh)[27][28] respectively. In any case, the impact of different input energy cost on the calculation results is examined using an appropriate parametrical analysis.

4.1 Lesbos Island

Lesbos island is one of the largest Greek islands (area 1630km^2, population 90,600), located in the northeastern part of the Aegean Sea. According to the available data, the electricity consumption of the island exceeds 250GWh (2005), while the corresponding peak power demand approaches 60MW. At the same time, the marginal electricity generation cost of the local thermal power station is almost 0.12€/kWh, presenting a mean annual increase of the order of 5%[5]. On the other hand, the island possesses very high wind potential, i.e. in several places throughout the island the long-term average wind speed approaches 8.5m/s, and significant solar potential, i.e. annual specific solar energy available equal to 1550kWh/m^2. However, in an attempt of the local network manager to protect the local weak electrical system from unwanted instabilities and also maintain the necessary power quality, the contribution of wind energy and photovoltaics is limited, theoretically[6] up to 30% and practically[29] up to 15% on annual basis. This is not the case for the wind energy penetration in the strong interconnected electrical networks (e.g. Denmark), where the contribution of wind energy may approach 20% on annual basis.

In this context, the only way to increase the RES penetration in the Lesbos island electrical system is to incorporate an appropriate energy storage system that shall guarantee the system stability and cover the energy demand on a scheduled way. Taking into consideration the quality of the local wind potential and the relative size of the island, the storage system contribution range currently recommended, even suggesting an annual participation of 20%, finally extends to an 80% proportion, i.e. 20%≤ε≤80%. According to the official data, the specific participation value means that the electricity provided to the consumption via the energy storage system annually ranges from 50GWh up to 200GWh. Note that the above mentioned energy amount can be produced by using wind parks (CF=25%, η_{ss}=0.7) of a rated power starting from 30MW up to 120MW. Currently, the already operating wind parks of the island are almost 10MW, contributing by almost 10% to the annual electricity consumption[30].

The systems selected to study comprise bulk energy storage systems and apart from the typical technologies of PHS and CAES, lead-acid batteries may also prove capable of supplying the necessary services in the electrical network of Lesbos. Due to the system's size and the storage system contribution percentage selected, the system energy autonomy range examined varies between 2hours and 24hours, i.e. the energy storage capacity required varies between 16MWh (ε=0.2, d_o=2hours) and 780MWh (ε=0.8, d_o=24hours), while the peak power of the energy storage system should be equal to 70.5MW (η_p=85%, ζ=1.0).

The first case analyzed concerns the electricity production cost of the energy systems under evaluation for low autonomy (d_o=2), while the corresponding input energy cost is assumed equal to 0.05€/kWh, a realistic value for typical wind parks of Lesbos[26]. According to the results obtained, even at low energy storage system contribution (ε=20%), the energy production cost is less than 0.1€/kWh for the lead-acid batteries configuration, figure (4). In fact, for low autonomy cases (d_o=2 hours) the lead-acid batteries seem to be the most beneficial of the solutions examined, while "ε" varies between 20% and 80%. What should be noted though, is the low energy density of the lead-acid batteries, thus leading to the employment of a large area[31] and therefore not entailing a possible application benefit over the unconditionally bulk PHS and CAES.

As the autonomy values increase over 6 hours, the PHS systems gradually become more attractive (figure (5)), especially where "ε" approaches 40%. As in the previous scenario, the total energy production cost of the energy storage subsystem is lower than the current marginal production cost of the existing thermal power stations (i.e. 0.12€/kWh). Only, for the very low energy storage system contribution (ε=20%) the lead-acid batteries show a lower cost than the PHS.

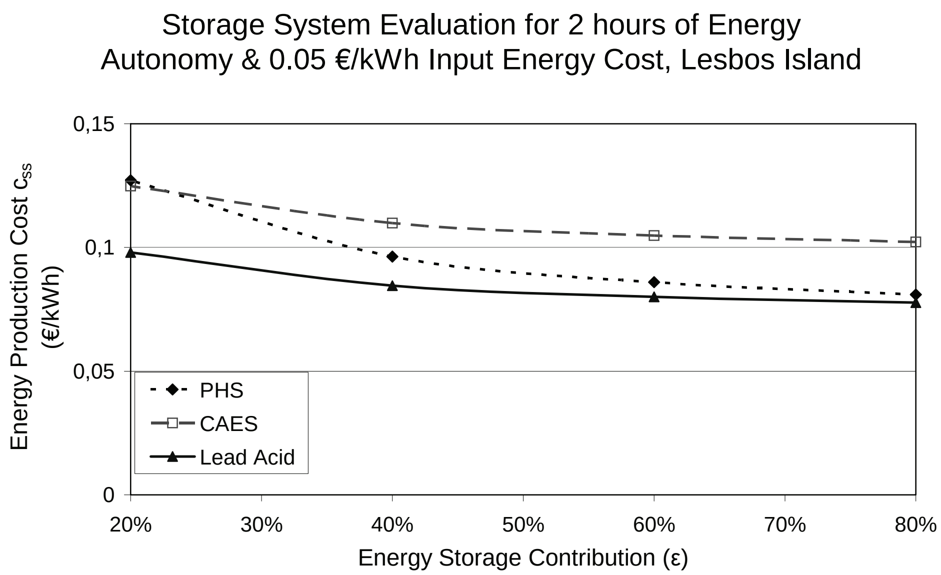

Figure 4: Electricity Production Cost of Selected Energy Storage Systems, Low System Energy Autonomy

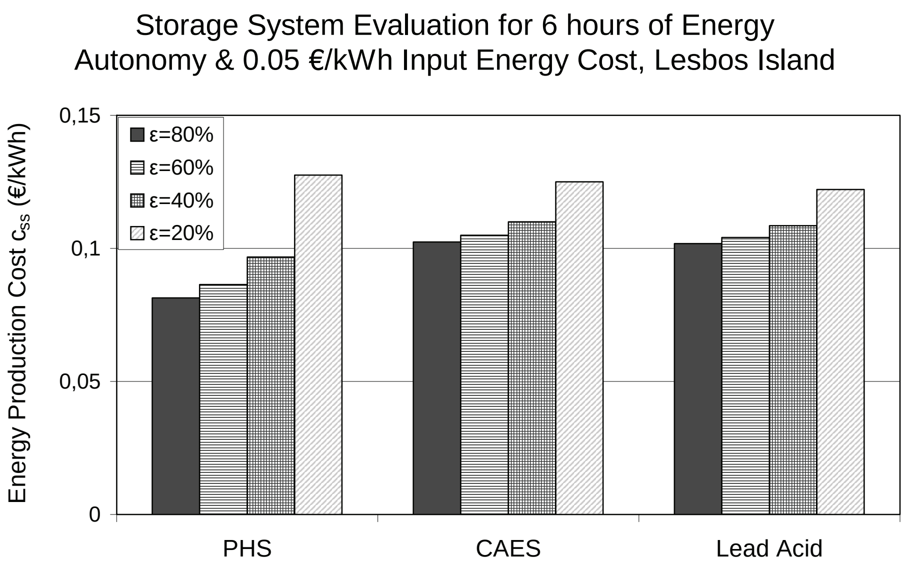

Figure 5: Comparing the Electricity Production Cost of Selected Energy Storage Systems, Medium-Low System Energy Autonomy

For greater autonomy encountered the PHS systems show the most favorable rates in almost the entire energy production participation spectrum, as displayed in figures (6) and (7). PHS and CAES show in fact no remarkable variation in relation to the autonomy increase (figures (6) and (7)). On the other hand, the lead acid batteries cost is strongly affected by the necessary duration "d_o" of energy provision called to satisfy. According to the results obtained, the CAES may only be considered in cases of low annual contribution (ε=0.2) and significant autonomy (over 6 hours), (see also figure (8)). Taking into consideration the fuel impact, since CAES does not show a great deviation when compared with PHS rates, a fuel price decrease may lead to the former supremacy.

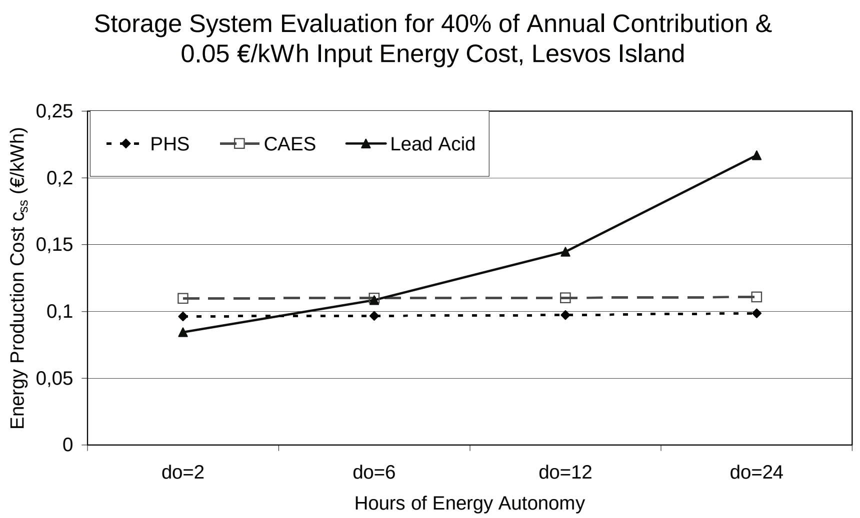

Figure 6: Electricity Production Cost of Selected Energy Storage Systems for 40% Annual Energy Contribution

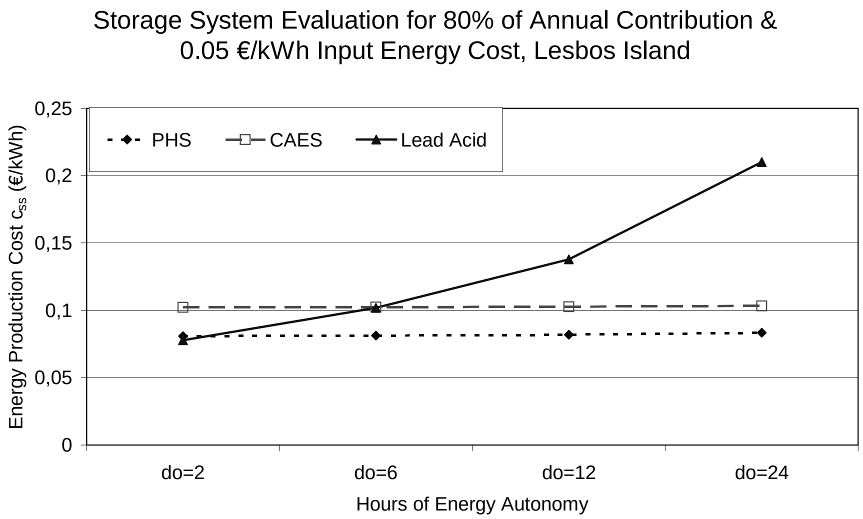

Figure 7: Electricity Production Cost of Selected Energy Storage Systems for 80% Annual Energy Contribution

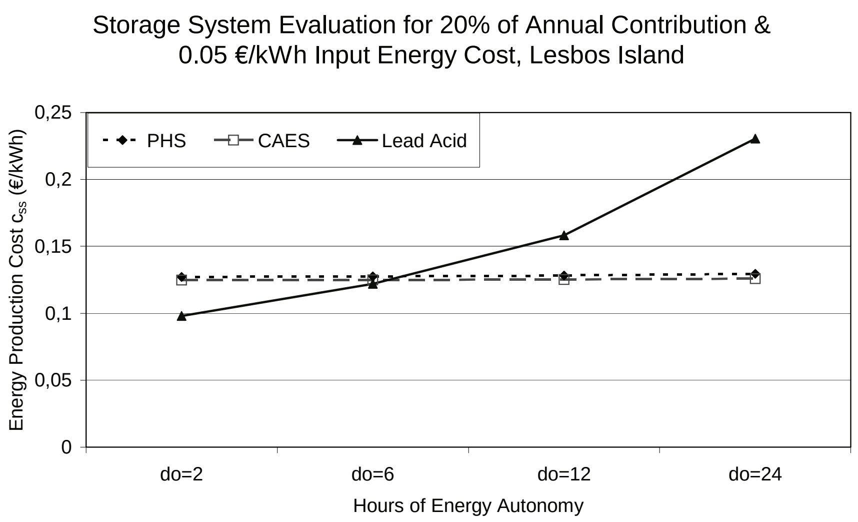

Figure 8: Electricity Production Cost of Selected Energy Storage Systems for 20% Annual Energy Contribution

Subsequently, it is interesting to mention that a remarkable energy production decrease is encountered as the energy system annual contribution "ε" increases, figure (9). This decrease is stronger for PHS compared to CAES and lead-acid batteries.

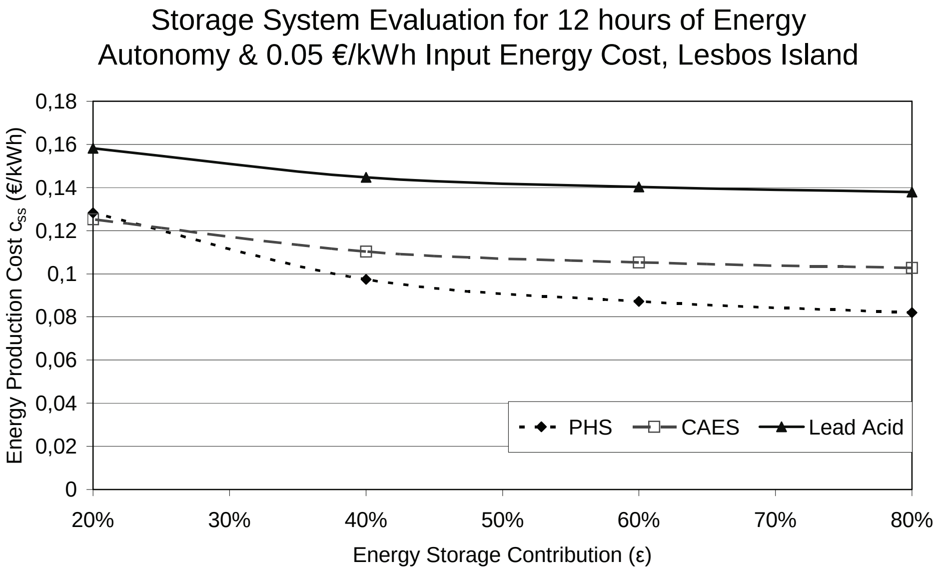

Figure 9: The Impact of the Energy Storage Contribution on the Electricity Generation Cost for Medium System Energy Autonomy

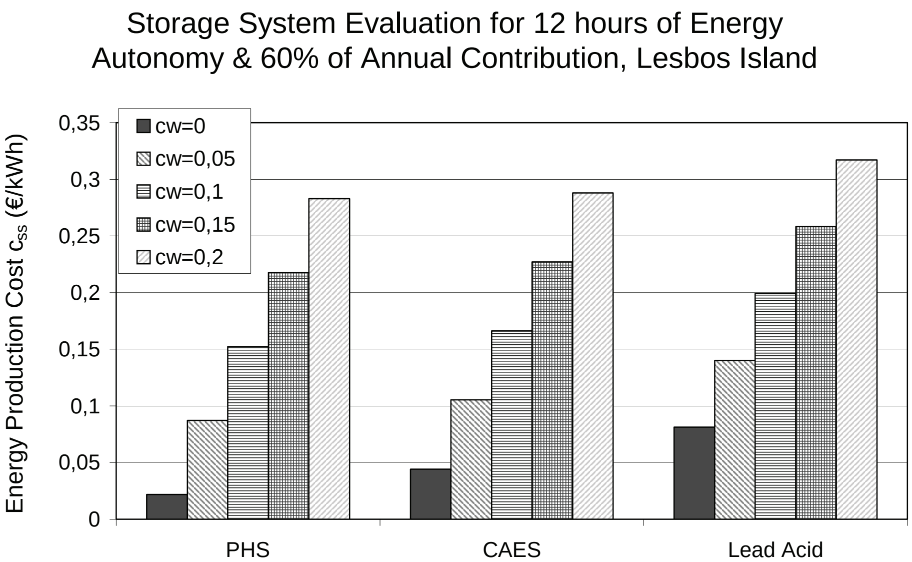

Figure 10: The Impact of the Input Energy Price on the Electricity Generation Cost of Selected Energy Storage Systems, Lesbos Island

One of the main parameters influencing the energy cost of the energy storage system is the input energy cost value "c_w". Note that in cases of an existing pricing for the energy input, the cost of energy needed to charge each of the storage systems comprises the most important factor (see figure (10)). According to the results demonstrated, the energy production cost for c_w=0 (using the rejected excess energy production of an existing wind power installation is very low (i.e. 0.022€/kWh for PHS, 0.044€/kWh for CAES and 0.081€/kWh for lead-acid batteries). However, a significant energy production cost is encountered as "c_w" increases.

Finally, as far as the CAES is concerned, when the input energy cost is zero, the fuel contribution in the overall specific cost configuration is thought to be catalytic. More precisely, in the present analysis, the share of specific cost attributed to the necessary fuel consumption exceeds 50% at all times and may even reach 80% of the total electricity generation cost.

4.2 Donoussa Island

The second case analyzed concerns the island of Donoussa which is located nearby the Naxos island, see also figure (3). To be more precise, the case study investigated refers to a tiny isolated electrical micro-grid, i.e. total annual electricity consumption of approximately 460MWh and peak load demand of almost 194kW. On the basis of the official data[5] available the corresponding electricity production cost approaches 460€/MWh. In fact Donoussa is a very small island (population 166 habitants - approximately 45 families- area of 14km²) where the main economic activities of the local society are fishing and tourism. The island has very good solar potential, since the annual mean solar energy approaches 1700kWh/m^2, at horizontal plane, hence one may examine the possibility to meet the electricity demand of the local community on the basis of a photovoltaic power station in collaboration with an appropriate energy storage system[27].

Taking into account the quality of the available solar potential, the proposed photovoltaic based system is expected (according to the hours of sunlight available and the corresponding load demand profile) to cover directly between 20% and 50% of the local electricity consumption. Therefore, the rest of load demand is left to be covered by existing internal combustion engines and the PV panels via the energy storage installation. In fact, the photovoltaic system if properly sized may -apart from the direct grid's partial needs- be able to cover the charging of the existing storage system. In this case, the energy storage subsystem can be employed in order to cover the rest of the consumption during the low (or zero) solar irradiance periods. Thus, the resulting contribution range of the corresponding energy storage system, as far as Donoussa is concerned, varies between 50% and 80%, i.e. $0.5 \leq \varepsilon \leq 0.8$.

In regard to the systems examined, the peak power met in the local network along with the expectation of a significant energy production provision, have both led to the exclusion of certain systems. The systems proposed for evaluation in such a small sized electrical grid are certain types of conventional batteries (Lead-acid and Na-S), Hydrogen Storage incorporating fuel cells (HS-FV), and the comparatively novel flow battery technology (Regenesys). Larger systems such as PHS and CAES are not to be examined since their viability depends strongly on the scale of the demands confronted[23][32]. The autonomy range undertaken suggests a minimum of 2 hours and a maximum of 24 hours to consider.

According to the results obtained regarding the Donoussa island, the following could be noted:

a. The most cost-effective solution appearing in cases of low energy autonomy examined (figures (11) and (12)), i.e. up to 20 hours, is the Na-S batteries. If we also keep in mind the high rates of energy density describing the current technology, the Na-S batteries may actually comprise a favorable solution for the load management of the island. In regard to a higher autonomy scale (24h) however, the Regenesys flow batteries do present a slight advantage (figure (13)).
b. Taking into consideration the Na-S batteries' limited operation, owed to their moderate depth of discharge, and provided that a higher autonomy is the dominant criterion, Regenesys flow batteries should be preferred. It must be underlined though that these technologies are more suitable for larger applications and are currently included so as to demonstrate their advantage over greater levels of autonomy.
c. In respect of the Hydrogen Storage (HS-FC), the non promising results appearing for a few hours of autonomy tend to mitigate for a higher duration of discharge. In fact, if one extends the autonomy up to 24 hours and for certain contribution percentages, the Hydrogen Storage coupled fuel cells may present one of the most attractive solutions to be considered[33].
d. Concerning the rest of the technologies investigated, it is clear that they have a similar behavior. What can be mentioned is the comparatively lower rate of cost increase presented by the lead acid batteries. In an overall evaluation however, the specific systems should not be thought as promising solutions.

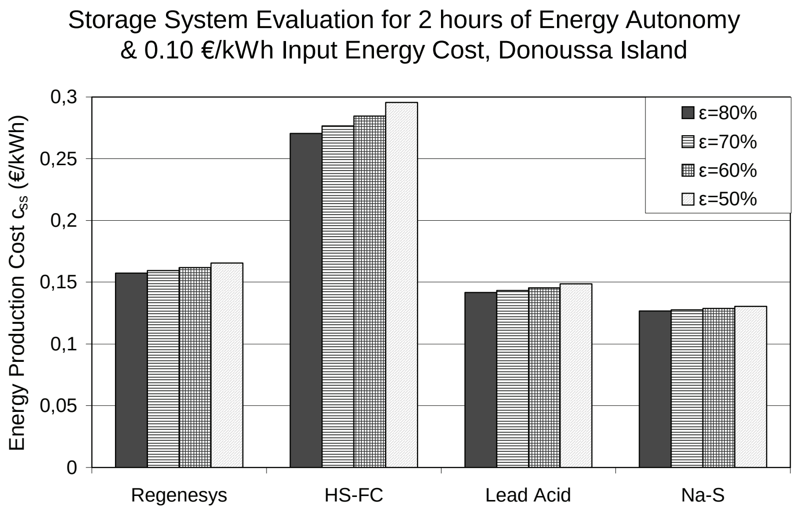

Figure 11: Comparing the Electricity Production Cost of Selected Energy Storage Systems, Low System Energy Autonomy

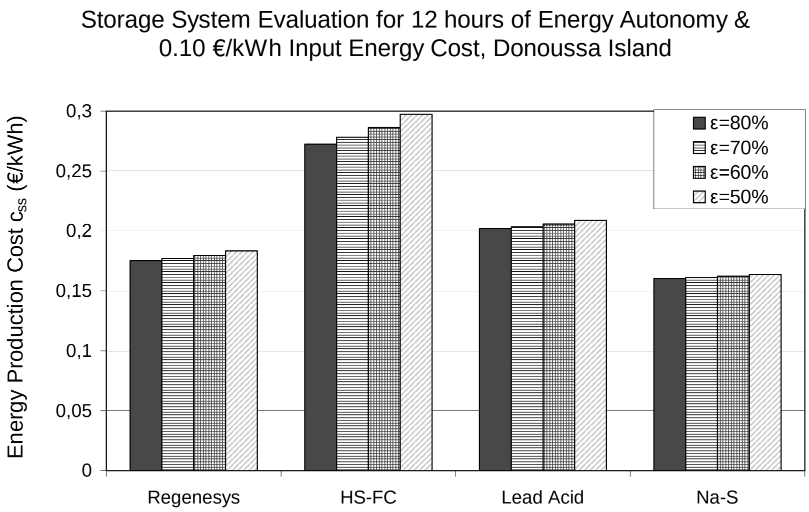

Figure 12: Comparing the Electricity Production Cost of Selected Energy Storage Systems, Medium System Energy Autonomy

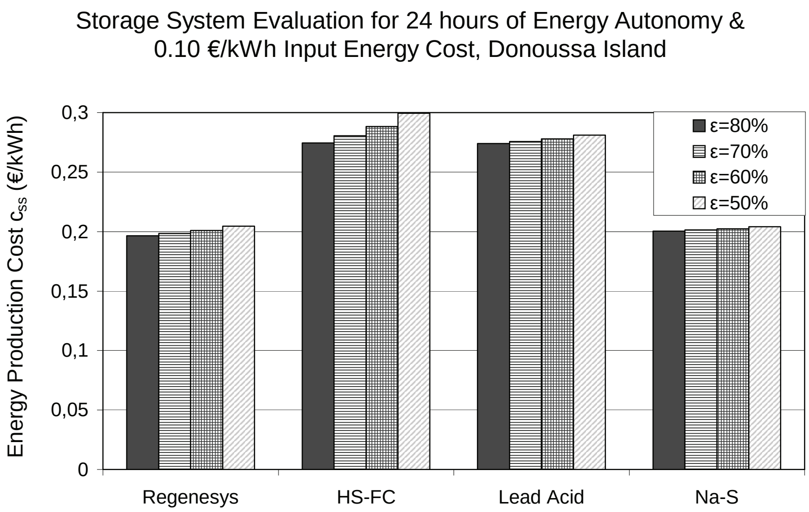

Figure 13: Comparing the Electricity Production Cost of Selected Energy Storage Systems, High System Energy Autonomy

To somehow decode the behavior of each energy storage system against the parameters of energy contribution "ε" and autonomy "d_o", a parametrical analysis concerning the calculated relative cost values has been carried out, see figures (14) and (15). As noted, the Hydrogen Storage cost is not affected by the energy autonomy increase, while the rest of the systems show a remarkable cost increase, figure (14). Lead-acid batteries present the greatest cost increase while Regenesys are described by the corresponding mildest.

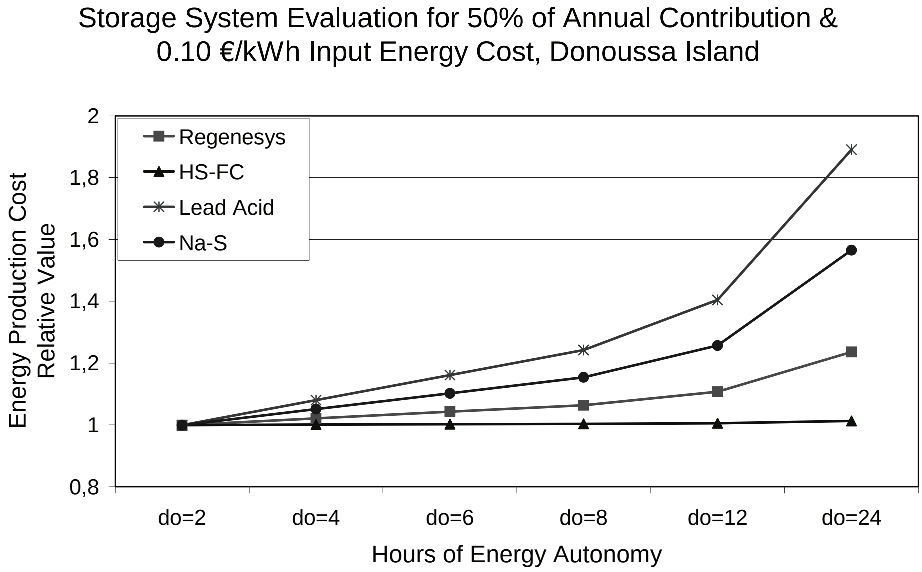

Figure 14: The Impact of Energy Autonomy Hours on the Relative Electricity Production Cost for Selected Energy Storage Systems

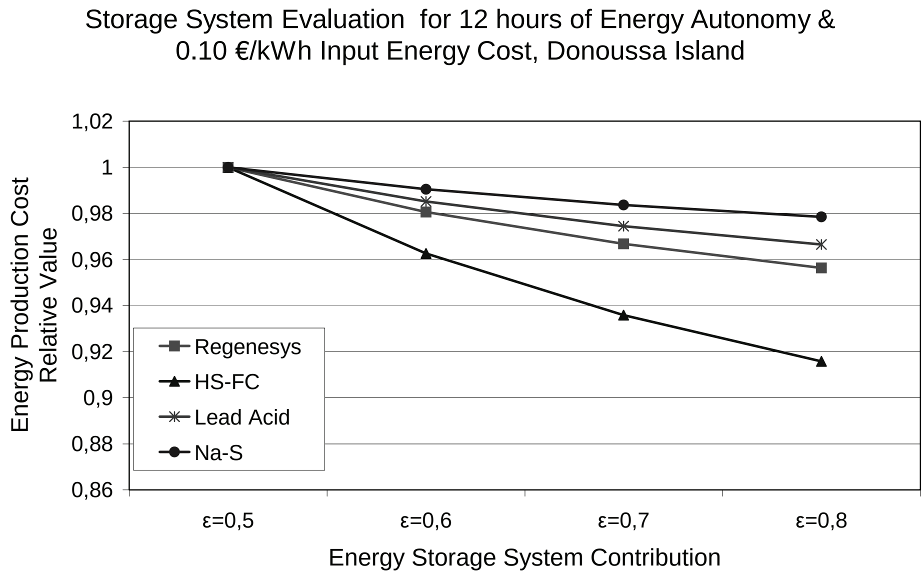

Figure 15: The Impact of Energy Storage Contribution on the Relative Electricity Production Cost for Selected Energy Storage Systems

Regarding the energy contribution parameter "ε" effect, the opposite behavior may be encountered, figure (15). The systems presenting the most important variation of the relative cost value in the autonomy range are less influenced by the energy contribution factor. On the other hand, when the storage system is asked to cover a greater annual production share, Hydrogen based and Regenesys systems demonstrate the most significant relative cost reduction.

Nevertheless, the determining factor of the cost variation is the input energy price achieved (see figure (16)). Besides, for the two extreme scenarios of ε=50%, d_o=24 hours, c_w=0.05 and ε=80%, d_o=2 hours, c_w=0.2, the input cost parameter contribution to the final cost value ranges between 45% and 95% correspondingly, always depending on the system type.

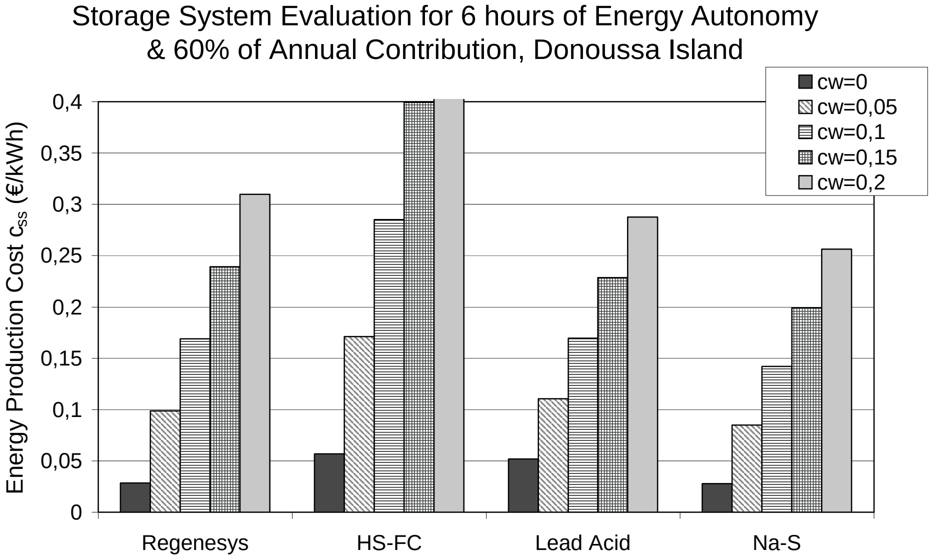

Figure 16: The Impact of the Input Energy Price on the Electricity Generation Cost of Selected Energy Storage Systems, Donoussa Island

5. Conclusions

In the present study, an integrated electricity production cost analysis for autonomous electrical networks based on RES and energy storage configurations is presented. The proposed analysis takes into consideration the initial cost of the energy storage equipment (based on the storage capacity and the corresponding nominal power), the input electricity and fuel costs, as well as the fixed and variable M&O cost of the entire installation.

Subsequently, the developed methodology is applied to two representative cases: one large and one very small isolated electrical micro-grid case, based on wind and solar potential exploitation respectively. Special attention is paid in order to demonstrate the effect of the selected energy storage systems' utilization on the electricity production cost value. Using the proposed model one may define the most appropriate configuration for each case investigated.

Keeping that in mind, the technologies of PHS, CAES and Hydrogen Storage coupled with Fuel Cells do not seem to be limited by the selected autonomy level, while presenting attractive results of electricity production cost for higher levels of annual contribution. On the other hand, the rest of the technologies examined (i.e. conventional and flow batteries), although presenting a relative cost advantage in low autonomy cases, are strongly affected by the autonomy factor. Thus, by increasing the autonomy, an analogous increase of the systems' production cost is to be expected.

What seems to be the catalyst for the storage systems' viability is the input energy pricing, clearly determining the cost ascribed to the systems' implementation and -at the same time- underlining the need for achieving a satisfying price for the systems' charging. Excluding the scenario that the energy storage system uses the excess electricity production (not absorbed by the local network due to low demand and grid stability constraints), the input energy cost represents a considerable percentage (in practical cases up to 70%) of the total electricity production cost.

Recapitulating, according to the results obtained, a properly sized RES-based electricity generation station in collaboration with the appropriate energy storage equipment is a promising solution for the energy demand problems of numerous existing autonomous electrical networks, providing clean energy and contributing to the diminution of the important environmental problems resulting from the electricity generation sector.

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COMBINED PHOTOVOLTAIC AND ENERGY STORAGE SYSTEMS AN INTEGRATED ELECTRIFICATION SOLUTION FOR SMALL ISLANDS

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Abstract

The numerous small Aegean Sea islands present serious problems related to insufficient infrastructure, low quality of electricity available at very high production cost, as well as problematic connection with the mainland. On the other hand, the high solar potential of the area may encourage photovoltaic based applications characterized by rather low maintenance support demands. In this context, an integrated electrification solution based on a photovoltaic generator along with an appropriate energy storage device is investigated. One of the main targets of the proposed solution is to maximize the solar energy exploitation of the area at minimum electricity generation cost, while special emphasis is given to the selection of the most cost-efficient energy storage configuration available. According to the results obtained the solution under investigation is not only financially attractive but also improves the quality of electricity offered to the local communities, substituting the expensive and heavily polluting operating thermal power stations.

Keywords: Electricity Generation; Energy Storage; Autonomous Electrical Network; Photovoltaic Generator; Electricity Production Cost; Small Islands

1. Introduction

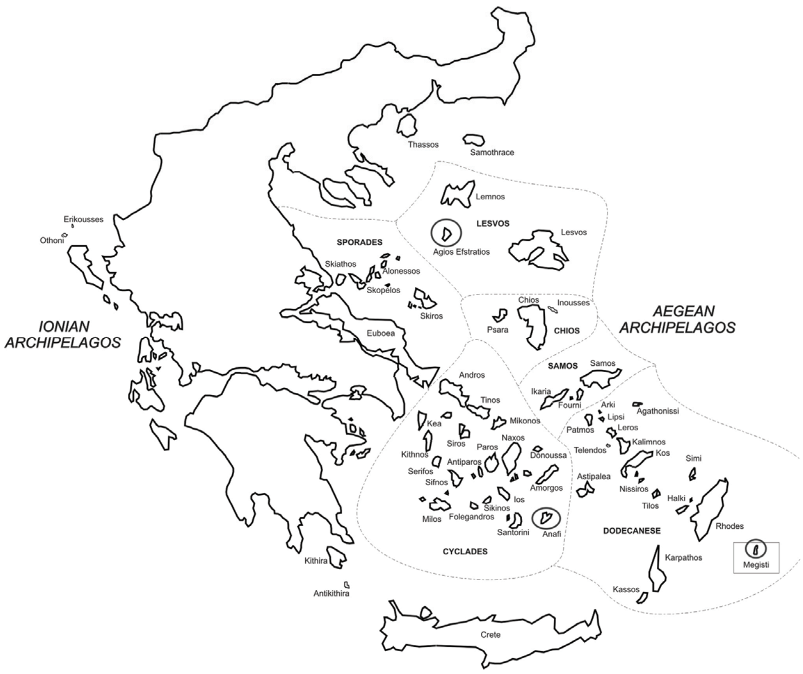

Figure 1: Aegean Archipelagos complex of islands

The numerous small Greek islands (less than 500 habitants) spread throughout Aegean Sea are located either in Northern Aegean Sea region or in Cyclades and Dodecanese complexes, figure (1). In all these tiny islands, a continuous decrease of population has been encountered during the last forty years. This is not the case for the summer season, where a considerable (more than 300%) increase of

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population is observed, due to the visiting tourists[1]. The major problems of these islands include[2] insufficient infrastructure, rare and problematic connection with the mainland, as well as low quality of electricity available at very high production cost. In this context, the electricity production cost[3], due to the small autonomous power stations (APS) utilized, is quite variable and extremely high, figure (2), while extensive grid failures (electrical black outs) arise all over the year.

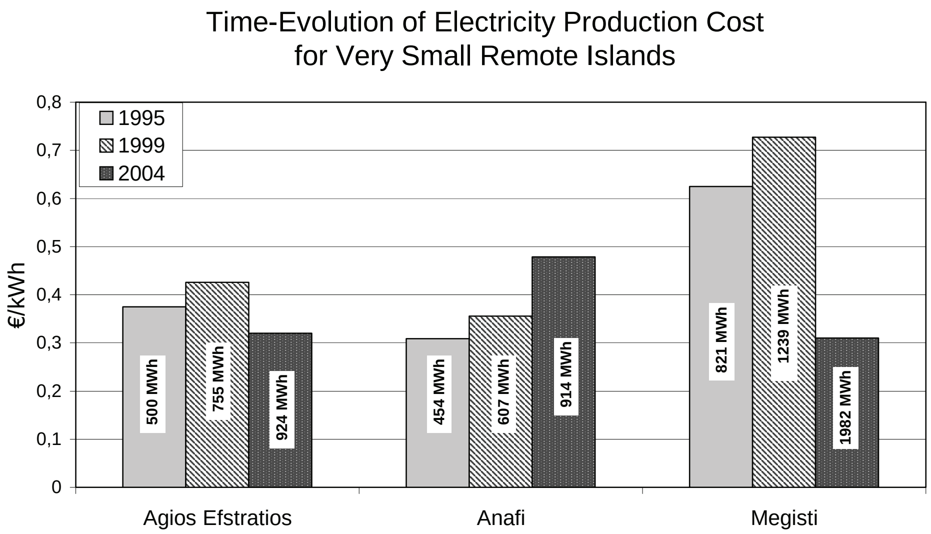

Figure 2: Time-evolution of electricity production cost

As a contribution to life quality amelioration of these isolated islands remaining habitants, an integrated solution is under investigation, based on 100% exploitation of the available renewable energy sources (RES) in combination with an appropriate energy storage configuration, in order to cover the local communities' needs incessantly. Taking into account the limited power requirements (normally less than 600kW) and the isolated character of the islands, the exploitation of the local solar potential may be more cost-effective[4] than the possibility of creating a small wind park (negative scale economies, increased maintenance needs). The rather low energy consumption is also a serious restriction of utilizing the available geothermal potential of some small islands (e.g. Anafi)[5]. In fact, the high solar potential of the area may encourage photovoltaic (PV) based applications taking advantage of the remarkable technology improvements and the ex-factory price reduction of the sector[6] as well as the significant financial incentives offered by the EU and the Greek State[7]. Also, photovoltaic systems offer the potential of extension, a critical point since the energy needs of the islands are changing all the time. Besides, photovoltaics are characterized by rather low maintenance support demands, thus minimizing the negative impact of the isolated character of these islands.

On top of this, electricity production based on (PV) technology is one of the most environmentally friendly ways to produce electricity, since it does not emit greenhouse gases and it does not consume finite fossil fuel resources. More precisely, PV stations:

- do not require liquid or gaseous fuel to be transported or combusted
- do not consume water resources for engine cooling purposes
- produce energy with zero noise, an important issue in areas that concentrate many tourists in relatively small regions.
- are also preferred for aesthetic reasons, in order to avoid the negative visual impact of thermal power stations (smokes, chimneys, etc).

From all the above it is implied that the environmental impacts of the electricity production are minimised, especially if these systems are harmoniously implemented into the existing, local, natural particularities of the environment, through good planning and well developed environmental impact studies.

From the technological point of view and in an attempt to face the variable availability of solar energy as well as the daily and seasonal electricity demand fluctuations of all these islands (see for example figures (3) and (4)), the idea of using a suitable energy storage system (ESS) in collaboration with the proposed PV generator is investigated in detail. Although the first installation cost of a combined PV-ESS power station is relatively higher than the corresponding cost of an equivalent thermal power station, the high solar potential and the extremely high production cost of local APS (figure (2)) undoubtedly provide a competitive advantage of the proposed solution even in terms of economic efficiency. On top of this, an energy storage system, when sized appropriately[8-13], not only can match a variable solar based energy production to a generally variable and hardly predictable system demand, but also improves the system reliability and contributes in the energy production cost reduction.

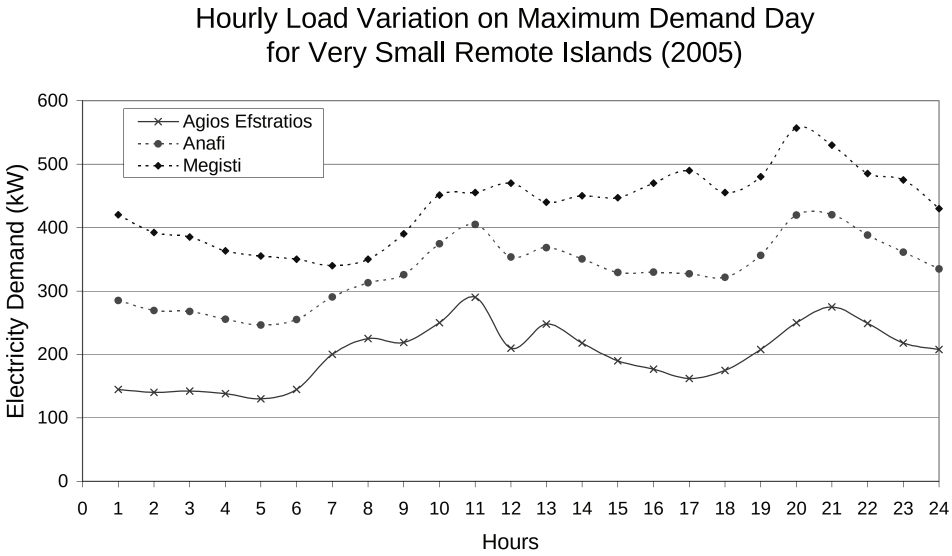

Figure 3: Daily electricity load demand variation of Aegean Archipelagos islands

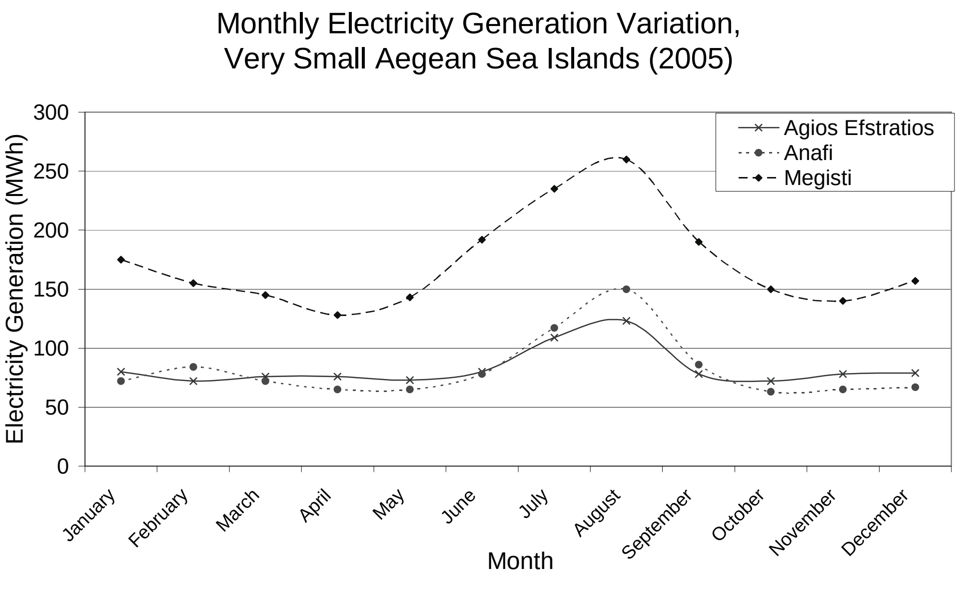

Figure 4: Seasonal electrical energy demand of small Aegean Archipelagos islands

In this context, an integrated electrification solution based on a photovoltaic generator, along with an appropriate energy storage device in order to replace the existing thermal power stations, is investigated. One of the main targets of the proposed solution is to maximize the solar energy exploitation of the area at minimum electricity generation cost, while special emphasis is given to the selection of the most cost-efficient energy storage device available. The complete methodology is applied to representative island cases with very interesting results.

2. Position of the Problem-Proposed Solution

In order to face the urgent electricity requirements of all these tiny Aegean Archipelagos islands on the basis of the available solar potential of the area, one needs:

a. The daily load demand of the island throughout the year (e.g. figures (3) and (4))
b. The solar potential of the area[14] throughout the year (figure (5))
c. The electricity generation cost parameters (e.g. figure (2))

Thus, it is necessary to collect[15] data concerning each small island's electricity production parameters as well as any available information describing local topography, solar irradiance and wind speed, demographic profile and economic activities.

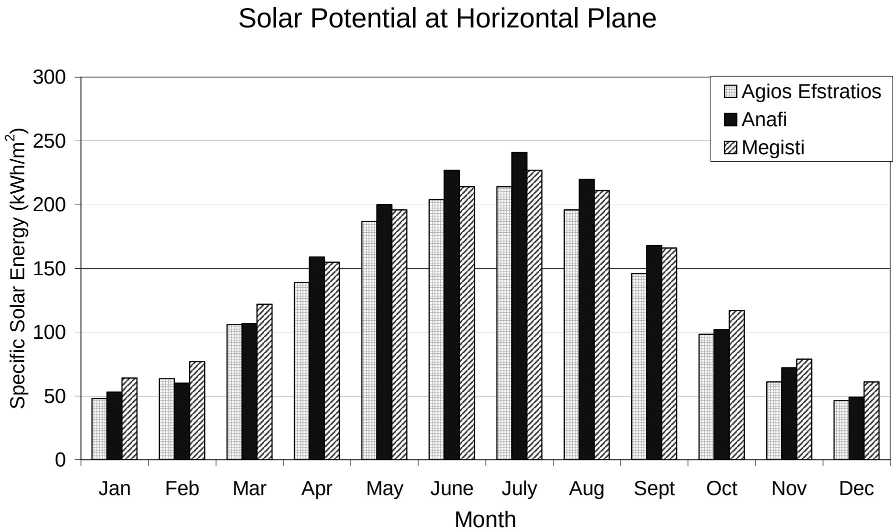

Figure 5: Available solar potential for the small Aegean Archipelagos islands[14]

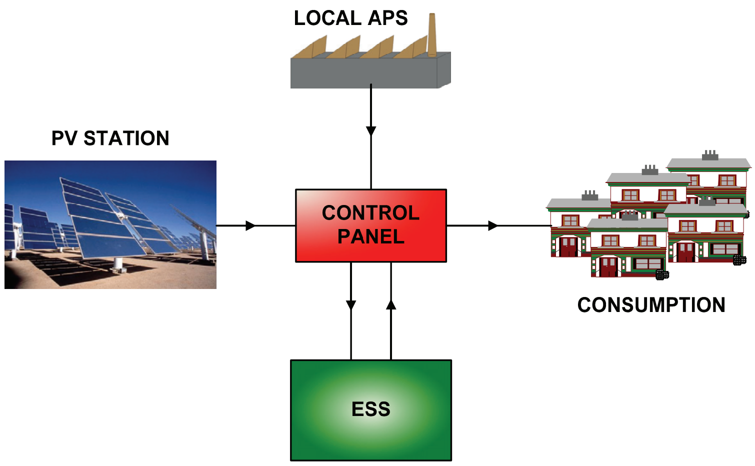

Figure 6: Proposed electricity generation configuration for small autonomous electrical grids

Subsequently, the proposed by the authors[4][13] integrated solution comprises a photovoltaic generator able to meet the electricity demand of the island as well as an appropriate energy storage facility that guarantees the local community energy autonomy for a desired time period. Besides, the existing (usually outmoded) thermal power stations may also be used either as a backup solution or to cover unexpected high load demand. More precisely, the proposed configuration (figure (6)) includes:

a. One or more photovoltaic generators based on the exploitation of the available solar potential. The rated power of the proposed installation is "N_{PV}".
b. A number of energy storage devices (e.g. lead-acid or Na-S batteries, a group of water reservoirs, etc.) combined with their corresponding energy production equipment (e.g. inverters, small hydro-turbines, etc.). The energy storage capacity of the installation is equal to "E_{ss}" and the input and output rated power values are "N_{in}" and "N_{ss}", respectively. The selected ESS should be able to cover the local network electricity requirements for "d_o" typical hours without the contribution of any other electricity generation device.
c. The existing thermal power units of the already in operation APS, with rated power equal to "N_o", may contribute to the local system electricity consumption under specific circumstances by "δE". The main target of the proposed solution is to minimize the contribution of the local APS to the local system electricity consumption ($\delta E \rightarrow 0$).

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

i. During daytime, if the energy production of the PV-based power station is greater than the local community consumption, the energy surplus is stored in the existing ESS. In case that the ESS is full, the excess energy is forwarded to low priority loads.
ii. During daytime, if the PV-based production is lower than the corresponding electricity demand and the ESS is not empty (i.e. $DOD \leq DOD_L$), the electricity deficit is covered via the ESS.
iii. During daytime, if the PV-based production is lower than the electricity demand and the ESS is practically empty (i.e. $DOD \geq DOD_L$), the electricity deficit is covered by the existing thermal power units, using diesel or heavy oil.
iv. At nights, if the ESS is not empty (i.e. $DOD \leq DOD_L$), the electricity demand is covered via the ESS.
v. At nights, if the ESS is practically empty (i.e. $DOD \geq DOD_L$), the electricity demand is covered by the existing thermal power units, using diesel or heavy oil.
vi. Finally, for practical reasons, the utilization of all available power units may be required in order to face unexpected energy production/demand problems or situations related to "Force Majeure" events, increasing the reliability of the local system.

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

3. Sizing the PV-ESS Based System

The present analysis concerns an autonomous small island electrical network with annual energy consumption equal to "E_{tot}" (figure (4)), while the corresponding peak load demand (figure (3)) is "N_p". In fact, taking into consideration that the PV energy production is available only during daytime, one should distinguish the load demand of the island in two parts, see also figure (3). More specifically, one may use the symbols "E_{t1}" and "E_{t2}" in order to describe the energy consumption during daytime (sunlight period) and nights, as well as the symbols "N_{p1}" and "N_{p2}" in order to describe the peak load demand of the local network during the same periods respectively. Note that, using the above definitions, the following relations are also valid:

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

and

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

In this context, one may also assume that the total night demand "E_{t2}" is covered mainly by the ESS, while the ESS contributes also during daytime, in case that the PV production is lower than the load demand (cloudy days, very high load demand). Accordingly, in order to describe the contribution of the storage system to the total energy consumption, we define the parameter "ε" as:

$$\varepsilon = \frac{E_{stor}}{E_{tot}} = 1 - \frac{E_{dir}}{E_{tot}} \tag{3}$$

where "E_{stor}" is the total energy contribution of the ESS to the annual electricity demand and "E_{dir}" is the energy demand covered directly by the existing power stations (mainly by the photovoltaic generator "E_{PVdir}" and complementary by the thermal power station "δE").

On the other hand, the photovoltaic generator contribution is expressed by the term "E_{PV}". The corresponding energy production is used during daytime to cover the local network load demand, while any energy surplus is stored at the ESS in order to be used at nights or during low solar irradiance periods to meet the consumption needs.

The main target of the proposed solution is to meet the local demand using electricity produced mainly by the photovoltaic generator in collaboration with an appropriate energy storage system (ESS), with rational production cost. Up to now the electrification solution[3] was based on the existing outmoded thermal power stations, which operate using diesel or heavy (mazut) oil with mean electricity production cost equal to "c^*" (figure (2)) and causing serious environmental and macroeconomic impacts[16][17]. For increased reliability purposes the most efficient thermal power units may be used as back up engines with annual energy contribution equal to "δE", where one should require "$\delta E \ll E_{tot}$".

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

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

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

Defining the capacity factor of the local electrical network "CF_p" and the PV-based power stations "CF_{PV}" using equations (5) and (6), i.e.:

$$CF_p = \frac{E_{tot}}{8760 \cdot N_p} \tag{5}$$

and

$$CF_{PV} = \frac{E_{PV}}{8760 \cdot N_{PV}} \tag{6}$$

one may calculate the necessary nominal power of the proposed PV-based power station as:

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

where "SF≥0" is an appropriate safety factor in order to guarantee that the PV-based power station can meet the local consumption daytime power demand, see also equation (2). In order to ensure the system reliability, one should take into account that, at the same time, either the ESS power units (inverters, hydro-turbines etc.) or the existing (back up) thermal power units may be used.

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

$$E_{ss} = d_o\left(\frac{E_{tot}}{8760}\right)\frac{1}{\eta_{ss}}\cdot\frac{1}{DOD_L} = d_o\cdot\frac{E_h}{\eta_{ss}}\cdot\frac{1}{DOD_L} \quad (8)$$

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

$$E_h = \frac{E_{tot}}{8760} \quad (9)$$

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

$$N_{ss} = \zeta\cdot\frac{N_p}{\eta_p} = \zeta\cdot\frac{E_h}{CF_p}\cdot\frac{1}{\eta_p} \quad (10)$$

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

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

$$N_{in} = \lambda\cdot N_{ss} \le N_{PV} \quad (11)$$

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

4. Financial Evaluation of the Proposed Solution

4.1 Initial Investment Cost

The total investment cost (after -n years of operation) of the proposed solution[18][19] is a combination of the initial installation cost and the corresponding maintenance and operation cost, both quantities expressed in present values. In this context, the initial investment cost "IC_o" takes into account the initial cost of the PV power station and the ESS as well as the balance of the plant, expressed as a function "f" of the initial cost of the PV power station, i.e.:

$$IC_o = IC_{PV} + f \cdot IC_{PV} + IC_{ss} \tag{12}$$

According to the available information[18][19][20] the purchase cost of the PV-based power station can be expressed by the following relation:

$$IC_{PV} = \mathrm{Pr} \cdot N_{PV} \tag{13}$$

where "Pr" is the specific price (€/kW) of the PV power stations, see for example figure (7).

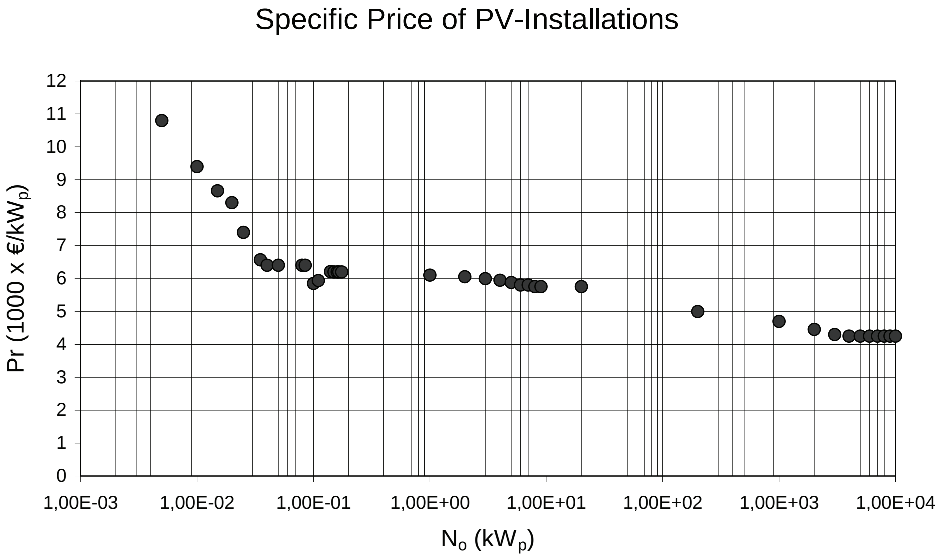

Figure 7: Specific price of existing PV-installations[20]

Accordingly, the initial cost "IC_{ss}" of an ESS can be expressed as a function of two coefficients. The first one "c_e" (€/kWh) related to the storage capacity and type of the system, and the second one "c_p" (€/kW) referring to the nominal power and type of the storage system in view of equation (11). Hence one may use the following relation:

$$\mathrm{IC_{ss}} = \mathrm{c_e} \cdot \mathrm{E_{ss}} + \mathrm{c_p} \cdot \mathrm{N_{ss}} = E_h \cdot \left[\frac{\mathrm{c_e} \cdot \mathrm{d_o}}{\eta_{ss} \cdot \mathrm{DOD_L}} + \frac{\mathrm{c_p} \cdot \zeta}{CF_p \cdot \eta_p} \right] \tag{14}$$

In order to obtain a first idea of the numerical values of the above mentioned parameters (i.e. DOD_L, η_{ss}, η_p, c_e, c_p) one may use the data of Table I, based on the available information in the international literature[21][22][23][24]. In the same Table I, the service period "n_{ss}" and the corresponding annual M&O factor "m_{ss}" for every ESS are also included. As it is obvious from Table I, a wide range of values has been found for most energy storage systems under investigation. In the present analysis the corresponding mean values have been adopted.

Table I: Major Characteristics of the Energy Storage Systems Examined[21][22][23][24]

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

According to the existing legislation[7][25] there is a considerable subsidization by the Greek State for PV-based applications on the basis of the current development law (e.g. 3299/04) or the corresponding National Operational Competitiveness Program. Actually the subsidy percentage "γ" equals to 45%-55% of the total investment cost.

4.2 Total Investment Cost

In addition to the initial investment cost one should also take into consideration the maintenance and operation cost of the entire installation, including the PV-based power station and the ESS. The M&O cost can be split[26] into the fixed maintenance cost "FC" and the variable one "VC". Expressing the annual fixed M&O cost as a fraction "m_{PV}" and "m_{ss}" of the initial capital invested (see [18,26] and Table I) and assuming a mean annual increase of the cost equal to "g_{PV}" and "g_{ss}" respectively, the present value of "FC" is given as:

$$FC = FC_{PV} + FC_{ss} = m_{PV} \cdot IC_{PV} \cdot \sum_{j=1}^{j=n} \left(\frac{(1+g_{PV})}{(1+i)} \right)^j + m_{ss} \cdot IC_{ss} \cdot \sum_{j=1}^{j=n} \left(\frac{(1+g_{ss})}{(1+i)} \right)^j \quad (15)$$

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

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

$$VC = IC_{PV} \cdot \sum_{k=1}^{k=ko} r_k \cdot \left\{ \sum_{l=0}^{l=l_k} \left(\frac{(1+g_k)(1-\rho_k)}{(1+i)} \right)^{l \cdot n_k} \right\} + IC_{SS} \cdot \sum_{j=1}^{j=ks} r_j \cdot \left\{ \sum_{l=0}^{l=l_j} \left(\frac{(1+g_j)(1-\rho_j)}{(1+i)} \right)^{l \cdot n_j} \right\} \quad (16)$$

with "l_k" and "l_j" being the integer part of the following equation (17), i.e.

$$l_k = \left[\frac{n-1}{n_k} \right] \quad \textit{and} \quad l_j = \left[\frac{n-1}{n_j} \right] \quad (17)$$

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

Recapitulating, the total cost "C" ascribed to the proposed PV-ESS based installation after "n" years of operation (in present values) may be estimated using equation (18).

$$C = IC_o \cdot (1-\gamma) + EC + FC + VC - \frac{Y_n}{(1+i)^n} + APS \Rightarrow \tag{18}$$

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

$$\mathrm{EC} = \delta E \cdot \mathrm{c_w} \cdot \sum_{j=1}^{j=n} \left(\frac{(1+\mathrm{w})}{(1+\mathrm{i})} \right)^{j} \tag{19}$$

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

Substituting equations (12), (15), (16) and (19) into equation (18) one gets:

$$C = \left[IC_{PV} \cdot (1+f) + IC_{ss} \right] \cdot (1-\gamma) + \mathrm{m_{PV}} \cdot \mathrm{IC_{PV}} \cdot \sum_{j=1}^{j=n} \left(\frac{(1+\mathrm{g_{PV}})}{(1+\mathrm{i})} \right)^{j} + \mathrm{m_{ss}} \cdot \mathrm{IC_{ss}} \cdot \sum_{j=1}^{j=n} \left(\frac{(1+\mathrm{g_{ss}})}{(1+\mathrm{i})} \right)^{j} + \\ + \delta E \cdot \mathrm{c_w} \cdot \sum_{j=1}^{j=n} \left(\frac{(1+\mathrm{w})}{(1+\mathrm{i})} \right)^{j} + VC - \frac{Y_n}{(1+i)^n} + APS \tag{20}$$

4.3 Comparison of the Available Solutions

The proposed PV and ESS-based configuration should be compared with the existing solution, which is based on the utilization of the existing thermal power station in order to cover the electricity demand "E_{tot}" of the local society. In this scenario the current electricity production cost is assumed equal to "c^*", while the annual electricity price escalation rate "e" should also be included[3]. More precisely, the total electricity production cost "C*" of the existing thermal power stations for a n-year time period can be approximated by the following relation, i.e.:

$$C^* = \mathrm{c}^* \cdot \mathrm{E_{total}} \cdot \sum_{j=1}^{j=n} \left(\frac{(1+\mathrm{e})}{(1+\mathrm{i})} \right)^{j} - \frac{Y_n^{TPS}}{(1+i)^n} \tag{21}$$

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

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

$$R = C^* - C \tag{22}$$

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

a. The increased reliability and the improved quality of the electricity offered by the PV and ESS-based solution.

b. The reduction of the environmental (air pollution, oil leakages, thermal waste etc.) and macroeconomic (exchange loss and political dependency due to oil imports) impacts.
c. The need for gradual replacement of the existing outmoded internal combustion engines in the course of time.

5. Application Results

The developed methodology is then applied to three typical cases representing the three distinct regions of Aegean Archipelagos, i.e. the island of Agios Efstratios (North Aegean), Anafi (Cyclades Complex) and Megisti (Dodecanese Complex), see figure (1) and Table II. During the present analysis emphasis is given first to calculate the impact of the PV generator nominal power on the energy balance of the installation and secondly to investigate the viability of an integrated PV and ESS-based electricity generation solution in comparison with the existing solution based on fossil fuel utilization. Finally, the impact of the available energy storage configurations on the financial behavior of the proposed solution is also examined.

Table II: Main Parameters of Small Islands Examined

Island	Peak Power Demand (kW-2005)	Total Annual Energy Consumption (MWh-2005)	Population (2001 census)	Area (km^2)
Agios Efstratios	290	987	307	43.2
Anafi	420	984	272	38.4
Megisti	560	2067	403	8.9

5.1. Brief Description of the Island Cases Analyzed

As already mentioned, three typical very small islands have been selected representing (figure (1)) the three major divisions of Aegean Archipelagos area. More precisely, Agios Efstratios is a small triangular volcanic island (307 habitants, area of 43km²) of North Aegean Sea, located between Lesvos, Limnos and Skiros islands. The topography of the island is typically Aegean, i.e. gentle slopes, absence of flat fields, low hills and sparse vegetation. The main economic activities of the local society are agriculture, merchant marine and tourism. The annual energy production of the local APS was only 990MWh for 2005. The peak load demand - approximately 290kW- appears during August 15, while the corresponding minimum value is 70kW (18 April), see also figure (4). Although the island has an outstanding wind potential, its isolated character and the small size of the local electrical network hinters the exploitation of the local wind potential. For these reasons, an abandoned wind converter of 110kW exists on the island, presenting major failures. However, the island possesses also high solar potential (figure (5)) encouraging the installation of a PV generator, with much lower maintenance needs.

Accordingly, Anafi is also a very small island (population 272 habitants -approximately 70 families- area of 39km²) at the southeast edge of Cyclades complex. There is a complete lack of fresh water in the island, thus it has no remarkable flora and fauna. The local terrain is quite relief, including rocky hills and absence of flat fields. At the west side of the island, there exist certain geothermal springs, not used up to now. The main economic activities of the local society are fishing and tourism. The annual energy production of the local APS was 990 MWh for 2005. The peak load demand - approximately 420kW- appears during mid-August, while the corresponding minimum value is 55kW (2 January). The island has very good solar potential, since the annual mean solar energy approaches 1700kWh/m^2, at horizontal plane (figure (5)). Besides, the traffic network of the island is only 2km, connecting the only village of the island to the small port.

Finally, Megisti was until recently the easterly European Union (EU-15) edge, located almost 72 miles from Rhodes. The island area is only $9km^2$ and the population is 403 permanent habitants (approximately 100 families). The local terrain is arid and rocky with several caves. The annual energy production of the local APS was 2100 MWh for 2005. The peak load demand -approximately 560kW- appears on August 13, while the corresponding minimum value is 120kW (8 May). The main economic activities of the local society are fishing and tourism, although in the past the habitants were distinguished merchants. The island has also excellent solar potential, since the annual mean solar radiation exceeds $1700kWh/m^2$, at horizontal plane (figure (5)). There is no traffic network in the island despite the existence of a small airport. In Table II one may find the available data concerning the parameters involved in the present analysis.

5.2. Energy Balance of the Proposed Installation

Applying the proposed analysis for Agios Efstratios island one may observe in figure (8) the contribution of the existing APS "δE" to the annual electricity consumption as a function of the photovoltaic generator peak power "N_{PV}" and the size of the ESS "d_o". Actually, there is a considerable "δE" decrease as "N_{PV}" increases leading to zero APS contribution for PV generator peak power equal to $950kW_p$ and d_o=24h. In this case the small island community covers its annual electricity needs almost exclusively on the basis of the available solar energy and the existing ESS. On the other hand, for lower "d_o" values the contribution of the local APS is greater than a given value, e.g. 23% and 48% for 12h and 6h of energy autonomy of the ESS respectively. In these two cases the penetration of solar energy is bounded by the capacity of the selected ESS.

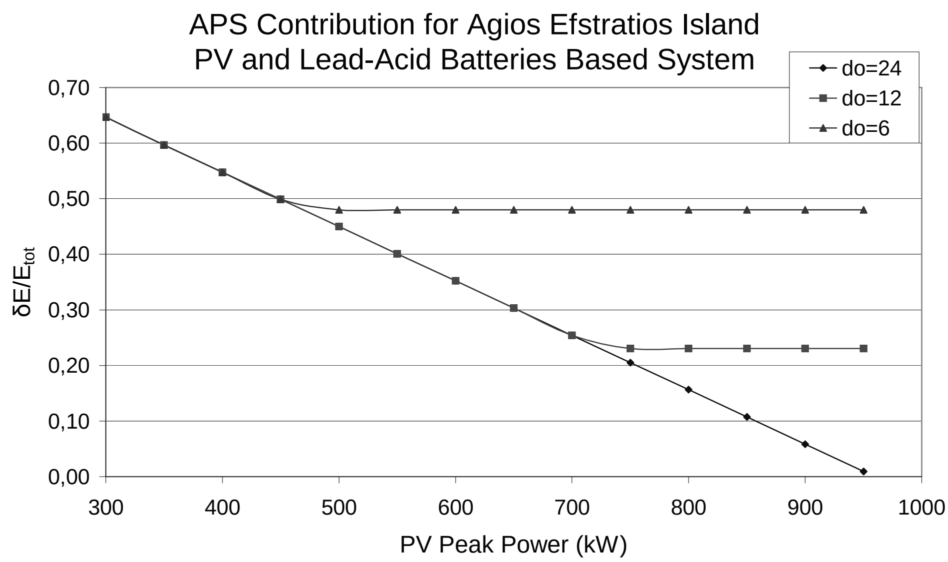

Figure 8: Contribution of local APS to the electricity consumption of Agios Efstratios island

This picture is also supported by the information of figure (9), where one may find the contribution "ε" of the ESS in the coverage of the annual energy consumption of the island. Thus, one may see an almost linear increase of "ε" with "N_{PV}", which for d_o=24h approximates 72%, while for the other two cases examined (d_o=12h and d_o=6h) is limited by the existing ESS capacity at 50% and 25%, respectively.

Another more interesting information is included in figure (10), where one may observe that in cases of low ESS capacity a considerable part of the PV generator production (up to 50%) is finally rejected, since it can neither absorbed by the consumption due to low load demand nor stored at the ESS due to the limited storage capacity of the installation. In order to get a comparative idea of the variation of all three parameters examined above one may find in figure (11) their distribution vs. the rated power of the PV generator for d_o=12h. As it is obvious from the results obtained at the point that the ESS contribution is stabilized due to its limited storage capacity, the local APS contribution remains also constant, while at the same time a considerable PV energy rejection is encountered.

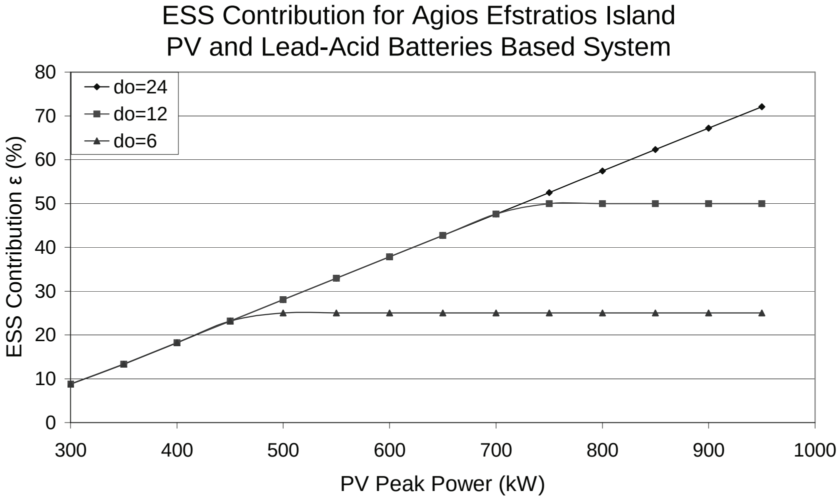

Figure 9: ESS participation to the electricity consumption of Agios Efstratios island

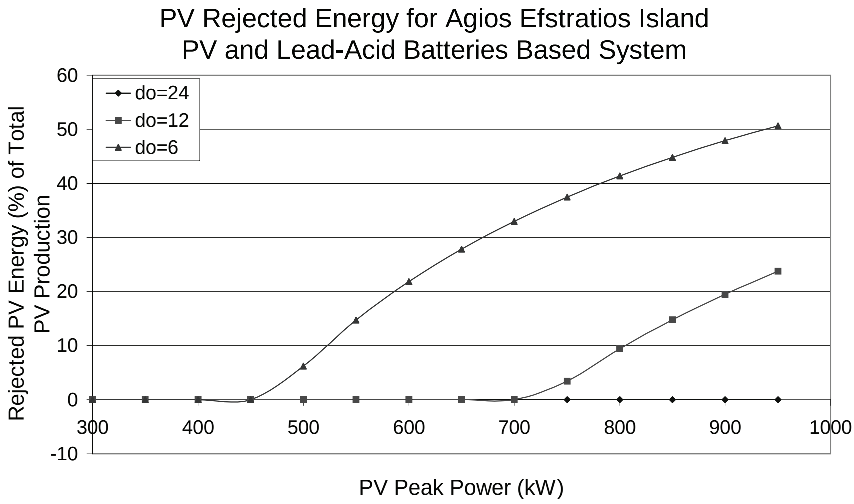

Figure 10: PV energy surplus for Agios Efstratios island

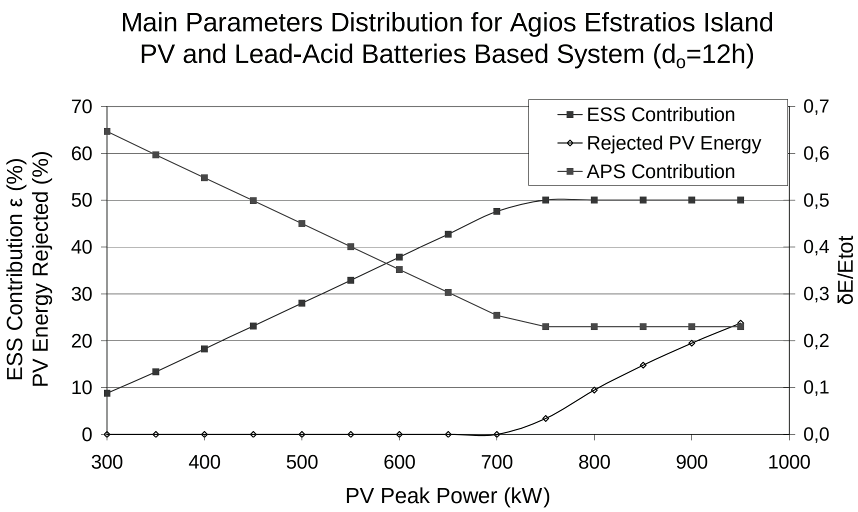

Figure 11: Distribution of the main parameters of the proposed PV-Lead acid batteries based electricity generation solution for Agios Efstratios island

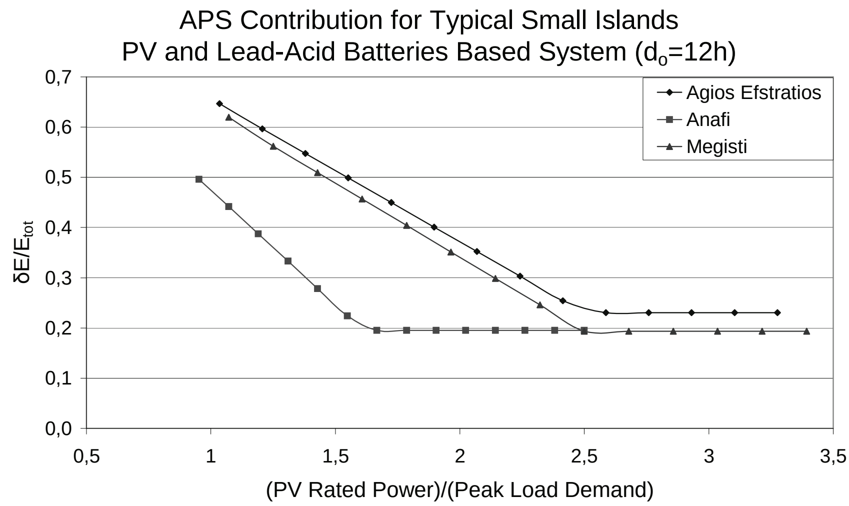

Figure 12: Contribution of local APS to the electricity consumption of typical small islands

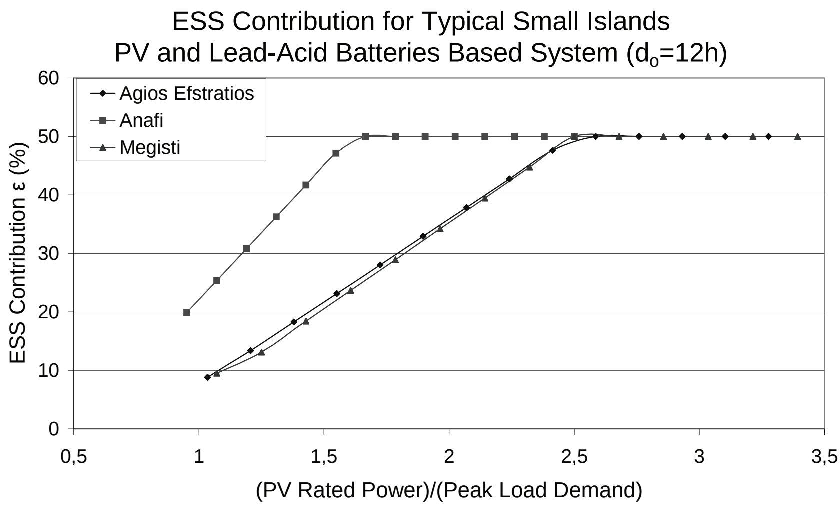

Figure 13: ESS participation to the electricity consumption of typical small islands

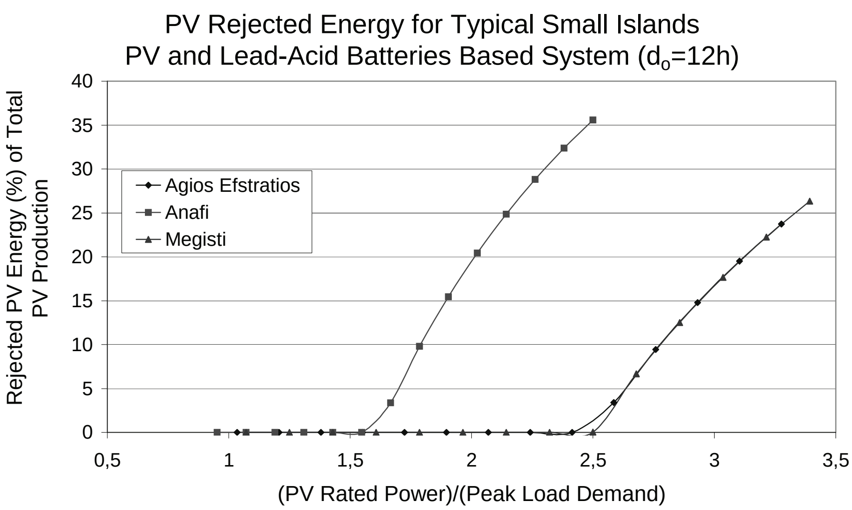

Figure 14: PV energy surplus for typical small islands

The same comments are also valid for Anafi and Megisti islands, see for example figures (12) to (14) for the d_o=12h energy autonomy scenario of the ESS. In fact, in figure (12) one may examine the local APS contribution decrease with rated power of the PV generator (expressed as a ratio of the corresponding network peak load demand). Due to the higher peak load demand of Anafi island network, this island presents a slightly different distribution. However all islands APS contribution converges to a constant value, which is higher for Agios Efstratios and lower for Megisti island, being however in all cases near 20%.

Accordingly, in figure (13) one may find the ESS annual contribution for all islands examined. It is interesting to note that all three cases present similar distributions, while their ESS contribution finally approaches the value of 50%, a value that is imposed by the desired hours of energy autonomy of the ESS, see also figure (9). Finally, the rejected PV energy production is demonstrated in figure (14) for all islands examined. It is worthwhile mentioning that there is no energy rejection as far as the ESS contribution is increasing, see also figure (11). After that point a remarkable energy rejection increase is encountered, which is higher for Anafi island and lower for Agios Efstratios case.

5.3. Financial Analysis Results

In the second part of the proposed analysis one may compare the life-cycle (n^*=30 years) total electricity generation cost values for all three islands investigated. In this context, in figure (15) one can see the total cost distribution for Agios Efstratios island as a function of the PV generator rated power for typical ESS capacity values in comparison with the corresponding total cost of the existing APS. For all "d_o" values analyzed, there is a minimum cost configuration which corresponds to approximately 950kW$_p$ for d_o=24h, 700kW$_p$ for d_o=12h and 450kW$_p$ for d_o=6h. Note also that almost all the PV-ESS configurations tested are most cost-effective than the solution based on the existing APS. Finally, the minimum cost solution is realized for medium energy autonomy of the system, i.e. d_o=12h, while the corresponding 30-year energy production cost (in present values) is 4.9M€ in comparison with the 6.4M€ required by the local APS during the same time-period. However, if this solution is selected, one should accept an annual contribution of the local APS equal to almost 23% of the annual energy consumption of the island. In the case that one requires minimum (zero) fossil fuel contribution the 950kW$_p$ and d_o=24h solution is the best alternative. In this case the 30-year energy production cost (in present values) is 5.1M€, slightly higher than the minimum cost one (4.9M€), in addition to the elimination of the environmental and macroeconomic impacts related to the oil consumption.

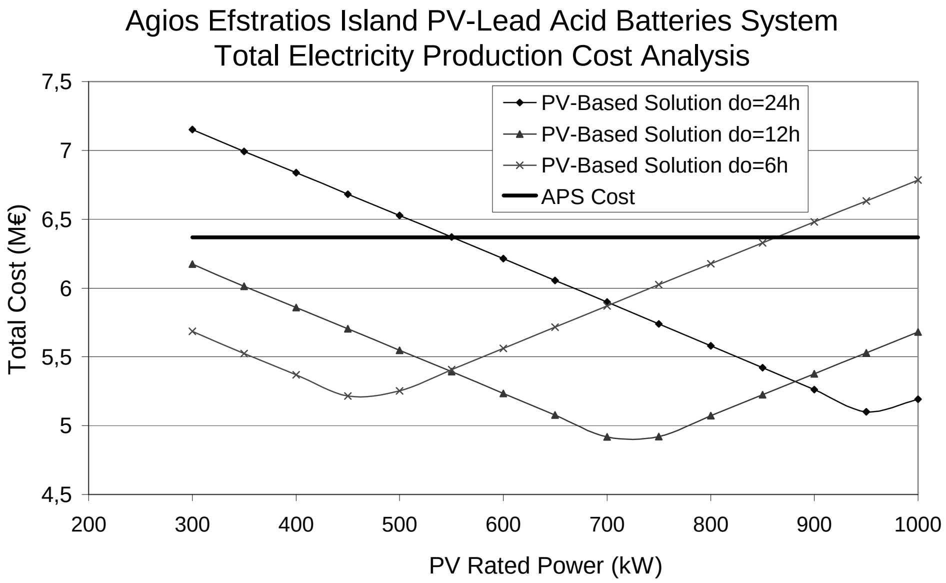

Figure 15: Total cost analysis of the proposed PV-Lead acid batteries electricity generation solution for Agios Efstratios island

The situation is quite different for Anafi island, taking into consideration the quite higher electricity generation cost and peak load demand of the island in relation to Agios Efstratios case. Besides, the solar potential of Anafi is also higher than Agios Efstratios. In fact, there is also a minimum total cost configuration, figure (16), for all ESS capacity values examined, which corresponds to approximately 850kW$_p$ for d$_o$=24h, 700kW$_p$ for d$_o$=12h and 450kW$_p$ for d$_o$=6h. In this island case, the minimum total cost configuration is achieved for 850kW$_p$ and d$_o$=24h, while the corresponding 30-year energy production cost (in present values) is 4.8M€ in comparison with the 9.4M€ required by the local APS during the same time-period. An additional benefit of the proposed solution is the practically zero oil contribution to the total energy consumption along with the corresponding environmental and macroeconomic benefits.

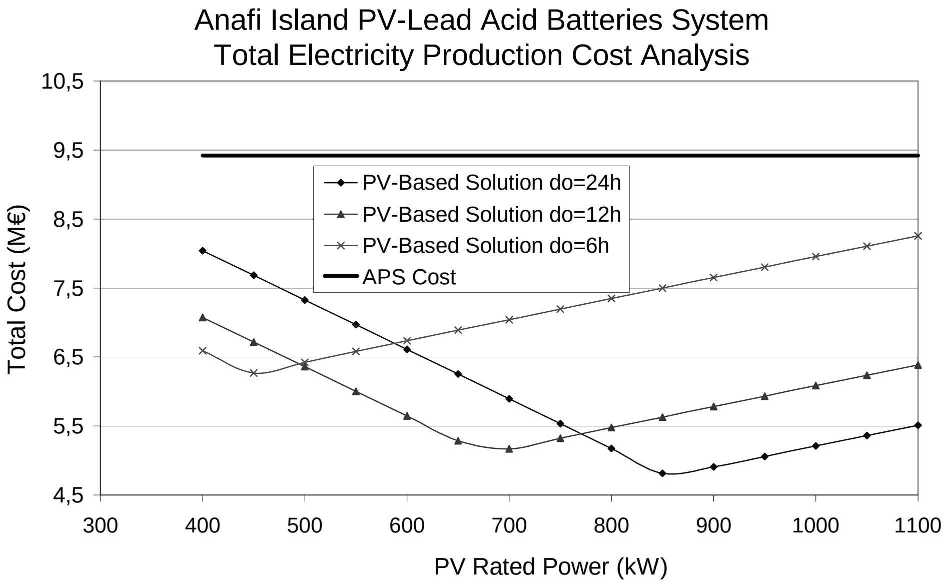

Figure 16: Total cost analysis of the proposed PV-Lead acid batteries electricity generation solution for Anafi island

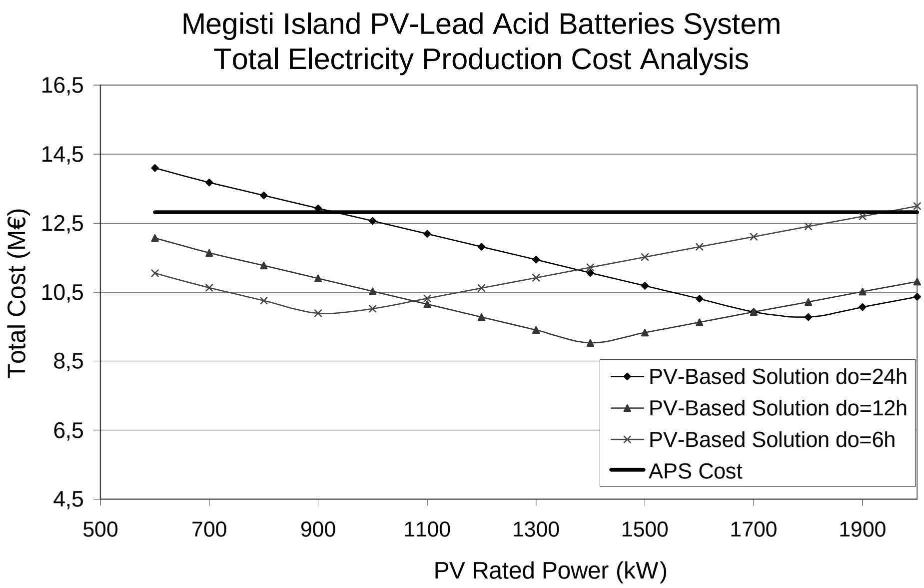

Figure 17: Total cost analysis of the proposed PV-Lead acid batteries electricity generation solution for Megisti island

Finally, the last case examined concerns the Megisti island, which is the one with the best solar potential (figure (5)) and the minimum electricity production cost of the examined small APS. On top of this, the annual energy consumption and the corresponding peak load demand of the island are almost double of the corresponding values of the other two islands. The results of the specific island characteristics lead to lower total cost savings of the proposed PV-ESS solution in comparison with the APS operation, figure (17). As in the previous island cases, there is also a minimum total cost configuration for all ESS capacity values examined, corresponding to approximately 1800kW$_p$ for d_o=24h, 1400kW$_p$ for d_o=12h and 900kW$_p$ for d_o=6h. On the other hand, the minimum cost solution is realized for medium energy autonomy of the system, i.e. d_o=12h, while the corresponding 30-year energy production cost (in present values) is 9.0M€ in comparison with the 12.8M€ required by the local APS during the same time-period. In case that the minimum oil contribution is selected, the proposed configuration is based on 1800kW$_p$ and d_o=24h, while the corresponding 30-year energy production cost (in present values) is 9.8M€, less than 10% higher than the minimum cost one (9.0M€).

Recapitulating for all test cases analyzed, the proposed PV-ESS based solutions present quite lower life-cycle cost values than the operation of the existing APS, imposing also considerable environmental and macroeconomic benefits. On top of this, for all cases a minimum cost solution may be located, which maximizes the cost savings of the configurations investigated.

5.4. Energy Storage Technology Impact

To get a clear cut picture of the selected energy storage technology impact on the total electricity production cost arising, four different energy storage technologies, i.e. lead-acid batteries, Na-S batteries, pumped-hydro (PHS) and fuel cells (FC) will be examined on the basis of the PV power installed and the ESS hours of autonomy selected. Actually, if the desired autonomy of the ESS is determined, a direct comparison of the systems under examination may be realized. The results currently presented, similar for all the three islands studied, refer to the island of Agios Efstratios.

Consequently, in figure (18) one may note the impact of the selected energy storage technology on the total electricity production cost for a desired autonomy of 24hours. More specifically, if the PV-ESS configuration employs either a PHS or a Na-S batteries system then the proposed solution proves to be cost-effective regardless the PV station's rated power. Moreover, for two of the combinations available, i.e. for a PHS or a Na-S batteries system able to provide energy for 24 consecutive hours and collaborating with a PV station of 1000kW and 900kW respectively, a minimum total cost solution is obtained. The total cost of this solution is less than 2/3 of the corresponding one referring to the existing electrification solution and thus demonstrates the proposed solutions' clear competitive advantage. In this context, the Na-S batteries solution may be the best alternative in cases that the local topography and the status of the existing water resources hinters the application of PHS.

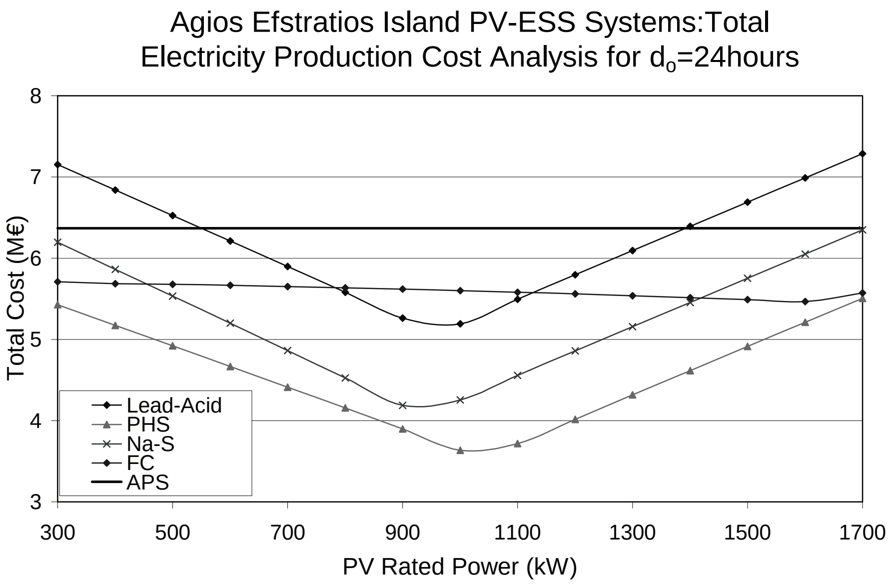

Figure 18: Comparison of the total cost distribution vs. PV rated power for various PV-ESS configurations. High energy autonomy case, Agios Efstratios island

On the other hand, the lead-acid batteries technologies investigated demonstrate relatively higher production cost, in some cases exceeding the one ascribed to the APS operation. More precisely, if the nominal power of the PV station is kept under 550kW or exceeds the 1400kW, the configurations available present higher electricity generation cost than the existing APS. However, the corresponding minimum total cost solution presents quite lower life-cycle cost value than the existing APS option. Concerning the FC alternative, one should note the relatively constant total cost distribution versus the PV station rated power, while the combinations available prove to be more attractive than the APS solution. In any case, the resulting costs, when compared to the analogous of PV-PHS and PV-Na-S batteries configurations, are 30% higher. Only for very high PV rated power values the FC solution becomes more cost-effective, underlining the potential applicability of this technology for larger autonomous electrical systems.

In figure (19), certain similarities regarding the cost behavior of the systems examined may be observed for the medium energy autonomy case (d_o=12h). More precisely, the PHS systems appear to be a marginally less expensive solution compared to the faintly more expensive Na-S batteries one. As in the previous figure, lead-acid batteries and FC demonstrate significantly higher production costs, with the latter still comprising the most unfavorable of the solutions, at least for the central part of the autonomy range examined. Besides, it is interesting to note that for the 12 hours autonomy case, regardless the photovoltaics' rated power, the local APS total production cost is constantly greater than the various solutions proposed. Moreover, between the range of 700kW and 800kW for the PV station's nominal power, one may encounter several attractive configuration proposals, especially in the cases of PHS and Na-S batteries.

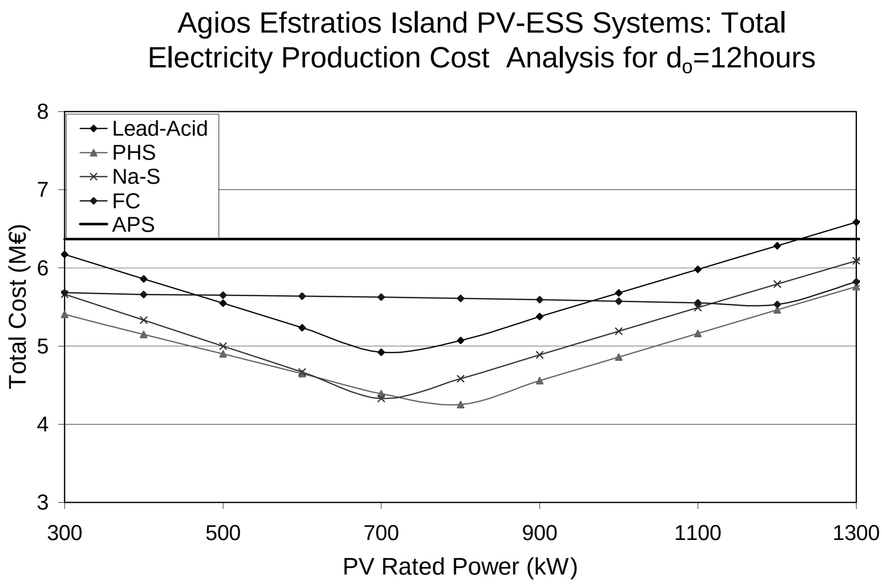

Figure 19: Comparison of the total cost distribution vs. PV rated power for various PV-ESS configurations. Medium energy autonomy case, Agios Efstratios island

Finally, in figure (20), where a lower energy autonomy value is to be considered (d_o=6hours), one may note that the total cost deviation range has narrowed considerably, not allowing for the designation of a clear solution-proposal to mind for. Nevertheless, it is the PHS and Na-S batteries that present the lowest of the resulting life-cycle production costs with lead-acid batteries and FC following. Although not presenting serious deviation, FC for low and lead-acid batteries for higher PV rated values demonstrate the higher costs for 6 hours of energy autonomy as well. Besides, if considering for the installation of a PV station exceeding 850kW, the proposed configurations en masse should not be preferred instead of the local thermal power station currently supplying the area.

Recapitulating, for all the energy autonomy cases investigated, the PHS along with the Na-S batteries systems comprise the two most attractive solutions to adopt, while for low and medium "d_o" values both solutions present almost the same total cost. It is worthwhile mentioning that the optimum (minimum cost) PV rated power value is decreasing (from 1000kW to 500kW), while the corresponding total cost value is increasing (from 3.6M€ to 4.9M€) as the desired energy autonomy value decreases. Altogether, the majority of potential configurations to adopt, apart from those included in the two selection spectrum edges (low PV power installed-high autonomy rates and vice versa), suggest the incorporation of both viable and cost-effective electricity supply solutions, able to efficiently substitute the up to now operating APS of the islands.

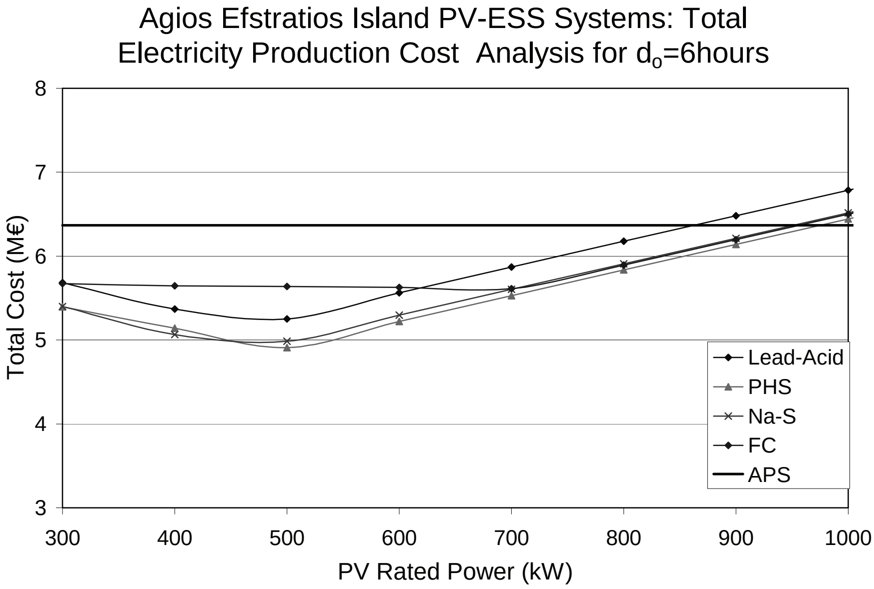

Figure 20: Comparison of the total cost distribution vs. PV rated power for various PV-ESS configurations. Low energy autonomy case, Agios Efstratios island

6. Conclusions

The possibility of using a photovoltaic generator along with an appropriate energy storage system in order to replace the existing thermal power stations used up to now to cover the electricity consumption needs of small remote islands is investigated. The proposed solution is encouraged by the high solar potential of the area, the rather low maintenance support demands of PV installations and the low quality of electricity available up to now at very high production cost. Moreover, PV systems require no imported fuel and produce no emissions, thus contributing on climate change mitigation and pollution reduction.

One of the main targets of the proposed solution is to maximize the solar energy exploitation of the area at minimum electricity generation cost, while special emphasis is given to the selection of the most cost-efficient energy storage configuration available. For this purpose, an integrated methodology is developed in order first to estimate the main parameters of the combined PV-ESS based configuration and accordingly to evaluate the economic viability of the proposed solution. The developed methodology is subsequently applied on three representative autonomous small island cases. The calculation results are very encouraging, since in all cases the proposed solution leads to quite lower electricity production cost than the existing thermal power stations. According to extensive calculations, the pump-hydro storage for the entire energy autonomy range and the Na-S batteries for medium and low energy autonomy cases are the most cost effective energy storage techniques. On top of this, the utilization of an appropriate ESS improves the financial behavior of the PV-based power station leading also to much higher solar energy penetration levels in the local energy market.

Additionally, taking into consideration the sensitive ecosystem of the islands and their particular cultural heritage, PV systems seem to be in accordance with a mild development and, furthermore, attract more educated and high standards tourists, thus contributing to their regional development. This fact will encourage further exploitation of the European financing and the attraction of investments in the erection of PV projects on the tourist installations and activities. As far as the energy policy is concerned, the wide application of PV systems in the Hellenic tourist areas will further promote RES applications at a national level. The above mentioned ideas will create a totally new dimension to the tourist offer of Hellenic islands and the creation of a new differentiated energy balance including a strong environmental direction.

Recapitulating, it is worthwhile mentioning that an integrated electrification solution based on the exploitation of the available solar potential in collaboration with an appropriate energy storage configuration is not only a financially attractive but also an environmental friendly solution for the existing small remote island communities. In fact, the proposed power stations are able to substitute the expensive and heavy polluting existing thermal power stations, improving the reliability of the local electrical networks and the quality of the energy offered.

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PART TWO

ELECTRICAL GENERATION IN ISLANDS

PRESENT SITUATION AND FUTURE PROSPECTS OF ELECTRICITY GENERATION IN AEGEAN ARCHIPELAGO ISLANDS

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Abstract

The Aegean Archipelago is a remote Hellenic area, including several hundreds of scattered islands of various sizes. In these islands more than 600,000 people are living mainly in small remote communities. The main economical activities of the islanders are apart from tourism, seafaring, fishery, agriculture and stock farming. One of the major problems of the area is the insufficient infrastructure, strongly related with the absence of an integrated and cost effective electrification plan. In this context, the present work is concentrated on analyzing the present situation and demonstrating the future prospects of electricity generation in the Aegean Archipelago islands. For this purpose, one should first investigate the time evolution of the corresponding electricity generation parameters (i.e. annual electricity consumption, peak power demand, capacity factor, specific fuel consumption) for the last thirty years. Subsequently, the corresponding diesel and heavy-oil consumption along with the electricity production cost for every specific autonomous power station of the area are investigated. Special attention is paid in order to estimate the contribution of renewable energy sources (RES) in the energy balance of each island. Finally, an attempt is made to describe in brief the most realistic electricity production solutions available, including the operation of hybrid RES-based power plants in collaboration with appropriate energy storage facilities. Additionally, the idea of connecting the islands of the area with the mainland and interconnecting them is also taken into consideration.

Keywords: Electricity Generation; Peak Load; Autonomous Power Station; Remote Islands; Wind Energy

1. Introduction

The Aegean Archipelago is a remote Hellenic area, including several hundreds of scattered islands of various sizes, see figure (1). For administrative purposes these islands are divided in two large groups, i.e. the islands belong either to the North or to the South Aegean region. In fact, the former area includes the prefectures of Lesvos, Chios and Samos, while the latter contains the prefectures of Cyclades and Dodecanese. On top of these islands, in the Aegean Sea one may find the Sporades complex, located in the NW of the Aegean Archipelago and belonging to the Magnesia prefecture (Thessaly-mainland), excluding the Skiros island, which is part of the Euboea prefecture. In addition to the islands already mentioned, one should mention the islands of Samothrace and Thassos, both situated in the north Aegean Sea and belonging to the Evros and Kavala prefectures respectively. Finally, in SE of Peloponnesus there exist the small islands of Kithira and Antikithira. In the present analysis the island of Crete, being the biggest Greek island, is excluded, since it is the subject of several independent studies by the authors and by other researchers[1].

According to official data[2], the permanent population of the area presents a rather divided picture. Thus, as shown in figure (2), permanent population increase has been noticed in the case of the South Aegean region during the last fifteen years, while in the case of the northern islands the permanent habitants' number remains relatively stable with a slightly declining trend. The main economic activities of the islanders, presenting a strong variation among different islands, are apart from tourism, seafaring, fishery, agriculture and stock farming. On the other hand, industry has not yet been developed.

Figure 1: Aegean Archipelago Complex of Islands

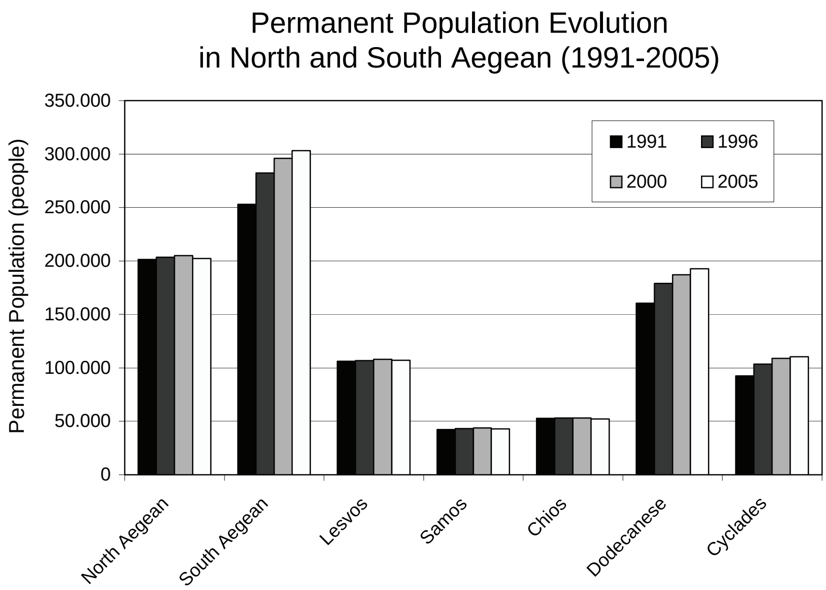

Figure 2: Permanent population evolution in the Aegean Archipelago region

Recapitulating, in Table I one may find some additional information concerning the Aegean Archipelago islands, i.e. area, permanent population, annual tourists' arrivals, major islands and biggest cities. One should also not disregard that most islands of S. Aegean face serious water shortage problems[3]. According to the existing data the biggest islands of the area are the islands of Lesvos, Chios, Rhodes, Samos, Lemnos, Naxos, Siros, Mikonos, Santorini, Paros, Karpathos, Kos, Kalimnos, Ikaria, Skiros and Skiathos. The biggest cities of the area are Mitilene, which is the administrative centre of the North Aegean region, Rhodes which is the biggest city of the Archipelago, Siros being the administrative centre of the South Aegean region, and Chios.

Table I: Basic data concerning the Aegean Archipelago region

Prefecture	Population (2005 estimations)	Area (km^2)	Annual Tourists Arrivals (2004)	Major Islands	Big Cities
Lesvos	107,050	2,154	135,023	Lesvos, Lemnos	Mitilene, Mirina
Chios	52,337	904	46,360	Chios	Chios
Samos	43,015	778	114,445	Samos, Ikaria	Samos
Cyclades	110,400	2,572	325,917	Paros, Siros, Mikonos, Andros, Naxos	Hermoupolis, Naxos, Tinos, Paros, Andros, Milos
Dodecanese	192,714	2,663	1,556,250	Rhodes, Kos, Kalimnos, Karpathos	Rhodes, Kos, Kalimnos

2. The Existing Electricity Generation System of the Islands

The electricity demand in the Aegean Archipelago islands has up to now been covered[4] by the existing (thirty two) Autonomous Power Stations (APS), based on internal combustion engines and gas turbines, which belong to the former Greek Public Power Corporation (PPC). In specific cases, like in those of Thassos, Samothrace and Sporades (excluding Skiros), the islands are connected to the nearest available mainland electrical network. The existing APS total installed capacity is approximately equal to 800 MW, while the corresponding electricity generation during 2005 is almost 2200GWh[5].

The rated power of the existing thermal power units varies from 100kW in the case of very small islands up to 36MW for the gas turbine operating since 1987 in Rhodes island. In figure (3) we demonstrate the number of "in operation" thermal power units (internal combustion engines and gas turbines) divided according to their rated power. Using the available information, approximately 220 thermal power units operate in the Aegean Archipelago, most of them being in operation for almost twenty years. The result of this situation is that several units present serious problems, being out of service for remarkable time periods, while their real output is almost 15% less than their rated power, especially during summer.

In order to facilitate the in depth analysis of the electricity generation problems in the Aegean Archipelago APS, one may divide the existing power stations in five subgroups, on the basis of their rated power, see also Table II. More precisely, the first group includes the existing big APS, with rated power higher than 50MW, like the ones of Rhodes, Lesvos, Kos-Kalimnos etc. The last group includes very small islands, with rated power less than 1MW. In this category one may find the tiny islands of Agios Efstratios, Donoussa, Megisti etc.

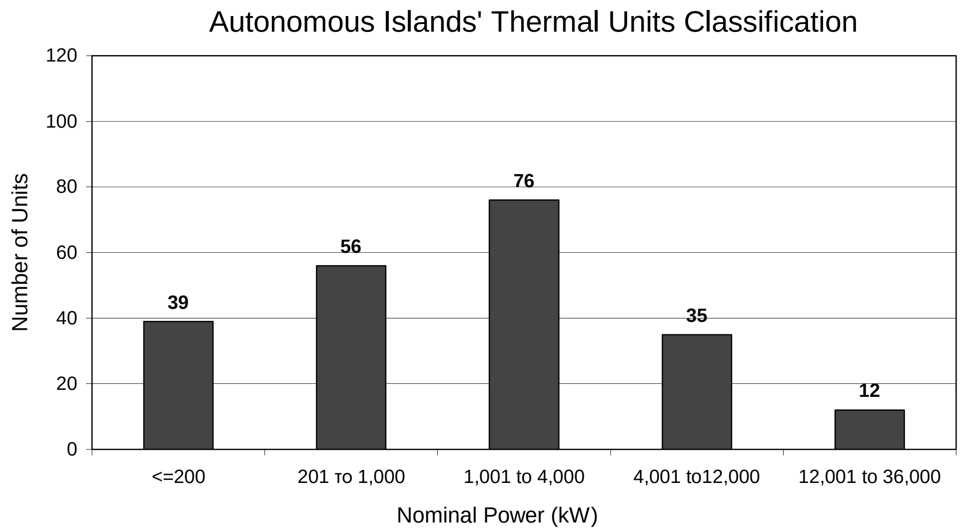

Figure 3: Existing thermal units in Aegean Archipelago on the basis of their rated power

Table II: Aegean islands classification in terms of APS installed capacity

Category (Scale)	APS Installed Capacity (MW)	Islands
Very Small	<1 MW	Agathonissi, Agios Efstratios, Anafi, Antikithira, Donoussa, Erikousses, Megisti, Othoni.
Small	>1 MW & <9 MW	Amorgos, Astipalea, Kithnos, Samothrace, Serifos, Sifnos, Simi, Skiros.
Medium-Small	>9 MW & <20 MW	Ikaria, Ios, Karpathos, Milos, Patmos.
Medium	>20 MW & <50 MW	Andros, Lemnos, Mikonos, Santorini, Siros.
Big	> 50 MW	Chios, Kos-Kalimnos, Lesvos, Paros, Rhodes, Samos

Comparing the "in operation" real power of the existing APS with the peak load demand of 2005, figure (4), one may easily conclude that in several cases there is a very narrow power security margin, hence the local APS do not guarantee the consumers' safe electricity supply, especially in occasions of serious malfunction of a major unit of the system or in cases of unexpected high load demand. On top of this, a remarkable power addition is necessary in order to face the continuously increasing power demand during the next few years.

Finally, one additional severe problem of the existing electricity generation systems is the intense electrical load demand fluctuations encountered in daily and annual basis, figure (5) and figure (6). According to the available information, the summer peak load demand may be almost five-times the minimum winter load demand, while even during the same day one may observe load demand variation between ±60% of the corresponding daily average power required. This situation, strongly influenced by the significant touristic activity, mainly during summer, poses additional problems on the electricity production system of the islands, leading a large portion of the existing thermal power units to quite low capacity (utilization) factor values.

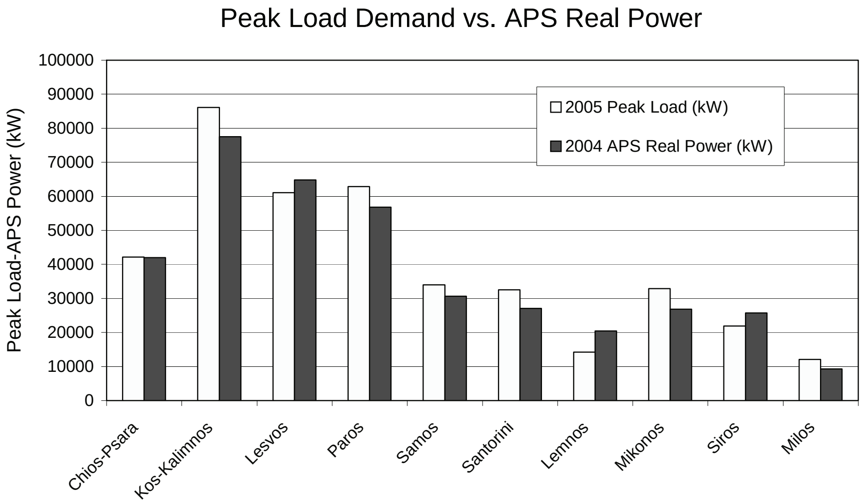

Figure 4: Peak power demand vs. "in operation" power in Aegean Archipelago islands

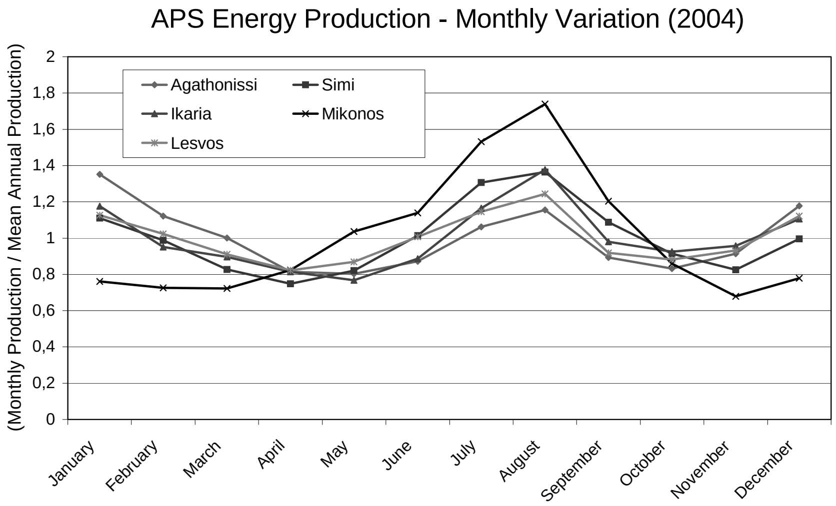

Figure 5: Annual electricity consumption variation in Aegean Archipelago islands

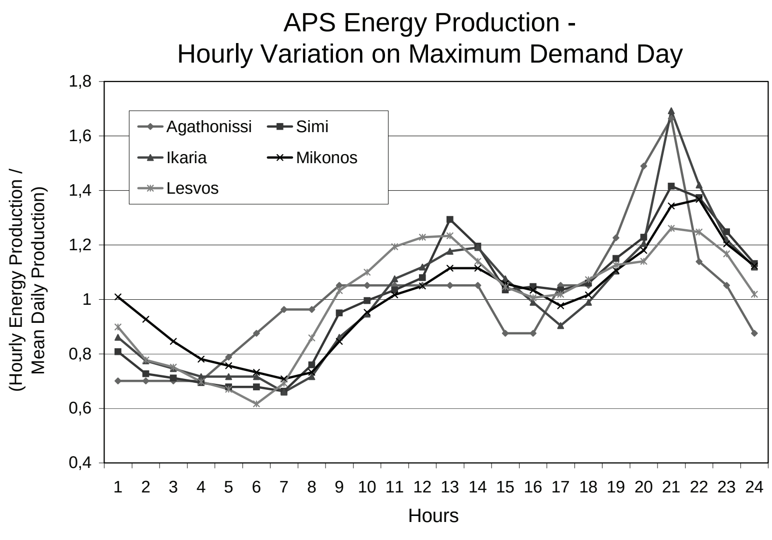

Figure 6: Daily electricity consumption variation in Aegean Archipelago islands

3. Electricity Generation Time-Evolution

In the following one should investigate the main parameters describing the electricity generation in the Aegean Archipelago islands in the course of time. Note that the figures presented take into account only the non-interconnected islands of the Aegean Archipelago during 2005, i.e. excluding Samothrace, Tinos, Andros etc. In fact, one may analyze the annual electricity production and the corresponding peak load demand for the 1975-2005 period. Accordingly, a short record of the RES contribution to the electricity generation of the non-interconnected islands under investigation is also conducted.

3.1 Electricity Generation

In all cases analyzed, a remarkable long-term electricity generation increase is encountered, which is more intense for the S. Aegean region islands than for the N. Aegean ones. As it results from figure (7) the annual electricity consumption at the beginning of the period examined in S. Aegean was less than the one of N. Aegean. This situation, being in accordance with the increased economic activity of the S. Aegean area, has been completely inversed since 1992. At this point, what is worth mentioning is that after 2004, the electricity generation in Rhodes island alone has surpassed the total electricity production of the entire N. Aegean region.

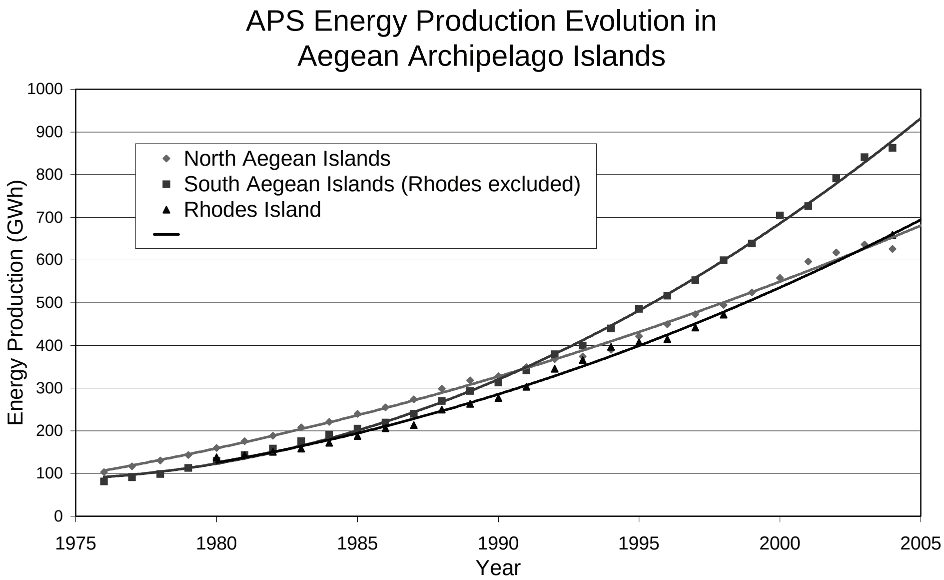

Figure 7: Electricity generation in Aegean Archipelago area

More specifically, according to figure (8), describing the electricity generation time-evolution for the N. Aegean islands, a remarkable electricity production/consumption increase is observed, since the 2005 value is between six and eight times the corresponding value of 1975. The biggest electricity consumption is encountered at Lesvos island (appr. 250GWh/y), while the corresponding values for Chios and Samos islands are approximately 175GWh/y and 125GWh/y respectively. Skiros, located in NW of the Aegean Archipelago, and Ikaria islands present rather fast electricity consumption increase, since their long-term mean annual escalation rate "ε" (see Appendix One, equation (A-1)) is more than 10%. Finally, in 2005 the entire electricity generation of the APS of the N. Aegean Archipelago is almost 680GWh/y.

Accordingly, the electricity generation increase for the islands of S. Aegean is much more intense, especially during the last ten years. This increase is almost exponential for the islands of Santorini (annual increase $\varepsilon \approx 13.6\%$) and Mikonos (annual increase $\varepsilon \approx 10.6\%$), mainly due to their explosive touristic activity, figure (9). In this context, the electricity generation of Kos-Kalimnos APS presents the highest value (exceeding the one of Lesvos island), i.e. approaching the 300GWh/y. Similarly, the

APS of Paros exceeds the 180GWh during 2005, while both APS of Siros and Santorini approach the value of 100GWh annually.

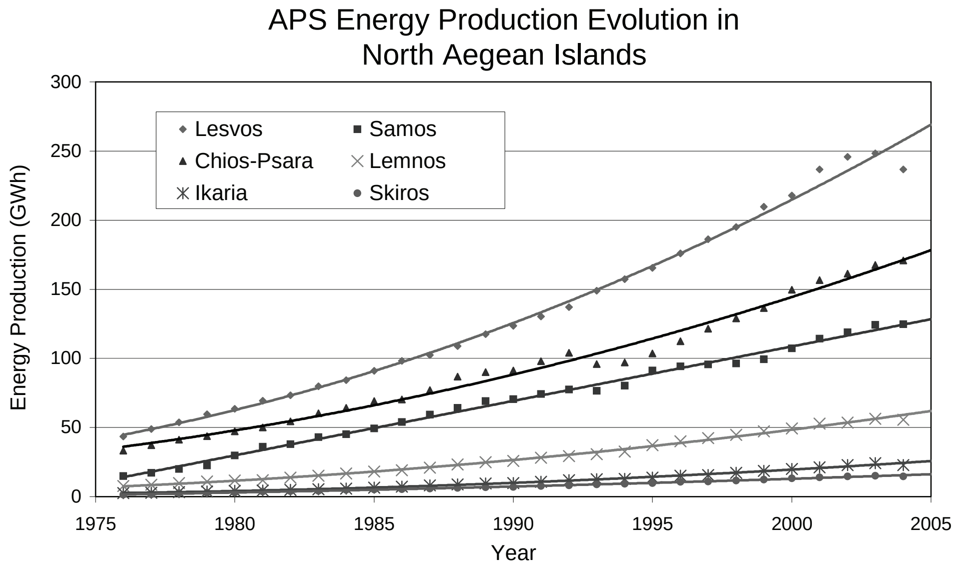

Figure 8: Electricity generation in North Aegean islands

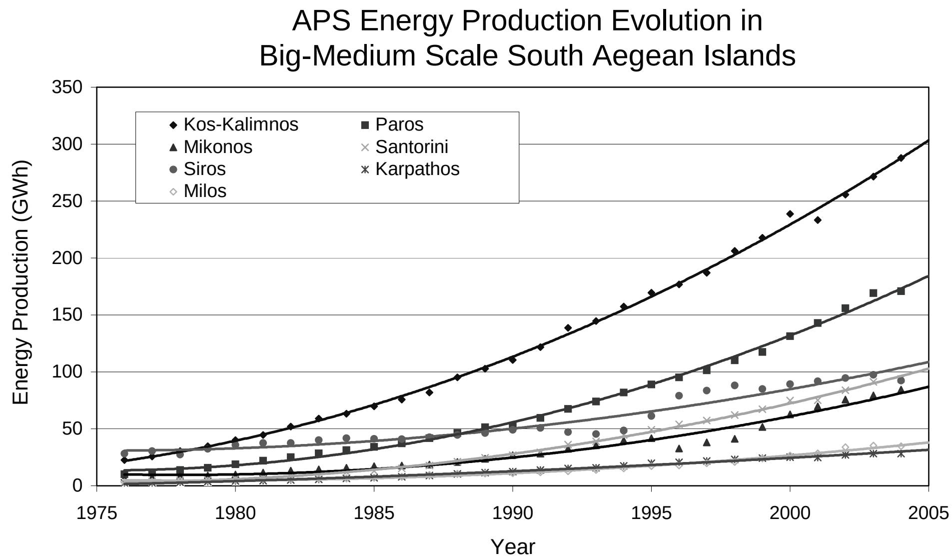

Figure 9: Electricity generation in South Aegean big-medium size islands

Subsequently, the electricity generation of the small size APS of S. Aegean show the same behaviour as the ones of the first group, see figure (10). In fact, most islands of the area present an over-linear electricity consumption increase, while the electricity consumption in 2005 is more than ten-times the corresponding value of 1975, leading to an average annual increase rate "ε" of almost 10% (see Appendix One, equation (A-1)). Summarizing, in 2005 the electricity generation of the APS of the S. Aegean Archipelago (excluding Rhodes) is 950GWh/y, hence the entire electricity consumption of the S. Aegean area (including Rhodes) is almost three times the corresponding value of N. Aegean.

The proposed analysis shows an increased interest for the very small islands of the Aegean Archipelago[6], taking into consideration their poor infrastructure and the dominant importance of the electricity production in everyday life. In figure (11) one may find the time-evolution of their electricity generation. In all cases examined, including the two tiny islands of north Ionian Sea (i.e.

Erikousses and Othoni islands), there is a remarkable electricity generation increase. The corresponding maximum annual electricity consumption does not exceed the 1GWh, excluding the Megisti island electricity generation, which slightly exceeds 2GWh.

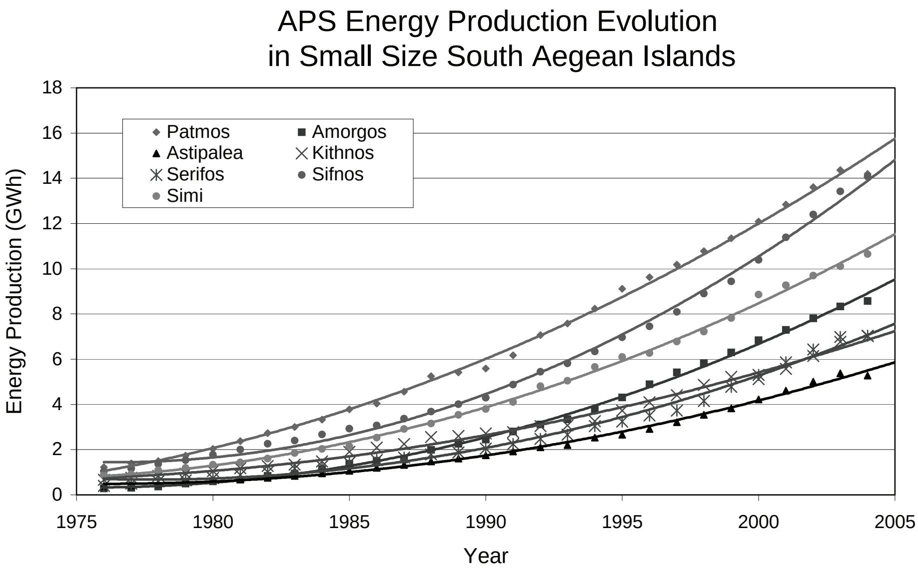

Figure 10: Electricity generation in South Aegean small-medium size islands

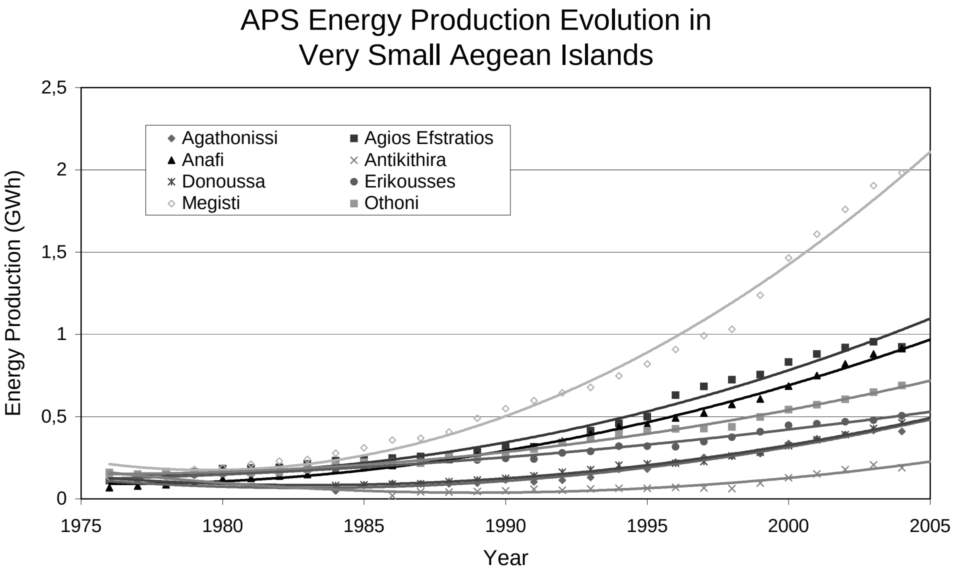

Figure 11: Electricity generation in Greek tiny islands

3.2 Peak Power Demand

According to the available official information[4][7], the peak power demand and annual energy production behaviour of most Aegean Archipelago islands present the same time variation (i.e. parabolic and in some cases exponential increase), resulting in long-term average annual increase rates "$\overline{V}$" of the order of 10% (see Appendix One, equation (A-2)). More specifically, the time evolution of the South Aegean islands is more intense than the one of the N. Aegean area, figures (12) and (13). For example, if one compares the peak load demand time evolution between the Lesvos and the Kos-Kalimnos APS, one should notice that although during 1975 the Lesvos peak power demand was two times the one of Kos-Kalimnos, after 1992 the latter surpassed the maximum load demand of Lesvos island. Therefore, during 2005 the peak load demand of Lesvos island is almost 20% less than the one of Kos-Kalimnos.

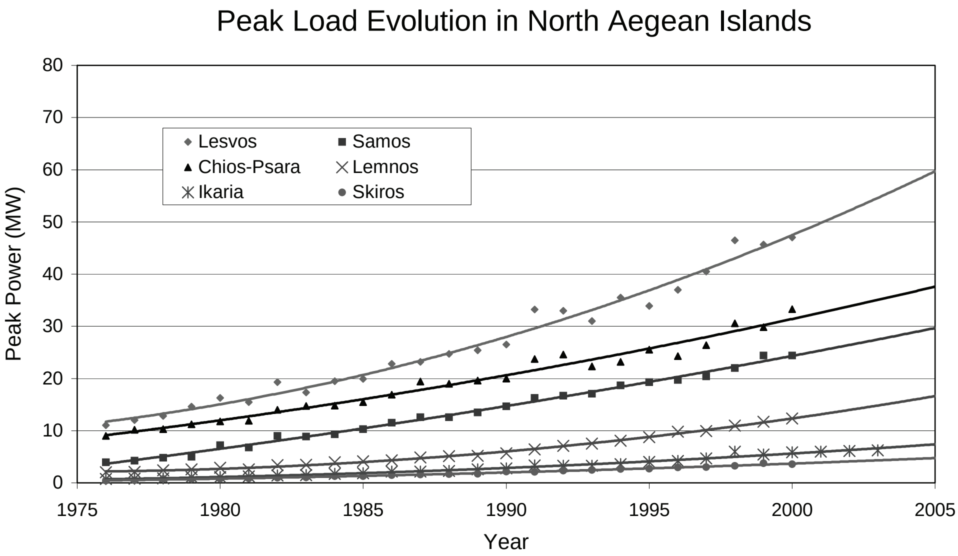

Figure 12: Peak load demand in North Aegean islands

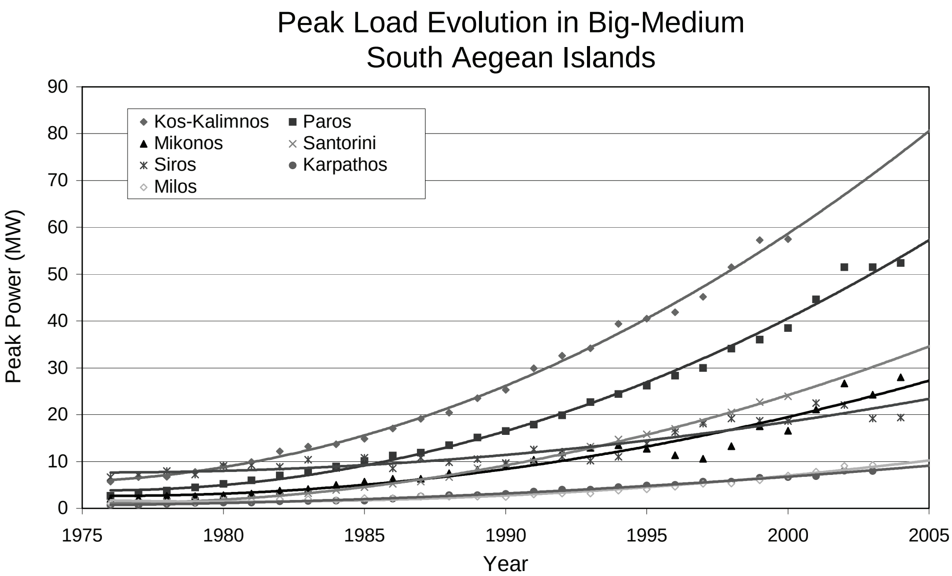

Figure 13: Peak load demand in South Aegean islands

In fact, the islands of Cyclades and particularly Santorini, Mikonos, Milos, Andros, Paros, Sifnos and Anafi along with Skiros and the Dodecanese islands of Kos-Kalimnos, Karpathos and Megisti, all apart from Skiros belonging to the South Aegean region, present the highest increase, mainly owed to the local tourist industry development, see also figure (14). Considering the time-evolution of peak load and energy production in relation with the rate of permanent population changes, one may safely support that the continuous increase of electricity needs is only partially attributed to the permanent population growth. Thus, the determining factors explaining this tendency seem to be the annual visitors' increasing figures and the corresponding improvement of the living standards. Hence, according to the data of figure (14), the annual tourist arrivals (most of them during the summer) increase significantly the population of the Cyclades and Dodecanese complexes, imposing thus an analogous electricity consumption increase when compared to low touristic activity periods. The situation is much more stable for the islands of the N. Aegean area.

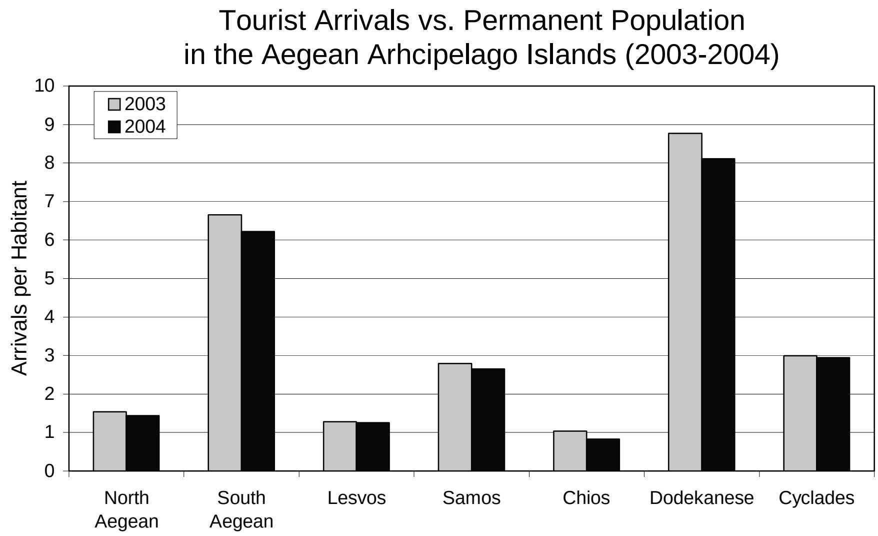

Figure 14: Tourist arrival vs. permanent population in the Aegean Archipelago regions

As already mentioned, in the majority of the islands examined the APS real capacity alone is either insufficient or hardly covering the expected electricity demand increase. The islands of Mikonos, Santorini, Milos, Kithnos and Serifos face the biggest problem. On the other hand, only some of the very small islands like Agathonisi, Agios Efstratios, Anafi and Antikithira are sufficiently supplied. A common strategy, recently adopted once again, dictates the impermanent installation of support units (e.g. gas-turbines) in order to serve for the islands' needs during the summer season. In this context, in May 2006, the Greek Ministry of Development approved the licensing of installing additional thermal electricity generation units of 85.7MW, so as to ensure the electricity demand satisfaction during the 2006 summer in thirteen (13) of the non-interconnected islands of the Aegean Archipelago, see also Table III[5]. However, by facing the urgent problems of the islands only on annual basis, one cannot apply a long-term energy strategy for the development of the area.

Table III: Additional thermal power to be installed in 2006

Island	Rated Power	Island	Rated Power
Karpathos	2MW	Kithnos	2MW
Rhodes	20MW	Lesvos	13MW
Lemnos	1MW	Milos	4MW
Mikonos	22MW	Paros	4MW
Samos	5MW	Sifnos	0.6MW
Siros	2MW	Chios	10MW
Megisti	0.1MW		

On the other hand, in order to ensure the islands' diachronic safe electricity supply one may consider several alternative solutions like the:

- Local APS permanent reinforcement
- Islands interconnection
- RES exploitation and hybrid systems development

3.3 Utilization Degree of Existing Thermal Power Units

Another important aspect related to the rational way of electricity generation in the Aegean Archipelago islands is the corresponding utilization degree (i.e. usually named capacity factor "CF") of the existing thermal power units. More specifically the numerical value of "CF" is defined as:

$$CF = \frac{E_y}{8760 \cdot N_o} \qquad (1)$$

where "E_y" is the annual electricity generation and "N_o" is the corresponding rated power of the existing "in operation" thermal units of the local APS. According to the most recent official data one may see in figure (15) the obtained values for the existing APS in the Aegean Archipelago area. In this figure one does not include the "CF" value of Rhodes island, which is almost 52% and is not comparable with the values of the other islands. In fact the average value of the APS under investigation is only 21%, while only ten (10) APS present utilization rate higher than 25%.

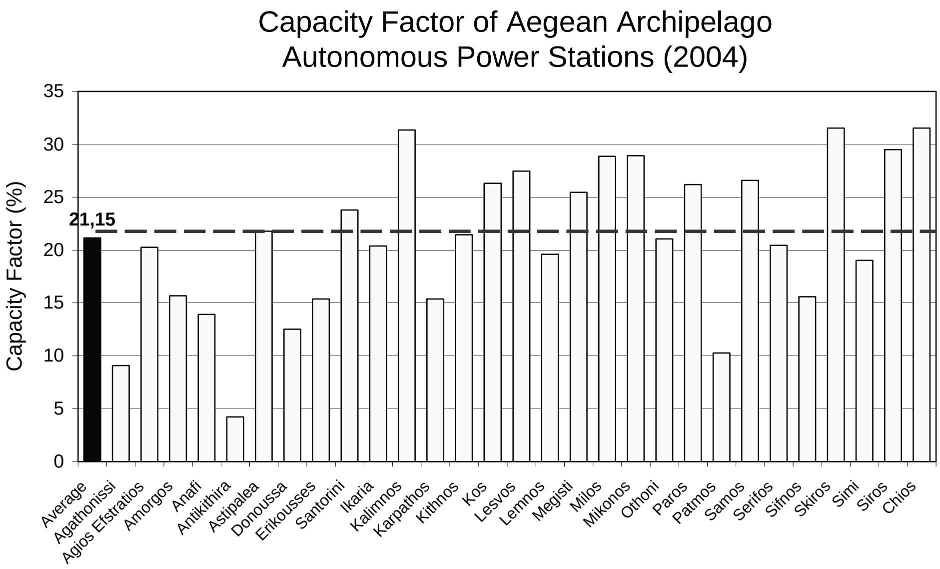

Figure 15: Utilization degree of existing thermal power units in Aegean Archipelago APS

The most rational explanations for this behavior are the following:

- Some of the thermal units of the APS present serious malfunctions, however these engines are included in the official "in operation" units of the island systems
- Most of the existing thermal units, being rather old, produce quite lower output than the officially recorded one, in order to avoid major damage of the equipment
- During summer most thermal units (especially gas turbines) present a lower real output (by approx. 10%) than in winter, due to modifications on their thermodynamic cycle characteristics and increased cooling problems
- The electricity demand presents highly seasonal variation, hence although during summer the "in operation" units hardly meet the electricity demand, during the rest of the year the load demand is much lower that the available power of the existing units.
- Finally, taking into consideration that in several APS exist thermal units being in operation for more than thirty (30) years, the technical availability of the aged engines to consider proves to be quite low.

On the basis of the reasons presented above the utilization degree of the existing equipment is very low, underlining the urgent need for new electricity generation solutions, based not only on fossil fuels but also on locally available renewable energy resources.

3.4 RES Contribution

The Aegean Archipelago is an area with excellent wind potential and abundant solar energy[8], while in some islands one may find remarkable geothermal reserves and considerable biomass feedstock. Unfortunately, the only RES exploitation activity "E_{RES}" is based on wind energy applications, hence in several islands one may find small or medium-sized wind parks, with the maximum installed wind power being less than 10MW. At this point it is important to note that the first wind parks have been installed in Aegean Archipelago islands since ’80s[9], while during 1990-1993 the installed by the Greek PPC wind power approached 30MW. Since then, one cannot mention any serious wind park creation activity by PPC, while the only activity encountered is due to private wind parks erection, mainly in the islands of Lesvos, Kos and Chios[10].

In fact, the major wind energy exploitation activity is encountered in Lesvos island, where during 2004 almost 28.7GWh of wind based electricity "E_{RES}" has been produced (see Appendix One, equation (A-3)), as well as in Chios (18.2GWh/y) in Kos (18.3GWh/y) and in Samos (17GWh/y) islands. The result of this moderate activity is the production of almost 110GWh of wind electricity, which represents only the r=5% of the corresponding annual electricity consumption of the area (see Appendix One, equation (A-4)). Using the most recent available official data, one may find in figure (16) that the maximum wind energy penetration is encountered in the islands of Karpathos (r=13.5%) and Lesvos (r=11.5%), while in certain islands, like the islands of Agios Efstratios and Rhodes the corresponding contribution is almost zero. The main reason reported by the experts for such a low wind energy penetration is the restrictions set to the wind energy contribution in order to maintain the local grids’ stability due to the stochastic wind speed behaviour and the strongly variable electricity consumption[11].

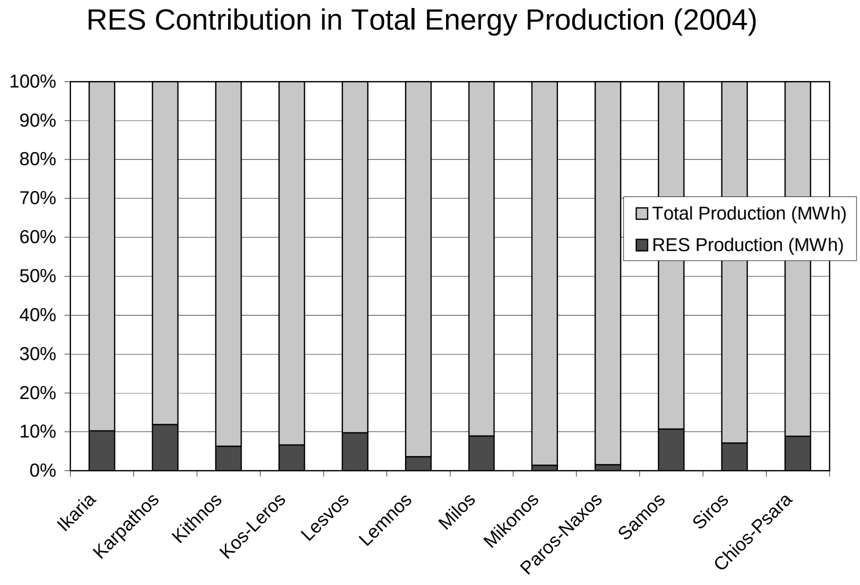

Figure 16: RES contribution in the total energy consumption of selected Aegean Archipelago islands during 2004

In order to obtain a clear cut picture of the RES contribution in the electricity generation problem of the Aegean Archipelago islands in the course of time, one may find in figure (17) the wind energy contribution for the last decade (1995-2004) for selected islands presenting a remarkable wind energy exploitation activity. As it is obvious from the data available, the corresponding wind energy contribution is in any case less than 15% (i.e. $r \leq 0.15$), while in most cases a remarkable increase is encountered, mainly due to individual private wind power investments. On the other hand, in other cases one may note a slightly decreasing trend, since the electricity consumption is continuously increasing and the installed wind power stagnates[12].

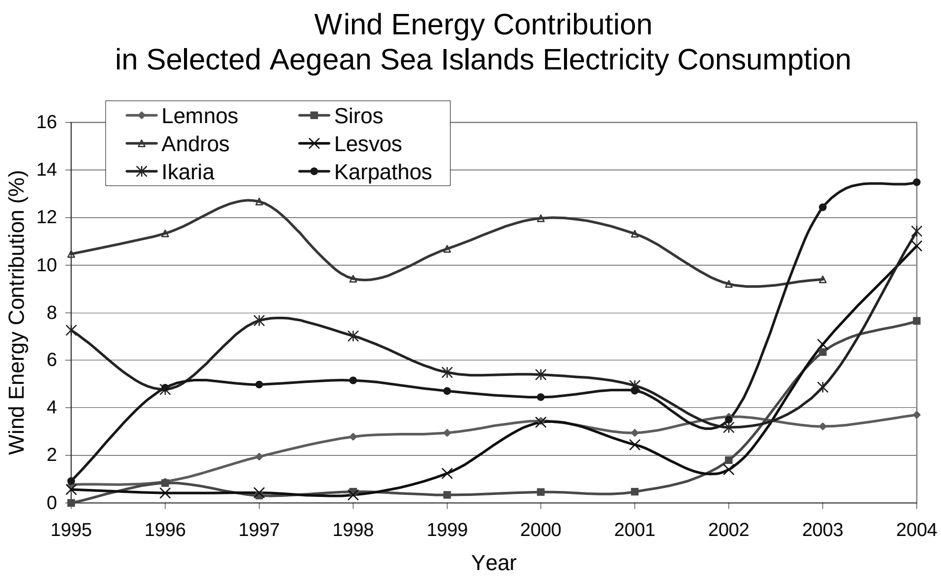

Figure 17: Time-evolution of wind energy contribution in the total energy consumption of selected Aegean Archipelago islands

4. Fuel Consumption and Electricity Production Cost

According to the available official information all the APS operating in the Aegean Archipelago area utilize diesel-oil and heavy-oil (mazut). More specifically, the annual diesel-oil consumption of all the APS of the area, including Rhodes, approaches 100,000tn of diesel and almost 400,000tn of Mazut. In figure (18) one may find the time evolution of the annual fuel consumption of the biggest APS of the Aegean Sea, i.e. Kos-Kalimnos, Lesvos, Paros, Samos and Chios. It is important to note that in all cases examined, a significant fuel consumption increase, being in complete accordance with the corresponding electricity generation amplification during the same period, may be observed; see also figures (7) to (11).

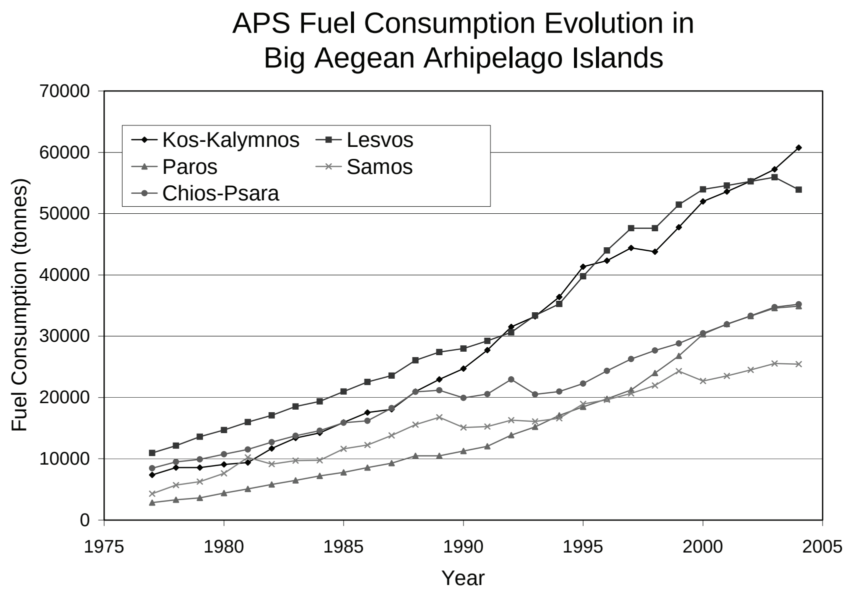

Figure 18: Time-evolution of fuel consumption of selected Aegean Archipelago islands

Besides, the average specific fuel consumption (SFC) of the "in operation" thermal power units defined as the ratio between the annual fuel consumption "M_f" and the corresponding electricity generation "E_y", i.e.:

$$SFC = \frac{M_f}{E_y} \qquad (2)$$

is slightly less than 250gr/kWh, while the corresponding value varies between 200gr/kWh and 300gr/kWh. The APS of Kos and Chios islands have the lowest SFC (less than 210gr/kWh), while most of the very small APS present values near 300gr/kWh.

The high fuel consumption and the pressing needs of maintenance of the outmoded internal combustion engines along with the small size and variable electricity generation of the existing APS impose a relatively high production cost value. In fact the current electricity production cost (see Appendix One, equation (A-5)), of big APS, figure (19), is approximately between c_{el}=80-200€/MWh, while the most cost effective APS is the one of Paros island with a marginal production cost "c_{el}" slightly less than 80€/MWh. The corresponding electricity production cost of the medium and small APS is between 150 and 400€/MWh (i.e. $150 \leq c_{el} \leq 400$), while for the very small islands one may observe values up to 1000€/MWh.

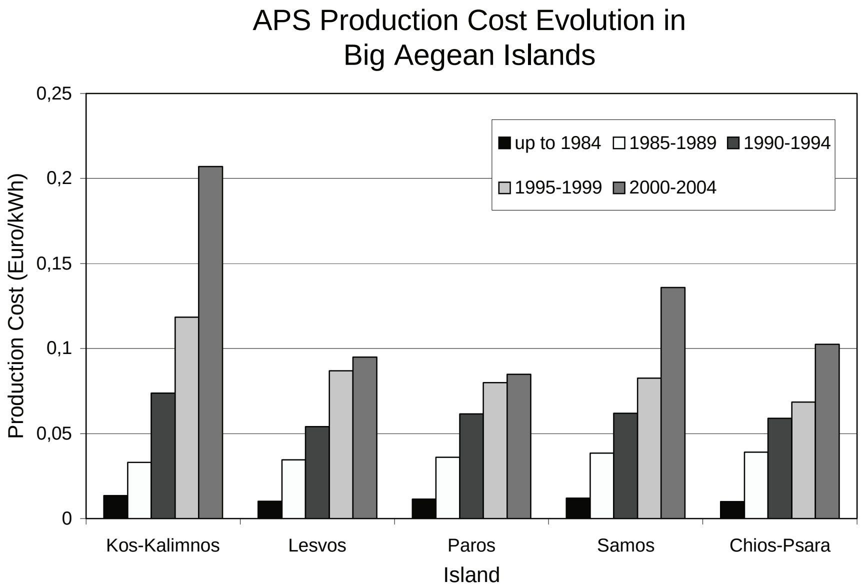

Figure 19: Time-evolution of electricity production cost of selected Aegean Archipelago islands

Another additional aspect concerning the electricity generation of the area is the considerable APS production cost increase in the course of time (in historical values). In several cases, one may observe current electricity production values that are almost ten-times the corresponding values of twenty years ago.

Comparing now the above mentioned values with the corresponding electricity price "p(t)" time series in the local market[13], one may note significant financial loss "δc(t)" (see Appendix One, equation (A-6)), for the vast majority of the existing APS, see for example figure (20). During the last twenty years, only the Chios island APS has been financially viable, this not being the case for all the other big APS. On top of this, it is worthwhile to mention that the APS production cost in most cases examined is much higher than the price offered by the local network administrator (PPC) to the wind based electricity production[1], being currently around 80€/MWh. The result of this analysis underlines that the operation of the Aegean Archipelago APS leads to severe financial loss (see Appendix One, equation (A-7)), for the Greek PPC, which is equal to approximately R(t)≈200,000,000€/year.

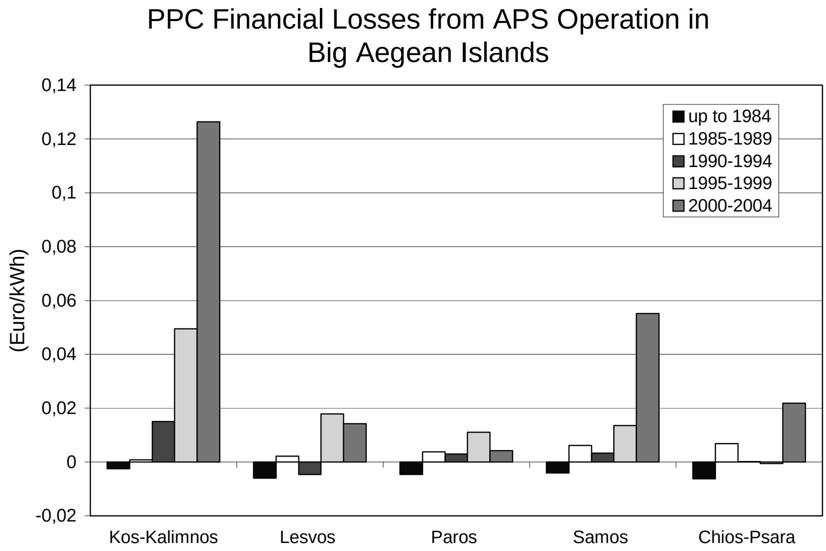

Figure 20: Time-evolution of electricity production financial loss/gain due to the operation of the APS in selected Aegean Archipelago islands

Finally, one should keep in mind that the legal frame ensuring the Greek electricity market liberalization has been established after the enactment of the law 2773/1999. This law, in order to keep up with the evolutionary circumstances and conditions describing the electricity market, has been gradually reformed taking into consideration the arrangements included in the laws 2837/2000, 2491/2001 and 3175/2003.

According to the new directive (2003/54/EC) dispositions, the non-interconnected islands defined as "isolated micro-grids" (total electricity consumption less than 500GWh during 1996) can be excluded by the proposed adjustment concerning the electrical market liberalization. Besides, emphasis should be laid to ensure the islands' safe supply.

More specifically, in the case of isolated micro-grids, to secure the safe supply of these islands, the production licences will only be provided to the Greek PPC. From this arrangement, the electricity production by RES, hybrid stations and own-producers is excluded (law 3468/06). Meanwhile, the PPC, as the non-interconnected islands' current administrator is assigned to ensure the isolated micro-grids' clear electricity supply and at the same time guarantee the long term financial efficiency of the particular systems, therefore retaining its dominant role in the operation of the islands’ networks.

According to the official version of the law concerning RES (3468/06) and in regard to the non-interconnected islands, the absorption priority ensured in the national grid and concerning the energy production of independent producers and the energy surplus by own-producers is not guaranteed in the case of non-interconnected islands. In case that the RES based electricity generation absorption leads to the local grid’s instability, the administrator is not obliged to adhere to the previous commitment, not safeguarding the prospect for higher RES penetration levels[1].

5. Presentation of the Available Electrification Solutions

The Aegean Archipelago area possesses[14] important RES potential, figure (21). In fact in the entire area long-term wind speed measurements[15] indicate annual wind speed values higher than 6m/s, while in some islands annual mean wind speed values up to 10m/s have been recorded. On top of this, the calm spell periods are rather limited[16], hence one may use wind energy to cover the electricity needs of the habitants throughout the entire year.

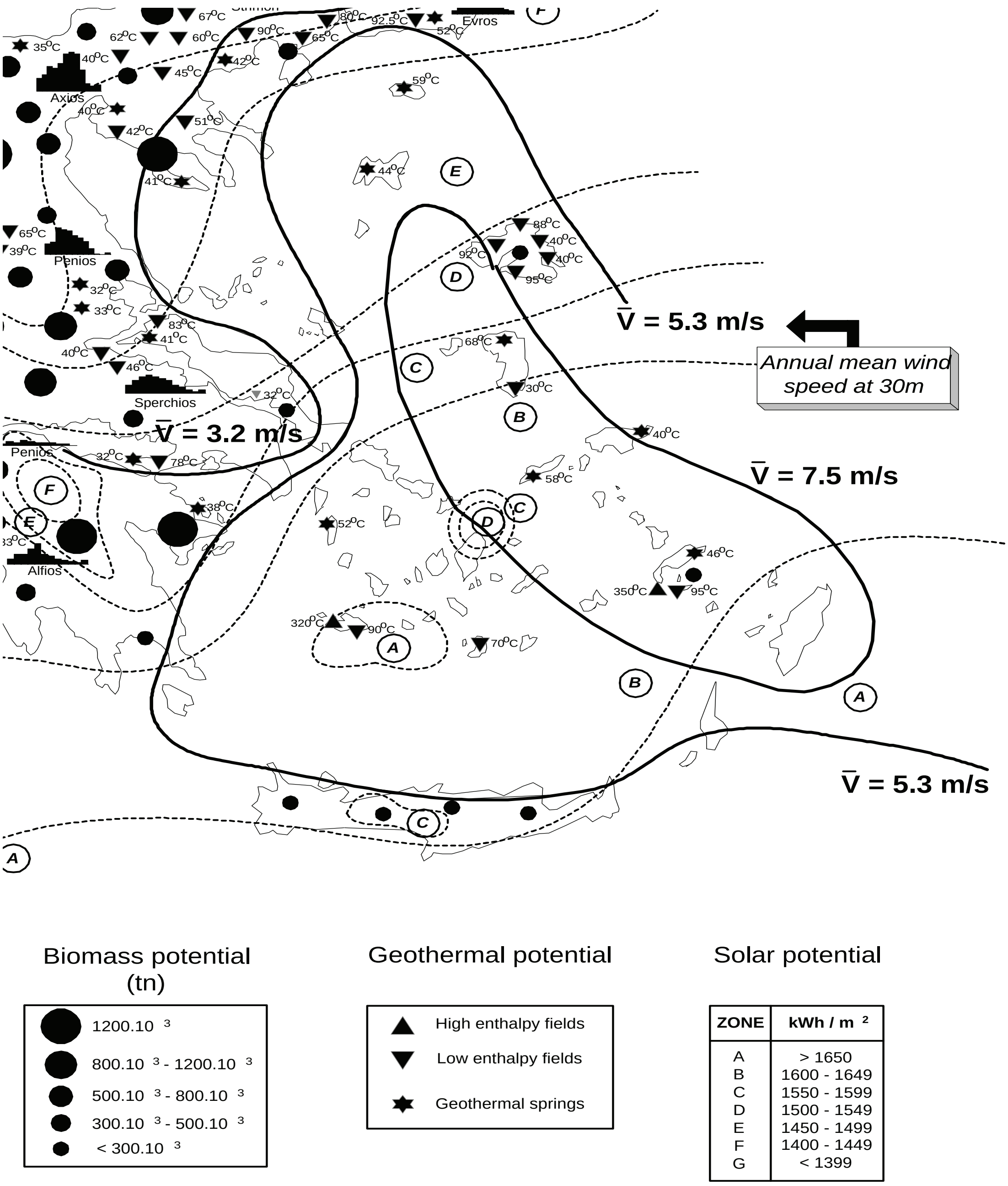

Figure 21: RES potential in the Aegean Archipelago region

On the other hand, the solar potential of the area is quite high, since in all cases exceeds the 1500(kWh/m^2)/year offering remarkable opportunities to meet either the thermal[17] or the electrical needs[18] of the local societies. More specifically, in the S. Aegean area the available solar potential is even higher, i.e. annual value higher than 1650(kWh/m^2)/year, especially during summer, hence contributing to face the corresponding excessive (due to tourism) energy requirement of this period of the year.

Additionally, in several islands of the Aegean Archipelago one may find remarkable geothermal fields[19]. In fact the most well known (since 1970) geothermal reservoirs are located in the islands of

Milos and Nissiros (geothermal fluid temperature 300°C). These two high enthalpy geothermal fields may be used in order to create two power stations of 100-150MW_e and 50MW_e respectively. Significant geothermal fields have also been located in Lesvos island, where the first 10MW_e power station is under schedule[5].

Finally, in various islands the existing biomass is used to cover thermal needs. The necessary raw material comes either from forest residuals or agricultural activities[20]. According to preliminary estimations one may produce annually almost 2000GWh of thermal energy. Unfortunately, the periodic biomass availability and the low energy density of the raw material[21] discourage any potential investment in the energy production area at the moment.

Despite the significant energy potential of the islands, the daily and seasonal variation of the local consumption in combination with the stochastic behaviour of the wind speed poses serious constraints on the wind energy contribution in the local electricity generation[11]. More precisely, the local network operator permits the penetration of wind power up to 30% of the instantaneous electricity maximum demand, in order to guarantee the local grid's stability in case that the available wind speed suddenly zeros. The result of these factors is a quite limited wind energy contribution to the local electricity consumption, see also figure (16).

The main obstacles for the exploitation of the available geothermal potential are the total absence of the necessary legal frame (up to law 3175/03) and the relatively small size of the existing electrical grids that cannot absorb the high geothermal potential of the area, e.g. Milos and Nissiros islands. Taking into account that all these islands are not interconnected, it is obvious that only small scale applications may be operated. However, these applications would not only partially exploit the existing potential but would not benefice from any scale economies either. Finally, the unsuccessful operation of the pilot geothermal power plant of 2MW in Milos island in 1987, which has been abandoned due to environmental impact claims by local habitants[22], jeopardize any similar activity during the next twenty years.

Finally, the scattering of the islands and the seasonal availability of biomass raw material discourage the systematic exploitation of the available biomass potential of the area. In fact, the existing biomass is used on individual basis, although the idea of cogeneration applications to cover thermal and electrical loads is under evaluation in several big or medium sized islands[23].

To face these problems, the authors have since the previous decade proposed several electricity generation solutions with remarkable positive side effects[24][25]. These solutions are based on the exploitation of the available RES potential in collaboration with appropriate energy storage facilities. Similar hybrid configurations are the most cost-effective solutions to meet the electrification requirements of the Aegean Archipelago with significant environmental and social benefits.

More specifically, for the small and very small islands or for regions with relatively low wind potential one may create photovoltaic based power stations along with energy storage (e.g. batteries) facilities[26] in order to replace the existing thermal power stations, operating at very high cost (higher than 200€/MWh). It is important to mention that according to the recently voted law for RES (3468/06) there is a significant price compensation for PV based electricity generation, which approaches the 450€/MWh.

Subsequently, for big and medium sized areas with high wind potential one may adopt the wind-hydro solution, based on the collaboration of wind parks and reversible hydro power stations operating as water pumping and energy production facilities[27]. In this case the wind parks face the corresponding load demand, while any energy surplus is stored via the water pumping system at a high level reservoir. In case of energy deficit, the water reserves are utilized via the hydro turbines of the installation to cover the excess power demand. In a more integrated concept[28] one may use the RES based energy production to enhance the water reserves of the local communities.

Finally, for the islands where remarkable geothermal potential exists one may develop an integrated energy production facility to meet electrical and thermal energy requirements of the local community. This solution would be much more financially attractive if the nearby to the geothermal field islands were interconnected. In fact the possibility of interconnecting the Aegean Archipelago islands with the mainland electrical network in order to create an integrated electricity transportation network presents serious advantages and disadvantages[29], the detailed presentation of them being out of the scope of the present paper.

In brief, the islands' interconnection, where possible, may gradually replace the local APSs operation and at the same time allow the absorption of large amounts of wind energy without causing the instability effects noticed in autonomous grids. On the other hand, such an electricity production strategy has to face the significant technological problems related to the undersea electricity transportation, the rather high first installation cost (approx. 3 million Euros per km of transportation grid) and the strong opposition of local societies claiming important environmental impacts.

Recapitulating, according to the conclusions of a recent report[29] published by RAE-PPC-HTSO, the interconnection of the north-eastern Cyclades islands is essential. The proposed solution suggests the interconnection of Siros to the Lavrio power station (possibly via Kithnos and Kea). Next, the current plan suggests the internal interconnection for the islands of Siros, Mikonos, Paros-Naxos, Andros and Tinos, therefore exploiting the already existing interconnection via Euboea as well. Finally, the plan supports that Milos should also be included in the previous group, in order for its geothermal field to be widely exploited.

6. Conclusions and Proposals

The Aegean Archipelago includes a large number of islands of various size scattered between the Greek mainland and the East coast of Asia Minor, where more than 600,000 people are living mainly in small remote communities. All these islands cover their electrification needs using outmoded APS based on thermal power units. In order to propose a realistic, environmental friendly and financially attractive solution, one first investigates the time evolution of the corresponding electricity generation parameters for the last thirty years.

According to the data analyzed there is a continuous and fast electricity consumption amplification, which in some cases exceeds the 10% on annual basis. On top of this, the peak power demand increase encountered is even higher, strongly questioning the capability of the existing thermal power units to meet the load demand especially during summer. In order to avoid major electrical grid failures during the touristic period, the up to now adopted solution is based on the annual installation of additional thermal power units. The absence of an integrated plan to face the urgent electrification problem of the area leads to low reliability solutions that cannot guarantee the necessary supply security. In this context one should also note the significant increase of imported oil consumption, imposing serious environmental and macro-economic impacts as well as extremely high operational cost. Unfortunately, the existing situation of the local electrical networks minimizes the contribution of RES in the energy production market.

Subsequently, an attempt is made to describe in brief the most realistic available electricity production solutions. In this context, one may include the operation of hybrid RES-based power plants in collaboration with appropriate energy storage configurations. Additionally, the idea of connecting the islands of the area with the mainland and interconnecting them is also taken into consideration. However, the implementation of this solution needs further analysis and discussion.

Recapitulating, one may clearly state that only by developing properly designed hybrid power stations based on RES exploitation and interconnecting some of the islands of the area it is possible to face the continuously increasing electricity demand of the area, with rational electricity generation cost, also minimizing the environmental impacts due to the diesel and heavy oil utilization.

APPENDIX ONE

1. *Annual electricity consumption increase "ε_i" for the year "i"*

$$\varepsilon_\iota = \frac{1}{E_i}\cdot\left.\frac{dE}{dt}\right|_i = \frac{1}{E_i}\cdot\frac{E_{i+1}-E_{i-1}}{2} \quad \text{(A-1)}$$

where "E_i" is the annual electricity generation during the year "i".

2. *Peak-load long-term (n-years period) average annual increase "$\bar{\nu}$"*

$$\bar{\nu} = \left(\frac{N_n}{N_o}\right)^{1/n} - 1 \quad \text{(A-2)}$$

where "N_i" is the peak-load demand during the year "i".

3. *Annual RES-based electricity generation "E_{RES}", T=1year=8760h*

$$E_{RES} = \int_0^T N_{RES}(t)\cdot dt = \sum_{i=1}^{8760} N_{RES_i} \quad \text{(A-3)}$$

where "$N_{RES}(t)$" is the corresponding load demand of the system and "N_{RESi}" is the mean load demand during the hour "i" of the year.

4. *Annual RES contribution "r" in the local electricity production balance*

$$r = \frac{E_{RES}}{E_{tot}} = \frac{E_{RES}}{E_{APS}+E_{RES}} = 1 - \frac{E_{APS}}{E_{APS}+E_{RES}} \quad \text{(A-4)}$$

where "E_{tot}", "E_{RES}" and "E_{APS}" are the total electricity consumption of the autonomous island network, the RES contribution and the participation of the local APS, respectively.

5. *Electricity generation specific cost "c_{el}"*

$$c_{el} = \frac{C_{tot}}{E_{tot}\cdot\sum_{j=1}^{j=n}\left(\frac{(1+e)}{(1+i)}\right)^j} \quad \text{(A-5)}$$

where "C_{tot}" is the total cost of the local electrical network, including[16] the first installation cost, the fixed and variable maintenance and operational cost of the equipment used, the imported diesel-oil cost as well as the labor and general administrative cost in present values. In equation (A-5) "e" is the electricity price annual escalation rate (e.g. e=3%) and "i" is the corresponding capital cost of the local market.

6. *Specific financial loss "δc" due to the electricity generation in Greek islands*

$$\delta c(t) = c_{el}(t) - p(t) \qquad \text{(A-6)}$$

where "p(t)" is the electricity price offered to the local habitants during the period "t".

7. *Annual financial loss (gains) due to the operation of the (j=32) Greek islands' APS*

$$R(t) = -\sum_{j=1}^{32} \delta c_j(t) \cdot E_j(t) \qquad \text{(A-7)}$$

where "$E_j(t)$" is the electricity consumption/production of the "j" island during the time period "t".

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THE WIND POTENTIAL IMPACT ON THE MAXIMUM WIND ENERGY PENETRATION IN AUTONOMOUS ELECTRICAL GRIDS

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Abstract

According to long-term wind speed measurements the Aegean Archipelago possesses excellent wind potential, hence properly designed wind energy applications can substantially contribute to fulfil the energy requirements of the island societies. On top of this, in most islands the electricity production cost is extremely high, while significant insufficient power supply problems are often encountered, especially during the summer. Unfortunately, the stochastic behaviour of the wind and the important fluctuations of daily and seasonal electricity load pose a strict penetration limit for the contribution of wind energy in the corresponding load demand. The application of this limit is necessary in order to avoid hazardous electricity grid fluctuations and to protect the existing thermal power units from operating near or below their technical minima. In this context, the main target of the proposed study is to present an integrated methodology able to estimate the maximum wind energy penetration in autonomous electrical grids on the basis of the available wind potential existing in the Aegean Archipelago area. For this purpose a large number of representative wind potential types have been investigated and interesting conclusions have been derived.

Keywords: Autonomous Electrical Networks; Wind Energy Absorbance; Wind Potential; Weibull Parameters; Wind Penetration Constraints; Stochastic Analysis

1. Introduction

The Aegean Archipelago is a remote Hellenic area, including several hundreds of various size scattered islands. According to long-term wind speed measurements[1] the area possesses excellent wind potential that can substantially contribute to the fulfillment of the local societies' energy requirements. More precisely, the annual mean wind speed of the area at 30m exceeds the 5.5m/s (figure (1)), while in many locations long-term average values approach the 10m/s[2][3].

On the other hand, in most islands the electricity production cost is extremely high (e.g. 0.5€/kWh) due to the utilization of small outmoded internal combustion engines consuming diesel-oil and mazut[4]. The current solution results to an annual electricity generation cost higher than 200M€, the fuel cost sharing more than 50%. On top of this, a significant insufficient power supply problem is often encountered, especially in the summer, taking into consideration that during the last 25 years the peak load demand increase approaches the 500%.

Taking into consideration the pressing need for additional electrical power and the availability of the existing wind potential one may expect a substantial new wind parks installation activity, which however is not the case[5]. Unfortunately, this rational evolution has not been realized, since in most cases the local autonomous electrical networks cannot continuously absorb the variable wind energy production[6], either due to low electricity demand or in order to protect the existing power units from operating near or below their technical minima[7][8].

In this context, the main target of the proposed paper is to present an integrated methodology able to estimate the maximum wind energy penetration in autonomous electrical grids, on the basis of the available wind potential, taking into consideration the stochastic behavior of the wind and the possible inconsistency between the variable electricity demand and the stochastic wind energy production.

Kaldellis J.K., 2007, *"The Wind Potential Impact on the Maximum Wind Energy Penetration in Autonomous Electrical Grids", Renewable Energy Journal, Vol. 33/7, pp.1665-1677.*

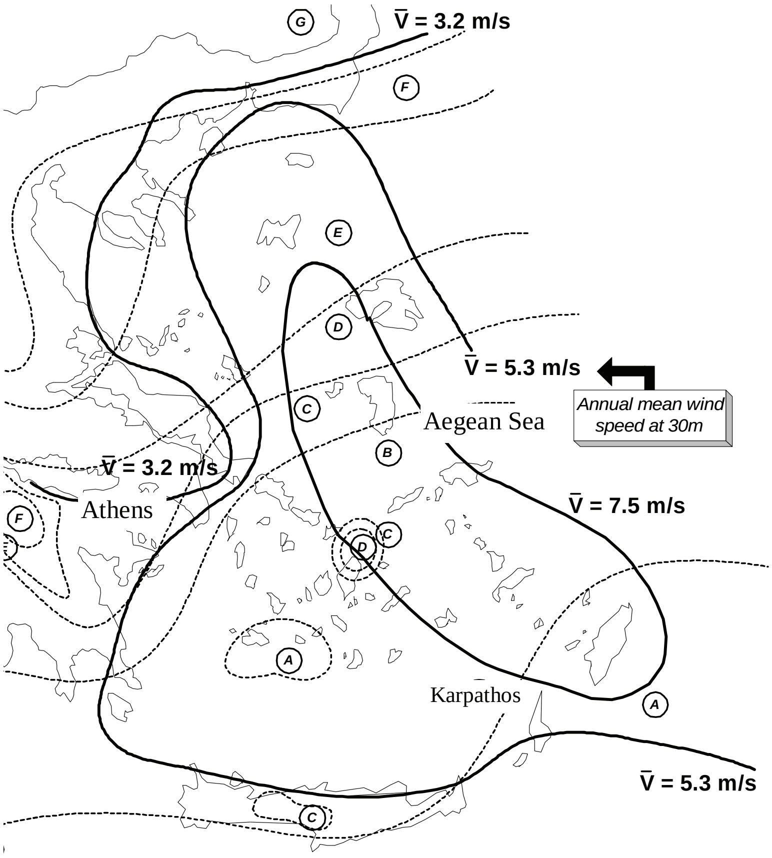

Figure 1: Wind potential in Aegean Archipelago

Special emphasis is laid in order to examine the impact of the available -in the Aegean Archipelago area- wind potential (figure (1)) on the corresponding wind energy contribution to meeting the local electrical needs. For this purpose a large number of representative wind potential types have been investigated and interesting conclusions have been derived.

2. Energy Production for Various Wind Potential Cases

2.1 Wind Potential Simulation

In most practical cases, the wind potential of an area is described either via wind speed and wind direction time-series (deterministic approach) or via the corresponding probability density distribution (stochastic approach), e.g. "f(V)", which defines the probability of the wind speed to be between "V-δV" and "V+δV" during a specific time interval. The above mentioned information results either from appropriate measurements or from existing simulation models of desired accuracy[3][9][10]. More precisely, using the "f(V)" value one can estimate (for a selected time period) the probability of the expected wind speed being between two specific values (i.e. $V_1 \le V \le V_2$) using the following relation:

$$P_V(V_1 \le V \le V_2) = \int_{V_1}^{V_2} f_V(V) \cdot dV \qquad (1)$$

One of the most user-friendly methodologies used to simulate the wind potential of a specific area is via the well-known Weibull formula, where one may estimate the probability density function on the basis of two numerical parameters[9][11]. More specifically, the corresponding probability density distribution "$f_w(V)$" is given as:

$$f_w(V) = \frac{k}{C} \cdot \left[\frac{V}{C}\right]^{k-1} \cdot \exp\left\{-\left[\frac{V}{C}\right]^{k}\right\} \tag{2}$$

where "C" is the wind speed normalizing factor and "k" is the corresponding shape factor. Both parameters are related to the mean wind speed of the area as well as to the corresponding standard deviation, via the well-known Gamma function[12], i.e.:

$$\overline{V} = C \cdot \Gamma\left(1 + \frac{1}{k}\right) \tag{3}$$

and

$$\sigma^2 = C^2 \cdot \left[\Gamma\left(1 + \frac{2}{k}\right) - \left(\Gamma\left(1 + \frac{1}{k}\right)\right)^2\right] \tag{4}$$

where "$\overline{V}$" is the average wind speed and "σ^2" the corresponding variance for the time period examined.

Using equation (2) one may also estimate the resulting wind speed duration curve, i.e.:

$$G(V \geq V_o) = \exp\left[-(V_o / C)^k\right] \tag{5}$$

In figures (2a) and (2b) one may find representative probability density distributions on the basis of equation (2). According to the information provided in figure (2a), as the "C" value increases the corresponding wind potential is higher, since the possibility to find high wind speed values is remarkably increased. On the other hand, as the "k" value increases the wind speed values are concentrated around their mean value (lower standard deviation), see for example figure (2b). Generally speaking, "C" values of the order of 5.5 describe areas with medium-low wind potential, while "C" values of the order of 8.5 describe areas with very high wind potential. According to figure (1) the "C" and "k" values appearing in the Aegean Sea area vary between 5.5 and 10 and between 1.2 and 2.1 respectively.

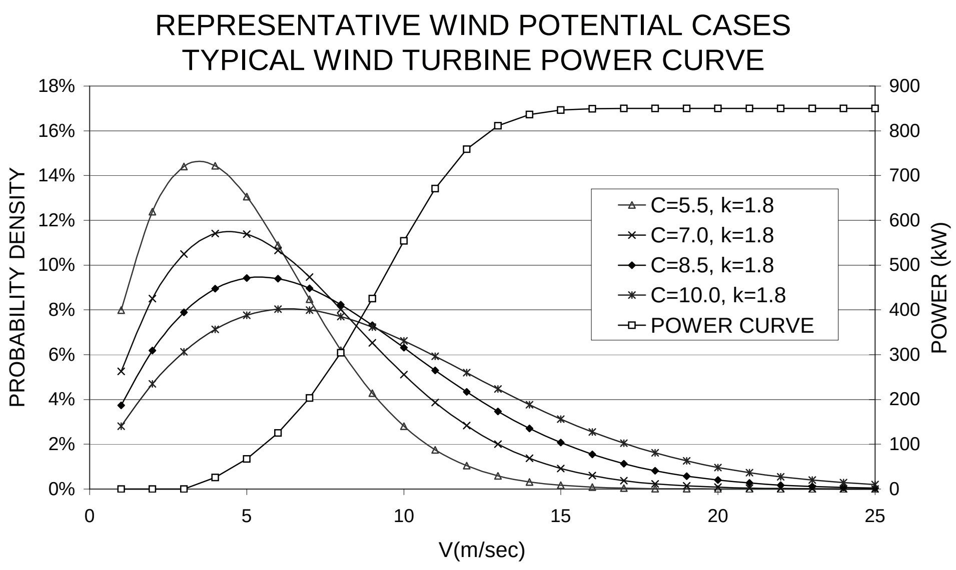

Figure 2a: Typical wind potential cases for the Aegean Archipelago area

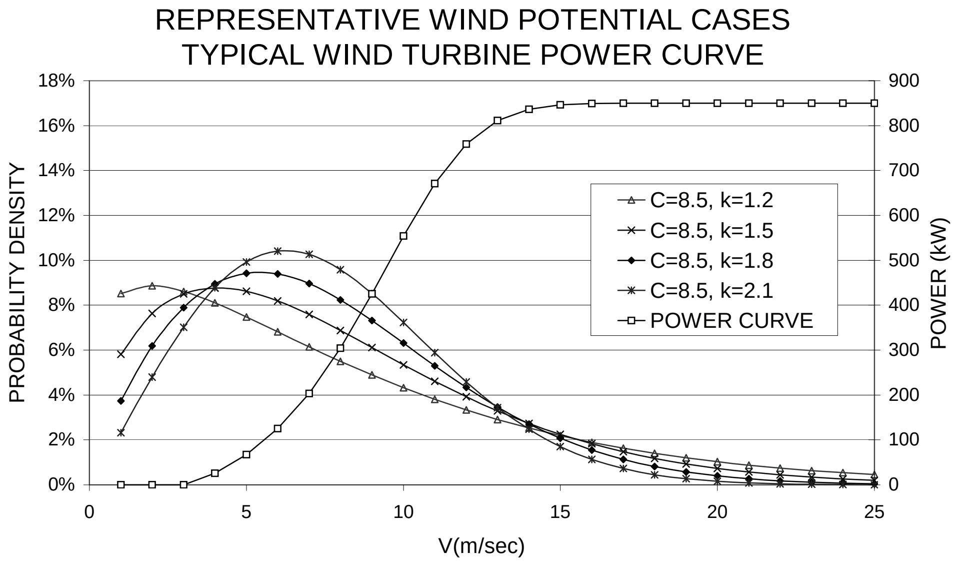

Figure 2b: Typical wind potential cases for the Aegean Archipelago area

2.2 Annual Wind Energy Production Calculation Methodology

Using previous work by the author[13][14], one may state that the exact value of a wind park energy production 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:

$$E = CF \cdot z \cdot N_o \cdot \Delta t - \delta E \tag{6}$$

where "δE" describes the line transmission and the transformer loss as well as any self-consumption of the power station, on annual basis, yet not related with the wind potential of the area. Accordingly, the capacity factor "CF" is expressed[15][16] as the product of the mean technical availability factor "Δ" and the mean power coefficient "ω" of the installation, i.e.:

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

More specifically, during their service-period wind turbines have a variable technical availability, depending on the technological status, the age and the location of the machine. In early 80's the technical availability of the first wind parks was approximately 60%, while at the beginning of the next decade the value of "Δ" outnumbered 90%. Nowadays, the new wind energy technology has achieved such a level of quality, that wind turbines obtain a technical availability of 99%[15][16].

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

$$\omega = \int_{V_c}^{V_F} \frac{N(V)}{N_o} \cdot f(V) \cdot dV \tag{8}$$

where the probability density function "f(V)" describes the local wind potential. As already mentioned, "f(V)" can be expressed using the well-known Weibull distribution, hence "ω" -for a given wind turbine power curve N(V)- is primarily a function of Weibull mean wind speed normalizing factor "C" and the corresponding shape factor "k".

2.3 Wind Potential Impact on the Wind Energy Generation

In this context, for the estimation of the wind energy yield of a specific wind park one needs the basic parameters of the available wind potential as well as the operational characteristics of the wind turbines to be used[11][16]. More precisely, the statistically averaged energy yield "E" of a wind turbine of rated power "N_o", located in a region where the wind potential is described by the corresponding Weibull (C,k) probability density function $f_w(V)$, can be computed[14][17] using the equation (6). For practical application purposes one may assume[15] that Δ=95%, while the "$N(V)/N_o$" distribution is given by the wind turbine manufacturer, properly modified to take into account the local ambient conditions (air density) impact[13], see also figures (2a) and (2b) for a typical pitch control medium-sized wind turbine.

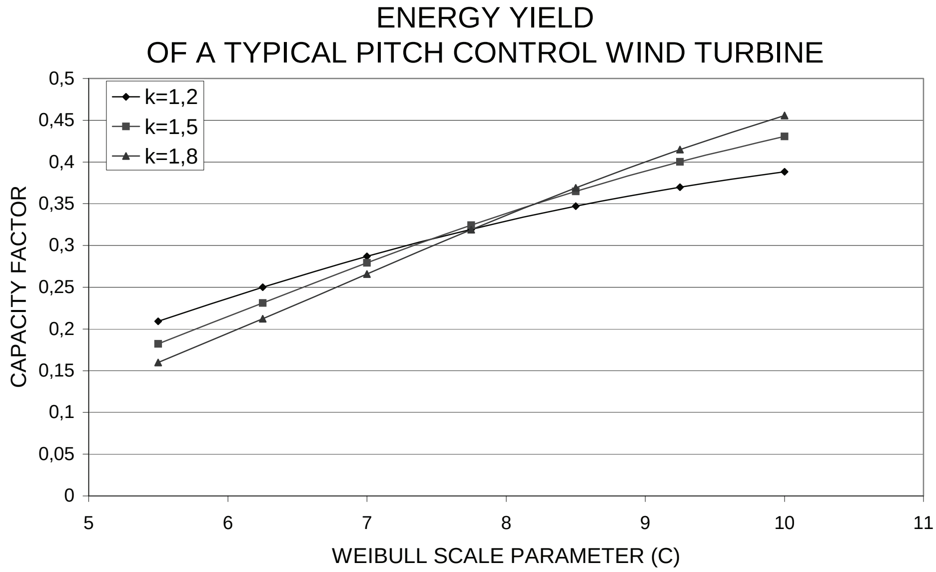

Figure 3a: Wind energy production for typical wind potential cases

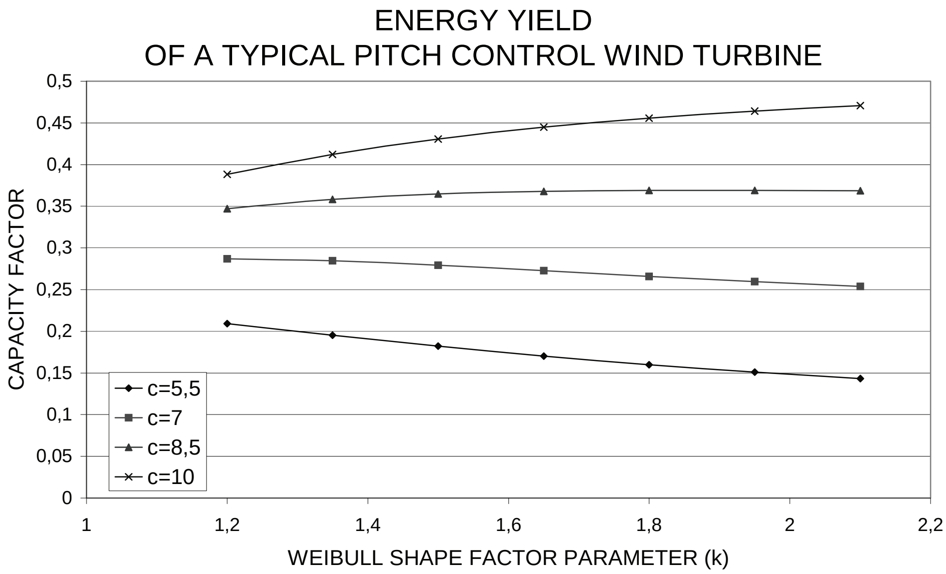

Figure 3b: Wind energy production for typical wind potential cases

Using the above presented analysis and recent work[16] by the author, the expected mean power coefficient distributions are presented in figures (3a) and (3b) As it results from these figures[14][16], the installation mean power coefficient (and hence the annual yield) is almost linearly depending mainly on the area wind speed normalizing factor "C", which is directly related to the corresponding mean wind speed ($\overline{V} \approx 0.9C$), see also equation (3). In fact, there is a significant "CF" value increase from 0.15 up to 0.45, underlining the dominant impact of the available wind potential quality on the expected annual yield. At this point it is interesting to note that for low "C" values the calculated "CF" values are higher for lower "k" values. This situation is inversed as "C" exceeds the value of 8.0.

This conclusion is validated also by the results of figure (3b), where for low "C" values the "CF" decreases as "k" increases, while the opposite behaviour is observed for very high "C" values. On the other hand, for medium high or high "C" values the impact of "k" is quite restricted, especially in the 7.0m/s to 8.5m/s "C" range, in which the majority of the existing wind park locations belong.

3. Wind Energy Penetration Calculation Methodology

The problem to be solved in the present study concerns the estimation of the maximum wind energy yield that is acceptable by an autonomous electrical network on the basis of the strongly variable distribution of the local grid load demand for various representative wind potential cases appearing in the Aegean Sea area, figure (1).

Hence, for the estimation of the maximum wind energy contribution one firstly needs the corresponding load demand. According to the available measurements[18] one may use either the long-term load demand time-series or the corresponding probability density distribution "f_L", see figure (4). In fact, one may estimate the probability "P_L" of the load demand varying between two specific values "N_{L1}" and "N_{L2}" as follows:

$$P_L(N_{L_1} \le N_L \le N_{L_2}) = \int_{N_{L_1}}^{N_{L_2}} f_L(N_L) \cdot dN_L \qquad (9)$$

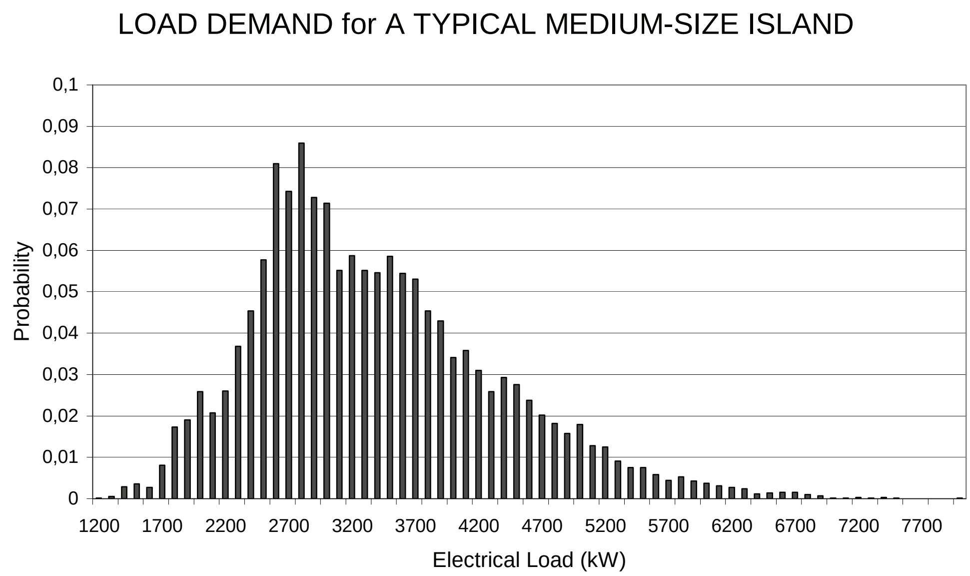

Figure 4: Electrical load demand for a representative Aegean Archipelago island

Subsequently, one should define the maximum wind power penetration acceptable by the local electrical grid "N_w^*" on the basis of the local electrical system constraints[7][8][19][20]. For this purpose one should take into account that the island autonomous electricity generation systems are based on diesel or heavy-oil powered internal combustion engines. These engines are not permitted to operate below a certain limit, in order to avoid increased wear and maintenance requirements. In the present analysis, for simplicity reasons, one has not explicitly taken into account the fact that the rated power of diesel-generators is discreet and not continuously varying. Also, one should take into consideration the algorithm that these units follow during their entering in the local network. However, these assumptions do not really affect the impact of the wind potential on the calculation results. Using the analysis of Appendix One, one may estimate the instantaneous maximum wind power penetration in the local grid "N_w*" as follows:

$$If \quad N_L(t) \le N_{d_{\min}}(t) \quad then \;\; N_w^* = 0 \tag{10}$$

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

$$If \quad N_{d\min}(t) \le N_L(t) \le (1+\lambda)\cdot N_{d\min}(t) \quad then \;\; N_w^* = N_L(t) - N_{d\min}(t) \tag{11}$$

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

$$If \quad N_L(t) \ge (1+\lambda)\cdot N_{d\min}(t) \quad then \;\; N_w^* \le \min\left\{\left[\lambda\cdot N_L(t)\right],\left[N_L(t) - N_{d\min}(t)\right]\right\} \tag{12}$$

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

Applying the proposed analysis on the load time-series of a typical island electrical system, one may estimate the resulting maximum wind energy penetration time-series in the local grid. Accordingly, one may reproduce the corresponding maximum wind energy penetration probability density profile "$f(N_w^*)$", figure (5). Thus, using the information of figure (5) one may state that the wind power contribution up to 360kW is absorbed for the entire period (when available), while there is no possibility of more than 2260kW wind power being imported to the local network, under the normal constraints that the local network manager imposes, see Appendix One.

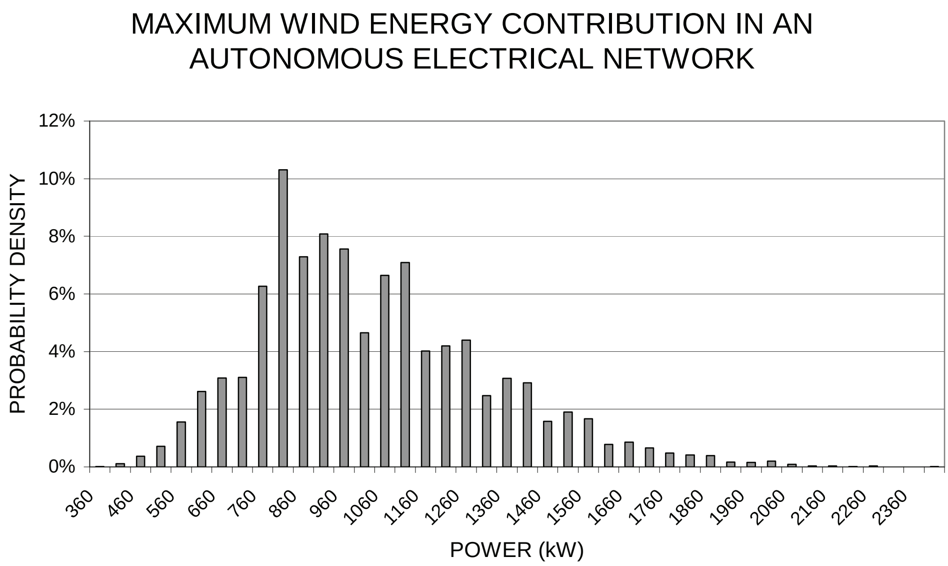

Figure 5: Maximum acceptable wind energy by a typical autonomous electrical network

At the same time, it is important to calculate the expected wind energy production by one or more wind turbines operating in the area under investigation, on the basis of the available wind potential, see section 2. Taking into account the available wind potential one may estimate the expected wind power output on the basis of the operational characteristics of the wind turbines to be used. More precisely, the expected wind power probability density distribution "$f_N(N_w)$" of a wind turbine of rated power "N_o" located in a region with wind potential described by the corresponding probability density function f(V) can be computed using the following equation:

$$f_N(N_w) = f_V(V; V = V(N_w)) \tag{13}$$

i.e. one should take into account all the cases that a specific wind turbine produces "N_w" kW. For this purpose the wind turbine power characteristic "N_w=N(V)" should be given by the wind turbine manufacturer, properly modified to take into account the local ambient conditions (air density) impact[21], see also figures (2a or 2b).

According to equation (13) one may estimate the possibility of the wind turbine output varying between "Nw_1" and "Nw_2" (assuming as a test case that C=8.5, k=1.8) by the following relation, see also figure (6), i.e.:

$$P_N(N_{w_1} \le N_w \le N_{w_2}) = \int_{N_{w_1}}^{N_{w_2}} f_N(N_w) \cdot dN_w \tag{14}$$

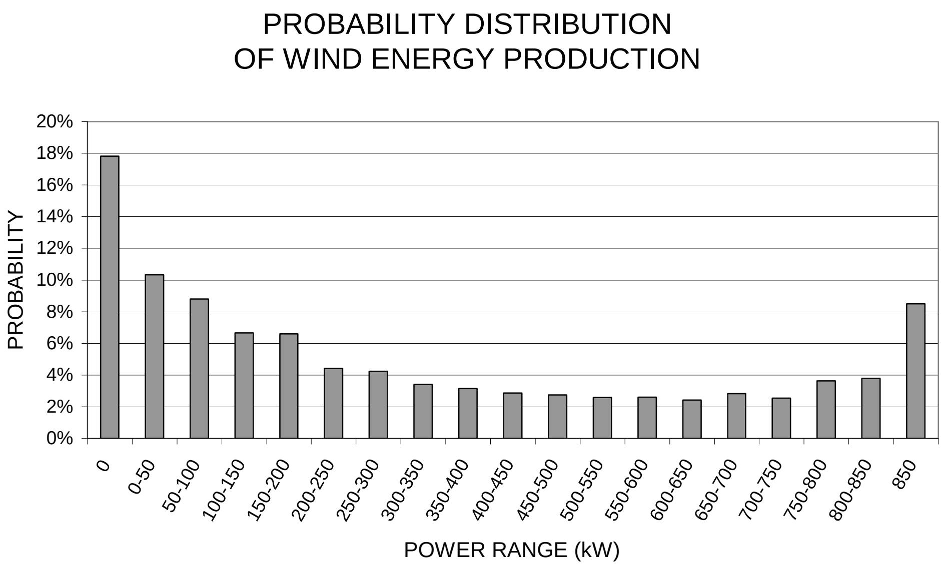

Figure 6: Wind energy production probability distribution for a representative Greek island

Using the data of figure (6) one may notice that for low wind speed periods the wind turbine yield is zero, while in cases that the local wind speed exceeds the wind turbine rated power (for pitch-controlled engines) the installation output equals the corresponding rated power.

Summarizing, one should mention that up to now we have computed the probability density distribution of the maximum accepted by the local network wind contribution (figure (5)) along with the corresponding wind energy production probability density profile (figure (6)), resulting by the local wind potential characteristics and the operational data of the wind turbines to be used.

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

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

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

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

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

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

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

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

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

Hence, the final wind energy contribution to the local system "E_f" can be calculated by the difference between the expected wind energy production (see equation (6)) and the corresponding statistically averaged wind energy surplus, thus one may write:

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

4. Application Results

The proposed methodology is accordingly applied to several representative wind potential cases appearing in the Aegean Archipelago region, see also figure (1). For comparison purposes one should use in all cases analyzed the electrical load demand profile of figure (4), which describes a typical autonomous electrical network of a representative medium size Aegean Sea island. According to the data presented the peak load demand of the system is almost 8MW, while the most commonly appeared load demand varies between 2600kW and 3000kW. Thus the corresponding annual energy consumption is approximately 30GWh/year. For this specific case one may examine two wind energy penetration scenarios. More precisely, the first part of the proposed analysis concerns a low wind energy contribution case, where the maximum wind power of the system is 850kW (i.e. slightly above the 10% of the corresponding peak load demand of the local network). This value has been estimated by the author[22] as the optimum techno-economic wind power penetration in autonomous electrical networks. Subsequently, the second scenario examined assumes the installation of three wind turbines of 850kW each, hence the corresponding wind power penetration slightly exceeds the 30% of the local system peak load demand during 2005, which used to be the maximum permitted wind power to be installed in an autonomous electrical system under the previous legislative frame[19].

4.1 Low Wind Power Penetration Case

Using the analysis presented in sections 2 and 3 we present in figure (7) the evolution of the wind energy contribution in the local electrical system as a function of Weibull "C" parameter. In all cases examined the wind energy contribution increases along with the "C" value. This amplification is more abrupt for high "k" than for relatively low shape factor values. This remark is also supported by the data of figure (8), where one may find the wind energy contribution variation in the local electrical network as a function of Weibull "k" value, for several representatives "C" values. More precisely, for medium low and medium wind potential cases, the wind energy contribution decreases as the corresponding shape factor value increases. This situation is inversed so long as the wind potential "C" value increases, hence for high wind potential cases (e.g. C=10) the wind energy contribution increases remarkably as the Weibull "k" attains higher values. The above described behaviour is in accordance with the relation between the energy yield and the corresponding parameters of Weibull distribution, presented in figures (3a) and (3b). As it is also obvious from figures (7) and (8) the expected annual wind energy contribution to the corresponding electricity consumption (30GWh/year) of the remote island is 5% (maximum) for low wind potential (low C and k) up to 11.5% for high wind potential (high C and k) cases.

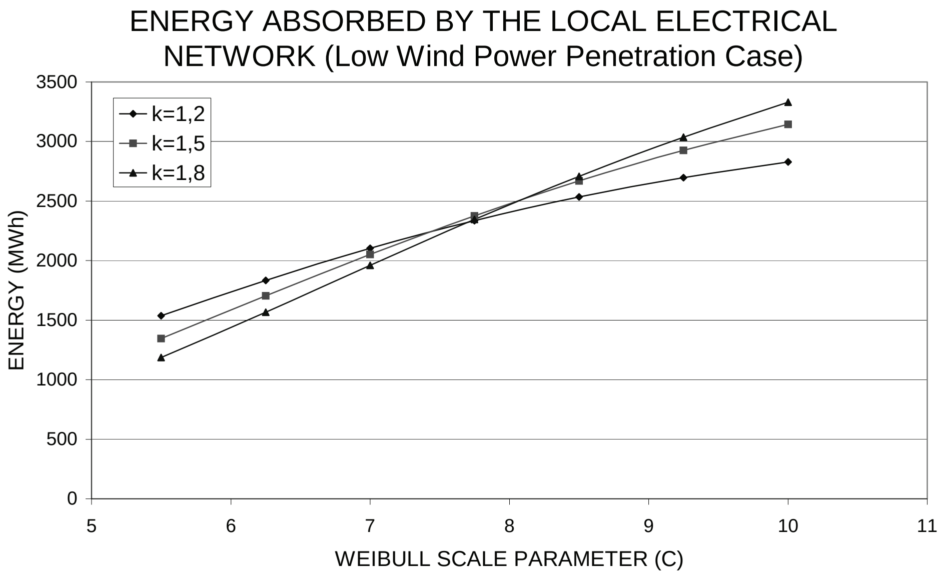

Figure 7: Wind energy absorbance by a typical island electrical network. Weibull scale parameter impact, low wind power penetration case

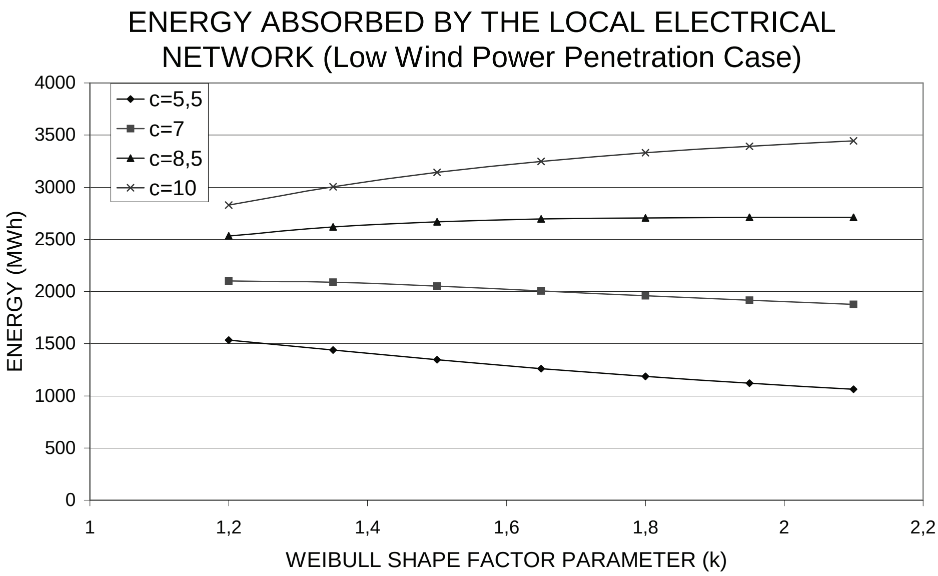

Figure 8: Wind energy absorbance by a typical island electrical network. Weibull shape factor impact, low wind power penetration case

Accordingly, one may investigate the wind energy absorbance percentage (i.e. the ratio of the wind energy absorbed by the local network divided by the corresponding energy yield of the wind power installations) by the local network as a function of Weibull's wind potential parameters. For this purpose one may observe in figure (9) that the wind energy absorbed by the local network is decreasing as the "C" parameter increases, for all "k" values examined. On the other hand, the wind energy absorption is increasing as the "k" value takes higher values, figure (10). At this point it is important to mention that in all wind potential cases examined the wind energy absorption by the local network is higher than 97.5%, which means that if the maximum wind power installed is equal to 10.5% of the local system current peak load demand, practically all the wind energy production is absorbed by the local grid. In this context, the maximum wind energy contribution in the local electricity consumption approaches the theoretical value of 11.5% on annual basis, which is however realized only for very high wind potential cases.

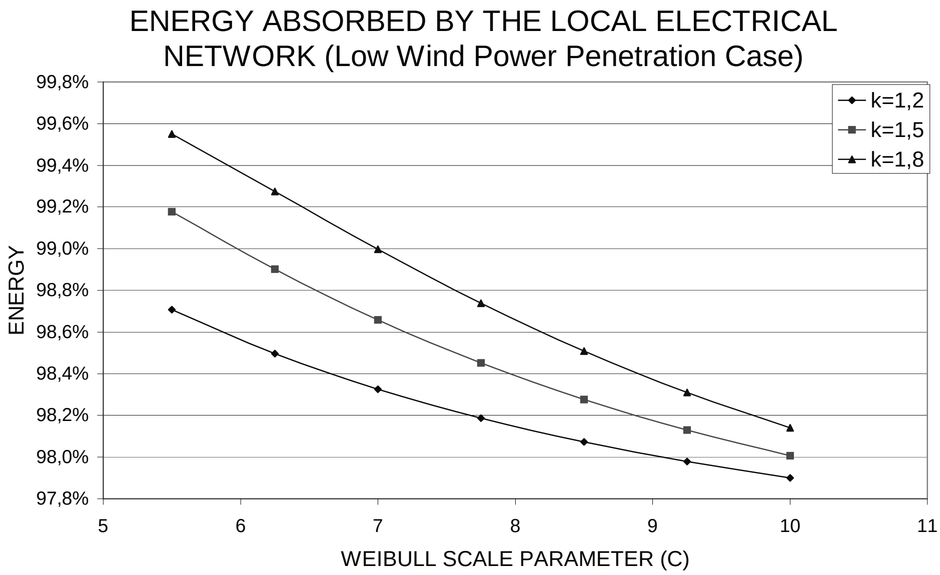

Figure 9: Wind energy contribution to a typical island electrical network. Weibull scale parameter impact, low wind power penetration case

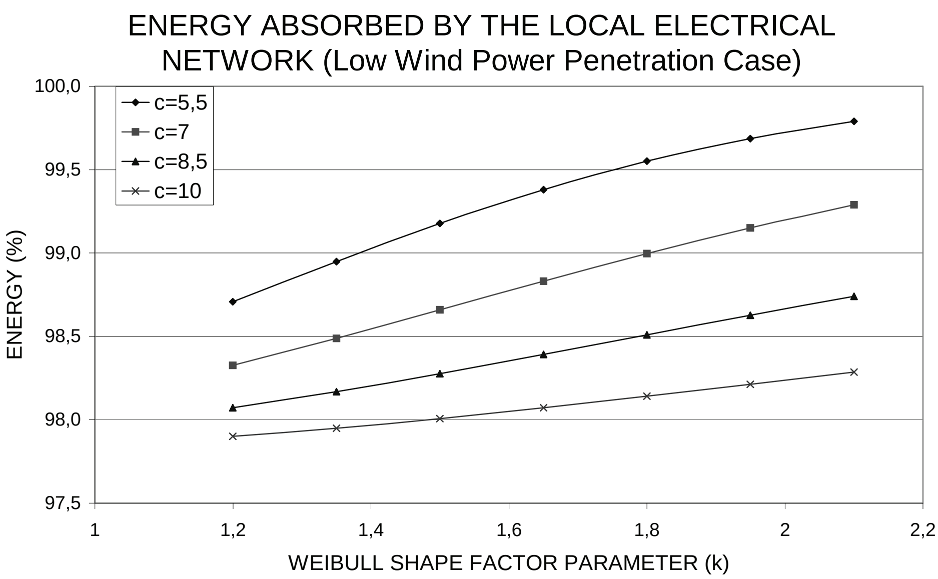

Figure 10: Wind energy contribution to a typical island electrical network. Weibull shape factor impact, low wind power penetration case

4.2 High Wind Power Penetration Case

Unfortunately the situation is not so encouraging for the high wind power penetration scenario. In fact the wind energy contribution to the local network is also increasing along with the "C" value (figure (11)), while this increase is still more abrupt for high "k" values. According to the results demonstrated in figure (12) the wind energy contribution increases as the shape factor value is amplifying, excluding the medium-low wind potential case (C=5.5). The main point for the high wind power penetration case (i.e. 2.5MW installed wind power) is that the maximum wind energy contribution is only 20% even for the excellent wind potential case (C=10), while for the low wind potential case (C=5.5) the corresponding value is less than 9.5%.

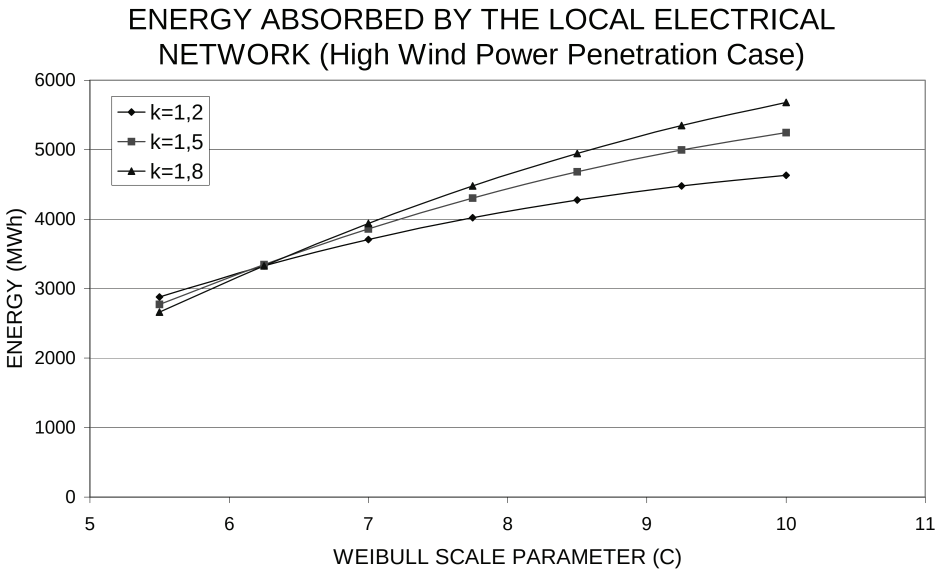

Figure 11: Wind energy absorbance by a typical island electrical network. Weibull scale parameter impact, high wind power penetration case

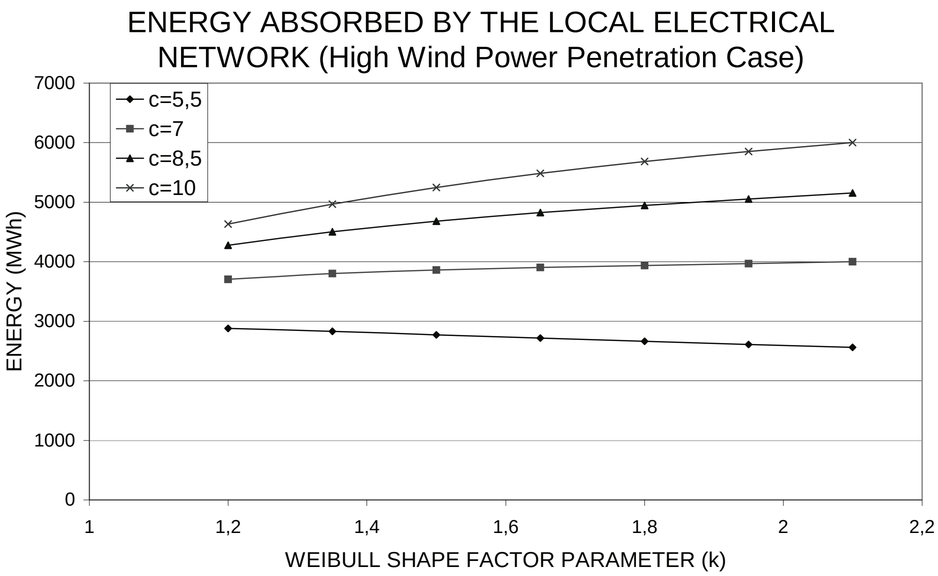

Figure 12: Wind energy absorbance by a typical island electrical network. Weibull shape factor impact, high wind power penetration case

Another important aspect resulting from the current analysis is the decreasing wind energy absorption percentage by the local electrical network as the "C" value increases (figure (13)), see also figure (9). More specifically, for very high wind potential cases only the 55% of the annual wind energy production of the 2.5MW wind park is finally absorbed by the local network, mainly due to the discrepancy between the wind energy production and the corresponding load demand. On the other hand, the wind energy contribution increases significantly along with the Weibull's shape factor value increase. This amplification is much stronger for medium-low wind potential cases, reaching values up to 85% of the corresponding wind energy production. On the contrary, for high wind potential cases this increase is much more moderate, figure (14), i.e. less than 65%.

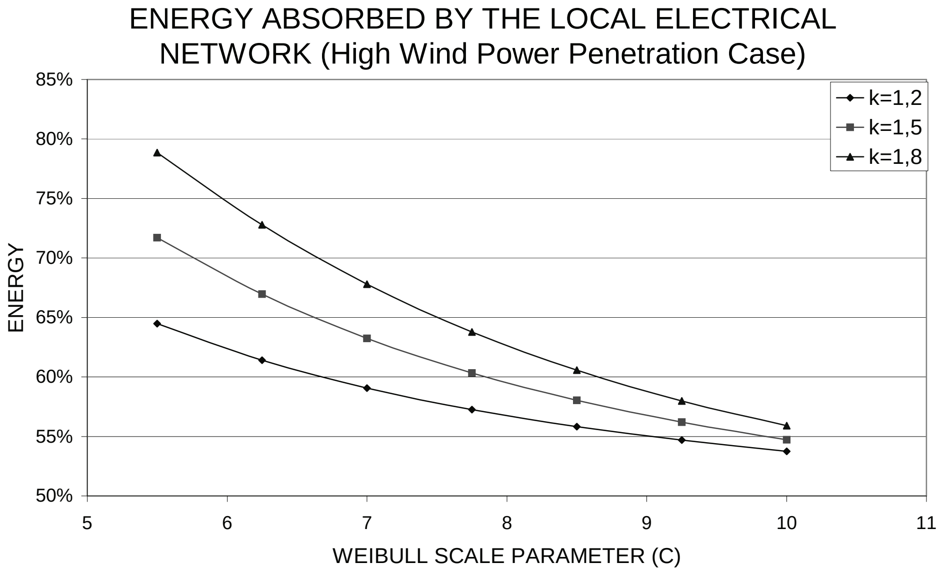

Figure 13: Wind energy contribution to a typical island electrical network. Weibull scale parameter impact, high wind power penetration case

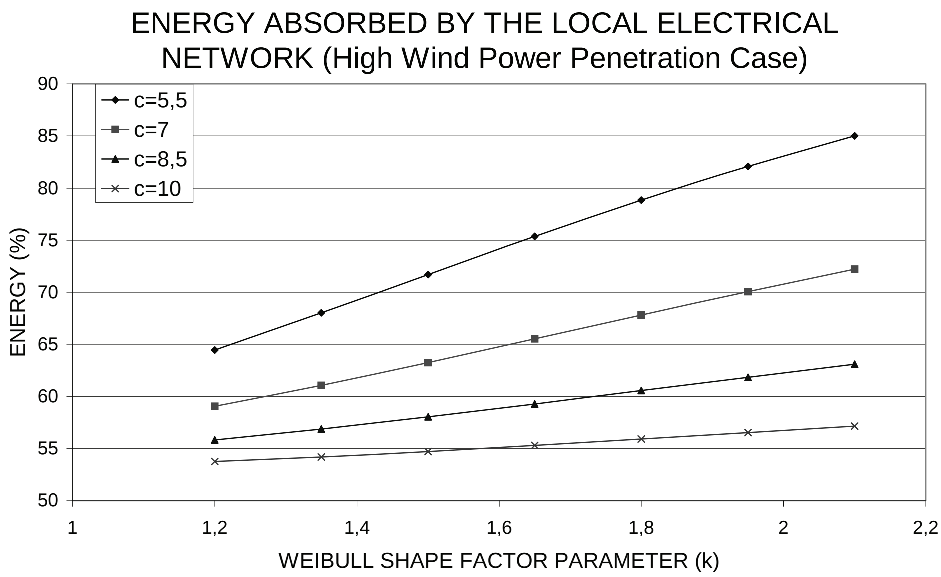

Figure 14: Wind energy contribution to a typical island electrical network. Weibull shape factor impact, high wind power penetration case

Recapitulating, according to the presented analysis there is a strict upper limit concerning the wind energy participation in fulfilling the electricity consumption needs of remote islands. This limit is dictated by the existing legislative frame, not permitting the installation of wind parks with rated power greater than a predetermined percentage of the local network's peak load demand during the previous year, and the operational behaviour of the existing thermal power stations (Appendix One). In fact, this wind energy participation limit is usually between 12% and 16%, not exceeding the 20% even at excellent wind potential cases. On top of this, the real wind energy contribution is much lower on a techno-economic basis, since no investor is going to erect a wind park in order to sell only the 60% of his annual energy yield[6]. Therefore, taking into consideration the highly variable electricity demand of the remote autonomous island networks and the stochastic wind speed behaviour, one should not expect a considerable wind energy participation in the local electricity production process, without serious energy management and energy storage strategies. Thus, for medium-low and medium wind potential areas the maximum annual wind energy participation is 13.5%, while for high and very high wind potential areas this value does not surpass the 20%, under the normal restrictions imposed by the local network operator.

5. Conclusions

An integrated methodology, able to estimate the maximum wind energy penetration in autonomous electrical networks on the basis of the available wind potential, taking into consideration the stochastic behaviour of the wind, is presented. Special attention is paid in order to examine the impact of the available wind potential in the Aegean Archipelago area on the corresponding wind energy contribution in the local energy balance.

According to the results obtained one may state that the wind energy contribution in the local electrical networks is increasing (in absolute terms) as the available wind potential becomes better. On the other hand, the wind energy absorbance by the local network decreases as the corresponding average wind speed value increases. On the basis of this conclusion, it is obvious that the existing legislative constrain concerning the upper wind power limit to be installed in a remote electrical system does not take into account the wind potential variation of the area, hence bounds the wind energy contribution to the fulfilment of the local societies electrical needs.

Additionally, the calculation results indicate that the maximum wind energy contribution is 20% for excellent wind potential areas, while in normal cases this value is in the range of 15%, excluding cases where remarkable energy storage facilities exist. On top of this, as the wind energy penetration increases the wind energy absorption decreases remarkably down to 55%, strongly questioning the viability of significant investments in the wind energy application sector.

Recapitulating, it is worthwhile to mention that the available wind potential strongly influences the wind energy contribution to the existing autonomous electrical networks. However, in any case, under the current legislative frame, there is no possibility of increasing the wind energy contribution in the autonomous electrical networks higher than 20% for excellent wind potential regions and higher than 15% for the vast majority of Aegean Archipelago islands. Only by developing appropriate energy storage systems it will be possible to increase the wind energy participation in the islands electricity demand, otherwise there is almost no possibility for remarkable new wind power addition, despite the excellent wind potential and the extremely high electricity production cost of the area.

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Appendix One

According to the available information[19][23] the island autonomous electricity generation systems are based on diesel or heavy-oil powered engines. In this context, one should note that these units are not permitted to operate below a certain limit, in order to avoid increased wear and maintenance requirements. This limit is mentioned as the "technical minimum" of each engine, hence the minimum output power of the "in operation" thermal units "N_{dmin}" is calculated as:

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

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 (i_{max}) of engines "in operation" during the year, should be also considered.

In addition, due to the stochastic behaviour of the wind one cannot disregard the probability of an unexpected loss of a significant part of the "in operation" wind parks. To avoid (or to minimize) loss of load events[24][21] 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, i.e. the "in operation" thermal units should be able to cover the instantaneous load demand "N_L", thus:

$$\sum_{i=1}^{i=i_{\max}} N_{d_i}^{*} \geq N_L \quad \text{(A-2a)}$$

However, in order these units to come into operation at their minimum fuel consumption (maximum efficiency) point one should require:

$$N_W^{*} + \sum_{i=1}^{i=i_{\max}} \xi_i \cdot N_{d_i}^{*} = N_L \quad \text{(A-2b)}$$

where "ξ_i" takes values approximately between 65% and 80%, on the basis of the operational maps of the existing diesel engines. In an attempt to satisfy the "economic" operation of the existing internal combustion engines in view of the desired wind energy penetration, one should carefully plan the dispatch of the thermal units of the local autonomous power station[25]. Hence, combining equations (A-2a) and (A-2b) assuming as well that one may use a single "ξ_i" value, one finally gets:

$$N_w^{*} \leq (1-\xi) \cdot N_L \quad \text{(A-2c)}$$

For practical applications equation (A-2c) is written in the following simplified and widely used form, i.e.:

$$N_w^{*} \leq \lambda_1 \cdot N_L \quad \text{(A-2)}$$

where "N^*_w" is the maximum acceptable by the local network wind power and "λ_1" is the corresponding maximum instantaneous participation limit, based on the operational characteristics of the existing thermal power units.

Finally, in order to avoid annoying system frequency excursions and increasing wear of the existing thermal power units, an additional penetration limit is also imposed, dictated by the instantaneous rate that the "in operation" units can compensate any power deficit of the system. This dynamic penetration limit[19] is characteristic of the local electrical network as well as the spatial distribution and the type of the system wind turbines[8]. Generally speaking, this limit "λ_2" is selected by the system operator (also incorporating subjective/personal attitude) and is up to now empirically set in the range of 20% to 40%. In case of emergency this value may drop down to 15% or even be zeroed[6]. In this context, the dynamic penetration constraint is expressed as:

$$N_w^* \le \lambda_2 \cdot N_L \tag{A-3}$$

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

$$\textit{If} \quad N_L(t) \le N_{d_{\min}}(t) = \sum_{i=1}^{i=i_{\max}} k_i \cdot N_{d_i}^* \qquad \textit{then} \;\; N_w^* = 0 \tag{A-4}$$

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

$$\textit{If} \quad N_{d\min}(t) \le N_L(t) \le (1+\lambda)\cdot N_{d\min}(t) \qquad \textit{then} \;\; N_w^* = N_L(t) - N_{d\min}(t) \tag{A-5}$$

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

$$\lambda = \min\{\lambda_1, \lambda_2\} \tag{A-6}$$

One should also take into account that according to the existing legislation, if the load demand is higher than the technical minima of the existing thermal power units, priority is given to the wind parks entering the local network. Finally,

$$\textit{If} \quad N_L(t) \ge (1+\lambda)\cdot N_{d\min}(t) \qquad \textit{then} \;\; N_w^* \le \min\left\{\left[\lambda \cdot N_L(t)\right], \left[N_L(t) - N_{d\min}(t)\right]\right\} \tag{A-7}$$

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. In most practical application cases the "λ" value is taken (as a rule of thumb) less or equal to 30%.

THE CONTRIBUTION OF RENEWABLES ON REDUCING THE ELECTRICITY GENERATION COST IN AUTONOMOUS ISLAND NETWORKS

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Abstract

The Aegean Archipelago is a remote Hellenic area, including several hundreds of scattered islands of various sizes. The electricity demand in the Aegean Archipelago islands has up to now been covered by the existing Autonomous Power Stations (APS) at very high electricity production cost. In order to face the continuous load demand increase an integrated solution based on the exploitation of the available renewable energy sources potential in collaboration with appropriate energy storage systems is investigated. According to the results obtained, the proposed solution is clearly more cost-effective than the operation of the existing thermal power stations, while remarkable environmental and macroeconomic benefits are also expected.

Keywords: Electricity Generation Cost; Energy Storage; Remote Islands; Renewable Energy Sources

1. Introduction

The Aegean Archipelago is a remote Hellenic area, including several hundreds of scattered islands of various sizes. The main economic activities of the islanders are apart from tourism, seafaring, fishery, agriculture and stock farming. The electricity demand in the Aegean Archipelago islands has up to now been marginally covered by the existing Autonomous Power Stations (APS), based on internal combustion engines and gas turbines[1][2]. Unfortunately, one of the major problems of these islands is the low quality of electricity available at very high production cost, figure (1). Besides, a continuous load demand increase is encountered during the last thirty years dictating the installation of new power stations throughout the entire area.

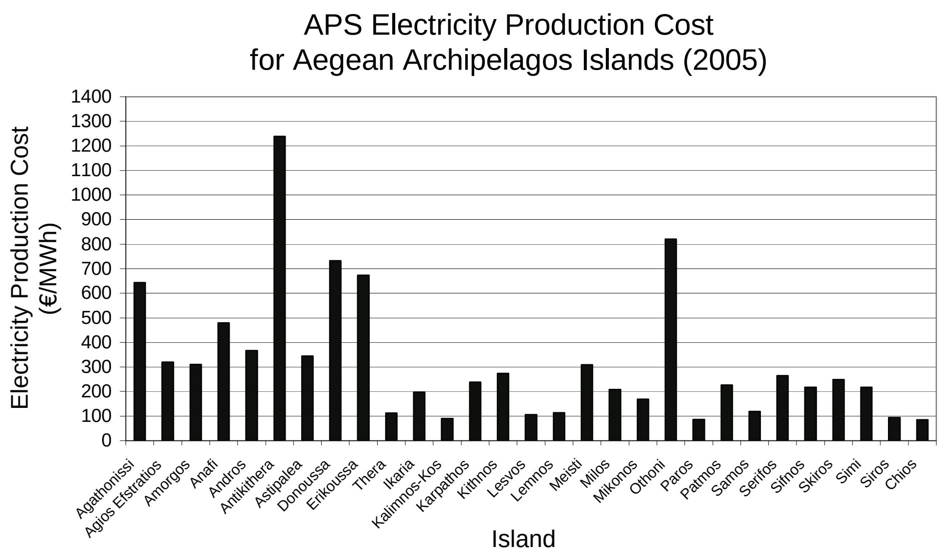

Figure 1: Electricity production cost of Greek Island APS (PPC, 2005)

Kavadias K.A., Zafirakis D., Kondili E.M., Kaldellis J.K., 2007, *"The Contribution of Renewables on Reducing the Electricity Generation Cost in Autonomous Island Networks", ICCEP-2007, "Clean Electrical Power" International Conference, IEEE, Capri, Italy.*

On the other hand, the Aegean Archipelago is an area with excellent wind potential and abundant solar energy, while in some islands one may find remarkable geothermal reserves and several biomass feedstock, figure (2). Up to now, the only renewable energy sources (RES) exploitation activity is based on wind energy applications[3][4], hence in several islands one may find small or medium-sized wind parks, with the maximum installed wind power being less than 10MW. The basic problem for the extended exploitation of RES (mainly wind and solar) is their variable or even stochastic availability; therefore, the corresponding energy production cannot meet in any case the variable load demand of the autonomous island electrical systems. On top of this, the local network operator (PPC) poses serious restrictions on the instantaneous participation of RES in the corresponding load demand, which seriously bounds the RES contribution in the local energy market[5][6].

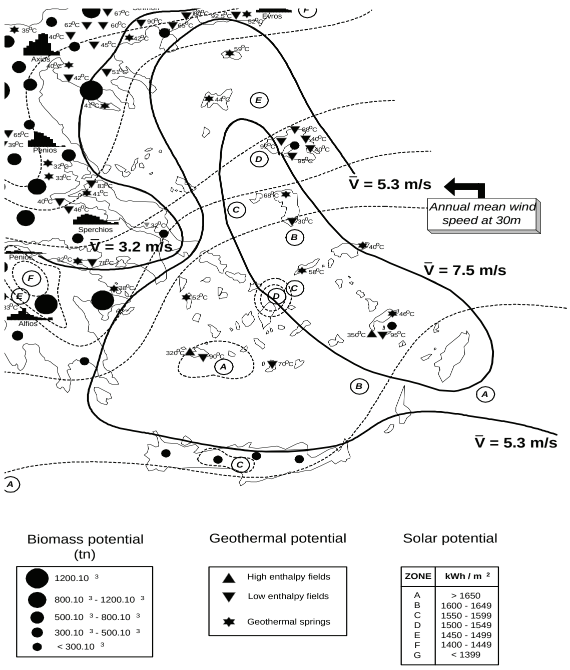

Figure 2: RES potential in the Aegean Archipelago region

To face these problems, the authors have since the previous decade proposed[7][8] several electricity generation solutions with remarkable positive side effects. These solutions are based on the exploitation of the available RES potential in collaboration with appropriate energy storage systems (ESS). Similar hybrid configurations may be the most cost-effective solutions to meet the electrification requirements of the Aegean Archipelagos with significant environmental and social benefits[9][10]. Hence, the present paper analyzes first the existing situation in the Aegean Archipelagos electricity market; afterwards it describes the above mentioned solutions and finally it evaluates the application results. According to the results obtained, the proposed configuration is definitely better than the existing situation, even in pure financial terms, including also serious environmental and macroeconomic benefits.

2. Description of the Current Electricity Generation Situation

According to the official data, approximately 220 thermal power units exist in the Aegean Archipelago (excluding Crete island) with total installed capacity equal to 800 MW, while the corresponding electricity generation during 2005 was almost 2200GWh. Unfortunately, most of the existing power units have been in operation for almost twenty years. The result of this situation is that several units present serious problems, being out of service for remarkable time periods, while their real output is almost 15% less than their rated power, especially during summer. Comparing the "in operation" real power of the existing APS with the corresponding peak load demand, one may easily conclude that, in several cases, there is a very narrow power security margin, hence the local APS do not guarantee the consumers' safe electricity supply.

In all cases analyzed, a remarkable long-term electricity generation increase is encountered, which is more intense for the S. Aegean region islands than for the N. Aegean ones. As it results from figure (3) the annual electricity consumption at the beginning of the period examined in S. Aegean was less than the one of N. Aegean. More specifically, according to figure (3), describing the electricity generation time-evolution for the N. Aegean islands, a remarkable electricity consumption increase is observed, since the 2005 value is between six and eight times the corresponding value of 1975. Accordingly, the electricity generation increase for the islands of S. Aegean is much more intense, especially during the last ten years. Besides, the peak power demand and the annual energy production behaviour of most

Aegean Archipelago islands present the same time variation (i.e. parabolic and in some cases exponential increase), resulting in long-term average annual increase rates of the order of 10%, see also figure (4).

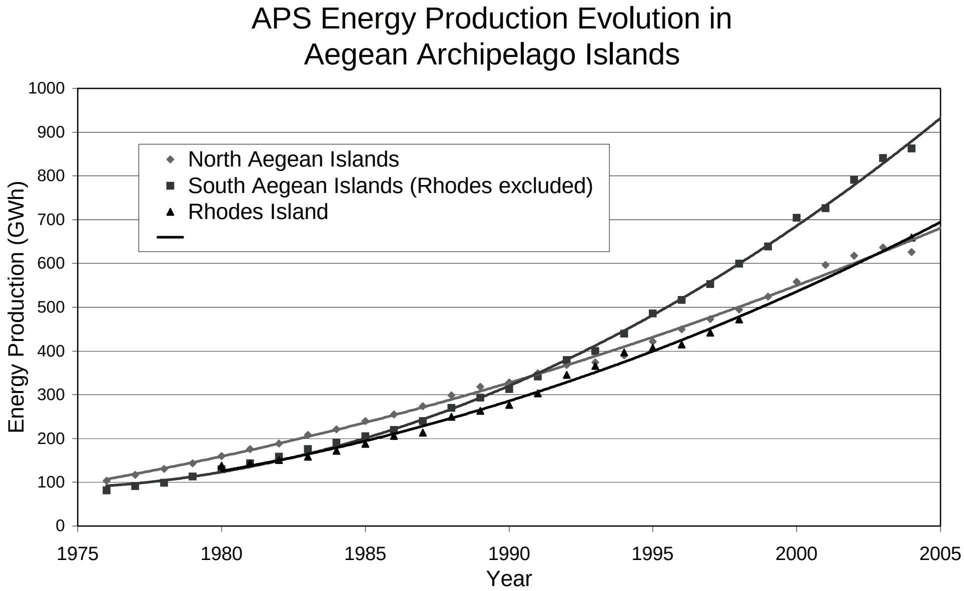

Figure 3: Electricity generation time-evolution in the Aegean Archipelago area

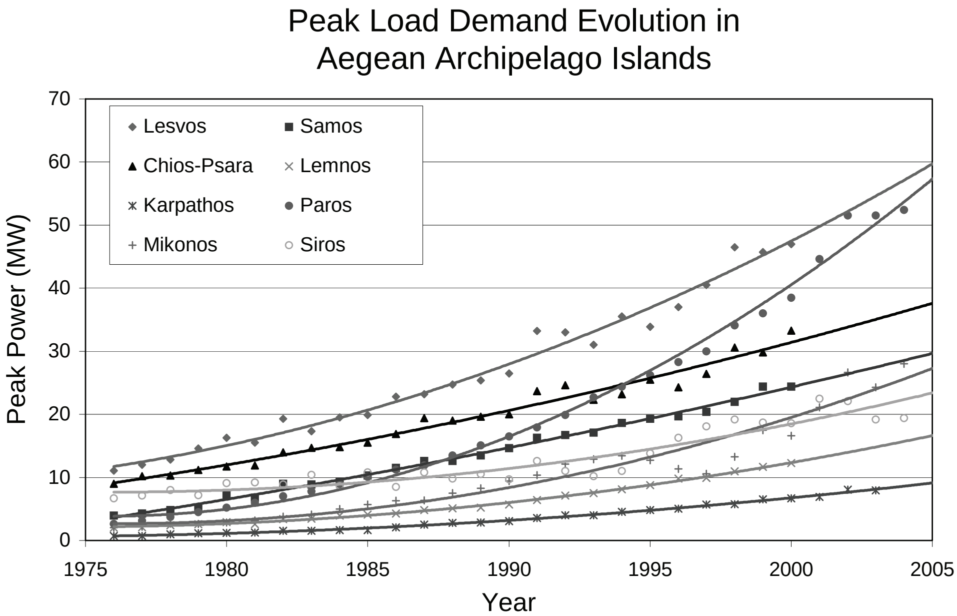

Figure 4: Peak load demand in selected Aegean Sea islands

One additional severe problem of the existing electricity generation systems is the serious electrical load demand fluctuations encountered in daily and annual basis, see for example figure (5). This situation, strongly influenced by the significant touristic activity, mainly during summer, poses additional problems on the electricity production systems of the islands, leading a large portion of the existing thermal power units to quite low capacity factors (utilization) values. Considering the time-evolution of peak load and energy production in relation with the rate of permanent population changes, one may safely claim that the continuous increase of electricity needs is only partially attributed to the permanent population growth. Thus, the determining factors explaining this tendency seem to be the annual visitors' increasing figures (especially during summer season) and the corresponding improvement of the living standards.

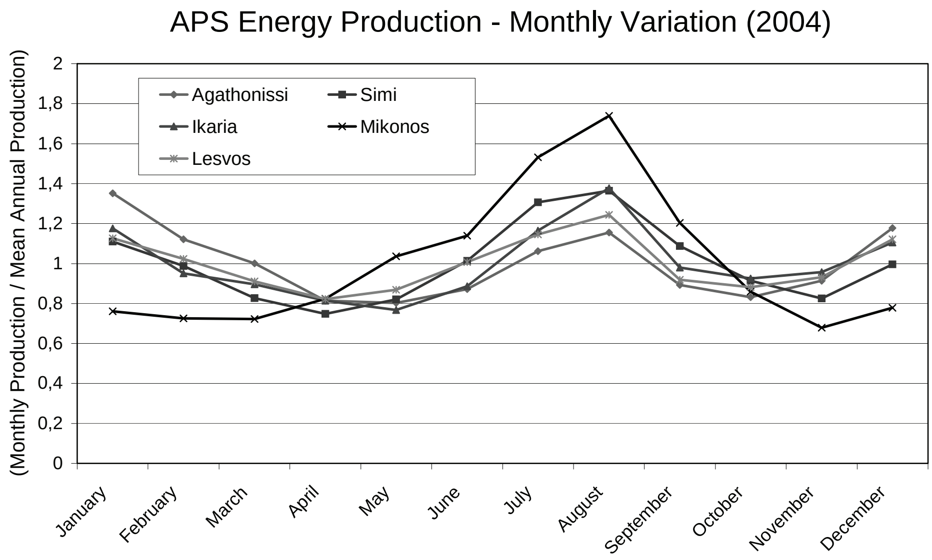

Figure 5: Annual electricity consumption variation in Aegean Archipelago islands

At this point it is worthwhile mentioning that despite the excellent wind potential and the abundant solar energy of the Aegean Archipelago the only RES exploitation activity is based on small scale wind energy applications[3][4]. Note that the first wind parks have been installed in Aegean Archipelago islands since '80s, while during 1990-1993 the total installed by the Greek PPC wind power approached 30MW[11]. Since then, one cannot mention any serious wind park development activity by PPC, while the only activity encountered is due to private wind parks erection, mainly in the islands of Lesvos, Kos and Chios.

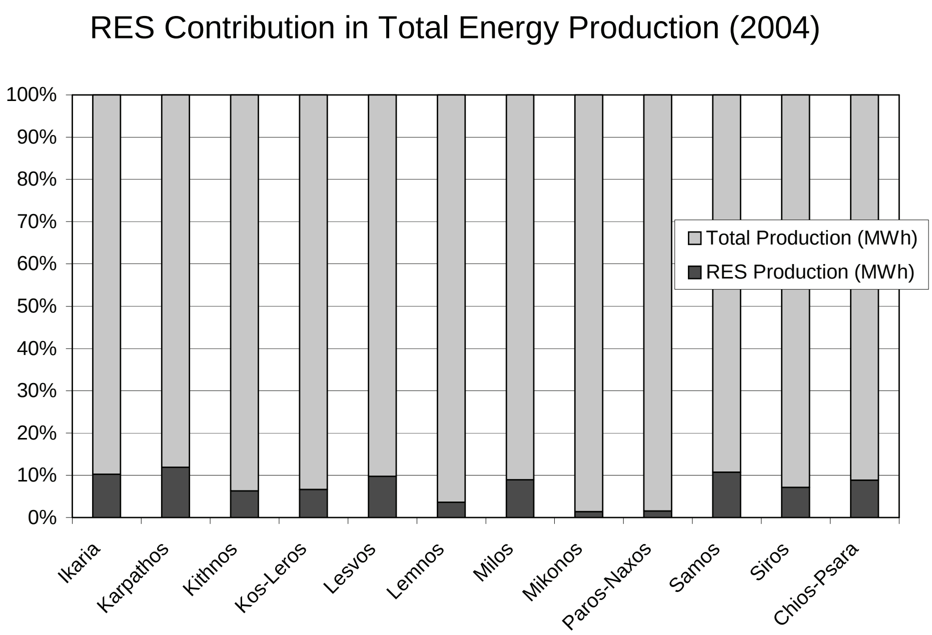

Figure 6: Wind energy contribution in the total electricity consumption of selected Aegean Archipelago islands during 2004

In fact, the major wind energy exploitation activity is encountered in Lesvos island, where during 2004 almost 28.7GWh of wind based electricity has been produced, as well as in Chios (18.2GWh/y) in Kos (18.3GWh/y) and in Samos (17GWh/y) islands. The result of this moderate activity is the production of almost 110GWh of wind electricity, which represents only the 5% of the corresponding annual electricity consumption of the area. Using the most recent available official data, one may find in figure (6) that the maximum wind energy penetration is encountered in the islands of Karpathos (13.5%) and Lesvos (11.5%), while in certain islands the corresponding contribution is almost zero. The main reason reported by the experts for such a low wind energy penetration is the restrictions set to the wind energy contribution in order to maintain the local grids' stability due to the stochastic wind speed behaviour and the strongly variable electricity consumption[12].

More precisely, the instantaneous RES penetration in the local electrical network is dictated first by the technical minima of the existing thermal power units[5]. Additional barriers exist[6] due to the stochastic behaviour of the wind and in order to avoid (or to minimize) loss of load events. For this purpose the local system operator should maintain full spinning reserve in the thermal power units, which suffices to cover the total load demand, in case of an unexpected loss of a significant part of the "in operation" wind parks. Finally, in order to avoid annoying system frequency excursions and increasing wear of the existing thermal power units, an additional penetration limit is also imposed, dictated by the instantaneous rate that the "in operation" units can compensate any power deficit of the system. The result of the above mentioned constraints is the limited wind energy participation in the islands electricity balance, figure (6). Recapitulating, until recently the local electricity utility (PPC) posed a 30% wind power penetration barrier to guarantee the local grid stability. However, even this strict limit has only theoretical value, since economic viability criteria[13] deteriorate the maximum wind energy contribution to single digit numbers (i.e. ≤10%).

3. Proposed Solution

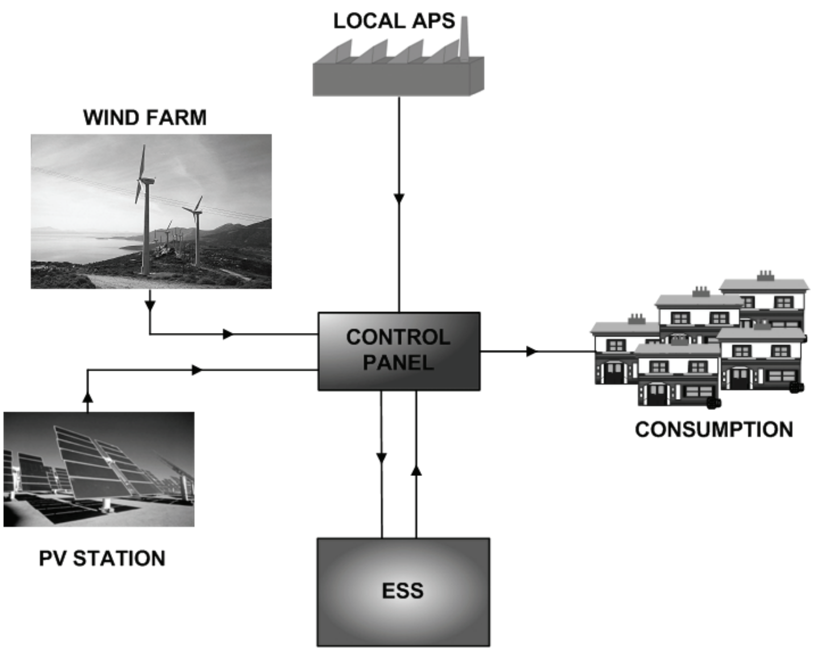

Figure 7: Proposed electricity generation configuration for autonomous electrical grids

Taking into consideration all the above mentioned information, the authors have proposed since 1995[7][8][14][15] an integrated solution based on RES (mainly wind or/and solar) power stations, able to meet the electricity demand of a typical island, as well as an appropriate energy storage facility that guarantees the local community energy autonomy for a desired time period. Note that an energy storage system, when sized appropriately[7][15], not only can couple a variable RES based energy production to a generally variable and hardly predictable system demand, but also improves the system reliability and contributes in the energy production cost reduction. Finally, the existing (usually outmoded) thermal power stations may also be used either as a back up solution or to cover unexpected high load demand. More precisely, the proposed configuration (figure (7)) includes:

a. One or more RES-based power stations

b. A number of energy storage devices (e.g. lead-acid or Na-S batteries, a group of water reservoirs, etc.) combined with their corresponding energy production equipment (e.g. inverters, small hydro-turbines, etc.).

c. The existing thermal power units of the already in operation APS. The main target of the proposed solution is to minimize the contribution of the local APS to the local system electricity consumption.

More specifically, for the small and very small islands or for regions with relatively low wind potential one may create[8][16][17] photovoltaic based power stations along with energy storage (e.g. batteries) facilities in order to replace the existing thermal power stations, operating at very high cost (higher than 200€/MWh), see figure (1). Subsequently, for big and medium-sized islands with high wind potential one may adopt the wind-hydro solution, based on the collaboration of wind parks and reversible hydro power stations operating as water pumping and energy production facilities[7][15][18]. In this case, the wind parks face the corresponding load demand, while any energy surplus is stored via the water pumping system at a high level reservoir. In case of energy deficit, the water reserves are utilized via the hydro turbines of the installation to cover the excess power demand. In a more integrated concept one may use the RES based energy production to enhance the water reserves of the local communities[19].

Finally, for the islands where remarkable geothermal potential exists (figure (2)) one may develop an integrated energy production facility to meet electrical and thermal energy requirements of the local community[20]. This solution would be much more attractive financially, if the nearby to the geothermal field islands were interconnected. In fact the possibility of interconnecting the Aegean Archipelago islands with the mainland electrical network in order to create an integrated electricity transportation network presents serious advantages and disadvantages[21], the detailed presentation of them being out of the scope of the present paper. In brief, the islands' interconnection, wherever possible, may gradually replace the local APSs operation and at the same time allow the absorption of large amounts of wind energy without causing the instability effects noticed in autonomous grids. On the other hand, such an electricity production strategy has to face the significant technological problems related to the undersea electricity transportation, the rather high first installation cost (approx. 3 million Euros per km of transportation grid) and the strong opposition of local societies claiming important environmental impacts.

4. Calculation Results

The developed methodology is accordingly applied to two representative Aegean Islands. The first being Karpathos and belonging to the medium scale Aegean islands, and the second, Megisti, representing the very small scale category. In this context, the application of a wind-hydro and a PV-Na-S configuration are investigated. More specifically, the wind hydro solution implementation, recommended for medium and big scale electrical grids[7][18], will be investigated for Karpathos island. Next, the PV-batteries solution, able to meet the electrification needs of a very small electricity network will be applied on the island of Megisti[8][16]. From the results obtained a clear picture concerning the viability of such schemes as well as the potential cost-effectiveness supported by the latter adoption, may be provided. Emphasis is also laid on serving the need for maximum RES participation in the islands' energy balance.

4.1. Wind-Hydro Solution for a Medium-Sized Island

Karpathos is a medium-sized island (population 6,565 habitants, area of 301km^2) of South-East Aegean Sea, belonging to the Dodecanese complex (the second biggest after Rhodes). Its major town is Karpathos with 2,088 habitants. The local terrain is characterized by rocky mountains with sharp slopes and absence of flat fields. The annual energy production of the local APS (which covers also the electricity requirement of nearby Cassos island - 990 habitants) was almost 29,000MWh for 2005. The peak load demand -approximately 7880kW- appears during summer, while the corresponding minimum value is 1400kW. The island has very high wind potential, since the long-term annual mean wind speed approaches 9.6m/s, at 10m height[22]. Besides, there is a quite large natural water reservoir (approximately 2,000,000m^3), which can be used during the application of the proposed wind-hydro solution.

Similarly to most Aegean Sea island, the evolution of the local APS production cost presents a remarkable mean annual increase (0.24€/kWh for 2005), while the contribution of fuel cost is almost 55%. The APS of Karpathos consists of seven operating internal combustion engines of total rated power 12MW. In the island there is (since 1991) a very small wind park of Greek Public Power Corporation (PPC) based on five (5x55kW) outdated WM-15S wind turbines, rated power 275kW[22].

To encounter the ongoing electricity demand increase, several wind parks collaborating with an appropriate ESS, in particular a pumped-hydro system (PHS), may be installed. Taking into account the wind potential of the area and the corresponding load demand time distribution, the corresponding ESS contribution varies[5][6] between 50% and 60%, i.e. $0.5 \leq \varepsilon \leq 0.6$. In the current analysis the parameter "ε" is taken equal to 55%. After having determined the annual contribution of the applied RES-based energy storage configuration, the autonomy period provided by the employed storage technology is examined.

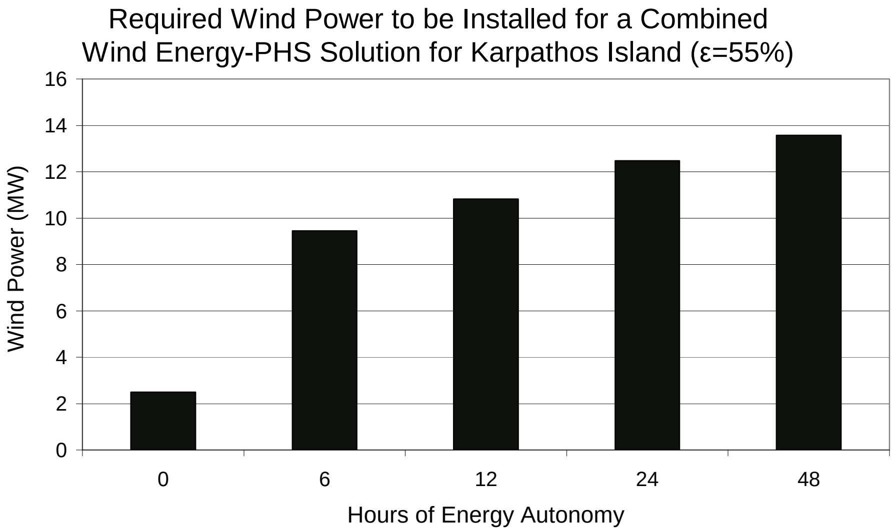

Figure 8: Wind power variation vs. desired hours of energy autonomy for Karpathos island

In figure (8), the wind power requirements for the safeguard of the wind hydro contribution depending on the energy autonomy selected (from zero autonomy to d_o=48 hours) are presented. The initial steep increase of wind power requirements, in fact quadrupling between zero contribution and 6 hours of autonomy, tends to normalize as the desired autonomy increases. If autonomy of 48 hours is selected instead of the corresponding of 12 hours, only a 25% increase of the wind power requirements should be expected. In terms of capacity, for a respectable energy autonomy provided by the proposed configuration, i.e. in the range of 24 to 48 hours, wind parks of rated power from 12.5MW to 13.5MW should be installed. In conclusion, since after a certain point of autonomy the wind power requirements are not considerably affected, the wind park component shall not entail the decisive impact factor differentiating the resulting electricity generation cost.

In figure (9), a break-down cost analysis of the various components synthesizing the wind-hydro configuration for 20 years of operation is presented. From the results obtained one may notice the dominant role of the input energy cost, determining the resulting cost for low autonomy (over 50% of participation for d_o=6 hours even reaching 75% for d_o=12 hours). The energy deficit appearing because of low autonomy values must be compensated by the local APS contribution, described by a considerably high energy price (0.24 €/kWh). As the autonomy supported by the proposed configuration increases further (more than d_o=12hours), the impact of the input energy cost, as expected, is minimized. Instead, it is the PHS and the wind park's initial costs that must be considered as responsible for the resulting total cost, with equal participation shares. Concerning the M&O costs for both the wind park and the PHS, a significant variation determining the total cost is not to be taken into account in the entire autonomy range examined.

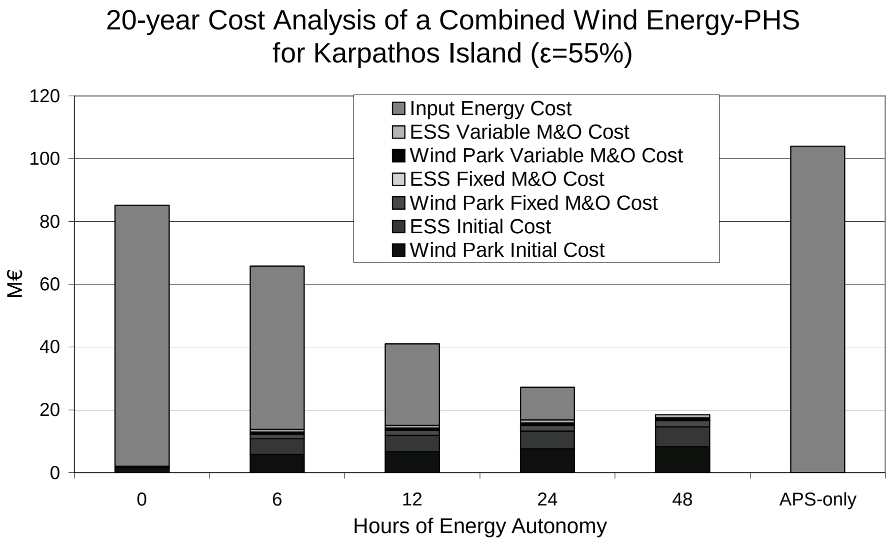

Figure 9: Long-term cost analysis of a combined wind-hydro electricity generation system

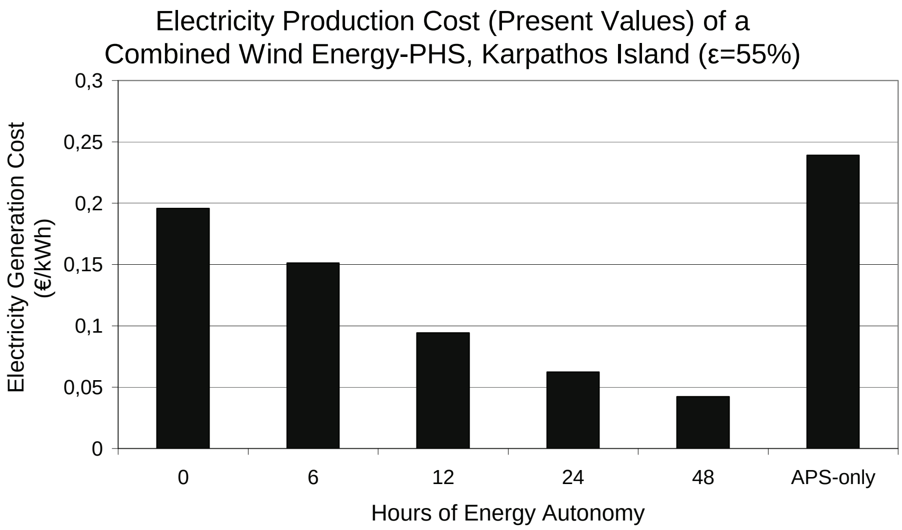

Figure 10: Electricity generation cost of a combined wind-hydro electricity production installation

What is interesting to note as well is the rapid cost decrease following the increase of the selected autonomy. For example, if 6 hours of autonomy are undertaken a total of 65M€ for the entire operational period examined is expected. If 48 hours should be adopted, less than 20M€ are necessary through the project's lifetime. A direct comparison of the obtained costs with the corresponding ascribed to the existing electrification solution reveals the proposed solution's clear advantage. In all cases examined, the cost-effectiveness of the wind hydro configuration is evident. For the extreme case of d_o=48 hours, the local APS lifetime cost is more than five times the one demonstrated by the

RES-ESS scheme. The main problem to be solved is the existence or not of appropriate locations for the installation of the entire wind-hydro solution as well as the significant installation capital required.

The above results are further explained in figure (10), where the specific electricity generation cost (€/kWh) is depicted. Similarly to the results of the 20-years total cost analysis, a remarkable reduction of the electricity production cost following the increase of the provided autonomy is encountered. In fact, for high autonomy values (greater than 12 hours), the estimated electricity generation cost of the proposed wind-hydro scheme appears to be lower than the recent law-supported (law 3468/06) sale price per kWh of wind energy generated in the non-interconnected islands of Aegean Sea (0.0846€/kWh). Thus, the financial viability of the investigated scheme is justified.

4.2. PV-Na-S Batteries Solution for a Small Island

Megisti was until recently the easterly European Union (EU-15) edge, located almost 72 miles from Rhodes. The island area is only 9km^2 and the population is 403 permanent habitants (approximately 100 families). The local terrain is arid and rocky with several caves. The annual energy production of the local APS was 2100MWh for 2005. The peak load demand -approximately 560kW- appears on August 13, while the corresponding minimum value is 120kW (8 May). The main economic activities of the local society are fishing and tourism. The island has also excellent solar potential, since the annual mean solar radiation exceeds 1700kWh/m^2, at horizontal plane[23]. There is no traffic network in the island despite the existence of a small airport.

Since it concerns a small scale island, Megisti's electrification needs may be confronted by the incorporation of an appropriately sized PV-batteries configuration. More specifically, the proposed scheme shall include a properly-sized photovoltaic station collaborating with a corresponding Na-S batteries energy storage system. An autonomy range from 2 to 24 hours, representative of the Na-S batteries capacity potential, is currently examined.

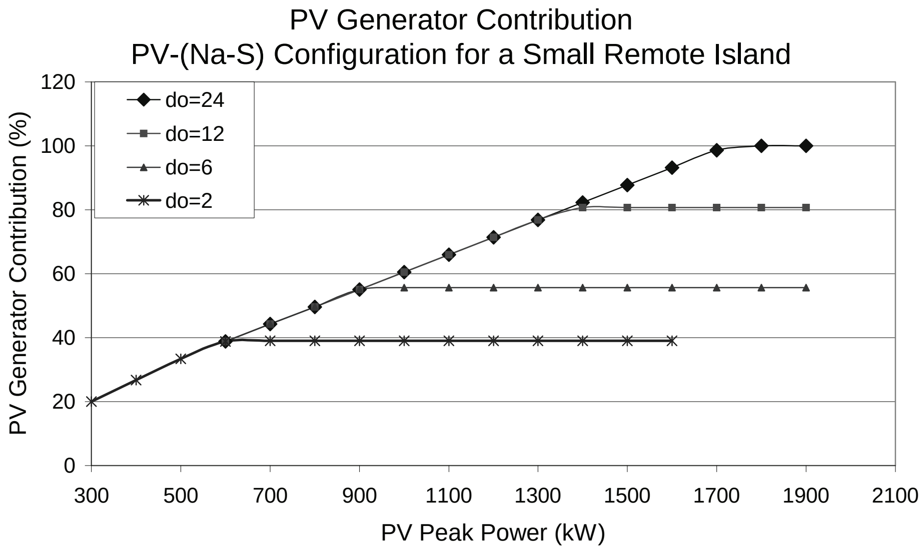

Figure 11: PV-Generator contribution in the electricity production balance of a small remote island

In this context, apart from seeking for the minimum possible electricity generation cost, one should also aim at maximum RES energy contribution. In figure (11) one may observe the variation of the PV generation contribution in relation with the PV-station's rated power and the values of selected autonomy. As noticed from the figure, an increasing trend describing all the autonomy cases may be encountered up to a certain critical point, determined by the selected energy storage capacity (i.e. "d_o" value). Afterwards, steady values for the PV generation contribution, regardless the additional PV power to install, must be considered. Consequently, the addition of more PV-power to a greater extent has no positive impact on the latter energy contribution share.

Concerning the factor of autonomy, if lower autonomy values are to keep in mind, analogous PV generation contribution rates should be expected. Moreover, an approximate 20% increase among the maximum contribution values supported by each autonomy case investigated is noted. It is interesting to see that for the d_o=24 hours case, the contribution of the local APS is practically zeroed, since the PV generator provides the 100% of the total electrical energy consumption of the local network, for PV rated power greater than 1700kW. On the other hand, for d_o=2 hours, the corresponding transom, responsible for 40% of PV utilization, is 600kW. After a closer inspection of figure (11) one may notice that in the range between 600kW and 1400kW several combinations presenting the same PV-generation contribution values may be encountered. Hence, to designate the most attractive solution available, one should co-evaluate the cost-effectiveness impact as well.

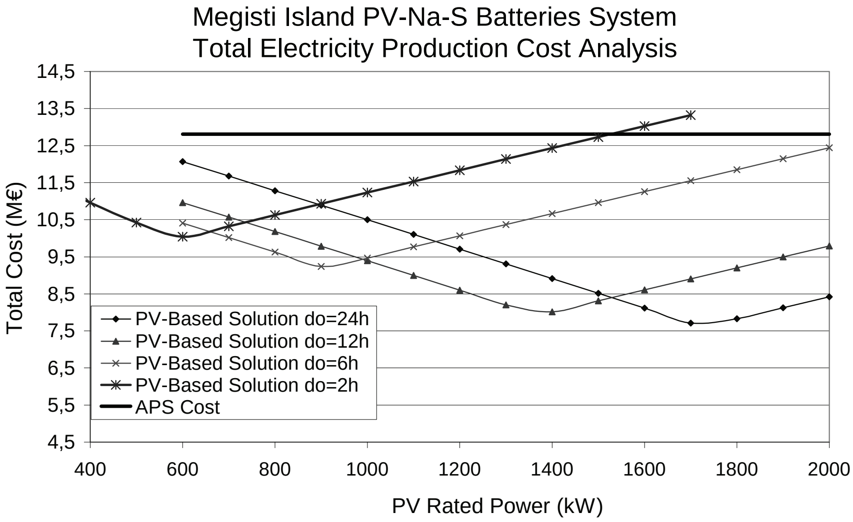

Figure 12: Electricity generation cost of a combined photovoltaic-(Na-S) batteries electricity production installation for a small remote island

In figure (12), the total lifecycle cost of the PV-Na-S configuration in relation with the autonomy and PV-power variations is illustrated. In all autonomy cases examined a minimum total cost value may be noted. For this to happen, a reduction trend previously describing the behavior of all 4 autonomy lines drawn is noticed. For lower autonomy, although minimum costs are achieved earlier (less PV-power required), higher total cost values are expected. Next, the minimum cost values arising for all the "d_o" cases examined correspond to the critical points emphasized previously and concerning the maximum PV penetration under minimum PV-power installed (see also figure (11)).

Consequently, if isolating each of the autonomy cases examined, the most cost efficient combination also supporting for maximum RES penetration may easily be drawn. However, since the PV utilization is not affected by the selected autonomy in the range between 600kW and 1400kW, only the criterion of cost-effectiveness may highlight the ideal solution. More specifically, up to 900kW, except for the 600kW case where 2 hours of autonomy should be preferred, 6 hours of autonomy are recommended, while for PV power installations greater than 1000kW and smaller than 1400kW, 12 hours of autonomy should be adopted.

In figure (13), the break-down cost of the resulting minimum cost configurations (depended on the PV power installed) for d_o=2h to d_o=24h presented, confirms the assumption previously cited, i.e. for lower autonomy values the PV-component is not the most critical cost component. As in the case of the wind-hydro, the low autonomy values resulting costs are dominated by the input energy cost, necessary to satisfy the local electricity demand. As the autonomy rates increase (>1000kW) and the PV utilization maximizes, minimum cost configurations employ bigger-scale PV stations, therefore entailing analogous cost shares.

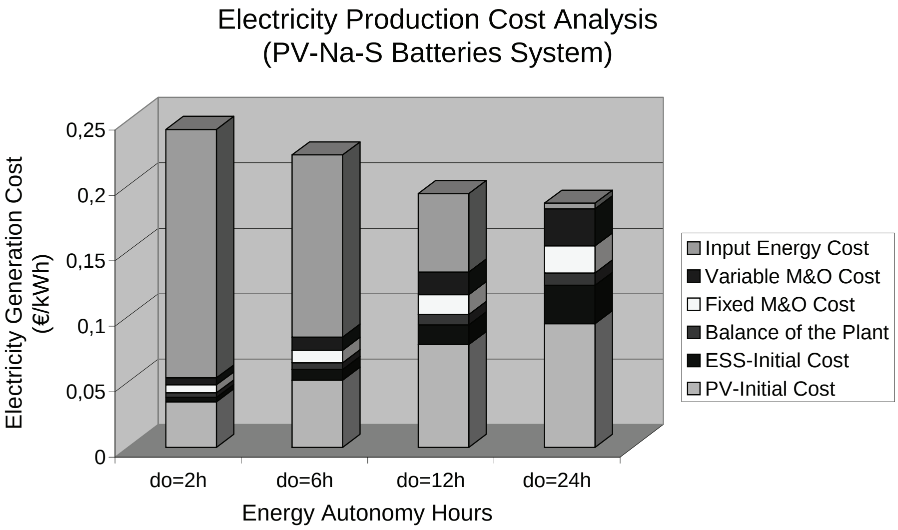

Figure 13: Electricity generation cost analysis of a combined photovoltaic-(Na-S) batteries electricity production installation for a small remote island

Recapitulating, for low autonomy values the component of input energy proves to be decisive. For example, for d_o=2 hours, an 80% contribution of the input energy part should be noted. On the other hand, when the autonomy maximizes (d_o=24 hours) the percentage of the electricity generation cost owed to the absorption of energy from the local network is minimized. In addition, the bigger scale PV-stations installed suggests corresponding cost shares. Either way, for high energy autonomy cases, photovoltaics comprise the main cost component.

5. Conclusions

The electricity generation problem in the remote Aegean Archipelago islands is one of the basic problems hindering the development of the local island communities. Actually, up to now the electricity offered by the existing outdated thermal power stations is often at low quality and the corresponding production cost is very high. To face these problems, the authors have elaborated an integrated solution based on the exploitation of the available wind-solar potential in collaboration with an appropriate energy storage system.

In this context, the present work has analyzed the existing situation in the Aegean Archipelago electricity market, taking into account the annual electricity consumption and the peak power demand time-evolution as well as the corresponding electricity production cost values. Accordingly, the above mentioned electricity generation solutions, based on RES exploitation, have been described in detail. Finally, representative application results have been demonstrated, while emphasis is given in presenting the RES contribution and the corresponding electricity generation cost values in comparison with the existing situation. According to the results obtained, the proposed solution is clearly more cost-effective than the operation of the existing thermal power stations, while remarkable environmental and macroeconomic benefits are also expected.

Recapitulating, one may clearly state that only by developing properly designed hybrid power stations based on RES exploitation and interconnecting some of the islands of the area it is possible to face the continuously increasing electricity demand of the area, with rational electricity generation cost, also minimizing the environmental impacts due to the diesel and heavy oil utilization.

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PART THREE

WATER MANAGEMENT

THE WATER SHORTAGE PROBLEM IN AEGEAN ARCHIPELAGO ISLANDS. COST-EFFECTIVE DESALINATION PROSPECTS

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Abstract

Increased water demand due to economic growth, irrigation needs, declining precipitation levels and over-abstraction of groundwater are all factors that create fresh water shortage problems in the Aegean Archipelago islands. In order to face pressing needs, water is transported by ships from the mainland or other neighbouring islands at a high cost. The objective of the present work is to analyse the current status of water shortage problem in the Hellenic islands and to provide reliable data concerning the water quantities being imported in the areas of Cyclades and Dodecanese. Furthermore, information concerning the cost of water transport in these areas is given. In parallel, the promising solution of desalination plants powered by renewable energy sources is proposed as a feasible, sustainable and cost-effective method for the water shortage problem of the Hellenic Aegean islands.

Keywords: Water Resources; Water Shortage; Water Transport; RES Powered Desalination; Water Production Cost

1. Introduction

Cyclades and Dodecanese are island complexes belonging in the South Aegean Prefecture and located in the Southeastern region of Greece and European Union (figure (1)). Capital city of the Prefecture is Hermoupolis of Syros island. The Prefecture covers an area of 5,286 sq. km and a percentage of 4% of the total area of the country. The region includes 79 islands, 48 inhabited and 31 uninhabited. Most of them are in rather long distances from the capital of the Prefecture.

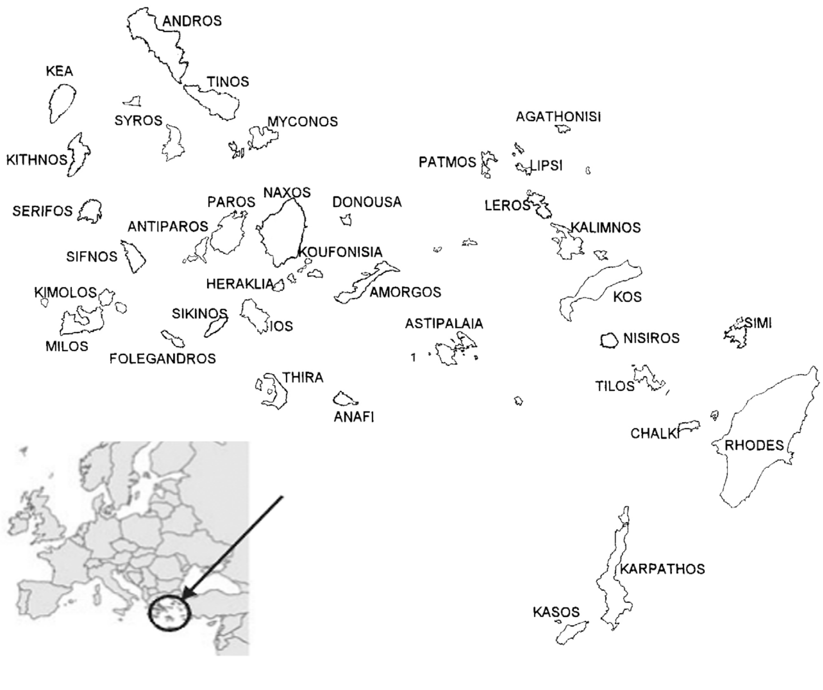

Figure 1: Map of Cyclades and Dodecanese

Kaldellis J.K., Kondili E., 2007, "The water Shortage Problem in Aegean Archipelago Islands. Cost-Effective Prospects", Desalination Journal, vol.216, pp.123-128.

The pleasant climate, the traditional architecture and the interesting cultural tradition all contribute to a significant increase of the tourism, resulting in the economic development of the region in general. However, the geomorphology of the area creates different development levels within the prefecture. Each island has its own special character. There are areas with significant development rates (such as Rhodes, Santorini, Kos, Naxos and Mykonos) and other small and rather poor islands. The competitive advantage of the area is definitely the tourism; however this activity is not stable, being affected by international conditions and fluctuations.

Other economic activities in the area are the agriculture, the stock-raising, the fishing and, in specific areas, the industry (e.g. Milos). In many islands there are small industrial units, mainly focused in local products and handicrafts manufacturing.

The development of the region has resulted in a remarkable increase of the population over the last three decades[1]. Table 1 provides basic information related to the area and the population of the region. As shown in this Table, the population was almost 270,000 in 1991 and 301,000 in 2001, showing an increase of 14% during the last decade. This impressing increase is mainly observed in the tourist areas and the larger islands of the Prefecture. The population is mainly concentrated in three big cities (Rhodes, Kos, Hermoupolis) and the six capitals of smaller islands (i.e. Kalimnos, Naxos, Paros, Tinos, Mykonos, Thira).

The Gross National Product (GNP) of the area increases more rapidly than the national average. According to recent data, the per capita GNP of the South Aegean Prefecture is around 124% of the average country's GNP per capita, which in turn corresponds to 76.9% of the EU average. Furthermore, the Prefecture's Unemployment Indicator is around 90% of the country's Unemployment Indicator.

2. Water Resources Management in the Aegean Archipelago Islands

Traditionally water has been a very valuable resource in the Aegean Sea region, mainly because of the low precipitation[2] and the specific geomorphology of the islands. Hence, the water resources in most of them are not sufficient to cover the continuously increasing needs. Particularly during the summer period, the population of the islands may be five times more than the winter, thus resulting in more intense water shortage problems. On the other hand, it is clear that the development and the quality of life in the islands depend mainly on the sufficiency of water resources. The water, however, is a renewable resource with a limited replenishment rate. Therefore, demand and supply must be kept in a balance; otherwise the water resources for the next generation are seriously endangered.

In general, classification of the water demand and consumption includes:

- urban users (commercial, permanent and seasonal domestic users),
- industrial, and
- agricultural users.

Industrial activities are rather limited in the islands under discussion. On the contrary, irrigation of the agricultural areas is a significant water consumer. The temporal distribution of water demand is also a serious parameter of the problem, since both the domestic and irrigation needs are increasing in the summer.

The most common water supply sources in remote areas with limited water resources are the ground reservoirs and dams -associated with water treatment plants, the desalination plants, wells and boreholes, water recycle and reuse (not commonly used yet) and the water transport by ships.The optimal solution for water supply in each case is determined from the local needs and characteristics, the quantitative and temporal distribution of these needs and the island's infrastructure. The parameters that determine the alternative solutions of the water shortage problem are the size and the population of the island, its geographical location, the economic activities, the population distribution throughout the year and the extent of the water shortage problem.

In case the existing domestic sources can not cover the water needs sufficiently, increasing water demand is covered by water transport in the Hellenic islands, either from the mainland or from neighbouring islands. It is noted that water imports cover urban users demand only. The costs associated with this method are very high, in addition to the fact that it is unsustainable and does not create any infrastructure for the long-term problem solution. Therefore, it should only be used in urgent circumstances when no other water resource is available.

Because of its significance, the water shortage problem has been studied by various researchers and the local authorities, either isolated or integrated with the energy demand problem. More specifically, an optimization approach for the planning of water systems has recently been proposed[3], with the development of a mathematical programming model that describes the operation of water systems with the total demand possibly exceeding the water availability. The evaluation of alternative solutions to the water resources management problem, taking also into account sustainability issues, is another interesting problem that has been tackled[4][5]. The possibility of renewable energy sources (RES) exploitation in desalination units has been described and analysed extensively[6][7][8], while integrated RES and desalination systems have been designed and assessed technically and economically[9][10]. Finally, detailed systems modeling for RES based desalination plants[11] and equipment sizing for the special case of wind-driven installations have been proposed[12].

The objective of the present work is to analyse the current status of water shortage problem in the Hellenic islands and to provide reliable data concerning the water quantities being imported in the areas of Cyclades and Dodecanese, in addition to cost data. RES powered desalination is proposed as a sustainable and cost- effective alternative solution for the water shortage problem. All the information originates from the department in charge of the Hellenic Ministry of Development and refers to the period of 1997-2005[13].

3. Cyclades Water Shortage Problem Analysis

3.1 Problem analysis for the whole Cyclades island complex

Cyclades is an island complex in South Aegean Sea, characterised by the large number of rather small size, dry in most cases, islands. The area has a very distinct geomorphology and presents high development rates, at least in some of the medium - big size islands, mainly due to the tourism.

The water shortage problem in Cyclades is very acute. The largest of them, Naxos and Andros, seem to be the only ones that have sufficient local water resources. Many infrastructure projects have been constructed in the region during the last decade, such as ground reservoirs (Naxos, Mykonos, Ios), desalination plants and water dams (Naxos).

On the contrary, for the smaller islands water is transported from the mainland and is stored in reservoirs to cover the demand for short time-periods. Water is transported in the islands of Amorgos, Koufonisia, Kimolos, Heraklia, Schinousa, Folegandros, Tinos, Sikinos, Therasia and Milos.

Figure (2) presents the water imports for years 1997-2005 in Cyclades islands, whereas figure (3) shows the water imports throughout the year for representative years of the examined period. Note that data for 2005 have not been confirmed officially yet. From figure (2) it is observed that the transported water quantities have almost quadrupled from 1997 to 2004. The main reason for this increase is that Milos, the largest of the islands using transported water, has started receiving large water quantities transported by ships only after 2002 (figure (4)).

In figure (3) it is obvious that the transported water quantities increase dramatically during the summer months. This variation shows the high seasonality of water demand, which, in many cases is the reason for not investing in infrastructure projects for water supply.

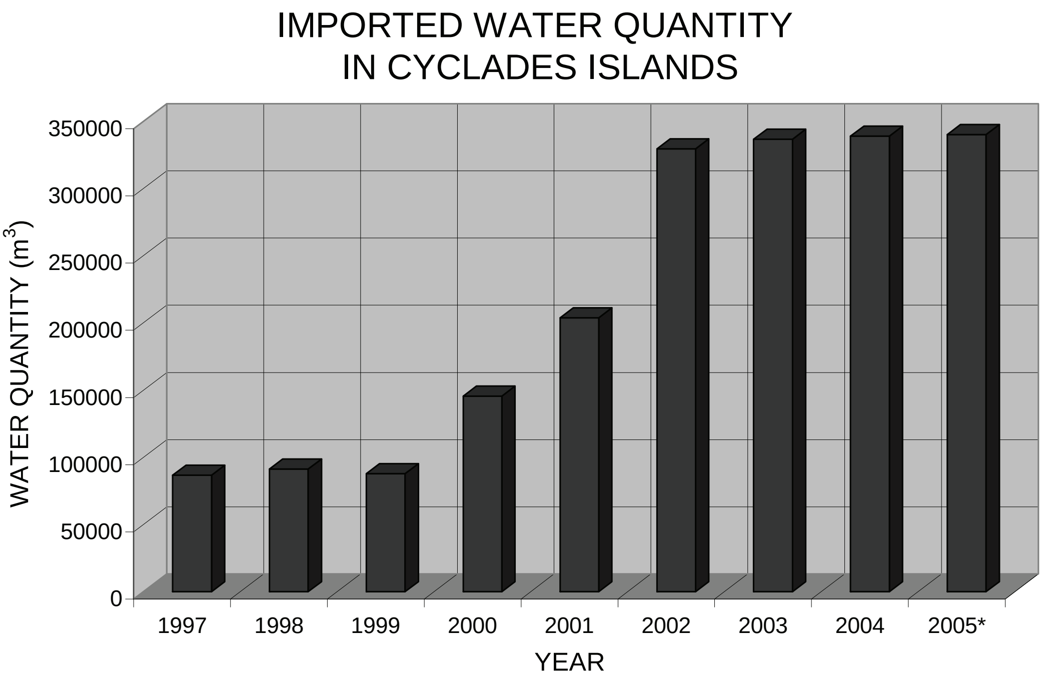

Figure 2: Total annual water imports time evolution in Cyclades

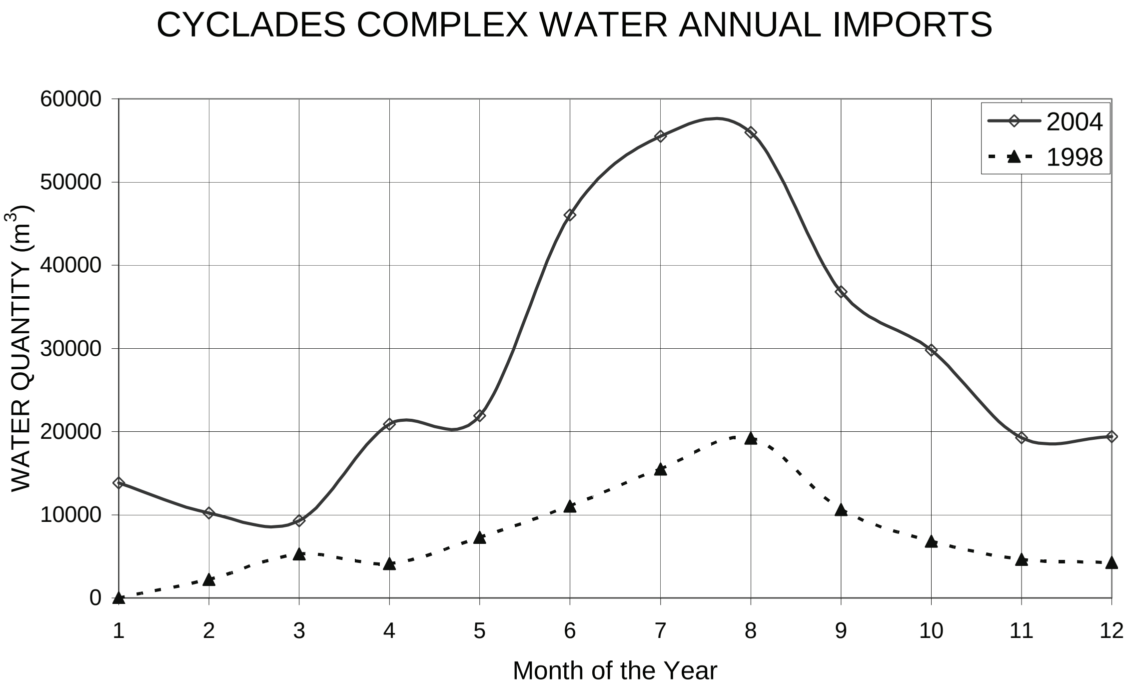

Figure 3: Transported water quantities in Cyclades throughout the year

The seasonal variation of water imports in the islands, shown in figure (3), is explained by the increased water demand during the summer. From statistical data, the visitors/tourists arrivals in years 2003 and 2004 in Cyclades are shown in Table2. From this data it is clear that the population of the islands in the summer is almost 3-4 times the winter population, taking also into account that in Cyclades most of the tourists arrive in summer, i.e. in a 3-4 months period.

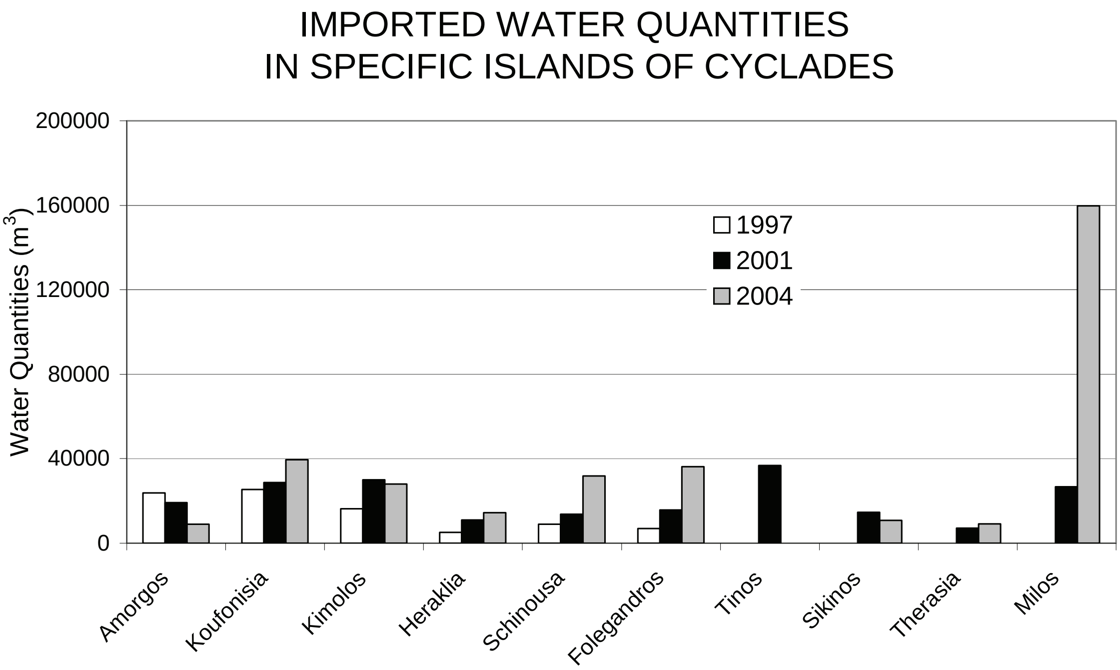

Figure 4: Transported water quantities throughout the year for various Cyclades islands

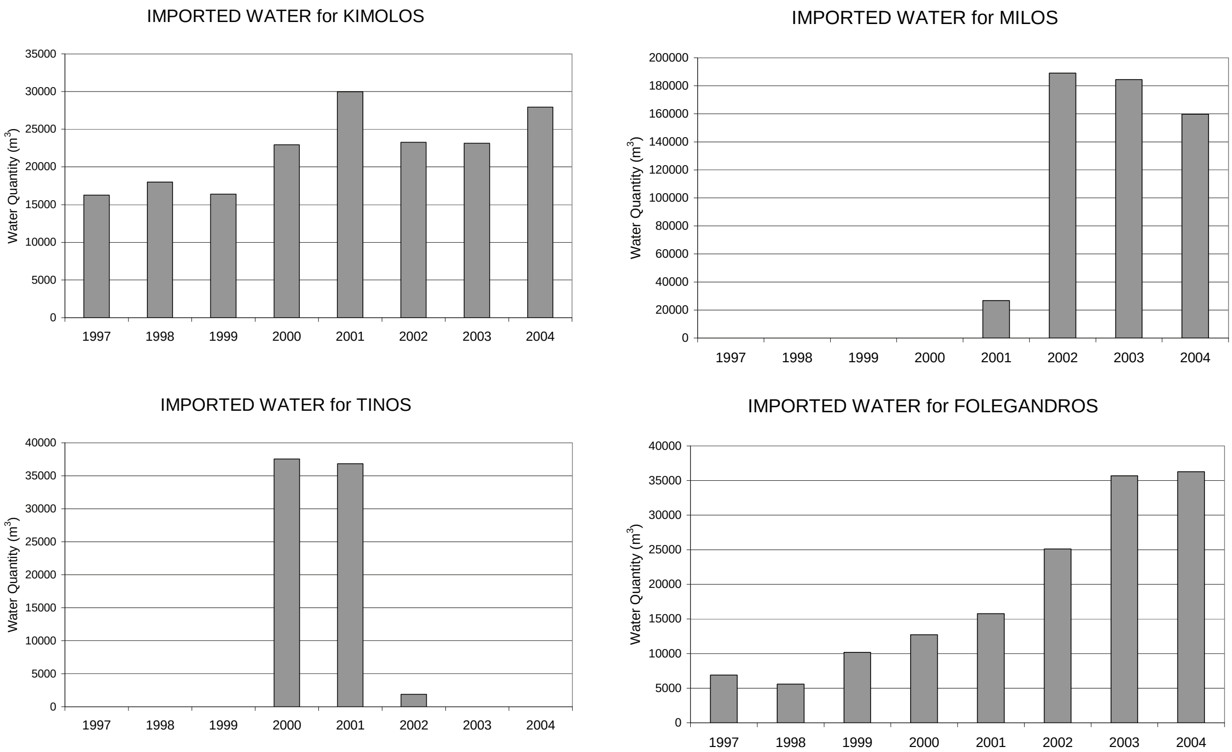

Figure 5: Water imports in various Cyclades islands, 1997-2004

3.2 Detailed Water Shortage Analysis for Selected Islands of Cyclades

In the following it is interesting to study the water shortage problem of selected islands in Cyclades, representative in size and in water demand patterns figure (5).

Kimolos is a medium size island, with a population of 800 people (permanent residents). The water imports in the island are rather constant throughout the years. Kimolos is very close to Milos and, thus, its activities are seriously affected by it.

Milos is a rather big island (5000 permanent residents) that has suddenly shown an increased demand in imported water. Actually this fact has affected seriously the water demand profile of the total area, as it has been shown earlier in figure (4). Milos has a serious increase in its tourism, thus increasing the water needs. At the same time, the island has excellent geothermal energy sources. The possibility of exploiting the geothermal energy for the operation of a desalination plant has been studied with interesting results[14]. The size and the infrastructure of the island allow the construction of a desalination plant that could also provide water to the closest islands (e.g. Kimolos).

Tinos (8000 permanent residents) is also an interesting case, since there was a need for imported water in years 2000-2001. However in 2002 a compact-type desalination unit has been installed and started operation, which covers the needs of the island since then.

Finally, Folegandros (650 permanent residents) is a characteristic example of a small and dry island, rather poor, showing continuously increasing tourism during the last years. This trend has been reflected in the water demand. Due to its geomorphology, Folegandros has no domestic water resources. Therefore, practically most of the water is imported and this demand increases continuously.

4. Dodecanese Water Shortage Problem Analysis

4.1 Problem analysis for the whole Dodecanese island complex

Dodecanese is an island complex in the Southeastern part of the country, in a long distance from the mainland. As in Cyclades, the development of these islands is also mainly affected by tourism.

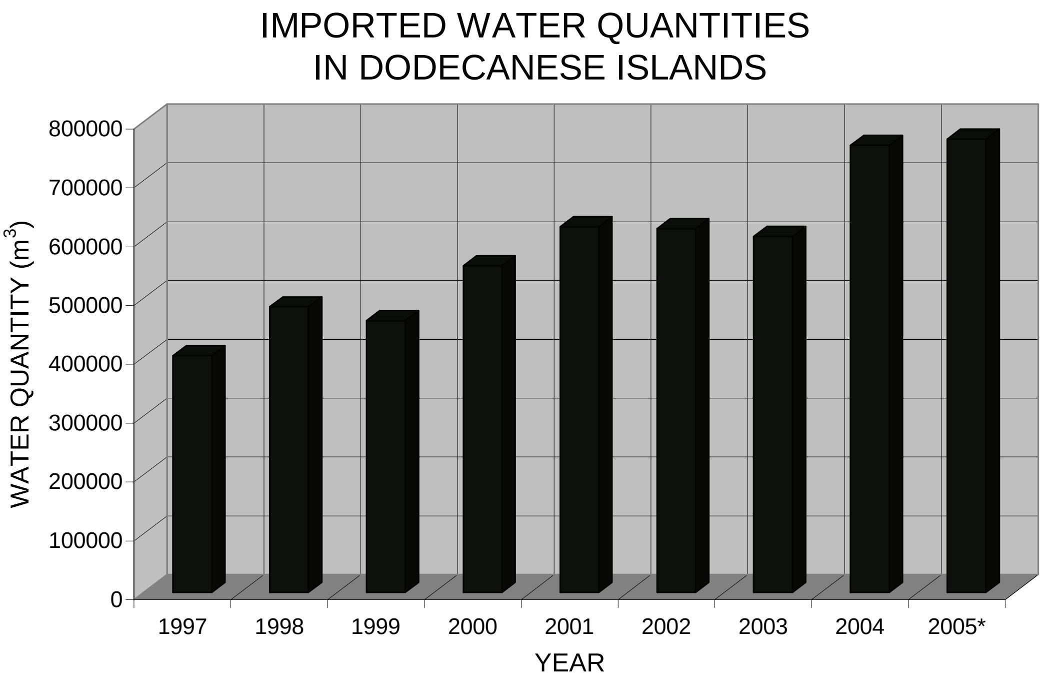

Figure 6: Water imports throughout the year in Dodecanese

Water shortage problem in Dodecanese is again, as in Cyclades, a difficult and intense problem. Rhodes and Kos, the largest and most developed islands of the region, have their own water resources and provide with fresh water the other, small islands that have not sufficient domestic resources. Water is transported in the islands of Agathonisi, Lipsi, Megisti, Nisyros, Patmos, Simi, Chalki, Pserimos and is stored in reservoirs that cover the demand for short time-periods. Desalination plants operate in Nisyros and Leros.

Figure (6) presents the water imports for years 1997-2005 in Dodecanese islands, whereas figure (7) shows the water imports throughout the year for representative years of the examined period. In figure (6) it is observed that the transported water quantities have a significant increase from year to year and in 2004 are almost double compared to the corresponding quantities of 1997. The main reason for this is the increase of water quantities demanded in the islands of Patmos and Simi, as shown in figure (8). These two islands have a significant increase in the number of tourists they receive during the last years.

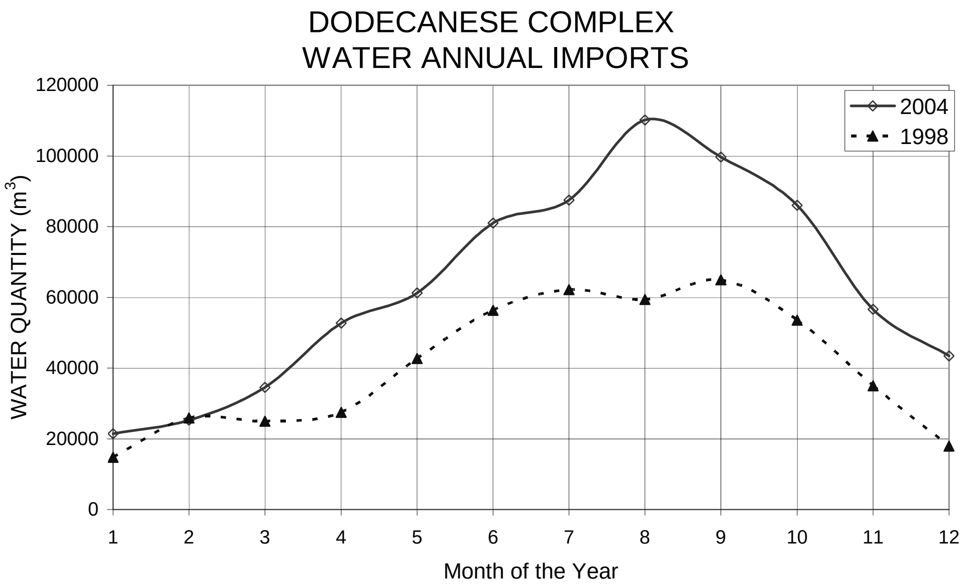

Figure 7: Total annual water imports time evolution in Dodecanese

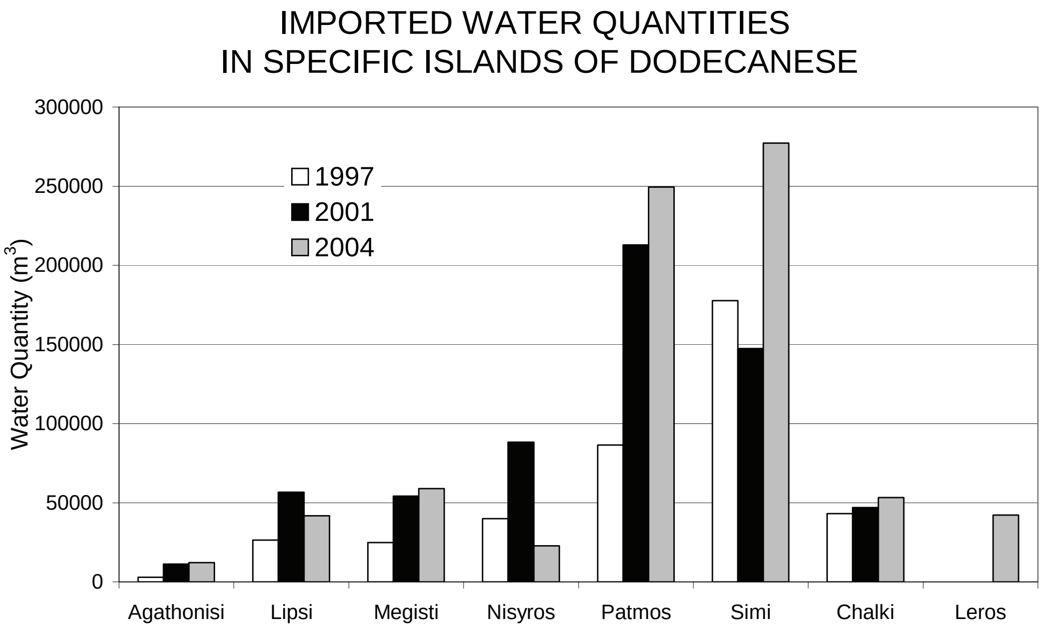

Figure 8: Transported water quantities throughout the year for various Dodecanese islands

From figure (7) it is obvious that the transported water quantities increase dramatically during the summer months, as it has also been observed in Cyclades islands. This variation shows the high seasonality of water demands, which, in many cases is the reason for not investing in infrastructure projects for water supply, as in Cyclades.

From statistical data, the visitors / tourists arrivals in years 2003 and 2004 in Dodecanese islands are shown in Table 3. It is clear from these data, taking also into account that in Dodecanese more than half of the total tourists arrive during the summer period, that the population of the islands in the summer is almost 2-3 times the winter population. This explains the seasonal variation of water imports in the islands, shown in figure (7).

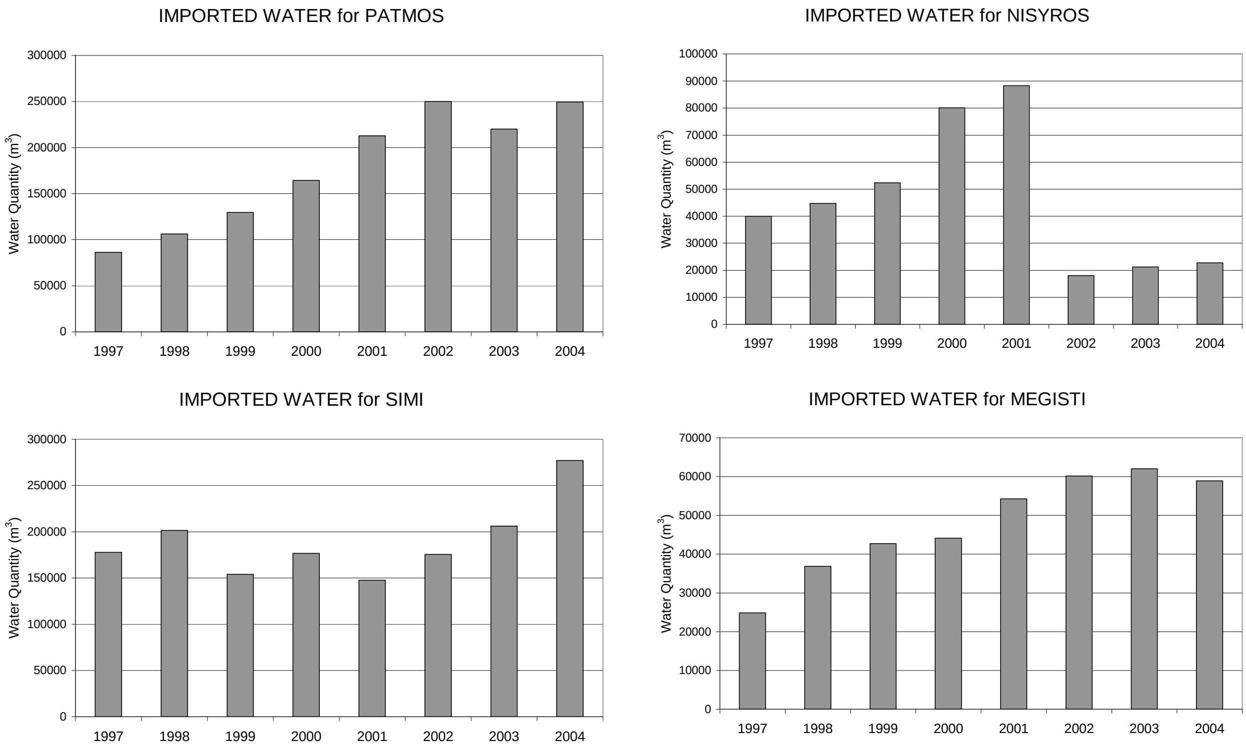

Figure 9: Water imports in various Dodecanese islands, 1997-2004

4.2 Detailed Water Shortage Analysis for Selected Islands of Dodecanese

Subsequently, it is interesting to study the water shortage problem of selected islands in Dodecanese representative in size and in water demand patterns (figure (9)).

Patmos is a medium size island, with a population of almost 3000 people (permanent residents). The water imports in the island increase in the last years mainly because Patmos is now receiving many more tourists than in the past.

Nisyros is a small island with a population of 940 people (permanent residents). The sudden decrease in water imports that appears since 2002 is attributed to the operation of a reverse osmosis desalination unit. Therefore, water demand is satisfied by the desalination plant and the needs for water imports have decreased dramatically.

Simi is a medium size island, very close to Rhodes, with a population of 2560 people. Simi has no significant domestic water resources; therefore all water demand is covered by transported water quantities that have increased significantly during the last 2-3 years. Simi has a remarkable tourist development. Furthermore, many visitors come from Rhodes only for one day. They also increase water demand; explaining thus the quite significant transported water quantities during the last years.

Finally, Megisti is a very small island, with a population of 300 people, and rather isolated in a long distance from the mainland and the rest of the Dodecanese islands. The continuous increase in water transported quantities is caused from a corresponding increase in the number of tourists.

5. The Economic Option of the Problem

Depending on the water supply method, the water cost varies significantly. In practice, the cost of water includes a fixed term, associated to the depreciation of the capital investment of the infrastructure and a variable cost term. For example, the desalted water has a significant operating cost, while the water from ground reservoirs and dams has a large fixed cost term, because of the high capital investment required.

Table 4 shows the corresponding water costs (in €/m^3) from 1997-today for water transported to Cyclades and Dodecanese, respectively. The water is transported to Cyclades mainly from the Athens area, while in Dodecanese the water is transported from Rhodes and Kos. This is the reason for the significantly lower costs of water transported in the area of Dodecanese.

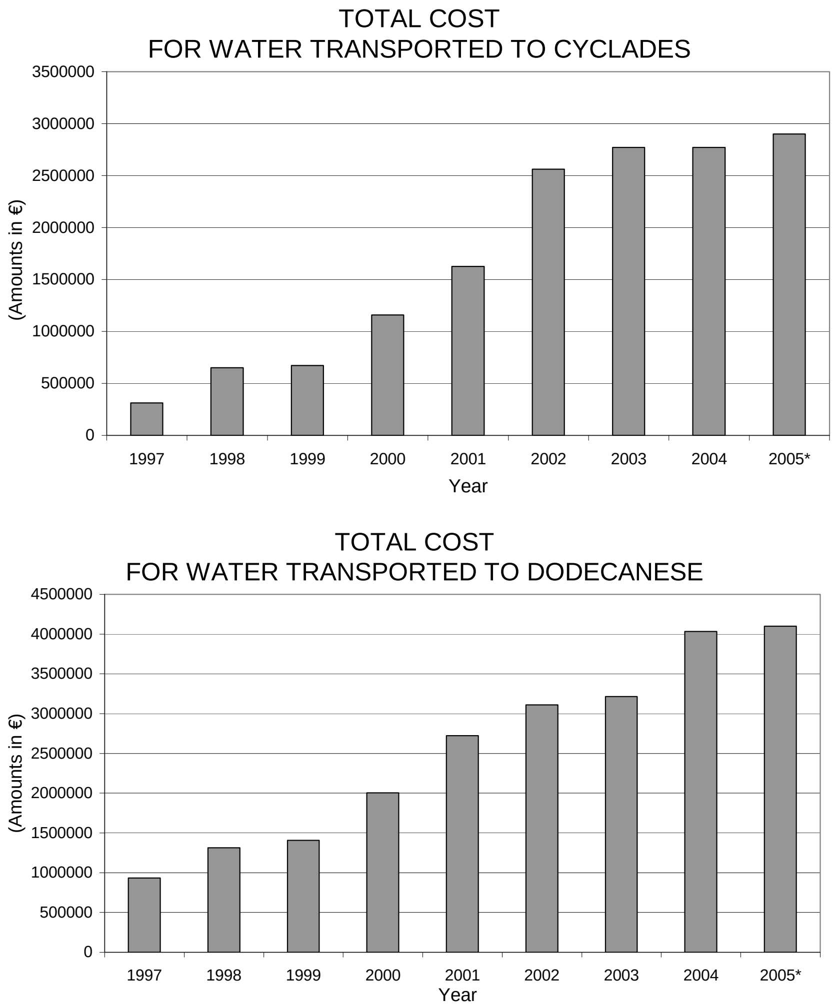

Figure 10: Total cost for water transported in Cyclades and Dodecanese islands[13]

Figure (10) shows the total amounts being paid each year for water transport in Cyclades and Dodecanese area. It is clear from the above mentioned data that a very significant amount of money (approximately 7,000,000€) is spent every year in order to cover the water needs in the islands of the

Aegean Archipelago. As a matter of fact, the water transport is not a sustainable and long-term solution to the water demand problem, since it is very expensive and it does not create any infrastructure for the future. It is an urgent solution to the problem but certainly not the best one.

On top of this, the above amount of money is paid from the local authorities (Prefecture, municipalities), and, in most cases, it is not passed to the consumers. In fact, the money being paid by the residents varies between 0.5€/m^3 (for small consumers) and 1.3€/m^3. Therefore it is a significant social cost, in addition to the fact that this method is unreliable and does not improve the water resources management problem of the areas.

6. Desalination Based on RES

6.1 Presentation of the RES Potential of the Area

The Aegean Archipelago includes several hundreds of small and medium-sized islands, being located in the South Eastern European edge. The entire area possesses excellent wind potential since in several islands the wind speed exceeds the 9m/s at 30m height (figure (11)). In this context, numerous wind mills have been operating in the area for many years, while during the last twenty years modern wind parks have been constructed[15] in several islands. However, the stochastic behaviour of the wind and the remarkable fluctuation of daily and seasonal electricity load, in almost all island grids, lead to substantial wind energy penetration limits[16], especially during the low consumption periods of the year. Thus, in many occasions electricity produced by the wind parks cannot be absorbed by the local network, hence it can be directed to supplementary activities such as water desalination at minimum cost.

On the other hand, all these Greek islands are located in regions having the regular benefit of an abundant and reliable solar energy supply, taking into consideration that the annual solar energy approaches the 1700kWh per square meter (figure (11)). It is also interesting to note that solar energy is much higher during the summer season, where the fresh water needs of the area are also significantly amplified.

Finally, in several sites an outstanding geothermal potential has been encountered (e.g. Milos, Nisyros, Santorini), due to the existence of high and low enthalpy geothermic fields of significant capacity. As already mentioned, the exploitation of the available geothermal potential, replacing oil-fired units[17], for the operation of desalination plants is a rather interesting option[14].

Recapitulating, the significant renewable potential of the area, which is up to now partially exploited, can substantially contribute to meet the energy requirements of appropriately

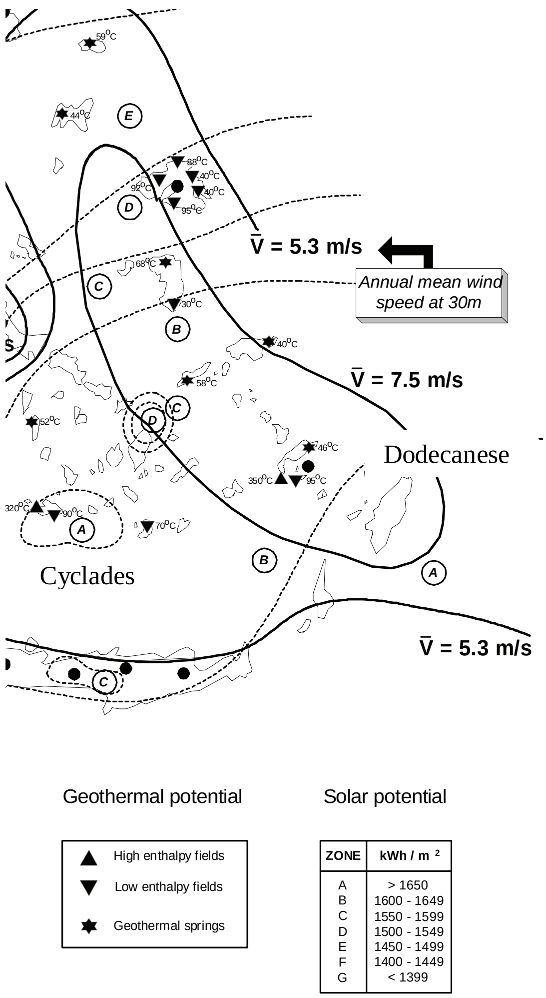

Figure 11: Renewable potential in Aegean Archipelago

designed desalination plants at reasonable cost. In fact, recently (July 2005) the Greek Ministry of Development opened a call for proposals, in order to subsidy by more than 40% new-erected desalination plants based on renewable energy sources (RES) utilization[18]. The first investments submitted are already under evaluation.

6.2 Desalination Technologies Cost

According to above analysis it is evident that in most Aegean Sea islands with significant water shortage, there is a wide availability of renewable energy sources. Therefore, RES based desalination units could provide an environment friendly, cost-effective and energy efficient method for the production of potable water. As mentioned above, various technical and economical issues concerning the alternative technologies for RES powered desalination plants have been investigated and analysed extensively from various researchers[5][7][8][10][11][12]. In all cases, the ultimate economic evaluation criterion is the specific water production cost.

The cost parameters that need to be taken into account are the investment cost, the energy cost, the consumables, the labour and the maintenance costs. Literature suggests a range of values for each desalination technology in conventional plants, i.e. plants covering their energy requirements from conventional energy sources (Table 5[5]).

As a general rule, a seawater reverse osmosis (SWRO) unit has relatively low capital cost and significant operating and maintenance cost, due to the high cost of energy and the membrane replacement. The major energy requirement for reverse osmosis desalination is for pressurising the feed water. Energy requirements for SWRO have been reduced to around 5kWh/m^3 for large units with energy recovery systems, while for small units this may exceed 15kWh/m^3. For brackish water desalination the energy requirement is between 1 to 3kWh/m^3 [5][17].

In case RES are used as energy sources of the desalination plant, the relative capital cost of each subsystem (power supply and demand by desalination) determines how appropriate a certain combination of energy and desalination process can be. The feasible renewable energy - desalination technology combinations are many today. Concerning the state-of-the art, wind energy, geothermy and photovoltaics seem to be a smart option. The financial attractiveness of similar applications is remarkably improved in case that the considerable energy demand of a desalination plant is covered by the electrical energy surplus of already operating RES based electricity generation plants[9][16]. In these cases, the cost of the energy input is quite low and the combined production of electricity and desalinated water strongly improves the economic performance of both applications.

6.3 Desalinated Water Production Cost

Taking into account the cost-benefit model presented by the authors[10] that expresses the total cost of a desalination plant as the sum of the initial installation cost and the corresponding maintenance and operation (M&O) cost, one gets the following equation, under the condition that the net present value of the investment becomes zero (NPV=0) after n* years of operation, i.e.:

$$c_W = \frac{(1-\gamma)}{f_w} \cdot \left\{ \frac{h_1}{UF} + h_2 \frac{d_w}{365} \right\} + \frac{\xi \cdot f_g}{f_w} + \frac{\varepsilon_{DP} \cdot c_e \cdot f_e}{f_w} \tag{1}$$

where "UF" is the desalination plant utilization factor defined as:

$$UF = \frac{V_t}{V_o} \tag{2}$$

expressing the number of days that the specific desalination plant operates at full capacity. Accordingly, see also Table 6, "d_w" expresses the number of typical days that the selected reservoir guarantees clean water autonomy of the system, without the operation of the desalination plant. Finally, one may write:

$$f_x = \sum_{j=1}^{n} \left[\frac{1+x}{1+i}\right]^j = \frac{1+x}{1+i} \cdot \left(1 + \frac{1+x}{1+i} + ... + \left[\frac{1+x}{1+i}\right]^{n-1}\right) \quad (3)$$

with x=g; x=e or x=w and "i" the corresponding market capital cost. All the other parameters appearing in equations (1) and (2) are explained in Table 6. Keep in mind that the energy required market price "c_e" depends on the local system electricity production cost. According to the available data[19], the marginal production cost of the islands' autonomous power systems varies between 0.15€/kWh and 1€/kWh, being in most cases quite higher than the corresponding production cost value from existing wind parks[20] and photovoltaic stations[21].

Applying the above described model one may estimate the expected desalinated water production cost (figure (12)). The cases analyzed include two extreme scenarios, one for small islands (daily capacity 100m^3/day) and one for medium-sized islands (daily capacity 2000m^3/day). In both cases the expected water production cost is less than 4€/m^3, present values, which is substantially lower than the prices appearing in Table 4. In fact, for the medium-sized island case the corresponding production cost is less than 3€/m^3, while this value is remarkably decreased with the operational years of the installation. On the other hand, the market price of the transported water is significantly increasing in the course of time (Table 4). The above presented desalinated water production cost values may further be decreased by using an appropriate optimal electricity-water management procedure[3][9], which is a challenging domain for future research.

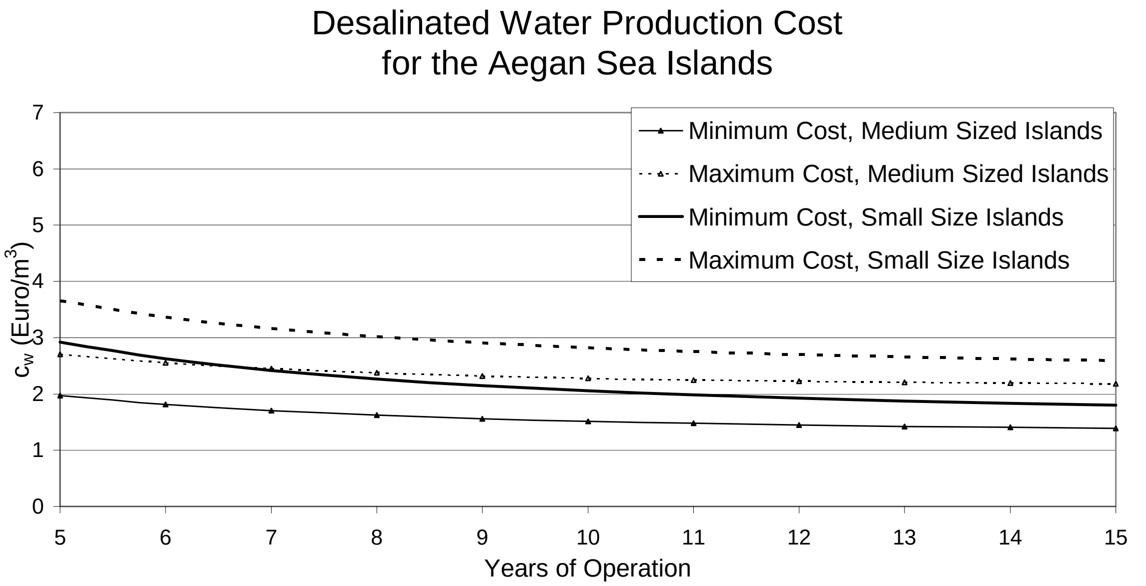

Figure 12: Desalinated water production cost on the basis of existing renewable energy resources exploitation in the Aegean Sea Islands

7. Conclusions

For the majority of the Hellenic islands, water resources are quite limited, thus restraining the economic development of the local societies. To face increased potable water requirements, more than 1,000,000m^3 of clean water are transported annually to these islands at a cost sometimes exceeding the value of 7€/m^3. Reliable and up to date data concerning the water quantities that are transported annually to each one of the Cyclades and Dodecanese islands have been presented, providing thus the opportunity for detailed study and analysis of the water demand and water shortage problem in these areas. Furthermore, the detailed cost data that have been provided can be used as a basis for alternative solutions evaluation in the critical problem of water resources management.

The construction of infrastructure projects for each island is avoided usually because of the high investment required and the seasonal variation of water demands. Therefore, it is expected that water will continue to be transported at least in the smallest and most dry Hellenic islands. However, in many other cases of medium - big size islands this urgent and expensive solution can be avoided. As a feasible, cost-effective and sustainable alternative solution, RES powered desalination is proposed, since the final cost of the locally produced water from renewable energy sources (RES) based desalination plants is expected to be quite lower than the corresponding transported water cost, without disregarding the considerable environmental, social and macro-economic benefits.

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ENERGY AND CLEAN WATER CO-PRODUCTION IN REMOTE ISLANDS ON THE BASIS OF A COMBINED PV-ENERGY STORAGE INSTALLATION

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Abstract

In several small or tiny remote islands spread throughout the Aegean Archipelago there is a significant electrical power shortage, while the water resources are quite limited. This unfavourable situation results in the operation of high cost autonomous thermal power stations and the transportation of fresh water of questionable quality at extremely high prices. Solar energy, i.e. the photovoltaic generators, can definitely contribute on solving these problems at a rational investment and minimum operational cost. In the present work a combined photovoltaic based and energy storage configuration is proposed in collaboration with an appropriate desalination plant. The proposed solution leads to significant solar energy penetration values contributing also to the environmental impacts reduction. Besides, peak water demands of the summer period can be satisfied through the operation of a desalination plant that will use the excess energy being produced by the aforementioned energy system. Next, the combined system is analysed in terms of its structure i.e. the components included, the appropriate sizing of each component, and, finally, the various different operational modes that occur, depending on the availability and demand of energy and water, as well as on the design of the energy and the desalination systems. The performance of the combined system is evaluated for various different cases. The proposed work concludes that the configuration investigated can efficiently fulfil the electrical energy and the clean water requirements of numerous remote communities on the basis of clean and reliable solar energy, improving the life quality of local habitants.

Keywords: Remote Islands; Photovoltaic Generator; Desalination; Energy Storage, Stand Alone Systems

1. Introduction

In several small or tiny remote islands spread throughout the Aegean Archipelago there is a significant electrical power shortage, while the water resources are quite restricted. This unfavourable situation results in the operation of high cost autonomous thermal power stations and the transportation of fresh water of questionable quality at extremely high prices, in order to face water demands. More precisely, according to the official data (figure (1)) the electricity generation cost for the majority of existing autonomous power stations (APS) varies between 0.1€/kWh for the big islands and 0.6€/kWh for the small ones[1]. At the same time there is a continuous water imports increase (figure (2)) exceeding the 1,100,000m^3 for 2006 and imposing an expenditure of more than 7,000,000€[2].

On the other hand the entire Aegean Archipelago area possesses very high solar potential (figure (3)), which in many areas approaches the 1800kWh/m^2 on an annual basis[3]. In this context, solar energy and more precisely the photovoltaic generators can definitely contribute on solving the energy demand and water shortage problems at a rational investment and minimum maintenance and operational cost[4]. In the present work a combined photovoltaic based and energy storage configuration (to face the limited availability of the solar irradiance available only during the daytime) is proposed in collaboration with an appropriate desalination plant[5]. The proposed solution leads to significant solar energy penetration values and decreases the operational hours of the existing internal combustion engines, contributing in parallel to the environmental impacts reduction[6]. Besides, peak water demands of the summer period can be satisfied through the operation of a desalination plant that will

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use the excess energy being produced by the aforementioned energy system[7]. In general, the fresh water quantities of desired quality that are produced from the operation of the desalination plant increase the water reserves of the local community and will be used to cover water demands.

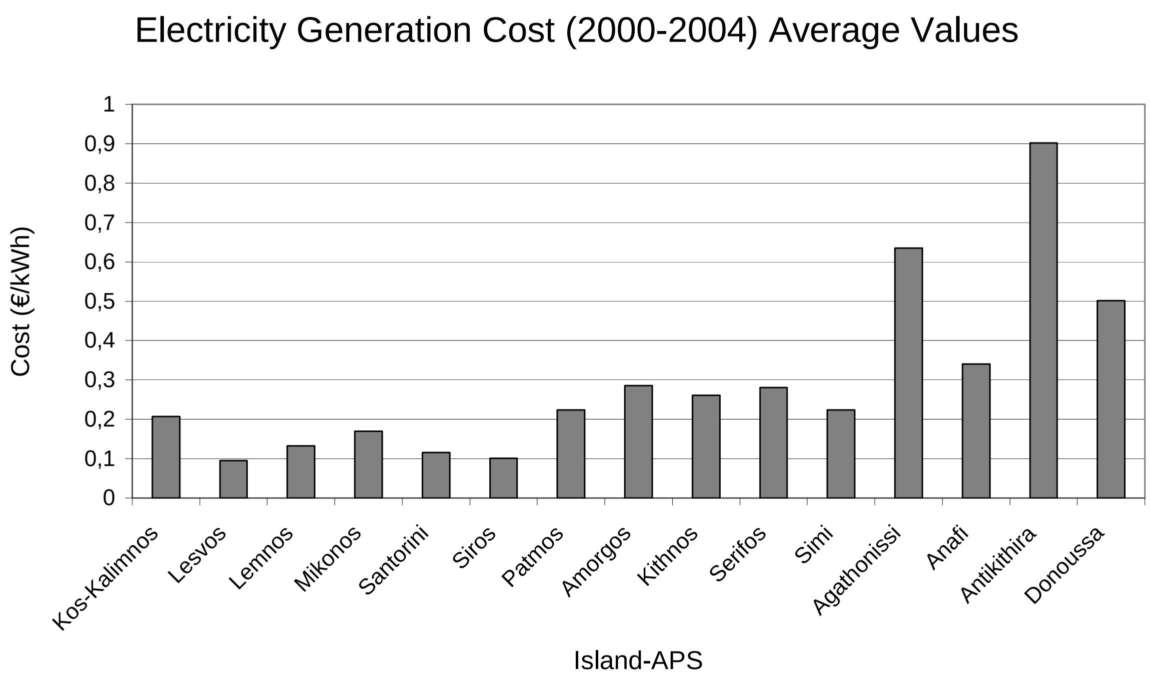

Figure 1: Electricity generation cost in representative islands

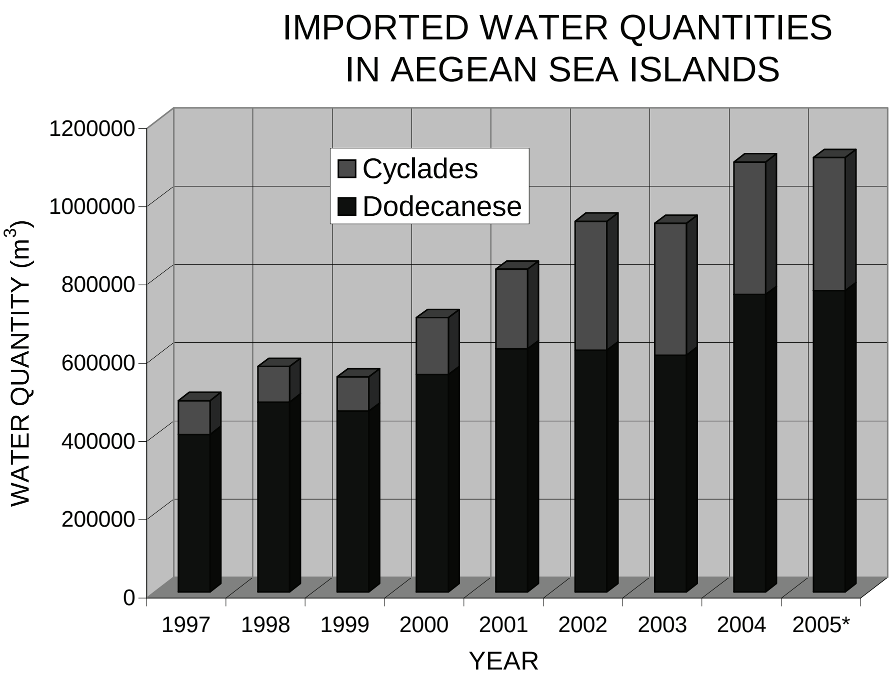

Figure 2: Total annual water imports time evolution in Aegean Sea Islands

WIND & SOLAR ENERGY IN GREECE

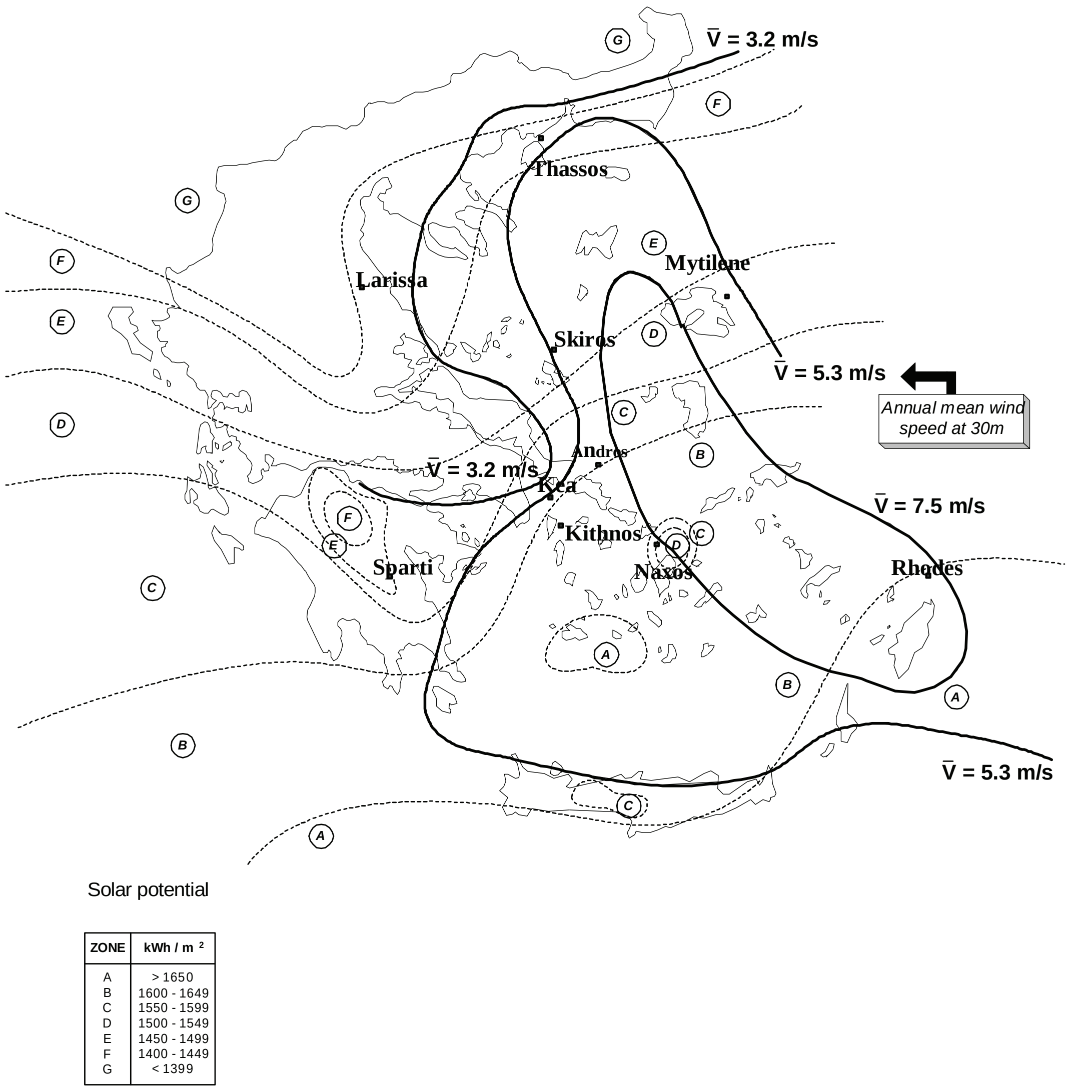

Figure 3: Solar potential in Aegean Archipelago

In the present work the combined system is analysed in terms of its structure i.e. the components included, the appropriate sizing of each component, and, finally, the various different operational modes that may occur, depending on the availability and demand of energy and water, as well as on the design of the energy and the desalination systems. The performance of the combined system is evaluated for various different cases.

2. Proposed Solution

In order to face the described problems, the possibility to create a combined PV-Energy Storage Station (PV-ESS) in collaboration with a Desalination Plant (DP) is investigated[2][7][8] on a techno-economic basis, figure (4). According to the authors, the proposed solution is the best possible method to cover the local electricity demand and the clean water shortage for the majority of the small Aegean Archipelago islands, with rational installation and minimum maintenance and operation cost.

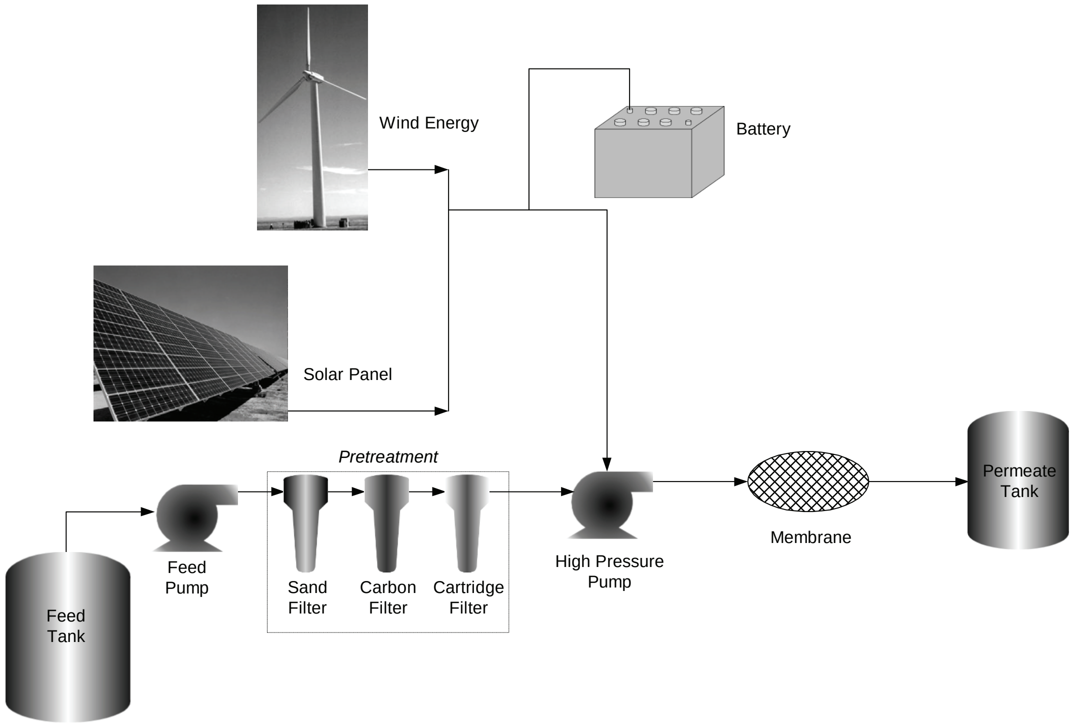

Figure 4: Proposed solution for a combined PV-ESS, including a desalination unit

More precisely, the most appropriate PV-ESS configuration -capable of facing both energy and clean water requirement problems of remote islands- is based, see figure (4), on:

a. One or more photovoltaic generators of "z" panels ("N_o" maximum power of every panel) properly connected (z_1 in parallel and z_2 in series) to feed the charge controller to the voltage required.
b. An energy storage configuration, e.g. lead acid battery storage system, for "h_o" hours of autonomy, or equivalently with total capacity of "Q_{max}", operation voltage "U_b" and maximum discharge capacity "Q_{min}" (or equivalently maximum depth of discharge "DOD_L").
c. A DC/DC charge controller of "N_c" rated power, charge rate "R_{ch}" and charging voltage "U_{CC}".
d. A DC/AC inverter of maximum power "N_p" able to meet the consumption peak load demand.
e. A properly sized desalination plant, able to absorb the energy surplus of the wind park and produce clean water from seawater, daily capacity "V_o".
f. The existing APS, based on internal combustion engines, so far used to fulfil the electricity demand of the local community; rated power "N_{APS}".

The main target of the proposed system is to cover local community’s electricity requirements "N_D" and water demand "V_w" on a regular basis, thus minimizing the fuel-oil consumption.

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

a. The solar generator feeds the local electrical network. Any energy surplus, according to the existing needs is forwarded:
   i In an appropriate ESS in order to store energy for nights or high demand periods.
   ii In an existing modular water desalination unit, usually based on reverse osmosis, in order to produce desalinated water of desired quality.

b. The solar energy is not absorbed by the local electrical system, while the energy surplus is bigger than the storage capacity of the DC/DC converter of the installation or the ESS is full. In this case the energy surplus is directed to the water desalination unit that will produce potable water to increase the water reserves of the local community.

c. The photovoltaic production is lower than the electricity demand. In this case the energy reserves of the ESS are used via the existing inverter(s) of appropriate size in order to cover the load demand of the system.

d. The water reserves of the local community are very low. In this case a part of solar energy is forwarded directly to the desalination plant. If the available photovoltaic production is not enough one may use the energy stored in the ESS.

3. Energy and Clean Water Production

The present analysis concerns an autonomous small island electrical network with annual energy consumption equal to "E_{tot}" and net (water demand minus the existing water resources) annual water demand equal to "V_{tot}", while the corresponding peak load demand is "N_p". In fact, taking into consideration the additional energy consumption of the desalination plant and that the PV energy production is available only during daytime, one should distinguish the load demand of the island in three parts. More specifically, one may use the symbols "E_{t1}" and "E_{t2}" in order to describe the energy consumption during daytime (sunlight period) and night respectively, while the symbol "E_{des}" is used for the energy consumption of the desalination plant. Note that, using the above definitions, the following relation is valid:

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

In this context, one may also assume that the total night demand "E_{t2}" is covered mainly by the ESS, while the ESS contributes also during daytime, in case that the PV production is lower than the load demand (cloudy days, very high load demand, excessive clean water demand). Accordingly, in order to describe the contribution of the storage system to the total energy consumption, we define the parameter "ε" as:

$$\varepsilon = \frac{E_{stor}}{E_{tot}} = 1 - \frac{E_{dir}}{E_{tot}} \tag{2}$$

where "E_{stor}" is the total energy contribution of the ESS to the annual electricity demand and "E_{dir}" is the energy demand covered directly by the existing power stations (mainly by the photovoltaic generator "E_{PVdir}" and complementary by the thermal power station "δE").

On the other hand, the photovoltaic generator contribution is expressed by the term "E_{PV}". The corresponding energy production is used during daytime to cover the local network load demand (including the energy consumption of the desalination plant), while any energy surplus is stored at the ESS in order to be used at night time or during low solar irradiance periods to meet the consumption needs.

The main target of the proposed solution is to satisfy the local demand using electricity produced mainly by the photovoltaic generator in collaboration with an appropriate energy storage system (ESS), with rational production cost. Up to now the electrification solution[1] was based on the existing outmoded thermal power stations, which operate using diesel or heavy (mazut) oil with mean electricity production cost equal to "c^*" (figure (1)) and causing serious environmental and macroeconomic impacts[9][10]. For increased reliability purposes the most efficient thermal power units may be used as back up engines with annual energy contribution equal to "δE", where one should require "$\delta E \ll E_{tot}$".

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

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

Defining the capacity factor of the PV-based power stations "CF_{PV}" using equation (4), i.e.:

$$CF_{PV} = \frac{E_{PV}}{8760 \cdot N_{PV}} \quad (4)$$

one may calculate the necessary nominal power of the proposed PV-based power station as:

$$N_{PV} = \max\left\{(1+SF)\cdot N_{p1}\,;\frac{E_{PV}}{8760\cdot CF_{PV}}\right\} \quad (5)$$

where "$SF \geq 0$" is an appropriate safety factor in order to guarantee that the PV-based power station can meet the local consumption daytime power demand "N_{p1}". In order to ensure the system reliability, one should take into account that, at the same time, either the ESS power units (inverters, hydro-turbines etc.) or the existing (back up) thermal power units may be used.

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

$$E_{ss} = h_o\left(\frac{E_{tot}}{8760}\right)\frac{1}{\eta_{ss}}\cdot\frac{1}{DOD_L} \quad (6)$$

where one should take into account the desired typical hours of energy autonomy "h_o", the maximum depth of discharge "DOD_L" and the energy transformation efficiency of the ESS "η_{ss}". In regard to the nominal output power "N_{ss}" of the storage unit, it is the power efficiency "η_p" that must be considered as well, i.e.:

$$N_{ss} = \zeta \cdot \frac{N_p}{\eta_p} \quad (7)$$

where "ζ" is the peak power percentage of the local network that the energy storage branch should be able to cover. Accordingly, the input nominal power "N_{in}" of the ESS depends on the available power excess of the existing PV generators and the corresponding probability distribution as well as the desired charge time of the installation and the energy requirements of the desalination plant. For practical cases and taking into account the limited availability of solar energy defining the charge and the discharge time period of the ESS, one finally may assume that the input nominal power is between 1.5 and 2.0 times the corresponding nominal output power.

Similarly, one should define the nominal capacity of the water desalination plant "V_o" (expressed in m^3/day) as well as the corresponding water storage capacity "V_{st}" expressing the size of the water reservoir. In this context, the desalination plant utilization factor "UF" is defined as:

$$UF = \frac{V_0}{V_t} = \frac{1}{\sum_{l=1}^{l=365} \frac{V_l}{V_0}} \tag{8}$$

while the water storage capacity is given as:

$$\frac{V_{st}}{V_t} = d_w \cdot \frac{V_t / 365}{V_t} = \frac{d_w}{365} \tag{9}$$

where "d_w" expresses the typical days of clean water autonomy of the system, according to the size of the fresh water reservoir "V_{st}" selected.

4. Feasibility Analysis of the Proposed Solution

The future value (after -n years of operation) of the investment cost of a combined energy and clean water production installation is a combination of the initial installation cost and the corresponding maintenance and operation (M&O) cost, both quantities given in current values. More specifically, the initial investment cost "IC_o" includes the market price of the photovoltaic generator along with the corresponding installation cost "I_{PV}"[4]. Additionally, the desalination plant's initial cost "IC_{DP}" should also be taken into account[11]. On top of this, energy and clean water storage systems' cost are also included, along with the corresponding cost of the necessary control devices. In cases that an APS is employed as a stand-by system, its initial cost value should also be taken into account[1].

Accordingly, the maintenance and operation (M&O) cost can be split into the fixed maintenance cost "FC_n" and the variable one "VC_n"[12]. The variable M&O cost mainly depends on the replacement of specific major parts of the installation, with shorter lifetime that the complete installation. For simplicity reasons, the variable M&O cost is not explicitly analyzed here. Furthermore, the corresponding term is incorporated in the fixed M&O cost.

More precisely, the annual fixed M&O cost of the energy production system can be expressed as a fraction "m" of the corresponding initial capital invested (assuming also an annual increase of the cost equal to "g_m") plus the energy production cost "c_D" by the APS (diesel generator). Keep also in mind that the APS electricity price escalation rate "e_D" (usually coincides to the fuel escalation rate) should be also included.

On the other hand, the corresponding annual fixed M&O cost of the clean water production plant is given as a function "m_{DP}" of the annual clean water production cost (an annual increase "g_D" is also included) plus the annual energy consumption cost ("ε_{DP}" is the specific electricity consumption of the DP, expressed[2][11] as kWh/m^3). As previous the input electricity cost escalation rate "e_E" should also be taken into account.

Recapitulating and using the extensive analysis of previous published work by the authors[2][4][11] one may express the present value of the electricity generation "c_e" and clean water "c_w" production cost of the proposed PV-based installation as:

$$c_e = \frac{\alpha+\beta\cdot\left(1-\frac{\Delta i}{1+i}\right)^{n*}}{\sum_{j=1}^{n*}\left[\frac{1+e}{1+i}\right]^j}\cdot\frac{IC_0}{E_{tot}}+m\cdot\frac{IC_0}{E_{tot}}\cdot\frac{\sum_{j=1}^{n*}\left[\frac{1+g_m}{1+i}\right]^j}{\sum_{j=1}^{n*}\left[\frac{1+e}{1+i}\right]^j}+c_D\cdot\frac{\delta E}{E_{tot}}\cdot\frac{\sum_{j=1}^{n*}\left[\frac{1+e_D}{1+i}\right]^j}{\sum_{j=1}^{n*}\left[\frac{1+e}{1+i}\right]^j} \tag{10}$$

and

$$c_W = \frac{\left[\alpha+\beta\cdot\left(1-\frac{\Delta i}{1+i}\right)^{n*}\right]\cdot IC_{DP}}{V_t\cdot\sum_{j=1}^{n*}\left[\frac{1+w}{1+i}\right]^j}+\frac{m_{DP}\cdot\sum_{j=1}^{n*}\left[\frac{1+g_D}{1+i}\right]^j}{\sum_{j=1}^{n^*}\left[\frac{1+w}{1+i}\right]^j}+\frac{\varepsilon_{DP}\cdot c_e\cdot\sum_{j=1}^{n*}\left[\frac{1+e_E}{1+i}\right]^j}{\sum_{j=1}^{n^*}\left[\frac{1+w}{1+i}\right]^j} \tag{11}$$

where:

α	is the invested own capital percentage
β	is the invested loan capital percentage
i	is the return on investment index
Δi	is the difference between the return on investment and the market capital cost
e	electricity generation cost annual escalation rate
w	clean water production cost annual escalation rate

In order to check the financial viability of the proposed solution one should calculate the total gains "G" of the entire installation for a given time period "T", i.e.:

$$G = \int_{t=0}^{t=T}(p_e-c_e)\cdot N_e(t)dt+\int_{t=0}^{t=T}(p_w-c_w)\cdot\dot{V}(t)dt \tag{12}$$

where the variables "p_e" and "p_w" denote the expected prices of selling electricity and clean water to the consumption. As it is obvious, in order the proposed solution to be financially viable the corresponding prices should be less than the current ones for the remote islands and the "G" value is positive.

5. Application Results

The proposed analysis is accordingly applied to two typical island cases (a small and a very small one) located in the Aegean Archipelago and presenting the electricity cost values of figure (1), i.e. electricity generation cost higher than 0.5€/kWh and imported clean water cost between 4.5€/m^3 and 7.0€/m^3. According to the official information[1][11] the annual electricity consumption of these islands is 10GWh and 1GWh, while the corresponding daily clean water demand varies between (V_o=100÷200 m^3/d) for the very small island and (V_o=10÷20 m^3/d) for the very small one.

Using the available data one may describe the typical annual water imports using the profile of figure (5). More specifically, the water imports are maximal during summer, mainly due to the increased visitors' number. In the next figure (6) one may also find the electricity surplus of a typical PV-battery based installation of 22.5kW, used to cover the electrical needs of an island community of 50 permanent habitants, while the average summer visitors' number is almost 50 persons per day. Comparing figures (5) and (6) one may easily conclude that the water imports present an almost similar profile with the PV-installation energy surplus, clearly supporting the idea of energy and clean water co-production in remote islands on the basis of a combined PV-energy storage installation.

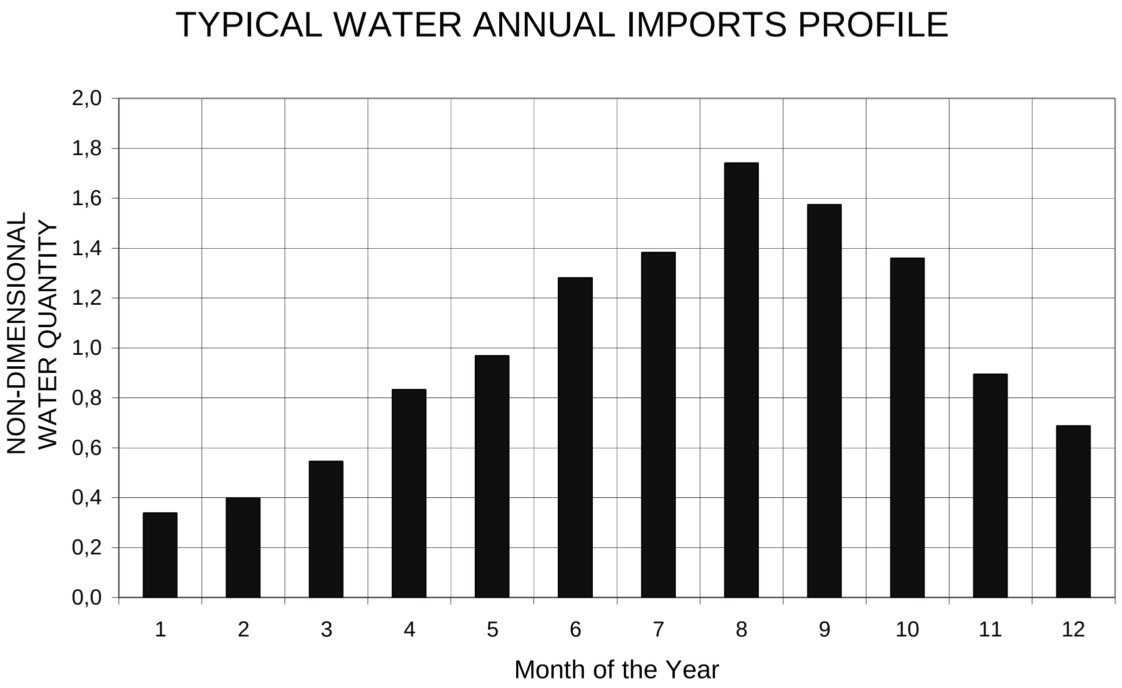

Figure 5: Typical annual water imports profile for Aegean Sea Islands

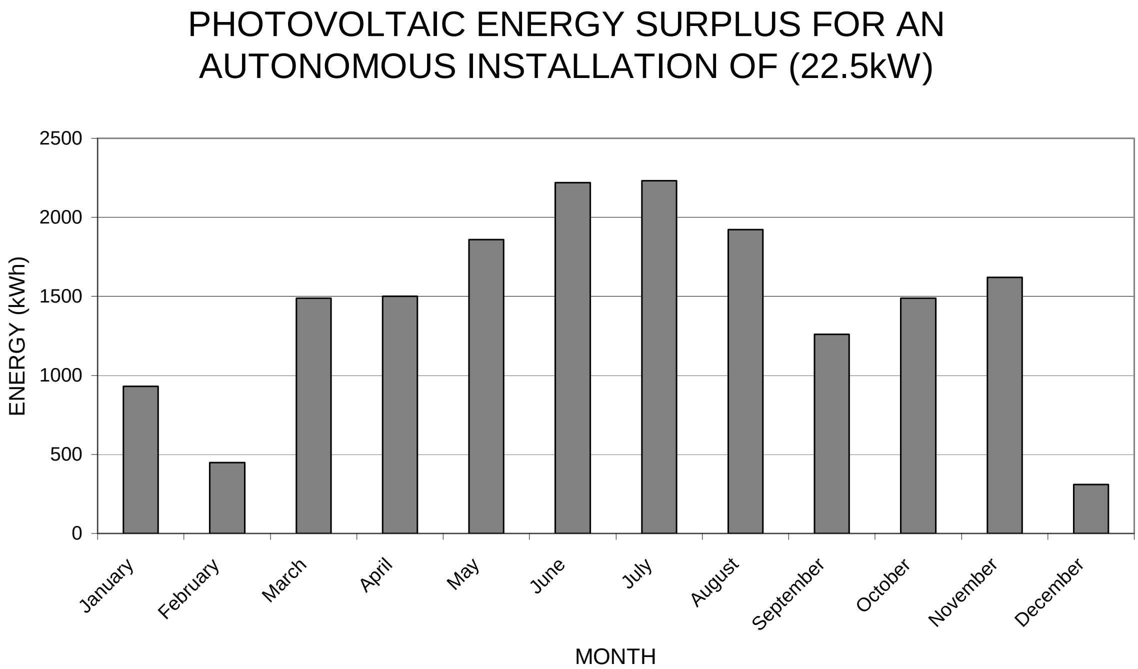

Figure 6: Electricity surplus profile for a PV-based installation in the Aegean Sea Islands

Subsequently, one may find the electricity generation cost for the two remote island cases analyzed (figures (7) and (8)) using the analysis of section 4. In both cases the maximum electricity generation cost is less than 0.3€/kWh, a substantially lower value than the corresponding value of 0.5€/kWh mentioned for these remote islands, figure (1). It is also important to note that the electricity generation cost is slightly increasing with the desired energy autonomy of the system without the utilization of fossil fuels. According to the detailed analysis carried out the Na-S batteries solution appear to have the minimum electricity generation cost, although all solutions tested are definitely more economically attractive than the operation of the existing autonomous thermal power stations.

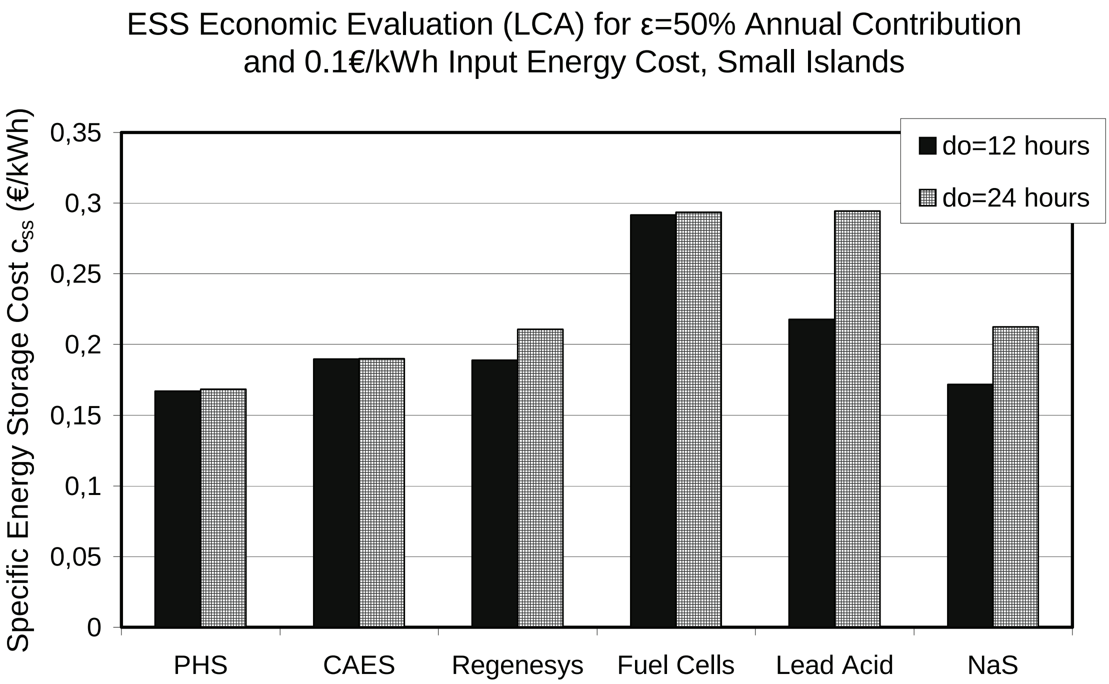

Figure 7: Electricity production cost for small islands

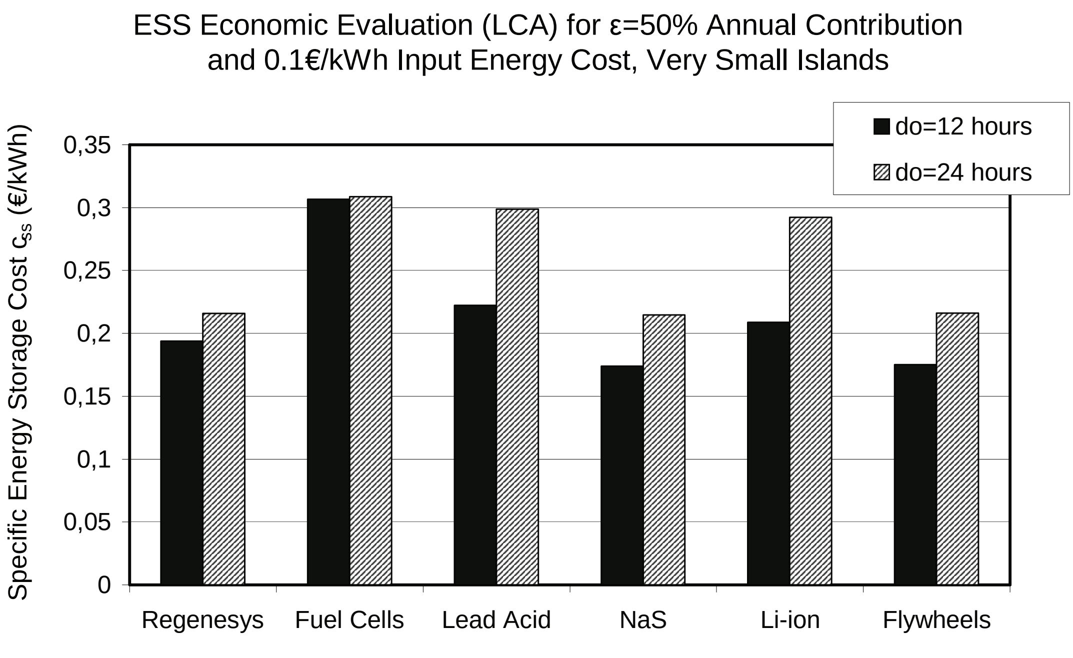

Figure 8: Electricity production cost for very small islands

Similarly, the clean water production cost on the basis of a PV-driven reverse osmosis desalination plant is less than 1.6€/m^3 for small islands (figure (9)) and 2.4€/m^3 for very small (figure (10)) ones. As it is obvious from the results obtained the clean water production cost is remarkably lower in cases that the desalination plant operates throughout the entire year (i.e. UF→1/300). Also one should also note that the clean water production cost decreases as the annual water cost escalation rate increases. However, even at constant clean water prices in the course of time, the clean water production cost is definitely lower than the current (imported) water prices of 4.5€/m^3 and 7.0€/m^3.

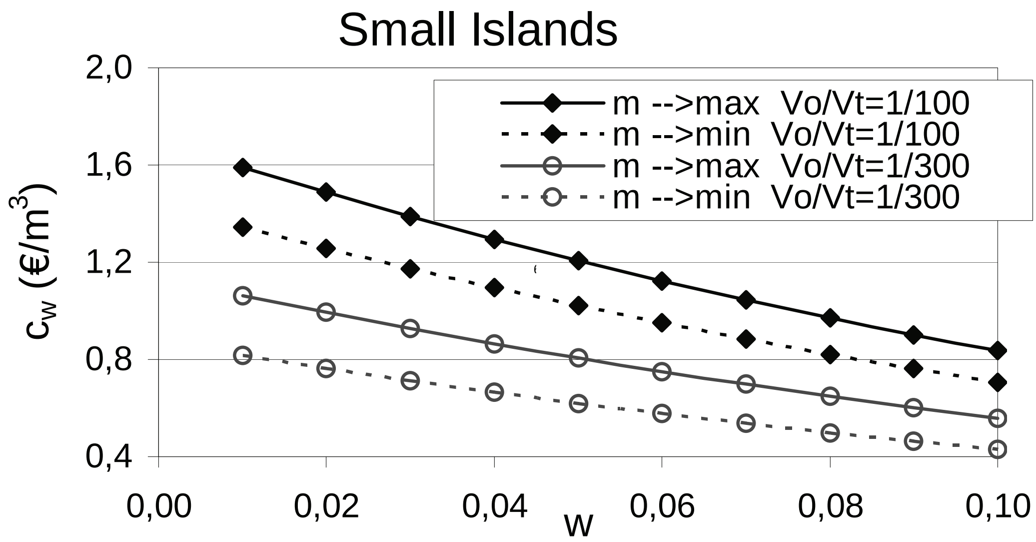

Figure 9: Clean water production cost for small islands

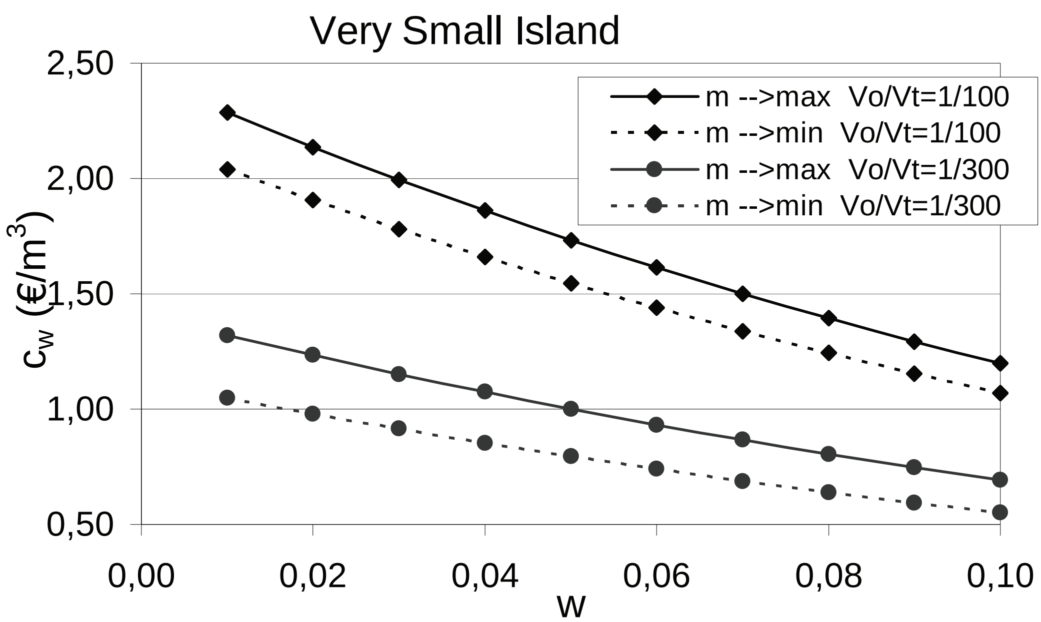

Figure 10: Clean water production cost for very small islands

Summarizing, one may state that the proposed solution offers the possibility for the remote island communities to meet their pressing electricity and clean water requirements on the basis of an environmental friendly and sustainable energy solution based on a properly sized PV generator in combination with the appropriate energy storage device.

6. Conclusions

The exploitation of solar radiation for the combined production of energy and water in remote areas has been proposed in the present work. More specifically, a complete energy-water system including PV generators coupled with a corresponding energy storage system in conjunction with a reverse osmosis desalination plant has been configured and sized in detail.

The proposed system covers the energy demands of a remote area increasing the solar energy penetration values, thus minimising the use of conventional thermal power stations and contributing the elimination of their corresponding environmental impacts. At the same time the surplus energy is stored in the energy storage system and is directed to the appropriately designed desalination plant producing potable water, thus covering domestically the water needs of the area in a sustainable way. In addition to the technical description, the proposed system has also been analysed in financial terms and its feasibility has been evaluated.

Various different states in the operation of the system have been described and the proposed method has been applied in two different case studies. In parallel to the environmental and sustainability gains, the incurring unit cost of electricity and water are also very promising compared to the corresponding ones of the conventional system. Therefore, in its results the work concludes that the configuration investigated can efficiently fulfil the electrical energy and the clean water requirements of numerous remote communities on the basis of clean and reliable solar energy, improving the life quality of local habitants.

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DEVELOPMENT AND OPERATION ISSUES OF A DECISION SUPPORT SYSTEM FOR WATER MANAGEMENT IN AREAS WITH LIMITED WATER RESOURCES

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Abstract

Due to the increasing significance of the water shortage problem, water supply chain management is evolving as one of the most difficult and urgent problems on a global basis. Furthermore, sustainability issues should be taken into account in water resources management in order to assess and avoid any unsustainable water supplies and allocations. The problem of the optimal water systems planning is imperative in cases where water may be supplied from various different sources, the demand may exceed availability and the users have conflicting requirements. The unit cost of water is different for each supply method, and its value varies for each specific allocation, therefore there is a clear optimisation scope in water resources management. The present paper investigates the need for the development and operation of a Decision Support System (DSS) for the optimal allocation of water resources to various users with conflicting demands. More specifically, the proposed system is able to evaluate different scenarios for various issues of the water system operation. Results of the DSS include the evaluation of different water supply and allocation scenarios, the water quantities that should be allocated to the each user and the quantities that should be supplied from each source. The system's core is an optimisation model that maximises the total value of the water use, assigning a time-varying priority to each user and taking into account the resources capacity, and the possibility (cost) of not satisfying the demand. The basic principle of the system is that the existing resources are optimally allocated, even in cases that not all the demands are satisfied. Technical and environmental parameters are taken into account in the optimisation problem. Special emphasis is given to the implementation of the method in specific Aegean islands with water shortage. Furthermore, the present work analyses the various technical and operating issues of the decision support system and investigates the circumstances under which such a system can be a valuable tool for the solution of water management problems in areas with water scarcity.

Keywords: Water Decision Support System; Mathematical Modeling; Water Systems Optimisation; Aegean Islands

1. Introduction

Water is a constrained natural resource and in many areas of the planet water shortage is considered to be possibly the most critical issue to be resolved. Water supply chain management and optimisation are evolving as the most difficult and urgent problems, since the water demand and availability vary significantly with time.

The aim of the present work is to propose the development and operation of a Decision Support System (DSS) that will facilitate the optimal operation of water systems. The system is based on a generic optimisation model that takes into consideration the whole set of problem features and parameters. Even cases where water demand exceeds water availability can be taken into account by assigning priorities to the users. The underlying idea is that the optimal allocation of the available

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water is an issue of crucial importance in the overall water resources management problem and should be determined according to the needs and the expected use of water.

During the last decades several methodologies have been developed in the design and operation of water systems, in the field of engineering. Optimization models[1][2] as well as decision support systems[3][4] have been implemented either for the optimal allocation of water resources or for the optimization of specific components of the water systems. In spite of the interest that has been shown in the water resource optimisation problem from various researchers and practitioners, there is always a scope for applied research in the development of tools that match local needs and take into account the specific characteristics of the area under consideration.

Water Decision Support Systems are a very interesting issue dealing with various aspects of water resources management problems, such as supply safety, quality and quantity management, costs and benefits. More formally, a Decision Support System is an integrated, interactive computer system, consisting of analytical tools and information management capabilities, designed to aid decision makers in solving relatively large, unstructured water resource management problems[5].

Integrated water resources management requires the consideration of a wide scope of social, economic and environmental aspects of resource use and protection. Usually, water DSS have one of the two following approaches: They either simulate water resources behavior in accordance with a predefined set of rules governing water allocation and infrastructure operation, or they optimize and select allocation and infrastructure based on an objective function and accompanying constraints. The DSS proposed in the present work relies on the optimisation approach, as it will be described in the next sections.

2. Water Resources Management in the Aegean Islands

Cyclades and Dodecanese are island complexes belonging in the South Aegean Prefecture and located in the Southeastern part of Greece, a region which is characterized by special architecture and interesting cultural tradition, pleasant climate, especially during summer and attracts many tourists. However, the temporal increase of population in combination with the local activities, mainly agricultural, commercial and rarely industrial, the low precipitation rates, the geomorphology of area and over-exploitation of groundwater resources, have led to extensive water shortage problems.

The water availability in the Aegean islands varies with time and definitely plays a critical role in the regional development and the living conditions of these islands. The local water resources are relatively limited, especially in the small islands. In many cases, where the water scarcity is extensive, the needs are partially or totally covered through ship transport, which is a temporary solution, because it does not form any infrastructure for the long-term solution of the problem.

Cyclades in particular is an island complex including many, arid in their majority, islands. The medium-large size islands, such as Syros, Naxos, Andros, Myconos, with high development of residential and tourist rates, have partially solved their water shortage problem with infrastructure projects, such as desalination plants, water dams and ground reservoirs. However, the smaller ones are forced to adopt short term solutions i.e. water transport by ships and the storage of it in water reservoirs. It must be pointed out that during the last decade a water volume of 1,620,000m^3 has been transported to Cyclades Islands with an overall cost 12,524,000€[6].

Accordingly, in Dodecanese Islands only the large-size ones, like Rhodes and Kos have their own water resources, while the majority of the rest acquire the demanded quantity through transport from the larger ones, even though during the last years some desalination plants have been constructed. The corresponding imported quantity in Dodecanese islands for the period 1997-2005 has been 4,508,000m^3 with an overall cost 18,739,000€[6].

Figure 1: Map of Cyclades and Dodecanesse islands

In some of the Aegean islands, the water supply problem is solved either partially or completely with the operation of local desalination plants, based on the Reverse Osmosis technology. Table I shows the present status as far as desalination units in the islands are concerned. In fact, many more desalination units are planned to be installed in the islands, to solve the acute water shortage problem of the last years, with serious considerations for the implementation of Renewable Energy Sources (RES) to cover their energy needs. In general, the cost of water from desalination plants is much smaller than the corresponding cost of transported water. In any case, in the proposed model the water cost from each different supply source is taken into account.

The other interesting characteristic of these island complexes (Cyclades and Dodecanesse) as far as their water resources are concerned is their geographical structure. In fact, in each complex, the islands are very close to each other. Therefore, when the water availability is constrained in some small islands while at the same time there is water surplus in a large island quite close to the small ones, the whole water resources management design should consider the possibility of the large island to be the supply source for the smaller ones. This will simplify complicated and difficult situations of considering each island separately and, at the same time, make an optimal use of the available financial resources for water infrastructure projects.

Therefore, it becomes obvious that the problem of water resources management becomes difficult and calls for the use of a reliable and well structured DSS, since a large number of alternatives should be considered, the problem has area and time dependent characteristics and many parameters affect the problem solution.

Table I: Desalination plants in Greece, as per 2007

Island	**Site**	**Water capacity (m³/day)**	**Year**
Syros	Ano Syros	120	1993
		250	2000
		500	2002
	Ermoupoli	800	1992
		800	1997
		250 (2 units)	2001
		800 (4 units)	2002
		744	2006
	Poseidonia	750 (3 units)	2002

Island	Site	Water capacity (m³/day)	Year
		500	2005
Ios	Mylopotas	1000	2001
	Punta	1000	planned
Mykonos	Korfos	2*1200, 500	1989
		3*800	2000
		700	2000
		2000	2001
		3*1500	planned
Paros	Naousa	1200	2002
	Paroikia	2*1200	planned
Sifnos	Kamares	500	2001
	Platys Gialos	250	2007
Tinos	Agios Fokas	500	2001
		500	2005
Santorini		380	1995
	Oia	210	1999
		270	2001
		320	2002
	Nomicos Conf. Center	63	~1995
Kimolos		110	2001
Megisti	Megisti	50	1990
	Mantraki	200	planned
Leros		200	2001
Nisiros	1.5 km from the port	300	1991
		350	2002
		500	planned

3. The Core of the DSS, an Optimisation Mathematical Model

Basic Characteristics and Structure of the Proposed Model

As mentioned above, the proposed Decision Support System relies on an optimisation model that identifies the optimal solution in the operation of the water system, taking into account:

- Various supply sources, each one with an associated possibly time varying water cost and a certain and possibly time varying capacity.
- Various users, each one associated with a time varying demand and an also time varying benefit created from the use of water (expressed as a monetary value per cubic meter of water).

The objective of the model is to determine the appropriate water quantities allocated to each user and the input flows from each supply source, keeping in mind that the total water availability may be less than the total demand. Therefore, there may be time periods that not all the demands will be satisfied. The allocation of the available water quantities will be made following the more sustainable principle that the real and most urgent needs must be satisfied first. In parallel, possible inefficiencies of the water system will be identified, such as serious shortages at a certain time periods, inadequate supply from some sources, extremely high cost solutions etc. Figure 2 shows a schematic representation of the system under consideration.

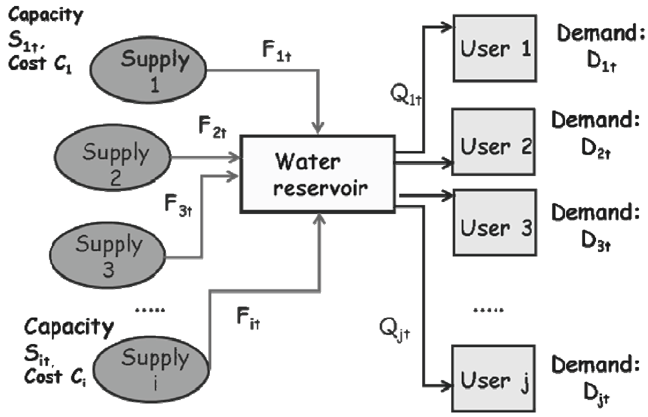

Figure 2: Schematic representation of the water system

The supply sources provide water in a real or virtual storage tank; the storage tank has a specific capacity (upper limit) and a low limit that should never be violated. In case there is no real storage tank, the lower and the upper capacity limits are set equal to zero and the water goes directly from the supply source to the user.

Water Supply

For the islands, the most common water supply sources are the following:

- Desalination units
- Ground Reservoirs
- Dams
- Water transport by ships
- Other own water resources (e.g. wells)

In fact the model can accommodate any type of water supply. The information that is required is the cost, capacity and any existing operational constraints. The supply limits are determined from the capacity of each specific source that possibly varies with time.

The supply costs may simply be considered as linear terms multiplying the corresponding water quantity or may follow more complicated economic functions. For example, the desalted water cost may be calculated as the sum of a fixed term, expressing the depreciation of the unit and a variable cost term or be expressed with a more complicated economic function, taking also into account various parameters of the unit's operation[7]; the same is valid for the ground reservoir and the dam. On the contrary, the water transported by ships has only a rather high variable cost term that is multiplied by the corresponding transported quantity.

Water demand

The most common water users are:

- The agriculture (irrigation).
- The urban use (including permanent and seasonal domestic and commercial use).
- The industry and, possibly, some other secondary uses.
- Other surrounding places that have serious water shortage and need to be supplied by the water supply sources under consideration and can be considered as discrete users with their own demand.

The upper limits of the quantities being delivered to the various users are the corresponding time-varying demands. In case the total water demand exceeds the available quantities, not all the requirements will be satisfied. This will definitely have some impacts to the users (e.g. cancellation or limitation of expansion plans, direct economic losses, decreased agricultural production etc.).

The allocation of the available water to users will be indicated by the optimization, following the priorities that will be set to the model. It should be emphasized that the model will allow the water demands to exceed the total availability, and, therefore, some users demands to be partially satisfied, since the water allocation will be done following certain and predetermined priorities. In fact, this is one of the most interesting parts of the work, sine the priorities that are set follow the value or the expected benefit from the corresponding use of the water and these ‘benefits’ are the parameters that multiply the quantities allocated to each user in the optimization criterion.

In any case, the discrepancy between the allocated quantity and the demand should be penalised. Actually these penalties are expressed as ‘cost terms’ in the objective function, caused by the water shortage for a certain user at a time period. The penalties reflect in some way the losses caused by the water shortage and must be time varying, since the consequences of the water shortage are not all the times the same for a user.

4. Mathematical Model Development

System parameters and variables

The variables and the parameters of the system are shown in Tables II and III respectively. The optimal planning problem will be solved in a predetermined time horizon. The length of the time horizon depends on the specific problem under consideration, the time period of the year and the desired use of the results[8].

Table II: Model Parameters

Parameter	Magnitude
Index i	Supply source, i.e. dam, ground reservoir, desalination unit, water transport
Index j	User, i.e. irrigation, urban sector, industry, other adjacent places
t	Time step in the horizon under consideration
B_{jt}	Benefit for the use of the water from user j at time interval t (in €/m^3)
D_{jt}	Demand of water from user j at time interval t (m^3)
Q_{jt}^{MIN}	Minimum water flow to user j at time interval t (m^3)
S_{it}	Capacity of the supply source i (m^3) at time interval t
P_{jt}	Penalty for not satisfying the demand of user j at time interval t (€/m^3)
C_{it}	Cost of water from supply source i at time interval t (€/m3)
V_{max}	Maximum volume of water that can be stored in the storage tank (m^3)
V_{min}	Minimum volume of water that should be stored in the storage tank (m^3)

Table III: Model Variables

Variable	Magnitude
F_{it}	Flow of water from supply source i at the time interval t (m^3)
Q_{jt}	Water flow allocated to user j at time interval t (m^3)
V_t	Water volume stored in the reservoir at time interval t (m^3)

Optimisation Criterion

The optimisation criterion that expresses the efficiency of the water system is the maximisation of the total water value, taking into account all the benefits from the water use, including environmental benefit and costs:

Maximize Total Value of Water = Maximize (Total Benefit – Total Cost)

$$\text{Total Benefit} = \sum_t \sum_j B_{jt} \cdot Q_{jt} ,$$

Total Cost = Supply Cost + Penalties for the discrepancy between demand and real supply to the users.

Hence, the Total Cost term in the objective function is expressed as:

$$\text{Total Cost} = \sum_t \sum_i C_{it} \cdot F_{it} + \sum_t \sum_j p_{jt} \cdot (D_{jt} - Q_{jt})$$

Therefore, the optimality criterion that maximises the total benefits and, at the same time, attempts to minimise as much as possible the costs and the differences between the quantities supplied to the users with their real requirements, is expressed as follows:

$$\text{Max} \sum_t \sum_j B_{jt} \cdot Q_{jt} - [\sum_t \sum_i C_i \cdot F_{it} + \sum_t \sum_j p_j \cdot (D_{jt} - Q_{jt})\,] \qquad (1)$$

As shown in the objective function (1), the Benefits from the allocation of a water quantity in user j vary with time. For example, the Benefits for the allocation of water in the urban sector (e.g. tourism) may be much more significant during summer, while the irrigation water will have a larger Benefit in another time interval. Therefore, the values of the Benefits for each user at each time period should accommodate the following issues / concepts:

- The potential results / impacts from the water use, either as revenues or profits from this specific use (e.g. income increase attributed to the water availability from the tourism sector or from the increase in agricultural production).
- A quantification of the regional development and welfare of the local community attributed to the water availability.
- An environmental benefit resulted from the water waste and the resource depletion elimination.

On the other hand, the Penalties for not satisfying part or all the demand should accommodate:

- The priorities among various competing users.
- The losses caused by the corresponding water shortage.

It may be emphasized that the Penalties caused by the water shortage do not express the same concept with the corresponding Benefits from the water use. Due to the acute character of water shortage, in many cases the supply cost is not seriously considered. Although the price of water usage is respectively high, its financial price does not reflect its worth neither it’s real cost, because it is considered as a renewable natural resource and a commodity. However, it is believed that a rational approach of this problem will effectively contribute into the sustainability of any implemented solution concerning the water shortage problem. The water price reaching the final consumers has to reflect its real cost and its usage value.The proper and rational quantification of the Benefits, Penalties and Costs could comprise the basis of rational water pricing.

Model Constraints

The model constraints impose limits on the problem variables and include:

The continuity equation in the water storage tank: $V_t = V_{t\ 1} + \sum_i F_{it} - \sum_j Q_{jt}$ (2)

Upper and lower bounds of the water in the reservoir: $V_{\min} <= V_t <= V_{\max}$ (3)

Capacity limitations of each supply scheme: $F_{it} <= S_{it}$ (4)

Flows allocated to each user should not exceed the corresponding Demands. Furthermore, it may be desirable to assign a minimum water quantity to some users.

$$Q_{jt}^{\min} <= Q_{jt} <= D_{jt} \qquad (5)$$

5. Decision Support System Operation

The need for a Decision Support System for the optimal water allocation in the islands originates from the fact that the availability almost never is able to satisfy demands, especially during summer. In practice, in most Greek areas, the responsibility for the allocation of water quantities to various users lies in the Municipalities. In periods when the users put competitive demands on the available water resources, the authorities are called to solve a complex and urgent problem of resolving these conflicts, possibly on a daily basis. Therefore, there is a need for a system that will support the solution of the problem in a rational and well justified way and will also protect the sustainability of the resource.

The problem that the system will be called to solve is defined as follows:

- For a certain geographical area that the system has been designed for
- For a certain planning horizon
- For given water supply (per source) and demand (per user)
  - o which are the optimal quantities that should be supplied from each different source of water?
  - o which are the optimal quantities of water that should be distributed to each of the users (water system response)?

In order to:

- o satisfy the demand according to a certain set of priorities
- o respect all operational and environmental constraints
- o maximize the expected total benefit from the use of the water
- o minimize the total operational cost of the system.

The architecture of the system consists of the following components:

- Data measurement and collection,
- Data processing – the tasks involved in registration of measurements into databases and their subsequent processing, retrieval, and storage;
- The optimisation model that has been previously described and is the core of the system
- A mathematical library / optimiser for the solution of the optimisation problem (LP, MILP, MINLP solver)
- An interactive graphical user interface for the interaction with the users, data input and gathering of the conclusions from the optimisation.
- Decision implementation – the formulation of actions to be implemented in solving a specific problem.

The design and the operation of the proposed DSS are determined by the area that will be implemented in many facets. For example, the number and type of users, the supply sources, the priorities that should be followed are area depended. Therefore, it is much preferable to develop a simple system adapted to the needs of a certain area rather than making it very generic, that it not going to be of any use.

Definitely, the implementation of the system’s results is a much more complicated issue and is affected by the water policy and strategy followed in a place. However, the assessment of various scenarios is facilitated with the use of the DSS.

6. Application Results

The mathematical model is applied in an island complex belonging to the Cyclades islands, in order to highlight the type of problems that can be solved and the type of the results that could be expected from this work. The basic problem parameters are shown in Table IV.

More specifically, the case study under consideration is the island complex of Naxos province. Naxos is the largest of the Cyclades islands, with a population of almost 20,000 inhabitants and an area of 448 $km^{2.}$ Naxos is surrounded by a number of smaller islands, called Mikres Cyclades that belong in the same province, namely the islands Heraklia, Schinousa, Donousa, Koufonisi, Amorgos. A map of the area is shown in Figures 3 and 4 and their water demands per user are shown in Figures 5 and 6.

Figure 3: Cyclades islands

Figure 4: The area under consideration

Naxos water supply sources are a dam with a capacity of 3 million m^3 water and a water ground reservoir with a capacity of 1,500,000m^3. There is no water transport by boats and there is no water desalination unit on the island.

Naxos has a significant agricultural sector as well as stock raising activities. The total water demand for irrigation and stock raising is almost 10 million m^3 per year. In addition, Naxos has significant tourism and some industrial activities. The total water demand of the domestic /urban users of the island is almost 2 million m^3, while the distribution of the demand in the agricultural and the urban sector are shown in Figure 5.

Table IV: Case study data

Time horizon	12 months, time step 1 month
Water Users	Urban Use- Naxos, Irrigation Use-Naxos, Small Cyclades (Heraklia-Schinousa, Koufonisi, Donousa, Amorgos)
Water Demand	(Figure 5, Figure 6)
Water supply cost	C_{1t}= 3 €/m^3, C_{2t}= 4,4 €/m^3, C_{3t}= 7 €/m^3

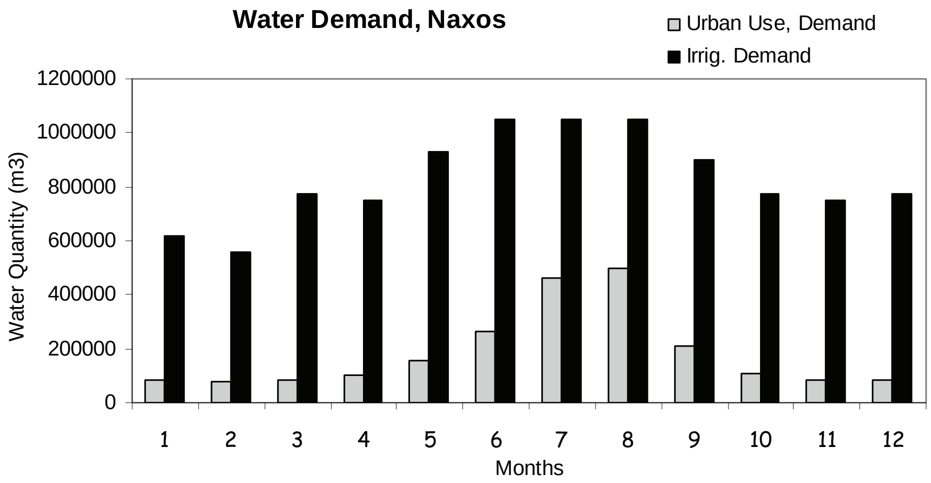

Figure 5: Water demand, Naxos island

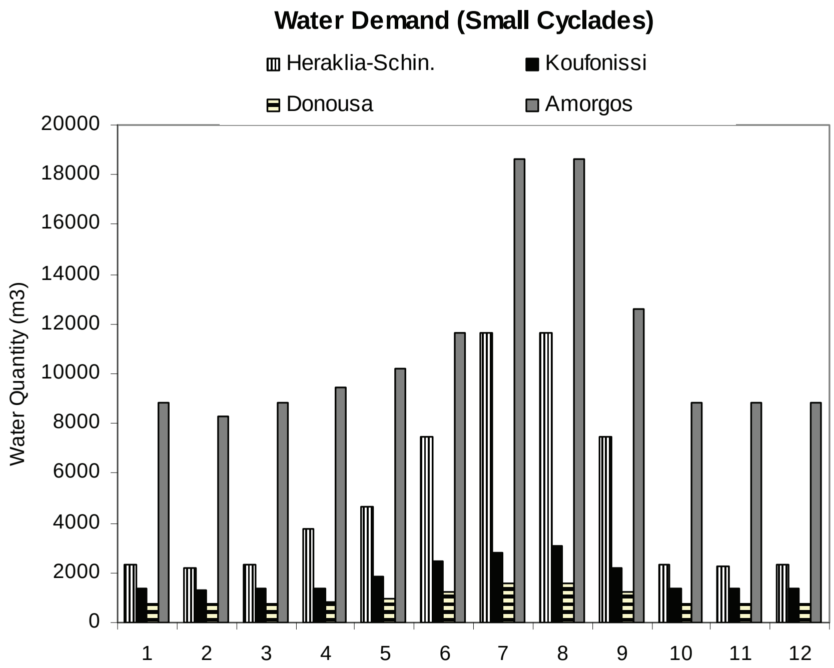

Figure 6: Water demand, Small Cyclades area

The type of results that the system will give are shown in Figure 7.

Depending on the relative values of the Benefits and Penalties for each of the users, the DSS may choose to satisfy fully the small surrounding islands needs and only partially the needs of the large island, at least as far as irrigation is concerned. Actually, this seems more rational, since the needs of the small islands are rather small and the water availability very critical for their development.

However, in other circumstances, there may be a partial and uniform satisfaction of water needs for all the users. In the results of the case study, all the demands of the Small Cyclades have been satisfied, as well as all the demands in the urban users of Naxos (Figure 7) and the irrigation demand has been partially satisfied, mainly because of the relative values of the Benefits and Penatlties that have been set in this particular problem.

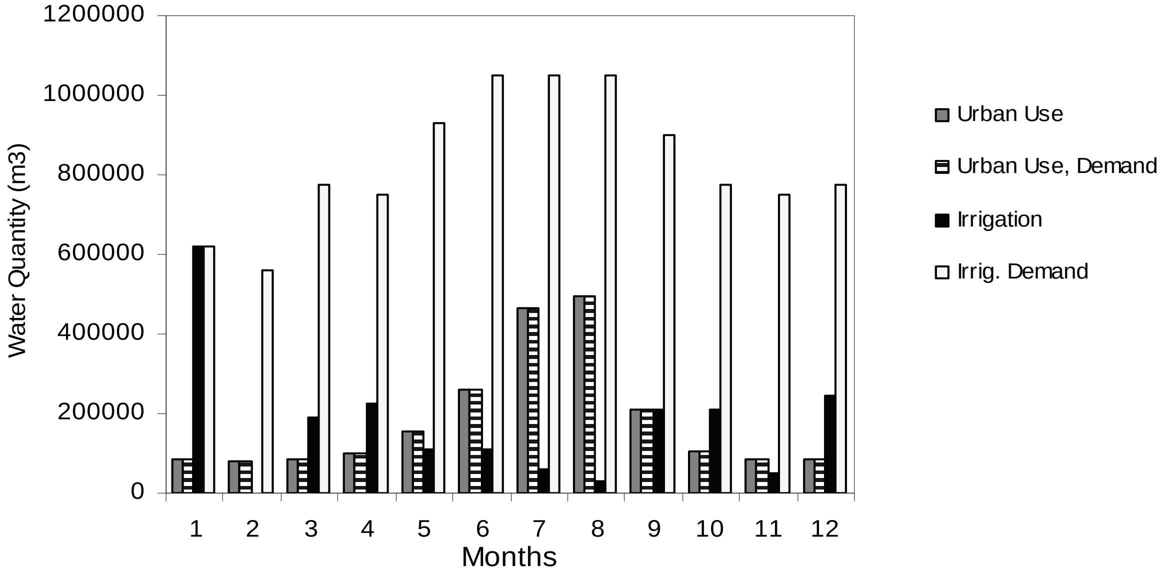

Figure 7: Results of water allocation in Naxos compared to demand

7. Conclusions and Significance

In the present paper a Decision Support System is proposed for the optimal allocation of water quantities in Aegean islands with limited water resources. The core of the DSS is an optimisation model that takes into account complex water systems with multiple supply sources and multiple users and the possibility of total demand exceeding water availability. The water allocation is based on the new idea of assigning benefits to the water use, expressing the value that the water has to each user in a certain area and time period.

This approach of water systems planning provides the capability of an integrated study and investigation of the role of all the system parameters and gives a better insight to the problem of the optimal allocation of water resources, considering the value and priorities of the water usage.

Critical success factors for the implementation of the proposed DSS for water resources management are its simplicity, easiness to be used, its clear and unambiguous results and its ability to evaluate area and time specific alternative scenario. Furthermore, the most important aspect may be the reliability of the data provided and, in conflict resolution cases, their ability to embed criteria and priority rules. The usefulness of these systems is obvious, since they will recommend sustainable use of the water, or, at least, they will facilitate the decision making process by providing quantitative performance measures for the significance of each alternative solution.

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PART FOUR

AIR POLLUTION

TRANSBOUNDARY AIR POLLUTION BALANCE IN THE NEW INTEGRATED EUROPEAN ENVIRONMENT

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Abstract

Ten out of the twelve new EU members, used to belong to the so-called "former eastern block", with a post WWII environmental policy radically different from the tendencies followed in Western Europe. The lack of conservation regulations has resulted in a rather harmful industrialization, regarding natural resources and environmental quality. While air pollution transfer is a phenomenon of transboundary level, there is a particular interest in examining the contribution of the new EU member-states to the environmental pressure faced by the older member-states and vice-versa. The current study utilises the official data for almost 20 years published by the European Monitoring and Evaluation Program concerning the transboundary transfer of NO_x and SO_2 in order to analyse the situation and discuss the present and future environmental policy regarding air pollution.

Keywords: Sulphur Dioxide; Nitrogen Oxides; Old EU Member; New EU Member; EMEP

1. Introduction

Since May 2004, twelve more countries have joined the European Union (EU), in its greatest expansion historically. Ten out of the twelve 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, having been politically isolated during the last decades, have been left behind in the implementation of any environmental protection policies.

The steadily growing agricultural and industrial production in Western Europe significantly improved the material standard of living since 1945. The high oil prices and the first signs of severe environmental degradation resulted in the development of environmental protection and energy saving policies that proved beneficial in local and regional level. At the same time the centrally planned economies of Eastern Europe realised their development in means of physical production growth especially in the industrial and energy sectors. This has resulted in widespread resources exploitation and environmental degradation[1].

While the struggle to improve the economic indicators 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[2][3]. Acid compounds that have been emitted in central Europe degradated forest and aquatic ecosystems of the Scandinavian Peninsula[4][5].

The recognition of the problem of certain air pollutants transboundary transfer throughout the European continent led in 1979 to the initiation of "The Convention of Long-Range Transboundary Air Pollution" (CLRTAP)[6], 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[7], 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[8].

By 1985 the 1st Sulphur Protocol has been issued and signed. Its agreements emphasized in the reduction of the sulphuric air pollutants produced in the signatory countries. More precisely the parties were expected to reduce their sulphur dioxide (SO_2) emissions by 30% relatively to their emission levels of 1980, in a period of 8 years, i.e. until 1993. That protocol was the main motivation for major investments -especially among the Western European counties- which promoted the massive installation of desulphurization units in the large-scale industrial plants. Furthermore, natural gas, containing only traces of sulphur, became the new environmental friendly option for all the energy consuming sectors although in the past it had only been utilized in the tertiary sector[9].

Nevertheless, the increase of road transport as well as the lack of any abatement measures resulted in the steady amplification of the nitrogen oxides production[10]. While in Western Europe it was mostly the extensive growth of the private vehicles fleet that was causing the problem, 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 oxides emissions below the 1987 levels until the year 1994.

During the same time the Regional Air Pollution Information and Simulation (RAINS) model has been developed by the International Institute for Applied Systems Analysis (IIASA). The model makes use of data about economic and energy development in order to identify the threats for the ecosystems and the human health that the air pollution causes. Most important is the integration of the model in a multi-pollutant approach including the assessment of emissions of sulphur dioxide, nitrogen oxides, ammonia, non-methane volatile organic compounds (VOC), and primary emissions of fine ($PM_{2.5}$) and coarse (PM_{10}-$PM_{2.5}$) particles[11].

Particularly the RAINS model has been applied on data regarding several European countries and its usability in terms of cost and environmental damage evaluation is prooved beyond any doubts[12]. The present paper is making use of EMEP data to provide figures that present the time evolution of the transfer of air pollutants from and to predefined country groups, in an original way. The study in the time-variable framework combined with grouped analysis provides a completely new dimension to the EMEP matrices. These data if used with the RAINS model may offer interesting estimations for the environmental and cost performance of the EU environmental policy. Finally, it is noteworthy that the latest version of IIASA models is GAINS which facilitates a joint approach concerning the greenhouse gases and air pollutants[13].

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[14]. Data from all the participating countries were collected in order to sort out solutions for minimizing the environmental damage with the lowest economical cost[15]. The second sulphur protocol was drawn under this perspective. 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. Subsequently the Gothenburg Protocol has been adopted in 1999 to abate acidification, eutrophication and ground-level ozone by cutting down the emissions of sulphur, NOx, VOCs and ammonia[16]. The most recent 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). In the same context the Clean Air For Europe (CAFE) programme has been established aiming to develop a long-term, strategic and integrated policy advice to protect against significant negative effects of air pollution on human health and the environment[17].

2. A Brief Spatial Analysis of the New Integrated EU Area

The EMEP network, utilizing data for the national air pollutants emissions, the local meteorological phenomena as well as the local land surface of each region, results in data about the transboundary transfer of air pollution among the countries that participate in the monitoring and evaluating program[18][19]. For the time period from 1985 until 2003 the development and use of the Lagrangian and the Eulerian models offered data matrixes presenting the annual masses of air pollutants being transferred across the European continent[20][21].

The new 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. Comparing the main parameters of the economies of the old and the new EU members states (Table I) one may state the following:

Figure 1: New integrated EU area involved in Transboundary air pollution transfer

- ✓ The population of the new EU members is almost the one fourth of the EU-15 population, while the corresponding area increase after the integration of the twelve (12) new members is 36.4%.
- ✓ The corresponding Gross Domestic Product (GDP) of the new EU members is slightly higher than 10% of the GDP of the EU-15, hence the per capita GDP value of the new members is less than the half of the one of the EU-15 average.
- ✓ The primary energy consumption of the new EU members is less than the 16% of the EU-15 corresponding value, therefore the per capita primary energy consumption is less than the 60% of the one of the EU-15 average.

Table I: Comparison between the (15) Old and the (12) New EU members

	Population (in millions)	*Area (km^2)*	*Pop. Density*	*GDP (BUS$)*	*GDP per capita (US$/cap)*	*Prim. Energy (10^{12} Btu)*	*Prim. Energy per Capita (MBtu/cap)*
EU-15	370.1	3,208,182	115	9824.5	26546	62438.4	168.7
New Members	104.4	1,167,563	89	1012.5	9698	10074	96.5

Taking into consideration the above information, the present study is based on defining an hypothetical border line between the old and the new member states, figure (1). In this way we are examining the air pollutants exchanged towards each direction.

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 by 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[22] and these were directly correlated to the high concentrations and deposition of airborne sulphur compounds and acidity[23]. 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[24]. Moving to the South, the former Czechoslovakia, Hungary and Slovenia are surrounding the eastern Austria. Finally northern Italy neighbours on Slovenia.

One may notice that from the present study are excluded several countries along the Western Europe as well as countries which are at the East of the aforementioned 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 have only recently joined the EU, there is a particularly increased interest in 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[25].

Finally very little data is available for the western Balkan countries, which used to form the ex-Yugoslavia. In the light of this fact and their way into the EU being heavily questioned, those countries have also been excluded from the current study.

3. Methodology Presentation

The transferred air pollutant mass "${}^{(k)}P_{i,j}(t)$" depends on the air pollutant "k", the year "t", the receiving country "i" and the emitting country "j".

More precisely, in the present analysis "k" stands for nitrogen oxides (NO_x) and sulphur dioxide (SO_2). Additionally the years "t" examined begin from 1985 and finish in 2003. Finally, countries "i, j" are chosen among: Austria (AT, i=1,j=1), Czech Republic (CZ, i=6,j=6), Estonia (EE, i=7,j=7), Finland (FI, i=2,j=2), Germany (DE, i=3,j=3), Hungary (HU, i=8,j=8), Italy (IT, i=4,j=4), Latvia (LV, i=9,j=9), Lithuania (LT, i=10,j=10), Poland (PL, i=11,j=11), Slovakia (SK, i=12,j=12), Slovenia (SL, i=13,j=13), Sweden (SE, i=5,j=5). The aforementioned countries are usually found in two separate groups (Table II).

In an attempt to define the total air pollutant masses imported to the country "i" from each member state of the other group of countries we may use the following equations:

Emission transferred from all new EU members to the old country "i"

$$ {}^{(k)}P_i(t) = \sum_{j=6}^{j=13} {}^{(k)}P_{i,j}(t) \qquad (i = 1, 5) \tag{1a} $$

Emission transferred from all old EU members to the new country "i"

$$^{(k)}P_i(t) = \sum_{j=1}^{j=5} {}^{(k)}P_{i,j}(t) \qquad (i = 6, 13) \tag{1b}$$

Table II: The two country groups involved

Examined Group	*Country*	*Symbols Used*
EU old members (i=1, 5, j=1, 5)	Austria	(AT, i=1, j=1)
	Finland	(FI, i=2, j=2)
	Germany	(DE, i=3, j=3)
	Italy	(IT, i=4, j=4)
	Sweden	(SE, i=5, j=5)
EU new members (i=6, 13, j=6, 13)	Czech Republic	(CZ, i=6, j=6)
	Estonia	(EE, i=7, j=7)
	Hungary	(HU, i=8, j=8)
	Latvia	(LV, i=9, j=9)
	Lithuania	(LT, i=10, j=10)
	Poland	(PL, i=11, j=11)
	Slovakia	(SK, i=12, j=12)
	Slovenia	(SL, i=13, j=13)

In this study we examine the total contribution of the old member states to every new member individually and vice versa. Therefore it is important here to notice that the suggested equations can be used to describe air pollutant transfer towards both directions. Given the case of one old member state receiving air pollution from the new members, "i" takes a specific value describing the receiving country, while "j" takes the corresponding values referring to all the emitting countries of the other group. It is noteworthy that if country "i" belongs to the old member states then as countries "j" one may use all the new members, i.e. j=6,13. For example the total amount of nitrogen oxides transferred from the new EU members towards Austria (AT, i=1) in 2003 can be estimated as follows:

$$^{(NO_X)}P_{AT}(2003) = \sum_{j=6}^{j=13} {}^{(NO_X)}P_{AT,j}(2003) = {}^{(NO_X)}P_{1,6}(2003) + {}^{(NO_X)}P_{1,7}(2003) + ... + {}^{(NO_X)}P_{1,13}(2003) \tag{2}$$

Subsequently the estimation of the total air pollutant masses exported from country "j" to each member state of the other group is described by the equation below:

Emission transferred from each old EU member "j" to all new countries

$$^{(k)}P'_j(t) = \sum_{i=6}^{i=13} {}^{(k)}P_{i,j}(t) \qquad (j = 1, 5) \tag{3a}$$

Emission transferred from each new EU member "j" to all old EU members.

$$^{(k)}P'_j(t) = \sum_{i=1}^{i=5} {}^{(k)}P_{i,j}(t) \qquad (j = 6,\ 13) \tag{3b}$$

Bear in mind that equations (3a) and (3b), similarly to equations (1a) and (1b), make use of the country groups presented in Table II. However, the former two equations refer to air polluting imports, while the latter group to exports. Given the case of one old member state exporting air pollution to the new members, "j" takes a specific value describing the emitting country, while "i" takes the corresponding values referring to all the receiving countries of the other group. For example, the total amount of oxidized sulphur transferred from Lithuania (LT, j=10) towards the old European Union members in 2003 can be estimated as follows:

$$ {}^{(SO_2)}P'_{LT}(2003) = {}^{(SO_2)}P'_{10}(2003) = \sum_{i=1}^{i=5} {}^{(SO_2)}P_{i,10}(2003) = {}^{(SO_2)}P_{1,10}(2003) + {}^{(SO_2)}P_{2,10}(2003) + ... + {}^{(SO_2)}P_{5,10}(2003) \quad (4) $$

In this way one may create for each air pollutant two two-dimensional (2-D) matrices including the time-evolution of the transferred air pollution from and towards each country member of the two subgroups interacting, see for example equations (5a) and (5b).

$$ \begin{bmatrix} {}^{k}P_i(t) & \xrightarrow{i=1,13\ (AT,DE,IT,FI,SE,CZ...,SL)} & . & . \\ {}^{k}P_i(t+1) & . & . & . \\ . & . & . & . \\ . & . & . & . \\ {}^{k}P_i(t+n) & . & . & . \end{bmatrix} \quad (5a) $$

$$ \begin{bmatrix} {}^{k}P'_i(t) & \xrightarrow{i=1,13\ (AT,DE,IT,FI,SE,CZ...,SL)} & . & . \\ {}^{k}P'_i(t+1) & . & . & . \\ . & . & . & . \\ . & . & . & . \\ {}^{k}P'_i(t+n) & . & . & . \end{bmatrix} \quad (5b) $$

Finally, one has the possibility to estimate -for each pollutant investigated- the net balance between the air pollutant mass exported to the other subgroup and the corresponding mass imported by all the countries members of this subgroup, i.e.:

$$ \delta^{(k)}P_i(t) = {}^{(k)}P_i(t) - {}^{(k)}P'_i(t) \quad (i=1,\ 13) \quad (6) $$

4. Transfer of Oxidised Sulphur Air Pollutants

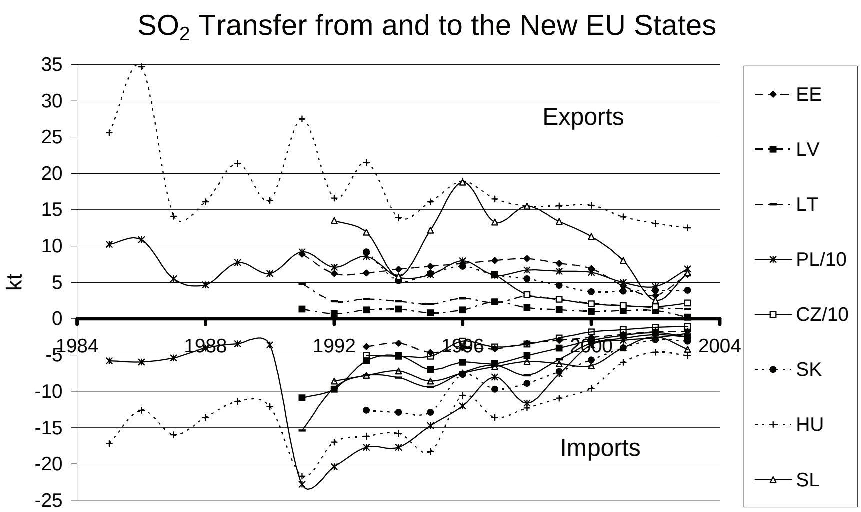

Figure 2: Transboundary SO_2 transfer from and to the New EU member States

Sulphur oxides are some of the major pollutants emitted mainly by the coal and heavy-oil combustion processes. Thus the basic polluters are the large-scale electricity generation stations as well as some forms of transport like overseas and heavy-duty road transport[26][27]. In the present study reference is only made to sulphur dioxide as it represents more than 99% of the emitted sulphur oxides. Mainly due to the collapse of the former centrally planed economies in the late eighties and early nineties the air pollutants emissions from the new EU member states present a declining trend, which reaches for the entire 1985-2003 period the 30% of the initial value. More precisely, regarding the sulphur dioxide emissions exported from the new to the old member states (figure (2)) one may notice that Poland has been the major exporter emitting 102kt and 63kt, in the beginning and the end of the time period analysed, respectively. It is noteworthy that in the figures 2, 3, 4, 5, 6, 8 the reader will find symbols of the form "Country Code/10". In these cases the correct amount of air pollutant transfered occurs from the multiplication of the presented figure by ten (10).

Hungary being one of the most industrialised countries of this region comes second in the sulphur dioxide emissions exportation, despite its relatively small size. While very little is known for the individual contribution of the Czech Republic in the emissions transferred to the old EU member states in the time period before the 1996 one may consider them as high due to the heavy industrialization of the country. As part of the ex-Yugoslavia, Slovenia provides minimum reported information about its individual contribution to the total exportation of sulphur dioxide to the western European countries, before 1991. However, the reported data after this year show that Slovenia is one of the key exporters of sulphur dioxide mainly to the neighbouring Austria and Italy. Finally the countries of the Baltic region appear to have minor exports of sulphur dioxide emissions to the old EU states. This is not only due to the fact that none of the Baltic States has land borders on any of the old EU members but also due to their relatively small economies together with the extensive dependence on nuclear energy.

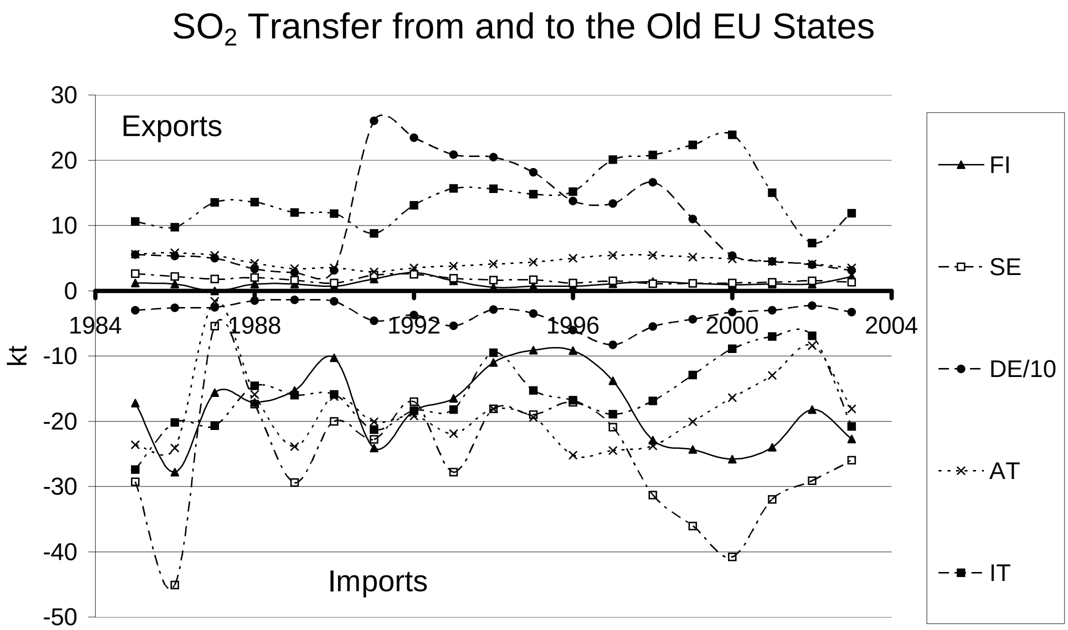

Figure 3: Transboundary SO_2 transfer from and to the Old EU member States

Having already analysed the oxidised sulphur emissions exported from the new EU members, it is of crucial importance to focus on their allocation to the neighbouring old member states. One may notice in figure (3) that the oxidised sulphur received by the old member states in 1985 was allocated to quantities ranging from 18kt for Finland to 30kt for Sweden and West Germany. In the following time-period and until 1998 the received amount of sulphur dioxide in each one of the examined countries presents a variation within the aforementioned limits. While this is the case for Finland, Austria and Italy, Sweden and mostly Germany present significantly different results. Although Sweden's peak receiving 46kt in 1986 may be considered as a spontaneous event, Germany seems to be heavily overburdened when compared to the other old members, especially in the time period that follows year 1990, receiving in 1997 more than 82kt. The presented situation, with Germany being the major SO_2 importing country, can be explained taking under consideration the extensive long border line shared with Poland, which has already found to be a key exporter of the air pollutant examined. Finally, during the period 1999 to 2003 one may notice a declining trend in the oxidised sulphur received from Germany and Sweden, although during 2000 Sweden imports present a significant local minimum (≈40kt). At the same time Italy and Austria SO_2 imports present a variable behaviour, with a noteworthy minimum during 2002. On the other hand Finland receives almost constant SO_2 quantity from the new EU members during the 1998-2003 period.

Baring in mind the data presented regarding the sulphur dioxide transferred from the eastern to western countries, special emphasis should be also placed on the vice versa approach. In figure (3) the data for the exported sulphur dioxide from the old member states are presented. Although Germany is the major exporting country already from 1985, it is interesting to notice that in year 1991 the exported quantities are severely increased and again gradually falling to the initial levels by year 2000. Note that in 1990 the unification of Western and Eastern Germany had taken place and as a result the data given for the sulphur dioxide exportations are summarised. As the German Democratic Republic has been emitting significant quantities of sulphur dioxide one may understand the evolution of the German emissions. However, in the time period 1992 to 2000 the economic transition of the eastern part of Germany resulted in the gradual shutdown of several of the heavy polluting industries or the major improvement of their environmental behaviour, therefore in 2000 the exported sulphur dioxide from Germany to the new EU members has declined to the level of 1985 and remain low for the next years. At the same time period Austria, Sweden and Finland -sorted by their emissions significance- have minor contribution to the total sulphur dioxide exported to the new member states. This is not the case for Italy, which during 1990 and 2000 exported significant SO_2 quantities towards the new EU members.

While the unified Germany has been the major sulphur dioxide exporter, in figure (2) one may notice that Poland is by far the major importer. Similar behaviour is also encountered for Czech Republic. As the major oxidised sulphur exchange between the old and the new EU members takes place between Germany and Poland it is obvious that the rest of the new member states (excluding Czech Republic) share a percentage not higher than 20% of the total new EU members imports, see also Section 6.

5. Transfer of Oxidised Nitrogen Air Pollutants

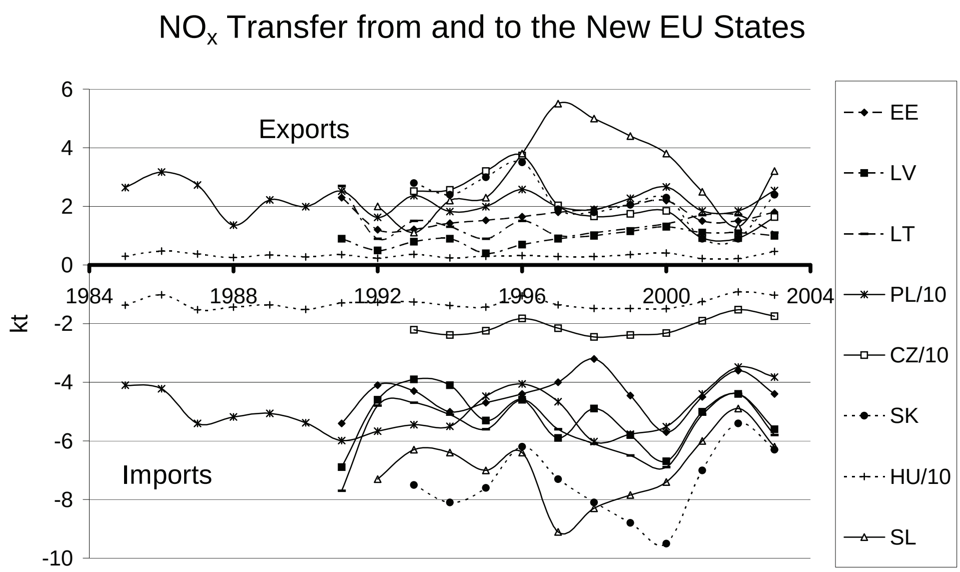

Figure 4: Transboundary NO_x transfer from and to the New EU member States

Oxidised nitrogen air pollutants are mostly produced by the transport sector due to the wide utilization of internal combustion engines[5]. Therefore the emitting sources are mainly non-stationary and are found spread throughout the urban areas as well as in the national road networks[28][29][30]. Bearing in mind the results presented for the oxidized sulphur exported by the new EU members, one may realize that the situation is not very similar regarding the nitrogen oxides exports (figure (4)). 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 for Czech Republic begin from 1997, the heavy industrialization together with the close neighbouring 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.

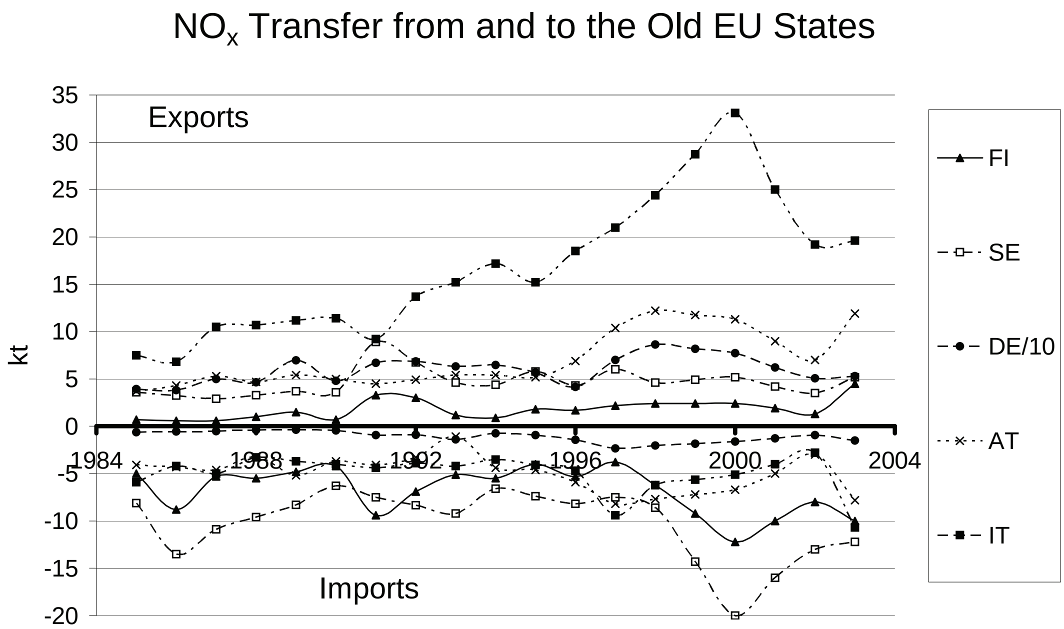

Figure 5: Transboundary NO_x transfer from and to the Old EU member States

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 (5)) that despite the fact that Germany is the main nitrogen oxides importer from the eastern EU members, other countries like Sweden and Finland are also receiving considerably high quantities, presenting an increasing trend during the end of the previous decade. However, after 2000 this situation is inversed and the NO_x imports of almost all old EU members involved is decreasing. Finally, it is important to note that a remarkable NO_x imports increase is observed for all five countries examined during 2003.

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 under investigation. In figure (5), 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 also 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 after 1996 to the new EU members more than 10kt of nitrogen oxides, presents a noteworthy contribution during the last decade.

Studying the allocation of the West Europe originated nitrogen oxides air pollutants, one may refer to figure (4) out of which becomes obvious that Poland is not only the major receiver of oxidised sulphur but also of oxidised nitrogen. Czech Republic, being inside 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 investigation receive individually quantities less than 10kt without any considerable variation during the period examined.

6. Discussion of the Results

Having already examined the evolution of the air pollutant quantities, which have been exchanged among the old and new EU members, one may try to assess whether the transboundary transfer of the oxidised sulphur and nitrogen is beneficial or not to every individual country. In this context, one may compare the net SO_2 and NO_x balance for 1993 and 2003. More specifically, the new EU states of Estonia, Czech Republic, Hungary and Slovenia have been exporting more SO_2 quantities than they import, figure (6). On the other hand, Poland has been the country harmed the most from the transboundary transfer of oxidised sulphur receiving almost 100kt of SO_2 during 1993. The situation is inversed in 2003, since Poland presented positive (by 50kt SO_2) net balance with the old EU members, see also figure (7). Finally, from the group of the new EU states also Latvia, Lithuania and Slovakia are harmed but their balance is remarkably improved in 2003. As a general conclusion concerning the SO_2 balance of the new EU members, one may underline the fact that during the last decade all countries, excluding Slovenia have ameliorated their net balance.

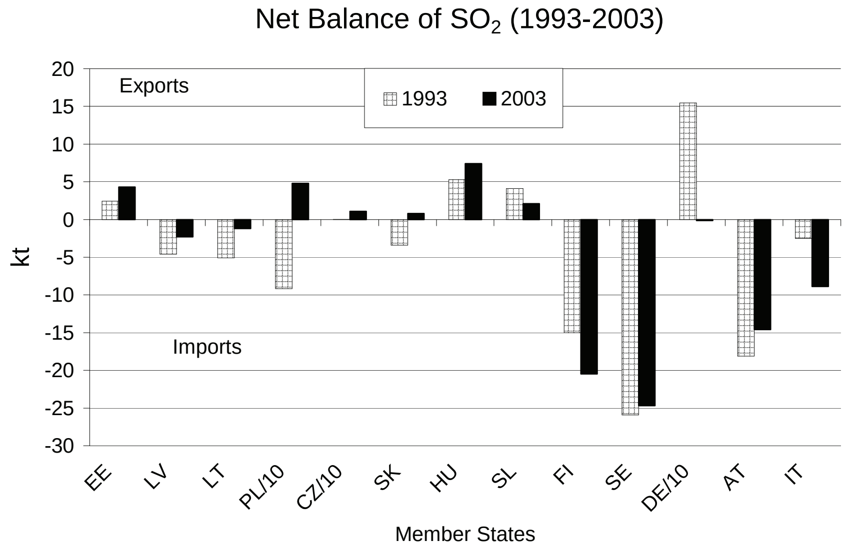

Figure 6: Net transboundary SO_2 balance for the Old and the New EU member States

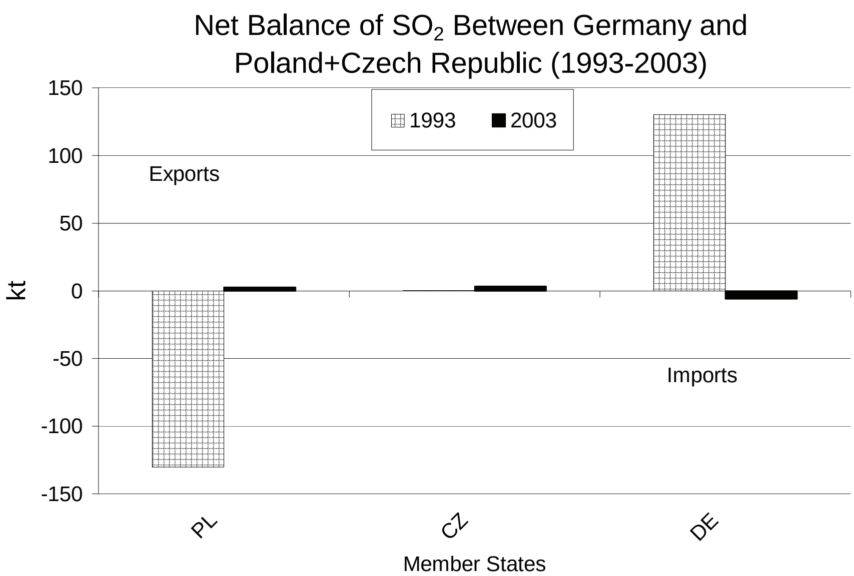

Figure 7: Transboundary SO_2 transfer between Germany and Poland-Czech Republic

Concerning the group of the old EU members (figure (6)), one may notice that apart from Germany all the rest countries are harmed from the transboundary transfer of SO_2. More precisely Finland, Sweden and Austria are receiving in average (15–23kt)/year more oxidised sulphur than what they export. The situation is much more severe for Italy, which although in 1993 is not remarkably influenced by the SO_2 TAPT phenomenon, in 2003 received almost three times higher SO_2 than 1993. Finally, as already mentioned, Germany during the period examined is largely benefited from the SO_2 exports. However, it is worthwhile to mention that Germany gradually decreases its SO_2 exports, hence during 2003 the net SO_2 balance is zeroed. This is also the case concerning the SO_2 balance between Germany and Poland and Czech Republic, figure (7).

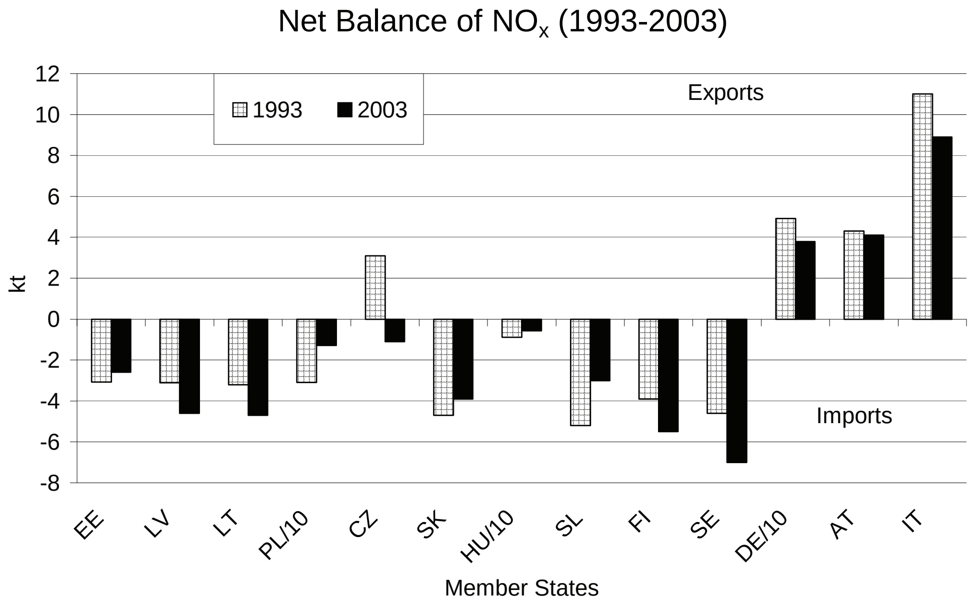

Figure 8: Net transboundary NO_x balance for the Old and the New EU member States

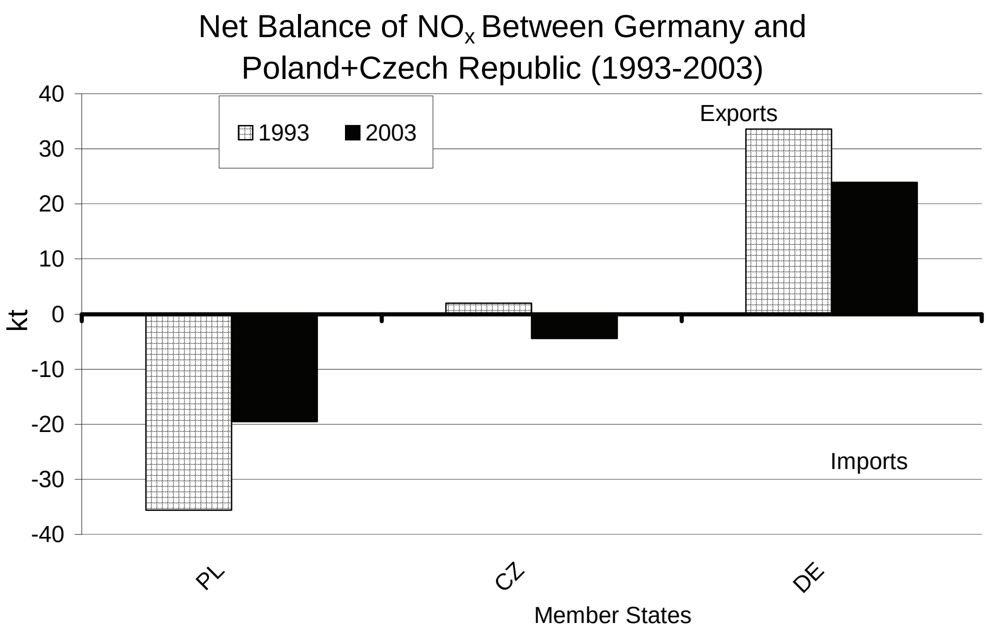

Figure 9: Transboundary NO_x transfer between Germany and Poland-Czech Republic

Regarding the transboundary transfer of the oxidised nitrogen (figure (8)) the situation is different for the new EU members as all of them (excluding Czech Republic) appear to have received bigger NO_x quantities than those exported. Among the least harmed countries one may find Estonia, Latvia and

Lithuania together with Slovakia and Slovenia. According to the calculation results Poland and Hungary are by far the biggest NO_x importers for the entire period examined, presenting however a decreasing trend, figure (9). In fact, like oxidised sulphur, Poland is the country harmed in major (especially from Germany, figure (9)), receiving 466kt more emissions than those exported, while Hungary is following with 165kt, for the entire 1985-2003 period analyzed.

As regards to the status of the old EU states towards the transboundary transfer of oxidised nitrogen (figure (8)), 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 3kt of NO_X more than its imports, while the relevant quantity for Italy is barely exceeding the 10kt. Finally, Germany is in this case as well the major benefited country exporting annually 50kt more oxidised nitrogen emissions than its imports, 50% of which is exported to Poland, figure (9).

7. 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 both oxidised sulphur and nitrogen, some of the other countries are benefited regarding one of the studied air pollutants. As such may be considered Estonia, Hungary, Slovenia as far as SO_2 is concerned and Austria and Italy for the NO_x emissions. However, all the rest of the countries analyzed have been harmed severely regarding both of the examined pollutants. Quite interesting is the case of Poland, which changes from SO_2 importer in 1993 to SO_2 exporter in 2003, while its NO_x imports are also reduced by 60% during the aforementioned period.

Transboundary transfer of pollution is a phenomenon not strictly bound to air pollution 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 and the significant degradation of the urban air quality and the historical monuments.

The analysis presented in the current paper refers to existing official data until year 2003 taking into consideration available information for almost twenty (20) years. In this context, 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 almost 20 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. It is the authors' belief that the Integrated Europe with the old, new and forthcoming member states can meet these needs sufficiently. For the near future the authors are preparing a study combining the results of the present paper with the use of the powerful RAINS model in order to assess the TAPT consequences at the economic and environmental sectors of the countries involved.

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APPLICATION OF AN AMBIENT INDEX FOR AIR QUALITY MANAGEMENT IN GREATER ATHENS AREA, GREECE

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Abstract

It is well known that atmospheric emissions of various pollutants, from stationary and mobile sources, affect air quality and public health. The impact of these emissions can be of a small (urban smog) or regional scale (tropospheric ozone, acid deposition), as a result of the transportation of pollutants in the atmosphere. The objective of this work is to adapt an ambient air quality index, for the assessment of the air quality in Greater Athens Area (GAA), Greece. For this purpose, concentration measurements of SO_2, NO_2, O_3, CO, and PM_{10} for a five-year period are used. Air quality data obtained by the Athens air pollution-monitoring network. Using a methodological framework of measuring air pollution levels and consequently by using the Air Quality Index (AQI) we focus on the analysis of the measurements on the assessment of air quality levels. Furthermore, by using the proposed framework a comparison of air quality in these five years is attempted.

Keywords: Air Quality Assessment; Public Health; Air Quality Index; Athens

1. Introduction

Air quality degradation in megacities is one of the most important problems inherited from the mid 70's. The increased industrialization and the simultaneous growth of the metropolitan areas are strongly related with the environmental problems. Since early 80's have become clear that atmospheric emissions of various pollutants affect the health of human beings and animals, damage vegetation, soils and deteriorate materials, and generally affect not only the large metropolitan areas but also the medium-size urban areas. Yet measuring environmental quality remains a difficult task as it lies at the interface of epidemiology, public health, and economics. Providing emissions or concentration information alone, is insufficient. Not only is it meaningless to the non-expert, but it also does not facilitate an easy comparison of different pollutants which might have very different impacts on population health and quality of materials.

Athens, a city of about 4 million inhabitants, faces serious air pollution problems like the vast majority of megacities worldwide. In that instance human activities play an enormous impact on its quality of life and public health. Concerning the air quality there are many sources and types such as photochemical smog, ozone and its precursors and suspended aerosol particles. The concentrations of ambient air pollutants, which prevail in GAA, are sufficiently high to cause increased frequency to the hospital admissions for cardiovascular and respiratory problems[1][2][3]. More specifically, several studies indicated that ambient air pollution correlated with children's respiratory morbidity[3][4][5][6]. In recent years, European Union's (EU) air quality standards are frequently exceeded in the GAA, especially concerning O_3 and PM_{10}[7][8][9]. These findings in combination with human health adverse effects make clear that availability of reliable environmental information is crucial.

Air is the prime resource, in addition to the land and water, for sustenance of life. Air pollution problems can be defined as the increase of the concentration of air pollutants in the ambient air, which adversely affect the human health and other exposed to these pollutants. The correct measure of air pollution is a very important parameter that qualifies the possibility of a reply to queries such as

Paliatsos A.G., Kaldellis J.K., Nastos P.T., 2007, "Application of an Ambient Index for Air Quality Management in Greater Athens Area, Greece",1st Conference on Environmental Management, Engineering, Planning and Economics (CEMEPE), June 2007,Skiathos, Greece.

whether a region is polluted or not, or how high the pollution level is. One way of assessing the air quality in an area is the use of environmental indices. The main objective of these indices is to measure air quality with respect to its effects on human health. Development of proper index and a mechanism to disseminate the index values to general public are essential for successful index system. Such an environmental index is the so-called Air Quality Index (AQI)[10]. In this way a characterization of the pollution level apart from the pollutant taken into account is obtained.

2. Materials and Methods

2.1. Area of Interest-Data

The GAA, like most metropolitan areas in the world, has significant air pollution problems. These problems are the result of high population density and the accumulation of major economic activities in this region, while the intense sunshine contributes to the high levels of photochemical air pollution especially during the summer months. The air pollution problems are often exacerbated by factors that favour the accumulation of air pollutants over the city, such as, topography (basin surrounded by mountains), narrow and deep street canyons and adverse meteorological conditions such as temperature inversions, low wind speed, high temperature, extensive periods of dryness[11].

The objective of this work is the use of AQI, as a tool, to provide information on GAA's air quality and associated health concerns for public. For this reason, the air pollution data used in the research consist of the hourly concentrations of ambient air pollutants: CO, NO_2, SO_2, O_3 and PM_{10} recorded by the network of the Greek Ministry of the Environment, Physical Planning and Public Works (MEPPPW). A detailed description of the MEPPPW network is found in relevant publication[11]. In the current work the hourly concentrations of ambient air pollutants in 7 of the MEPPPW's network stations are examined, during the 5-year period 2001-2005. The 7 stations can be classified into two categories: a) The urban station (Patission (PAT)), located close to the centre of the city of Athens and b) the peripheral stations, which are located at the north to east edge of the urban area: (Agia Paraskevi (AGP) 10km to the NE, Thrakomakedones (THR) 12km to the N, Galatsi (GAL) 3km to the NNE, Liossia (LIO) 10km to the NW, Lykovrissi (LYK) 8km to the NNE and Maroussi (MAR) 7km to the NNE of the Athens centre).

2.2. Description of air Quality Index

The AQI is a complex index and is calculated by compounding appropriately the concentrations of ozone (O_3), nitrogen dioxide (NO_2), sulphur dioxide (SO_2), carbon monoxide (CO) and particles with aerodynamic diameter less than 10 μm (PM_{10}). It converts the air pollutant concentrations into simple arithmetic values on a scale of 0 to 500. These arithmetic values correspond to various air quality categories. Intervals on the AQI scale are related to the potential health effects of the daily measured concentrations of the above mentioned air pollutants. The AQI numerical ranges of 0-50, 51-100, 101-150, 151-200, 201-300 and 301-500 are assigned verbal descriptors of “good”, “moderate”, “unhealthy for sensitive groups”, “unhealthy”, “very unhealthy” and “hazardous”, respectively. Each category corresponds to a different level of health concern[10].

Deductively, the AQI constitutes an improvement of the air pollution index PSI[12][13][14][15] and includes an additional intermediate category described as “unhealthy for sensitive groups” as well as individual index for PM_{10} concentrations[10]. In the interests of this additional intermediate category, when AQI values are between 101 and 150, members of sensitive groups may experience health effects. This means they are likely to be affected at lower levels than the general public. For example, people with lung disease are at greater risk from exposure to ozone, while people with either lung disease or heart disease are at greater risk from exposure to particle pollution. The general public is not likely to be affected when the AQI is in this range[10].

The values of the individual indices together with the corresponding concentrations of air pollutants that form them are shown in Table I. In Table I, for each pollutant the breakpoint concentrations, corresponding to each category, are not on a linear scale. Breakpoint concentrations have been defined by EPA[10] on the basis National Ambient Air Quality Standards and on the results of epidemiological studies of the effects of single air pollutant on human health[16]. Serious problem is that the evaluation of the AQI referred to a measuring site and not to a single air pollutant. In the atmosphere several air pollutants are present simultaneously and the effects on human health due to the simultaneous presence of different pollutants in the atmosphere should be considered. In the evaluation of the AQI corresponding to a measuring site, where more than one pollutant is monitored, the used procedure assumes the maximum individual index among those for the air pollutants monitored[10]. Actually, the category corresponding to the pollutants with the highest individual index value would be assumed at least as that corresponding to that location. Triantafyllou et al.[17] gave a detailed description of the developed AQI.

Table I: Breakpoints for the AQI individual indices[10]

Index value	O_3 8 hr μgr/m^3	O_3 (*) 1 hr μgr/m^3	PM_{10} 24 hr μgr/m^3	SO_2 24 hr μgr/m^3	CO 8 hr mgr/m^3	NO_2 1 hr μgr/m^3
0-50	0-125	-	0-54	0-89	0-4.4	(**)
51-100	126-165	-	55-154	90-377	4.5-9.4	(**)
101-150	166-204	245-322	155-254	378-586	9.5-12.4	(**)
151-200	205-244	323-400	255-354	587-815	12.5-15.4	(**)
201-300	245-735	401-794	355-424	816-1580	15.5-30.4	1225-2350
301-500	(***)	795-1186	425-604	1581-2628	30.5-50.4	2351-3837

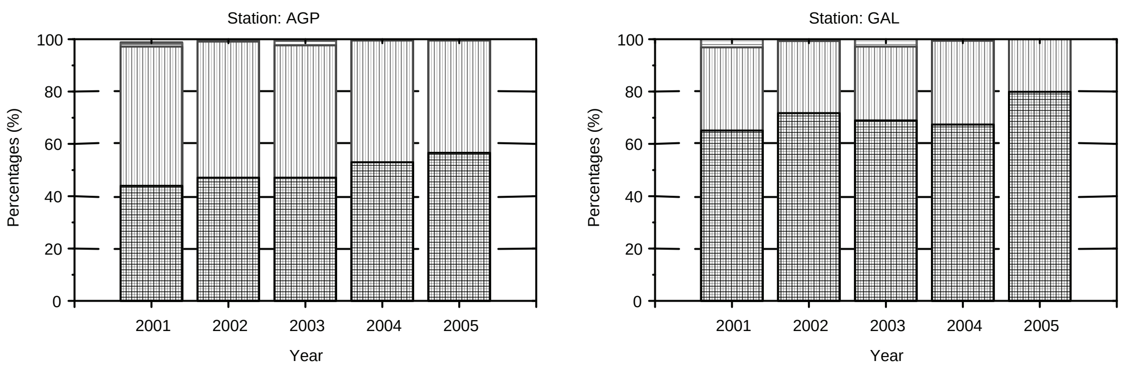
(*) The AQI for ozone is based on the 8-hr average ozone concentrations. However, there are some regions where an AQI based on 1-hr ozone concentrations may be more helpful.

(**) Due to the absence of national standards for NO_2 concentration levels, the determination of AQI is only allowed for values greater than 200.

(***) When the 8-hr average ozone concentrations exceed the value of 735μgr/m^3, then the AQI determination should be based on 1-hr concentrations.

3. Results and Discussion

The AQI values are calculated for the selected 7 representative monitoring sites, located in the GAA. Figure (1) shows how the percentage of incidence of each air quality category changes during the examined period over each measuring site.



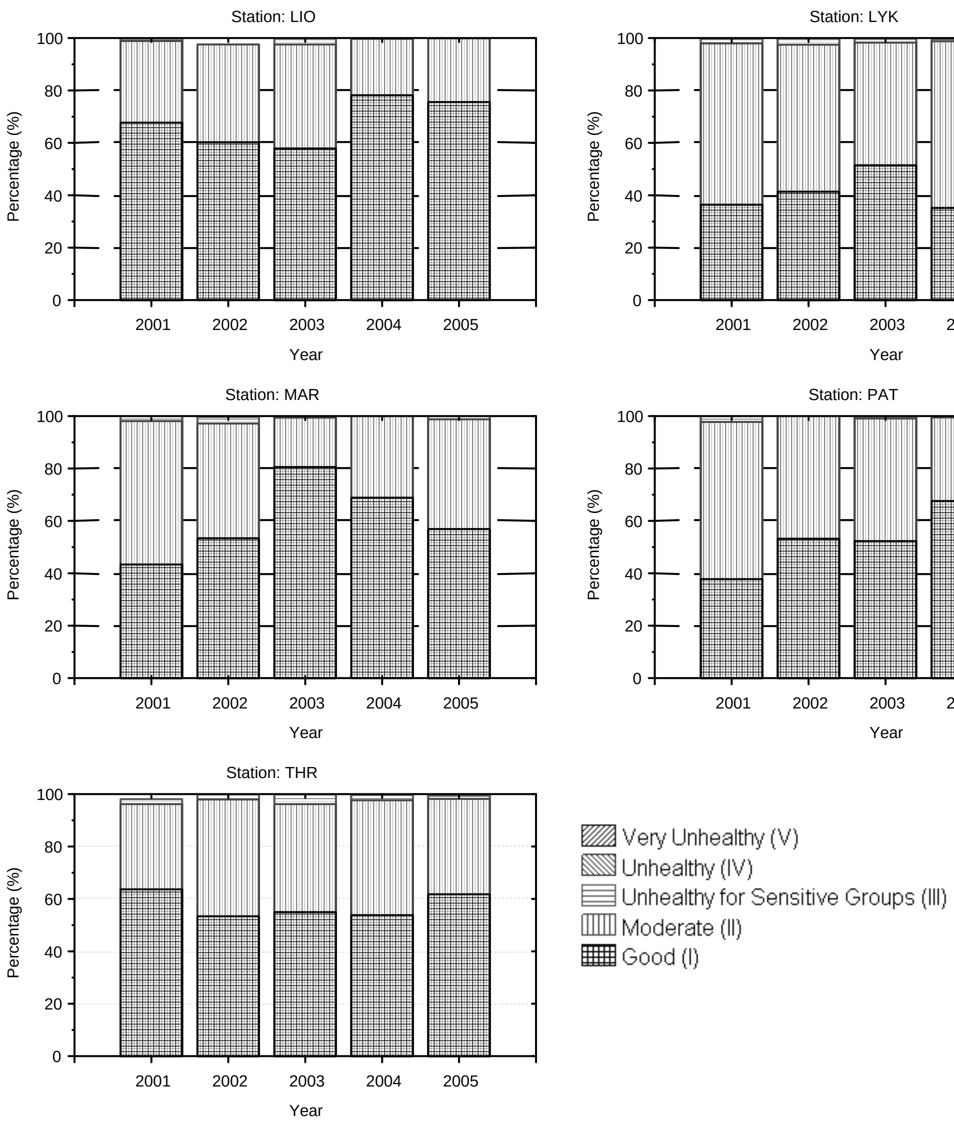


Figure 1: AQI-based percentages of air quality categories through the years over seven measuring sites in the GAA

Station AGP: The five air quality categories are observed to some percentage. Air quality category I (or differently named "Good") is rather the prevailing one and its percentage is ranged between 44% and about 56%. The percentages of air quality category II ("Moderate") are ranged between 43% and 53%, while those of category III ("Unhealthy for sensitive groups") are in between 0.5% and about 2%. The percentages of air quality category IV ("Unhealthy") are ranged between 0% and 0.3%, while those of category V ("Very Unhealthy") are in between 0% and about 1%).

Station GAL: Only three air quality categories are observed to some percentage. Air quality category I ("Good") is the prevailing one and its percentage is ranged between 65% and about 80%. The percentages of air quality category II ("Moderate") are ranged between 20% and 32%, while those of category III ("Unhealthy for sensitive groups") are ranged between about 1% and 3%. During 2005 (the last year of measuring) the percentage of "Unhealthy for sensitive groups" category was reduced to 0%.

Station THR: The "Good" air quality category (Category I) is the prevailing one and its percentages ranged between 53% and 64%. The percentages of air quality category II ("Moderate") are ranged between 33% and 45%, while those of category III ("Unhealthy for sensitive groups") are ranged between 1% and 4%. The percentages of air quality category IV ("Unhealthy") are ranged between

0.3% and 2%. During the last year of measuring (2005), a 0.3% of “Hazardous” air quality category (or Category VI) was observed.

Station LIO: Only three air quality categories are observed to some percentage. Air quality category I (“Good”) is the prevailing one and its percentage is ranged between 58% and about 76%. The percentages of air quality category II (“Moderate”) are ranged between 24% and about 40%, while those of category III (“Unhealthy for sensitive groups”) are ranged between about 1% and about 3%.
Station LYK: The percentages of air quality category I (“Good”) are ranged between 35% and about 46%. The air quality category II (“Moderate”) is the prevailing one and its percentages ranged between 52% and about 64%, while those of category III (“Unhealthy for sensitive groups”) are ranged between about 1% and about 3%. During 2004 a 0.3% of air quality category IV (“Unhealthy”) was observed, but this was reduced to 0% in the next year.

Station MAR: More or less, three air quality categories are observed to some percentage. Air quality category I (“Good”) is the prevailing one and its percentage is ranged between 43% and about 81%. The percentages of air quality category II (“Moderate”) are ranged between 19% and about 55%, while those of category III (“Unhealthy for sensitive groups”) are ranged between 0.3% and 2.5%. During 2002 a 0.3% of air quality category IV (“Unhealthy”) was observed but no other air quality incidents of “Unhealthy” air quality levels appeared in the following years.

Station PAT: Only three air quality categories are observed to some percentage. Air quality category I (“Good”) is rather the prevailing one and its percentage is ranged between 38% and about 68%. The percentages of air quality category II (“Moderate”) are ranged between 32% and 60%, while those of category III (“Unhealthy for sensitive groups”) are ranged between 0.3% and about 2%.

Comparing the percentages of incidence for each one of the air quality categories over all the measuring sites through the examined 5-year period, more or less it becomes clear that there is a small increase or at least a stabilisation of the air quality category I (“Good”). A different behaviour is noticed in measuring site LYK, where there is an increase in the percentages of air quality category II (“Moderate”), while the percentages of air quality category I (“Good”) decrease.

4. Conclusions

In the present work an assessment of the air quality in the greater Athens area is attempted by the use of air quality index. Data about the air pollutants concentrations measured over this area through the years are used for the calculation of the Air Quality Index (AQI). The temporal variation of the AQI is studied and the results are analyzed in terms of air pollution daily levels in the area.

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THE CONTRIBUTION OF RENEWABLE ENERGY SOURCES ON REDUCING THE AIR POLLUTION OF GREEK ELECTRICITY GENERATION SECTOR

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Abstract

The Greek electricity generation system, mainly based on the use of local lignite and imported heavy-oil, is assumed responsible for more than one half of CO_2, for almost 80% of SO_2 and for approximately one third of NO_x national emissions. This fact, along with the considerable energy consumption increase during the last 25 years, results in serious difficulties on fulfilling the EU Directives concerning the Large Combustion Plants and the reduction of the greenhouse gas emissions for Greece. On the other hand, renewable energy resources -like hydro, wind and solar energy- used extensively for electricity production throughout the world, are practically air-pollution free on a life cycle base analysis. In this context, the objective of the present work is to quantify the pollution caused from the Greek electricity generation system as per now and that avoided with the exploitation of RES. More precisely, the present work investigates the specific air pollution emission factors related with the electricity production from fossil fuels in Greece, estimate the air pollution avoided due to the exploitation of the available hydro and wind potential on annual basis since 1990 and the corresponding potential contribution of the renewable energy sources on significantly reducing the above mentioned pollutants. The results of the work indicate that the renewable energy sources may, in the near future, contribute significantly on minimizing the environmental impacts of the electricity generation sector, including the emissions of carbon dioxide and other various harmful gases, at rational investment cost.

Keywords: Carbon Dioxide; Sulphur Oxides; Nitrogen Oxides; Greenhouse Gas Emissions; Wind Energy; Hydropower; Oil Imports; Investment

1. Introduction

The Greek electricity generation sector is based -as far back as the early 60's- on the usage of local lignite and imported heavy oil. In fact, the mainland's electrical grid is mainly supported by 15 major thermal power stations rated at 8200 MW. More specifically, the existing electricity generation units are mainly based on the local lignite reserves -eight (8) power stations with 5300 MW of installed capacity- while the corresponding capacity share for the oil and natural gas along with the operating combined cycle stations reaches 2900 MW[1][2]. The second sub-sector includes the non-interconnected Aegean Archipelago islands, where the approximately 250 thermal power units[3] comprise 13 Autonomous and 19 Local Power Stations on top of the Crete island autonomous power network[4], all operating on the basis of imported amounts of diesel and heavy oil. In the interconnected electrical system one may also find fifteen (15) large hydropower stations in conjunction with several (100) other small ones with total capacity 3100MW[5]. Apart from the hydro power units, additional RES contribution derives mainly from the existing wind parks, installed power 750 MW[6][7].

In figure (1), one may first configure the increasing rate of national electricity consumption demand during the time period examined, as well as the dominant share of fossil fuels (up to 90%) in the local electricity generation fuel mix. Accordingly, the electrical demand time evolution described by a mean annual increase rate of 4.0%, well represents the last 25 years under study. The corresponding percentage for the coming decade is estimated at an annual increase between 3% and 4% since the authors expect an average value of 3.5%.

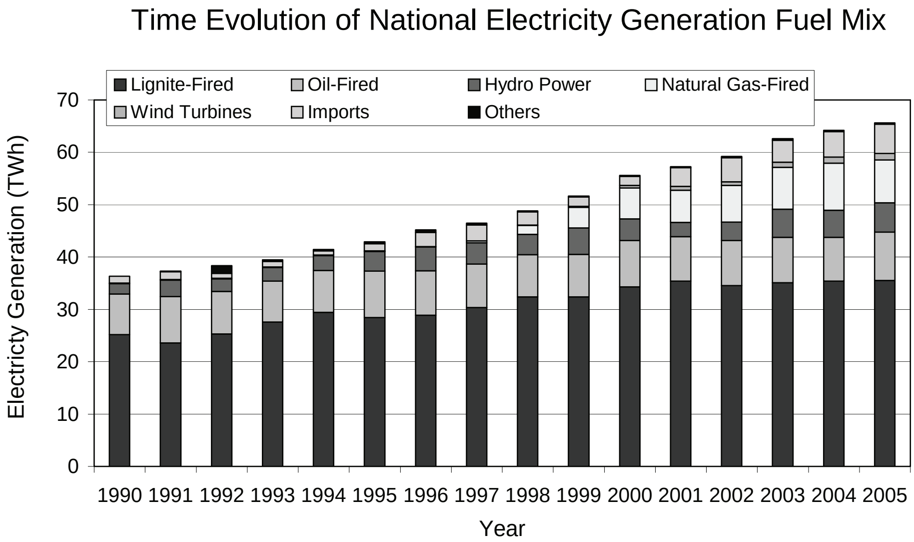

Figure 1: Greek electricity generation fuel mix time evolution

Taking into consideration the significant contribution of lignite and oil in the local electricity generation, the electricity production process is assumed responsible for more than one half of CO_2, for almost 80% of SO_2 and for approximately one third of NO_x national emissions[8][9][10]. More specifically, the above mentioned fossil fuels utilization is accused (see figures (2) and (3)) of serious environmental damage caused by air emissions (i.e over 55 Mtons of CO_2 and approximately 360 ktons of SO_2 and 75 ktons of NO_x annually), water and land resources use, water discharges and solid waste generation.

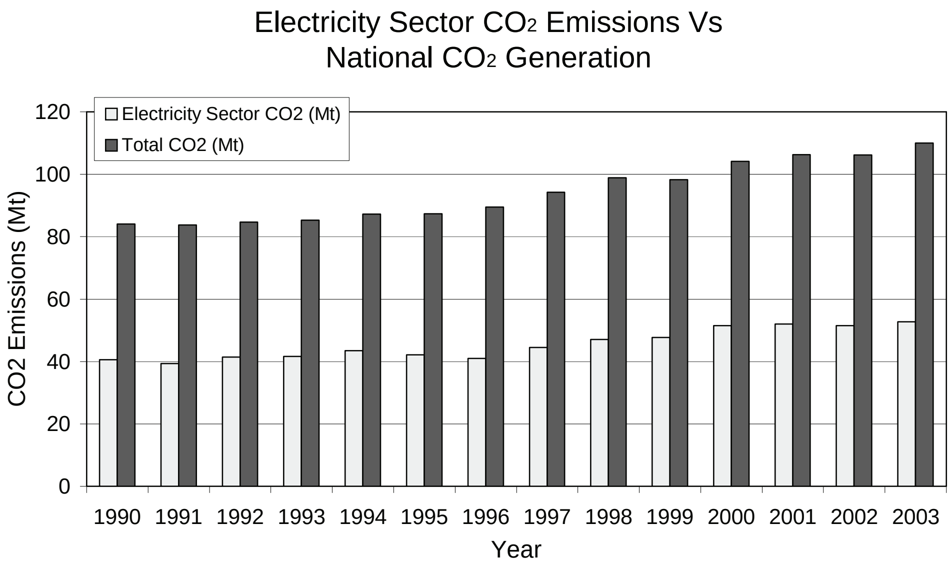

Figure 2: Contribution of electricity sector in the national CO_2 emissions

Taking also into consideration that during the last 25 years considerable energy consumption increase has taken place in view of the local economy development and standard of living improvement, Greece faces serious difficulties on fulfilling the EU Directives concerning the reduction of the greenhouse gas emissions and the protection of the local population from the dangerous toxic effects of various harmful gases and particles release, like nitrogen oxides, sulphur dioxide etc., e.g. the commitment of the local electricity generation sector to accomplish the Large Combustion Plants Directive (2001/80/EC). Additionally, the +25% CO_2 emissions' target set for the period 2008-2012, always with regards to the 1990 levels, is currently expected to finally reach the levels of 40% during the remaining time, figure (4).

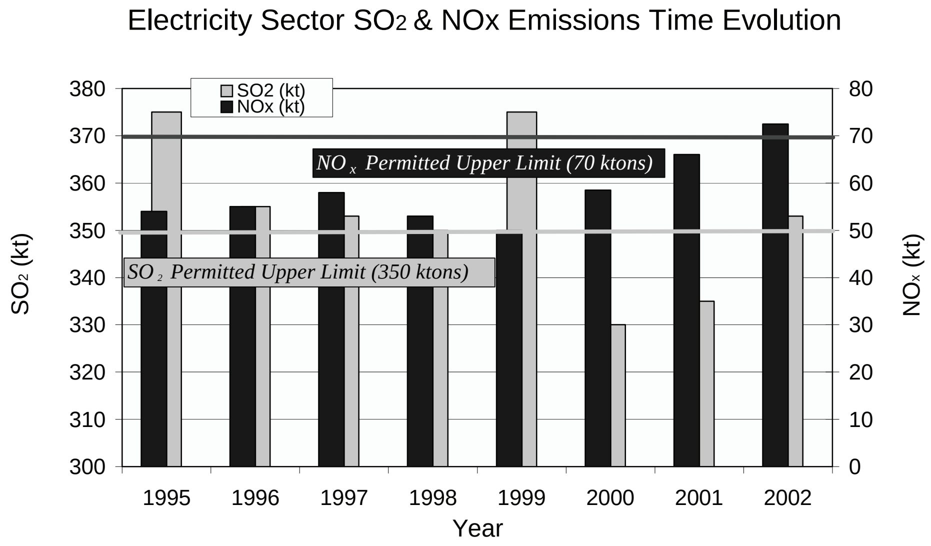

Figure 3: Electricity sector SO_2 and NO_x emissions time-evolution

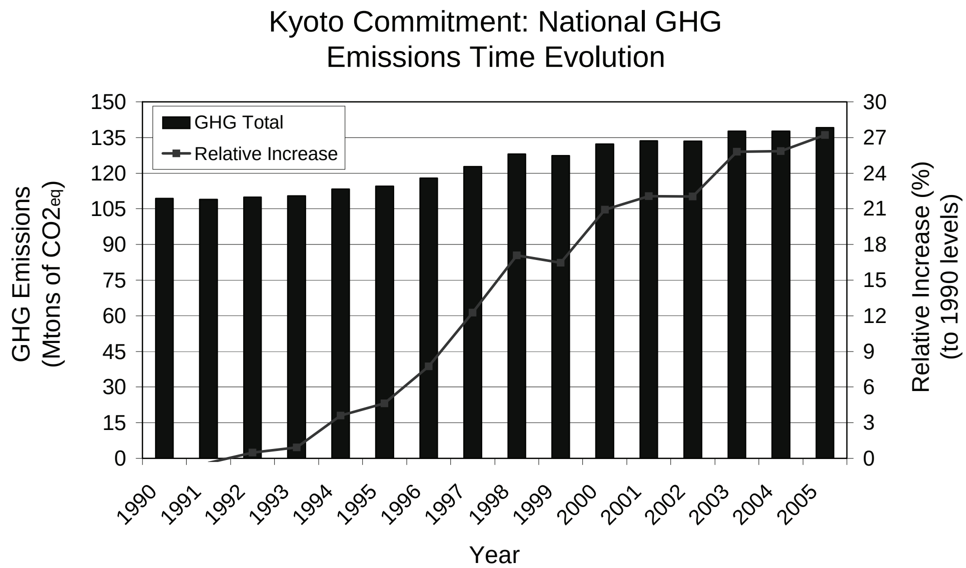

Figure 4: National GHG emissions time-evolution

On the other hand, renewable energy resources -like hydro, wind and solar energy- used extensively for electricity production throughout the world, are practically air-pollution free on a life cycle base analysis. In this context, the present work investigates first the specific air pollution emission factors related with the electricity production from fossil fuels in Greece. Next, the air pollution avoided due to the exploitation of the available hydro and wind potential is predicted on an annual basis for the last fifteen years. Finally, the potential contribution of the renewable energy sources on significantly reducing the above mentioned pollutants is estimated on the basis of the corresponding EU targets included in the relevant EU-Directives (e.g. 2001/77/EC). Finally, a macroeconomic cost-benefit analysis concerning the remarkable RES contribution in the local electricity balance, substituting imported oil, is carried out.

2. Emission Coefficients Related to Electricity Generation

One of the main inputs of the present study is the estimation of the specific air pollution emission factors related with the electricity production from fossil fuels in Greece. The analysis is based on recent long-term official data concerning the operation of the existing thermal power stations.

In order to get a clear-cut picture of the electricity related air pollution burden on every consumer, an attempt is made to express the main flue gases (CO_2, SO_2 and NO_x) production as a function of the amount of electrical energy reaching the consumers, i.e. electricity delivered to the consumption. The present analysis includes the total efficiency of the corresponding thermal power stations and line transmission losses (1%-5%) from the power stations to the main consumption centers. Thus, the coefficients given are expressed in gr (or kg) of air pollutant released per kWh consumed. For this purpose one may use measurements concerning the annual flue gas emissions of every thermal power unit of Greek electricity generation system along with the corresponding net electricity generation, modified in order to estimate energy line transmission losses. In this context, the CO_2, SO_2 and NO_x emissions factors (e_{CO2}, e_{SO2}, e_{NOx}) of the entire fossil fuel based electricity generation in Greece are defined as:

$$e_{CO_2} = \frac{(m_{CO_2})}{E_{ff}} \quad (1)$$

$$e_{SO_2} = \frac{(m_{SO_2})}{E_{ff}} \quad (2)$$

$$e_{NOx} = \frac{(m_{NOx})}{E_{ff}} \quad (3)$$

where "m_{CO2}, m_{SO2} and m_{NOx}" are the annual mass (equivalent) production of the above mentioned air pollutants and "E_{ff}" is the annual energy yield of the local thermal power stations, including line transmission losses. For the accurate estimation of the corresponding numerical values, the statistically weighted average values based on detailed previous work by the authors[8][9][10] are taken into consideration. Actually, one may use the corresponding emission factors for every Greek thermal power station for a ten-years time period investigated.

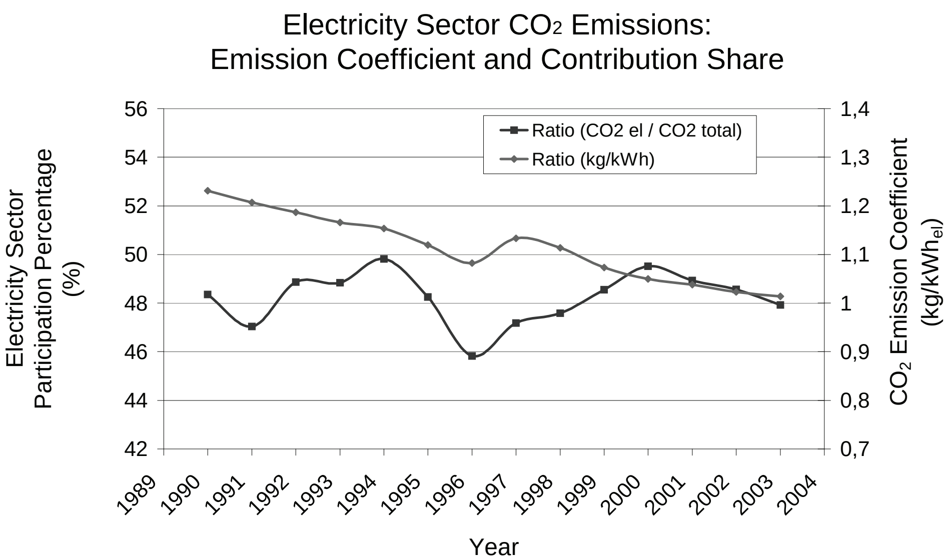

Figure 5: Electricity generation CO_2 emission factors

The present analysis results are summarized in figures (5) and (6), where one may find the time-evolution of the (e_{CO2}, e_{SO2}, e_{NOx}) emission factors. Using official data for the last fifteen years it is concluded that the CO_2 emission factor presents a steady gradual decrease from 1.23kgr/kWh$_e$ to 1.03kgr/kWh$_e$, mainly due to the substitution of local lignite by imported natural gas. Similarly, the SO_2 emission factor time-evolution shows initially a slight decrease, while after 2000 the corresponding value is stabilized around 6.5gr/kWh$_e$. This is also the case for NO_x emission factor time-evolution, where an average value of 1.5gr/kWh$_e$ is encountered.

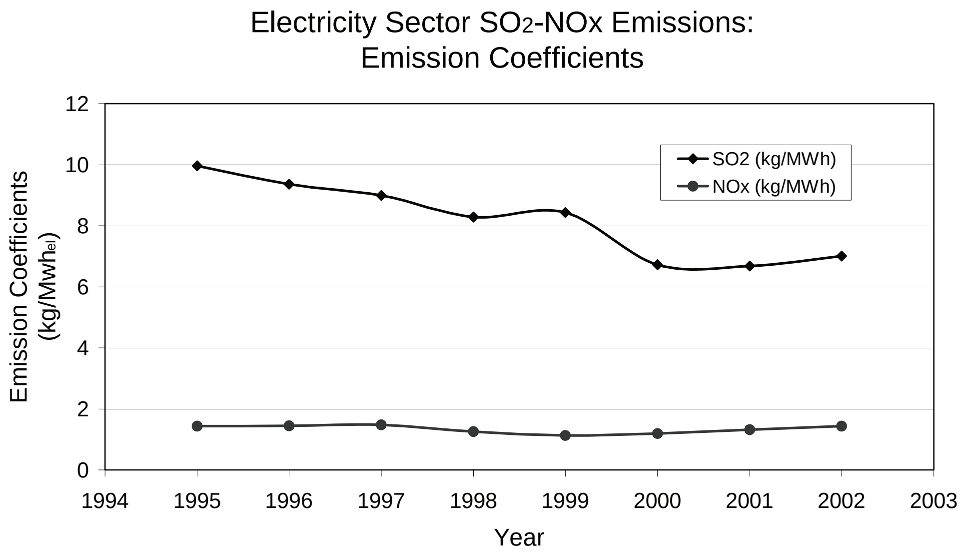

Figure 6: Electricity generation SO_2 and NO_x emission factors

In order to present a fair comparison, one should also take into consideration the corresponding emission factors, resulting from the existence of hydro power stations and wind parks. Since the operation of these power stations is air pollutants free, their main air pollution impact (on the basis of an LCA) comes from the equipment construction and the erection and decommissioning of the relative power stations[11][12][13][14]. Using available data from the international literature one may use the values suggested in Table I. As it is obvious from the data available, the hydro and wind related emission factors are really very small justifying their omission during a first approximation analysis.

Table I: Air Pollution Emission Coefficients from Hydropower stations and Wind Parks[25][26][27][28]

Study	CO_2 (gr/kWh$_e$)		SO_2 (gr/kWh$_e$)		NO_x (gr/kWh$_e$)	
	Wind	Hydro	Wind	Hydro	Wind	Hydro
E.U. (The facts)	7	4	0.087	-	0.036	-
Externe Project	8.2	-	0.079	-	0.032	-
An overview of wind energy status	10-17	7-8	0.01-0.032	0.018-0.021	0.014-0.043	0.034-0.040
Life-cycle assessment in the renewable energy sector	6.1	4.6	0.033	0.006	0.031	0.037

3. RES Contribution on Reducing Air Pollution

Renewable energy resources -like hydro, wind and solar energy- are used extensively for electricity production throughout the world, due to their limited environmental impacts[15][16][17][18][19]. In this context, the air pollution avoided due to the exploitation of the available hydro and wind potential in Greece is predicted on an annual basis for the last fifteen years.

In Greece, up today, exist fifteen (15) large hydro power (LHP) stations of total capacity of 2950MW and almost one hundred (100) small hydro power (SHP) stations, total rated power 120MW[5]. According to the official data concerning the energy yield of the existing hydro power stations considerable 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 (7), is 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.

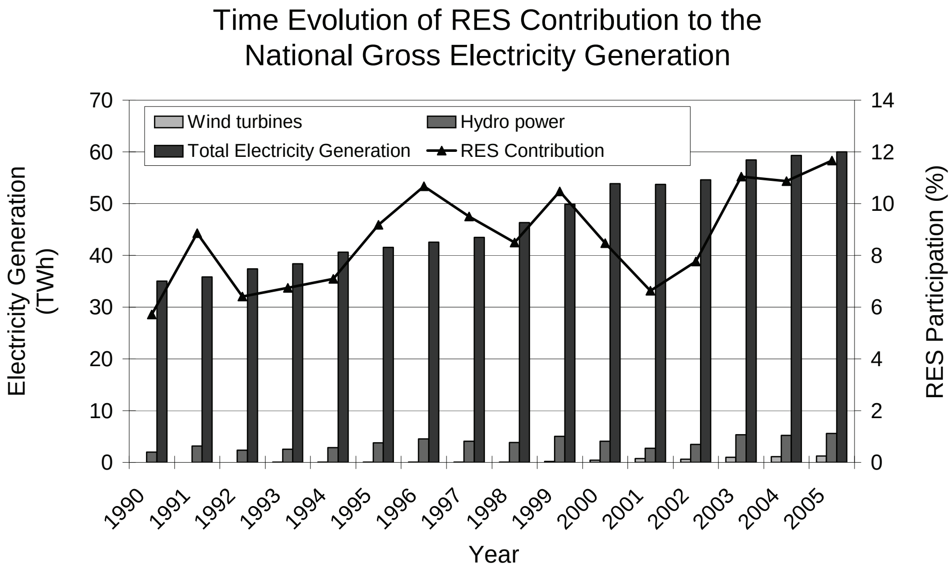

Figure 7: RES contribution to the national electricity generation

Additionally, according to the existing official data (end of 2006) in Greece, there exist approximately 1050 commercial wind turbines, while their corresponding rated power is 750MW. It is important to mention that the Greek wind energy programme[20] started in 1982, when the Greek PPC installed the first wind turbines 5x20kW (M.A.N.) on a research wind park on the island of Kythnos. Since then, wind energy applications showed a very unsteady development history and only after 2000 wind energy started to remarkably contribute to the national electricity consumption. Since then, the new wind parks erection is encouraging; however the entire wind parks contribution is hardly 2% of the national electricity consumption, figure (7).

Thus, using the official data, see also figures (1) and (7) the average annual contribution of existing RES-based power stations, mainly large hydro and recently wind parks, in the local electricity consumption is approximately 10%, while in specific years hardly surpasses the 12%.

However, even this moderate contribution saves annually (e.g. 2005) almost 10Mt of CO_2, 30kt of SO_2 and 7kt of NO_x, on top of all the other environmental benefits related with the replacement of fossil fuels by the exploitation of the available renewable potential. In fact, one may find in figures (8a) and (8b) the estimated annual air pollution avoided distribution during the last fifteen years time period. For practical purposes one may assume that the operation of the RES-based power stations does not replace a specific type of thermal power stations, hence the results obtained are representative of the national fuel mix.

Additionally, in order to fulfill the 2010 targets dictated by the corresponding E.U. directives and the approved international agreements (e.g. Kyoto protocol) the installation of approximately 7GW of cumulative RES power (mainly supported by wind energy and small hydro units, ex-works cost (Pr_{WT}=) 600€/kW and (Pr_{SH}=) 1100€/kW respectively), is required. The corresponding annual increase of the RES share (base year 2005) in the national electricity generation should approach the 10%, a very ambitious value not expected to be accomplished. In any case, in the next section one should estimate the expected air pollution reduction as well as the corresponding capital required.

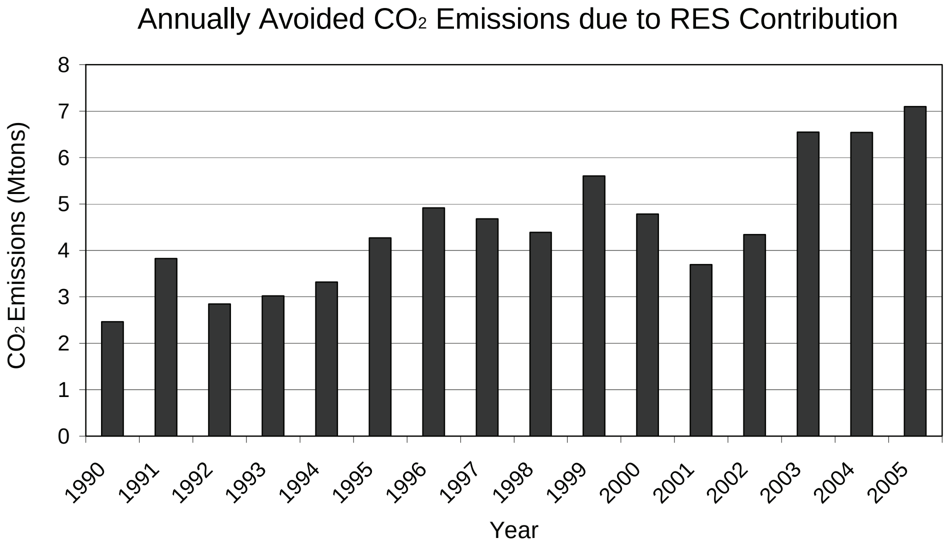

Figure 8a: CO_2 emissions avoided due to the RES electricity generation

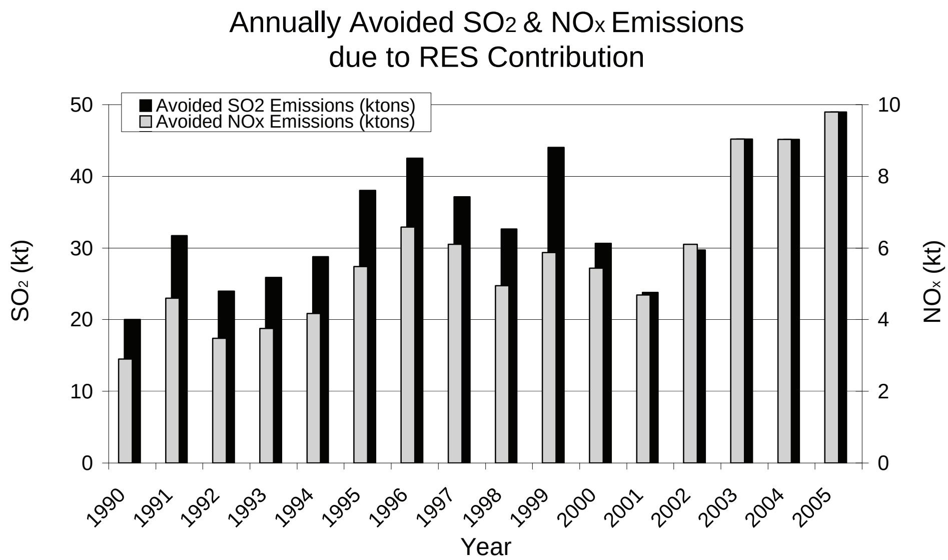

Figure 8b: SO_2, NO_x emissions avoided due to the RES electricity generation

4. Evaluation of Increased RES Penetration Strategies

In order for the 2010 national target to be achieved (20.1% of gross electricity generation covered by RES) various scenarios and strategies concerning the future RES penetration are evaluated on the basis of air pollution reduction, investment requirements and exchange losses avoided. More specifically, the implementation of the basic scenario proposed by Greek State[21] requires the installation (figure (9)) of (N_{WT}=) 3000MW of wind parks, (N_{SH}=) 200MW small and (N_{LH}=) 150MW large hydro as well as some MWs of biomass powered thermal power stations and photovoltaic parks. In this context the initial capital required "IC_{tot}" is expressed by the following relation, i.e.:

$$IC_{tot} = N_{WT} \cdot \Pr_{WT} \cdot (1 + f_{WT}) + N_{SH} \cdot \Pr_{SH} \cdot (1 + f_{SH}) + N_{LH} \cdot \Pr_{LH} \cdot (1 + f_{LH}) + N_{oth} \cdot \Pr_{oth} \cdot (1 + f_{oth}) \quad (4)$$

where "f" expresses (f≈15-30%) the first installation cost coefficient[5][7] and the subscripts "WT", "SH" "LH" and "oth" are used for wind turbines, small and large hydro and other RES-based power stations, respectively. The corresponding total investment required is approximately 3.5 billion euros, or equivalently 700-1000 (M€) million euros per year. Note that although the majority of the equipment required is imported, a remarkable (≈30%) part of the initial capital invested is absorbed by the local economy, contributing thus to an increase of the national GDP.

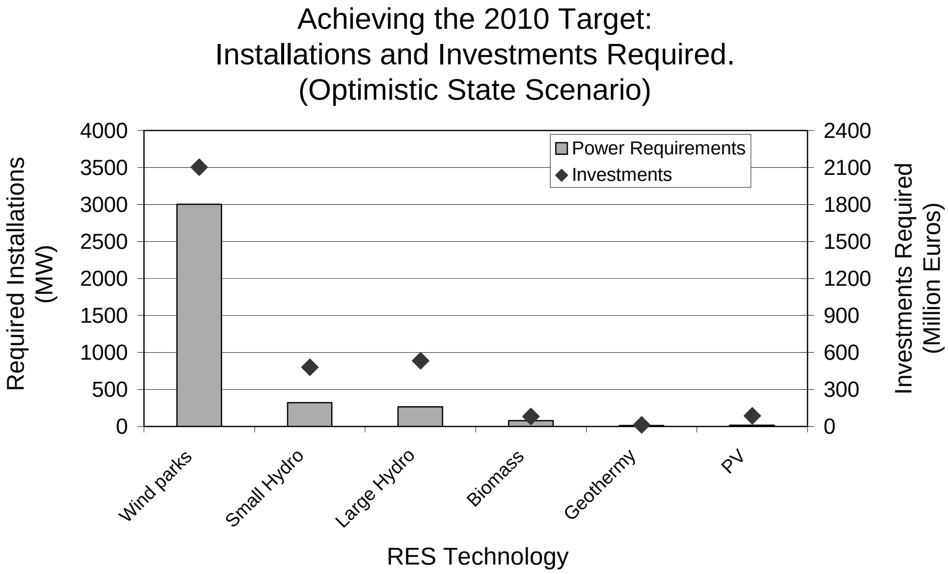

Figure 9: RES-based power stations required to achieve the 2010 E.U. target for Greece

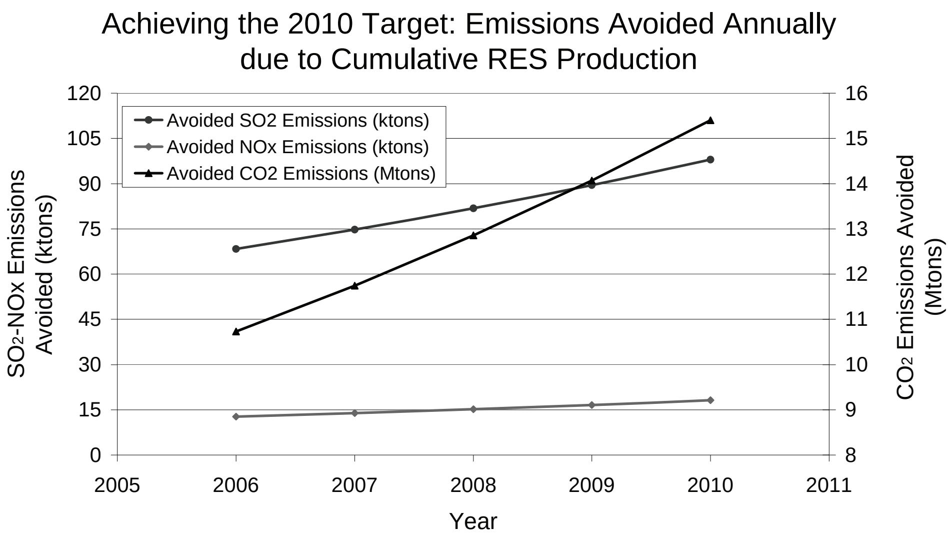

Figure 10: Expected annual emissions avoided up to 2010 due to RES utilization

In case that the above mentioned (State supported) scenario is realized, one may also estimate, using the analysis of Section 3, the corresponding emissions avoided. In fact, in figure (10) one may find the annual emissions avoided due to the new and the already operating RES-based power stations for every year between 2006 and 2010. According to the calculation results the enhanced RES participation is expected to save for example during 2010 more than 15.5Mtn of CO_2 (see also figure (8a)) and almost 100ktn and 18ktn of SO_2 and NO_x (see also figure (8b)) respectively, contributing on the reduction of the above mentioned electricity generation air pollutants of the order of 2% per annum. On the basis of the proposed scenario, the quantity of avoided air pollutants by the end of 2010 represents almost the 25% of the corresponding air pollutants quantities, contributing significantly in the compliance with the national Kyoto commitments and the Large Combustion Plants Directive (2001/80/EC).

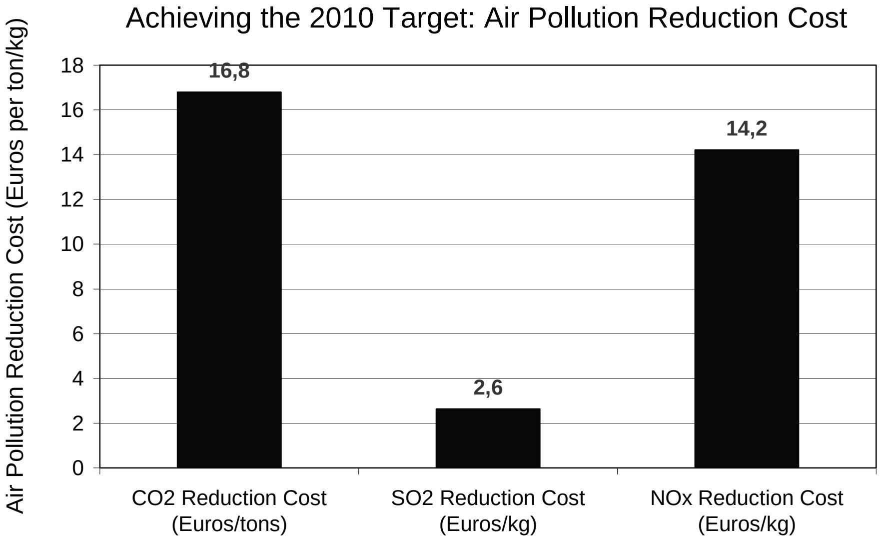

Figure 11: Annual emissions avoided cost analysis

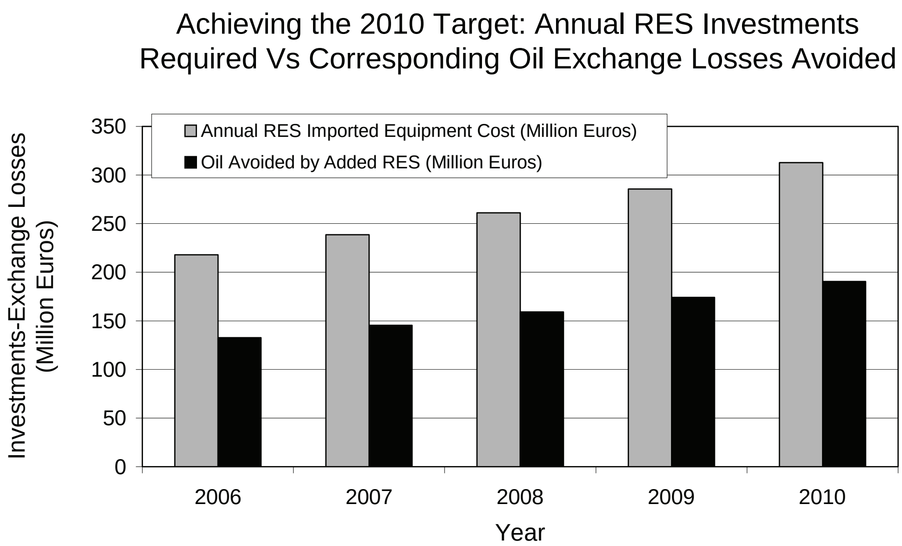

Figure 12: Comparing the macroeconomic data related with the expected RES penetration (assumed oil price 65€/bbl)

Taking into consideration the initial capital required and the air pollution avoided due to the implementation of RES-based power stations, the corresponding air pollution reduction cost (figure (11)) varies between 2.8€/kg of SO_2 up to 14.2€/kg of NO_x avoided. Also for every tone of CO_2 not released to the environment the corresponding cost is almost 17€/tn. On the other hand, emphasis should be laid on the European Union Emission Trading Scheme implying serious financial surcharge in case of increased CO_2 emissions. Actually, this damage is strongly depended on the rather unstable allowances price of CO_2 emissions even crashing down to 0.13€/t during June 2007, having peaked at 30€/t a year before. Nevertheless, estimations and forecasts[22] concerning the future CO_2 allowance price converge at a range of 20€/t -30€/t up to the year 2012. In this context, one may also mention that the price to pay for avoiding 1 tonne of CO_2 emitted by a conventional thermal power station (such as combined cycle units operating on natural gas) with mechanisms for capturing CO_2 is suggesting a cost of 25-40€/t of CO_2 avoided. Any case given, to both considerably and economically efficiently reduce the air pollution levels, a large scale integration of RES is necessary[23][24].

On the other hand one should not disregard the annual exchange loss avoided, in case that the new RES-based power stations substitute oil-fired or natural gas based thermal power stations, figure (12). As it is obvious, the money spent to import the necessary equipment is less than the macroeconomic cost resulting from the corresponding oil-imports during two successive years, while the service period of these RES-based power stations exceeds the twenty (20) years. Note also that the above mentioned power stations have also limited maintenance and operational cost[5][7], which is less than 2% of the initial capital invested on annual basis. On top of this, the imported energy exchange loss is strongly depending on the unstable and continuous increasing prices of oil and natural gas in the international market.

5. Conclusions

The interaction between the main air pollution (CO_2, SO_2 and NO_x) emission factors caused by the fossil fuels based electricity generation and the amount of electrical energy reaching the consumers, i.e. electricity delivered to the consumption, has been modelled in the present work. In addition, the annual air pollution avoided with the use of RES during the last fifteen years time period has been estimated.

Accordingly, the air pollution reduction, due to the expected faster penetration of the renewable energy sources in the local electricity market, on the basis of the national Kyoto commitments and the Large Combustion Plants Directive is estimated. Finally, the investment cost for the penetration of RES in the Greek energy system has been calculated for the selected percentages of RES contribution and the resulting values have been used to estimate the corresponding specific cost (€/kg) of the avoided air pollutants.

According to the results obtained, despite the up to now fair participation of the existing hydro power stations and wind parks on reducing the air pollutants, the renewable energy sources may, in the near future, contribute significantly on minimizing the environmental impacts of the electricity generation sector, including the emissions of carbon dioxide and other various harmful gases, at rational investment cost.

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PART FIVE

ENVIRONMENTAL ISSUES

Macroeconomic and Environmental Impacts of Wind Energy Applications in Greece. The Public Opinion

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Abstract

During the last decade, wind energy has been the fastest growing energy sector for electricity production in various European countries. In previous studies extended public opinion surveys highlight a remarkable negative public attitude of local people against wind power stations, based on visual and noise impact. However, in most areas analyzed the general public attitude is in favour of new wind parks. The present work analyzes the social impact of existing wind parks on the nearby communities according to the opinion of the people living in their proximity. According to the data analyzed, there is a serious contradiction between the general belief of positive macroeconomic and environmental impacts of wind parks and the increased visual intrusion and noise pollution mentioned. This serious inconsistency may explain the firm social acceptance of wind energy applications in Greece, although in several cases an important portion of local people claims remarkable visual and noise annoyance from existing wind turbines.

Keywords: Wind Energy; Environmental Impacts; Macroeconomic Impacts; Social Attitude; Public Opinion Survey

1. Introduction

During the last decade, wind energy has been the fastest growing electricity production sector in various European countries, achieving annual expansion rates in the order of 30%[1]. In this context, the installed wind power in Greece has also been significantly increased from 40MW to 300MW during the period 1999-2002[2]. At the same period, requests for new wind parks above 11000MW exist in the Ministry of Development, so as to take advantage of the project total cost subsidization by 30% up to 50%. Unfortunately, during the last five years, the new wind parks erection has been remarkably decelerated, despite the requirements of the E.U. 2001/77/EC Directive, dictating 20.1% contribution of renewable energy sources to the national electricity consumption by 2010[3].

In excess of several technical problems, like limited local electrical network capacity and serious infrastructure problems, one of the main reasons delaying the wind energy applications in some areas, is the serious local population reaction claiming important environmental impacts[4]. In previous studies extended public opinion surveys highlight a remarkable negative public attitude of local people against wind power stations, based on visual and noise impact. However, in most areas analyzed, the general public attitude is in favour of new wind parks[5], taking into consideration the positive environmental and macroeconomic impact of wind power installations on the local societies.

Thus, the present work analyzes the social impact of existing wind parks on the nearby communities according to the opinion of the people living in their proximity. For this purpose, the last part of the public opinion survey carried out all over Greece during the last five years, concerning the local habitants' attitude towards existing wind parks is presented. The results collected are analyzed in view of the machines' general acceptability. One of the major targets of the present analysis is to explain the inconsistency encountered between the firm social acceptance of wind energy applications and the remarkable visual and noise annoyance reported[6] from existing wind turbines.

Kaldellis J.K., Kavadias K.A., 2007, *"Macroeconomic and Environmental Impacts of Wind Energy Applications in Greece. The Public Opinion", 1st Conference on Environmental Management, Engineering, Planning and Economics (CEMEPE), June 2007, Skiathos, Greece.*

2. Position of the Problem

In order to systematically investigate the public attitude towards wind energy applications in Greece, the Soft Energy Applications and Environmental Protection Laboratory of TEI Piraeus has first scheduled and subsequently conducted[7][8] a public survey in several representative Greek territories, presenting wind energy development interest. During the entire investigation, emphasis is laid on the following topics:

- ✓ The degree of public knowledge on wind energy applications
- ✓ The public awareness about the environmental and macro-economic impacts of wind energy
- ✓ The public attitude towards existing and new wind parks

For the implementation of this research one has examined the established ways of conducting similar studies. For increasing reliability and due to the country idiosyncrasy the technique based on personal named or unnamed interviews was selected. More specifically, during this survey the questionnaires were completed in the interviewer's sight, while most respondents filled in their name and phone, for confirmation purposes. It is also important to note that all the respondents were living near the existing wind parks (maximum distance 20km), they belonged to groups of various professions and educational status, while the 45% of them were men. The public response was encouraging, since almost one out of two of the persons asked answered the questions eagerly.

The last point to be arranged was the number of interviews needed to draw safe conclusions[9]. As it is obvious, the reliability of the results derived is strongly depended on the size of the approved sample used, since the outcome uncertainty is normally decreasing with the square root of the sample size[10]. Due to the geographical diversity of the study and the manpower needed, a sample number in the range of 100 to 150 questionnaires was assumed acceptable, while 50 interviews were set as the lower limit.

Table I: Demonstration of the questionnaire used (Part C) in the present public opinion survey

Question 1		**The wind converters or wind turbines:**
Possible Answers	a	protect the environment and reduce the quantity of imported oil
	b	destroy the environment
	c	consume large quantities of fuel
	d	worsen the environment but economize on energy
	e	I am not aware of their effect on the environment and the oil import
Question 2		**The wind converters or wind turbines of your territory:**
Possible Answers	a	are visually annoying
	b	have no visual impact on me
	c	are not aesthetically right
	d	I have no opinion on their aesthetic impact
	e	make the area attractive
Question 3		**The noise of the wind turbines in your territory:**
Possible Answers	a	is too loud
	b	is too annoying
	c	does not actually disturb me
	d	is covered by the surroundings
	e	is pleasantly heard, in relation to their valuable energy
Question 4		**Do you actually agree with the installation of wind turbines in your territory?**
Possible Answers	a	YES, I do
	b	NO, I don't
	c	I would agree if only I had proof of their usefulness
	d	I am not interested in this matter
	e	I have no formed opinion

For the preparation of the questionnaire a large number of scientists have collaborated, including statistics experts, sociologists and market survey experts. The questions relative to the subject investigated are summarized in (Table I), along with the possible answers. The first two introductory questions (not included in Table I) asked, guarantee that the people being interviewed are familiar with the subject examined. According to the entire sample analyzed (665 questionnaires) 96% of the people interviewed are familiar with the basic wind energy principles. Recapitulating, one may clearly state that the samples used have the necessary size to be statistically sound and credible, hence only the 4% is excluded from further analysis.

3. Results Presentation

As already mentioned, in the current analysis emphasis is set in investigating the public opinion on the macroeconomic and environmental impact of existing wind power stations in representative Greek locations. For this purpose, two specific regions have been selected, presenting a quite different attitude towards wind turbines. Hence, the first area investigated is the S. Euboea island, where in the past serious conflicts between the wind park developers and the local citizens have been encountered[11]. The sample used includes 128 respondents, while the survey was carried out during 2001-2003. The second area analysed is Chios island. Chios is a medium-sized island of the NE Aegean Sea, possessing very high wind potential. In this island, since 1991 exist several private, municipality or PPC-owned medium-sized wind parks. Local habitants' general attitude (sample of 248 interviews, survey period 2003-2004) towards wind turbines is quite different from the S. Euboea one[6].

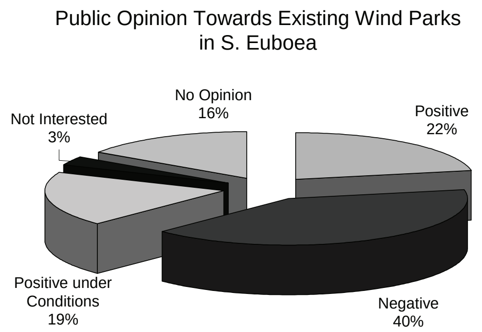

Figure 1: Public opinion towards wind parks

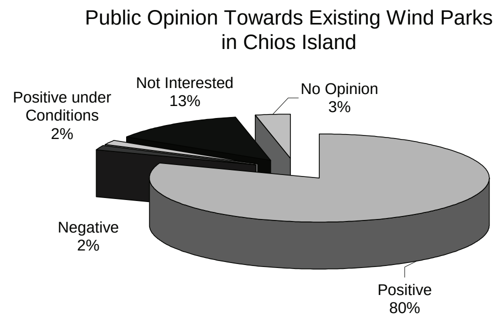

Figure 2: Public opinion towards wind parks

More precisely, there is a great diversity of the acceptability degree of existing wind parks among the windiest territories of the country. In fact, according to the results obtained for the S. Euboea case, the public opinion is actually divided, figure (1). Thus, almost 4 out of 10 (40%) of the respondents clearly disagree with the operation of the wind parks in their region, while 22% definitely accept the wind turbines in their neighborhood. An extra 19% of the habitants tolerate them under the precondition of their proved usefulness. A sound explanation of the public attitude towards wind turbines encountered in S. Euboea may be the remarkable concentration (≈120MW) of numerous large wind converters, in a relatively short time. On the contrary, in the Chios island local habitants' general attitude towards wind turbines is completely different from the S. Euboea one. More specifically, the respondents' vast majority (80%) is positive to the development of wind power stations, figure (2). Only a very small minority (2%) was expressed negatively for the existing wind converters, while another 2% supported wind farms under the precondition of proper operation.

The general social attitude of local people towards existing wind parks in S. Euboea is also supported by the answers given in the first question concerning the macroeconomic and environmental impact of the corresponding wind energy applications. As it is obvious from figure (3) almost the 50% of the respondents mention negative impact of the wind parks on the local environment. However, more than two thirds of them (34% of the total sample) accept the contribution of wind turbines on fossil fuels saving. In fact, almost seven out of ten (34%+34%) of the local habitants mention that wind energy reduces the oil imports. At the same time almost the entire sample of Chios island (figure (4)) accepts that the existing wind parks contribute on reducing oil imports and only a small minority notes that existing wind turbines worsen the environment. The opinion expressed by the Chios island habitants is in accordance with the information of figure (2), describing their general attitude towards existing wind power stations.

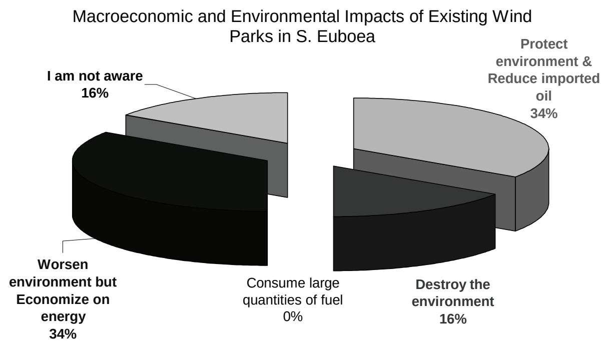

Figure 3: Macroeconomic and environmental impacts of wind parks, the public opinion

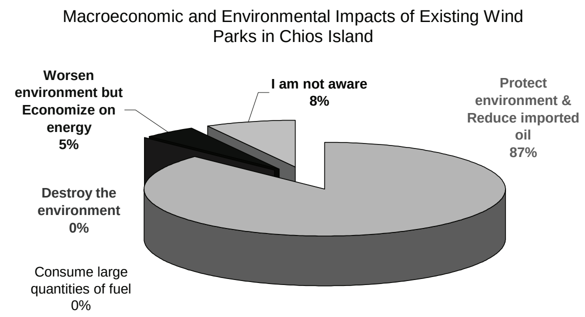

Figure 4: Macroeconomic and environmental impacts of wind parks, the public opinion

It is also worthwhile to mention that according to the results of the public survey carried out in S. Euboea the majority (46%) of the inhabitants expresses negative visual impact of wind turbines, while another 16% believe that the existing machines are not in harmony with the landscape, figure (5). On the other hand, only 6% likes the sight of these machines whereas 19% do not mention any visual intrusion. Subsequently, it is interesting to mention that the portion of the respondents supporting that the noise of the wind turbines is either too loud or too annoying is 25%, while one should not disregard that almost the 30% of the sample (figure (6)) declares that any wind turbine noise is covered by the surroundings.

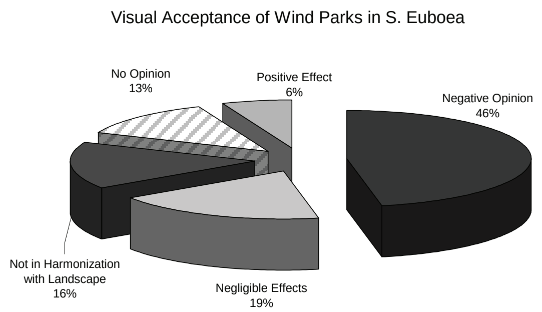

Figure 5: Wind turbines visual impact

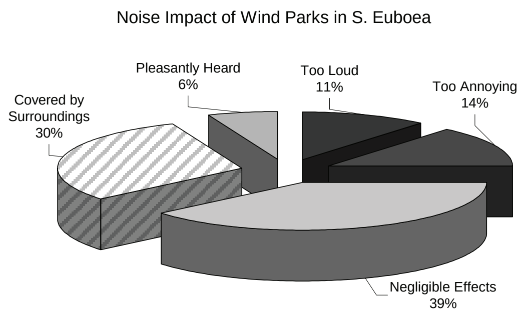

Figure 6: Wind turbines noise impact

In this context one should also take into consideration that the situation is quite different in Chios island, where the vast majority of the respondents do not point out any visual intrusion, while 3 out of 10 are fond of wind energy installations in their neighbourhood. Only 8% of the sample mentions negative visual impact of wind turbines, while another 6% declares that these machines are not in harmony with the landscape. Similarly, the vast majority (60%) is not bothered by the wind turbines' operation, while only 8% of the sample finds wind turbine noise too annoying. On the other hand, two out of ten of the respondents state that the wind parks sound emissions can be characterized as pleasant in view of their useful energy production.

4. Discussion of the Results

Wind turbines are man-made devices that produce useful electrical energy exploiting the wind potential of an area. In this context, modern wind turbines -with a hub height of 60÷100 meters and a blade length of 30÷60 meters- constitute an artificial addition on the local scenery[12]. However, in any case that man places new structures in a terrain, the character of the terrain immediately changes. Thus, it is a matter of taste -to a large extent- how people perceive that wind turbines fit into the landscape. Similarly, annoyance by wind turbines' noise emissions is also a highly psychological phenomenon. Generally speaking, no landscape is ever completely quiet, since birds, animals and human activities create sound. In fact, when the wind hits different objects at a certain speed, it will start making a sound. More precisely, during the last twenty years, serious effort has been devoted for the creation of more quiet machines, paying detailed attention to both the design of the blades to avoid boundary layer separation and to mechanical parts of the machine. As a result, noise is characterized as a minor problem for modern carefully sited wind turbines. Of course in specific cases, sound reflection or absorption from terrain and building surfaces may change the sound picture in different locations, imposing increased annoyance to local habitants.

On the other hand, a wind turbine of rated power "N_o", produces during its service life ("n"-years) considerable useful energy amounts, thus contributing on reducing the fossil fuels consumption (mainly locally extracted low quality lignite in Greek mainland and imported oil in Greek islands) as well as eliminating the emission[13][14] of several air pollutants, like CO_2, SO_2, NO_x, TSP etc.

More specifically, one may estimate the expected annual specific wind-based electricity production "E_y" per kW installed (kWh/(kW.year)) of a wind turbine using the following relation:

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

where "CF" is the capacity factor of the installation taking[15] long-term values between 25% and 35%. The corresponding specific oil quantity "M_f" (kg/(kW.year)) replaced may be estimated as:

$$M_f = \frac{E_y}{\eta . H_u} = \frac{CF \cdot 8760}{\eta . H_u} \tag{2}$$

where "η" is the efficiency of a typical thermal power plant (approximately 30%) and "H_u" the corresponding specific calorific value of the fuel used, e.g. H_u=40,000kJ/kg of diesel-oil.

Finally, the exchange loss saved from the operation of 1kW of wind power in Greece, expressed as a ratio "ε" in relation with the initial specific cost "Pr" (€/kW) of the imported equipment used, is written as:

$$\varepsilon = n \cdot \frac{c_f \cdot M_f}{\mathrm{Pr}} \tag{3}$$

where "c_f" is the specific cost of the imported oil (e.g. 50€/bbl). Recapitulating, by combining the equations (1) to (3) and using typical values for the parameters involved, "ε" takes values between 5.5 and 8.0, thus the exchange savings are between five and eight times the money spent for the purchase of the necessary machines.

On top of this, one should also take into consideration the significant air pollutants avoided "M_i" due to the operation of wind parks replacing existing thermal power stations. In fact one may write:

$$M_i = n \cdot E_y \cdot e_i \qquad (i = CO_2, SO_2, NO_x, ...) \tag{4}$$

The numerical values of the corresponding emission coefficients "e_i" may be based on the existing published[13][14] information, e.g. $e_{CO2}\approx 1kg/kWh_e$, $e_{SO2}\approx 6g/kWh_e$, $e_{NOx}\approx 4g/kWh_e$, etc. At this point one should underline the fact that in most cases the public opinion is in full accordance with the outcome of comprehensive scientific studies, explaining in this way the general positive social attitude towards wind power applications. However, in specific extreme cases increased effort and attention during the wind turbines siting would remarkably contribute on avoiding unnecessary annoyance of human societies and local ecosystems.

5. Conclusions

An extensive study is conducted concerning the public attitude towards wind energy applications, in several Greek territories possessing high wind potential and investment interest. According to the data analyzed -sample of 665 respondents in several representative Greek territories-, there is a serious contradiction between the general belief of positive macroeconomic and environmental impacts of wind parks and the increased visual intrusion and noise pollution mentioned. This serious inconsistency may explain the firm social acceptance of wind energy applications in Greece, although in several cases an important portion of local people claims remarkable visual and noise annoyance from existing wind turbines.

In authors opinion, wind industry should continue placing the same effort on reducing the environmental impacts of new wind power installations as on being techno-economic attractive, in order to increase the public acceptance of wind energy applications. In this context, local habitants, if properly informed, recognize that the gradual wind energy penetration in the local fuel-mix is going to ameliorate the existing macro-economic situation without invoking the long and short-term hazards of thermal and nuclear power stations.

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DETERMINING THE ENERGY PAY-BACK PERIOD OF PV-BATTERY STAND ALONE SYSTEMS: CASE STUDY GREECE

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Abstract

On the numerous small and medium-sized islands of the Aegean and Ionian Archipelagos one may encounter several thousands of remote consumers unable to appreciate a direct electricity utility supply. In this context, the utilization of photovoltaic driven stand alone systems instead (e.g. PV-battery system), comprises an appreciable alternative to be considered. Managing to dimension a PV-battery stand alone configuration shall ensure the coincidence of energy production and energy demand, thus improving the PV plant's electricity generation profile. Apart from the appropriate selection and dimensioning of such a system, the determination of its actual contribution in terms of sustainability is thought to be of equal concern. More precisely, in the present study, an investigation concerning the ratio of energy required during the construction, installation, maintenance and final decommissioning of such schemes to the useful energy output guaranteed on a life-cycle scale, shall reveal the real energy balance effectiveness of the configurations considered. For this purpose, combinations of commercial photovoltaic panels in collaboration with selected battery storage systems examined shall designate the most attractive of the solutions in terms of energy payback.

Keywords: Photovoltaic; Battery; Stand Alone; Energy Payback Period

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]. In fact, on the numerous small and medium-sized islands of the Aegean and Ionian Archipelagos one may encounter several thousands of remote consumers unable to appreciate a direct electricity utility supply, this often leading to the use of small diesel-generator sets, delegated to cover the electrification needs at very high cost.

On the other hand, in all these Hellenic areas the available solar potential is very high, approaching annual values of 1800kWh/m^2. In this context, the utilization of photovoltaic driven stand alone systems instead of diesel-electric generators (e.g. PV-battery system), comprises an appreciable alternative to be considered[3][4]. On top of this, increased interest has been demonstrated in the Greek region in concern to the installation and utilization of photovoltaic systems due to the recent governmental motivations, strongly subsidizing the PV-installations especially in the non-interconnected islands' area.

Managing to dimension a PV-battery stand alone configuration shall ensure the coincidence of energy production and energy demand, thus improving the PV plant's electricity generation profile. Apart from the appropriate selection and dimensioning of such a system, the determination of its actual contribution in terms of sustainability is thought to be of equal concern. For this purpose one should first determine the optimum dimensions of an appropriate stand alone photovoltaic system, able to guarantee the coverage of remote consumers energy demand located in typical Greek territories using long-term measurements[5], under the restriction of minimum initial cost[6]. Accordingly, special emphasis is laid on the detailed energy balance analysis of the selected configurations[7], since the

__Zafirakis D., Fragos P., Kavadias K.A., Kaldellis J.K., 2007,__ "Determining the Energy Pay-Back Period of PV-Battery Stand Alone Systems: Case Study Greece", 2nd International Conference "The Case of Energy Autonomy: Storing Renewable Energies", IRES-II, Eurosolar, November 2007, Bonn, Germany.

proposed methodology has the ability to investigate the energy behaviour of any stand-alone photovoltaic system on an hourly basis at least.

Finally, the primary objective of this current study, is to investigate the ratio of energy required during the construction, installation, maintenance and final decommissioning of the proposed installation to the useful energy output guaranteed on a life-cycle scale. More precisely, the proposed analysis shall reveal the real energy balance effectiveness of the configurations considered. In this context, combinations of commercial photovoltaic panels (e.g. Si-based, cadmium telluride etc.) in collaboration with selected battery storage systems examined shall designate the most attractive of the solutions in terms of energy payback.

2. Proposed Configuration

As already mentioned an autonomous photovoltaic-battery based system is one of the most interesting and environmental friendly technological solutions for the electrification of remote consumers or entire rural areas.

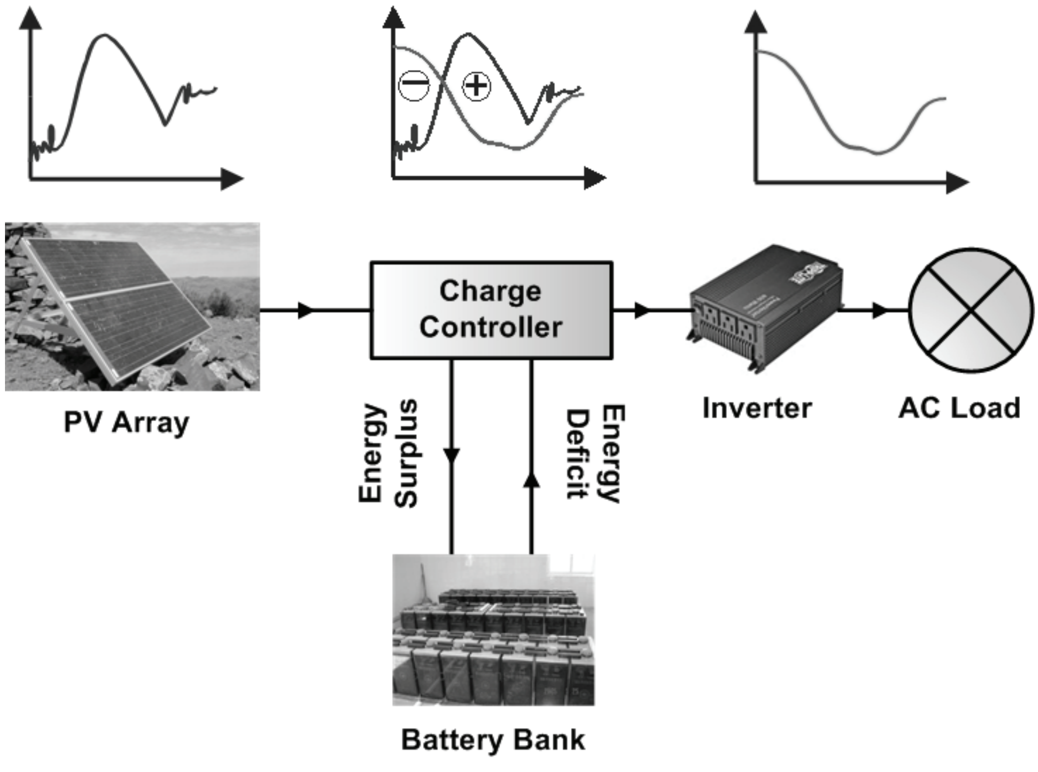


Figure 1: Typical PV Stand-Alone Configuration

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

i. A photovoltaic system of "z" panels ("N_o" maximum power of every panel) properly connected (z_1 in parallel and z_2 in series) to feed the charge controller to the voltage required
ii. A lead acid battery storage system for "h_o" hours of autonomy, or equivalently with total capacity of "Q_{max}", operation voltage "U_b" and maximum discharge capacity "Q_{min}" (or equivalently maximum depth of discharge "DOD_L")
iii. A DC/AC charge controller of "N_c" rated power, charge rate "R_{ch}" and charging voltage "U_{CC}"

iv. A DC/DC inverter of maximum power "N_p" able to meet the consumption peak load demand where "N_p" is the maximum load demand of the consumption, including a future increase margin (e.g. 30% and $N_p \leq 5kW$). For the complete simulation of the proposed system one needs, apart from the electricity demand profile (e.g. figure (2)), the solar radiation and ambient temperature at the installation site (figure (3)) as well as the operational characteristics of all the components (e.g. photovoltaic panels power curve at standard day conditions, inverter efficiency, battery bank characteristic etc.) composing the stand-alone system under investigation.

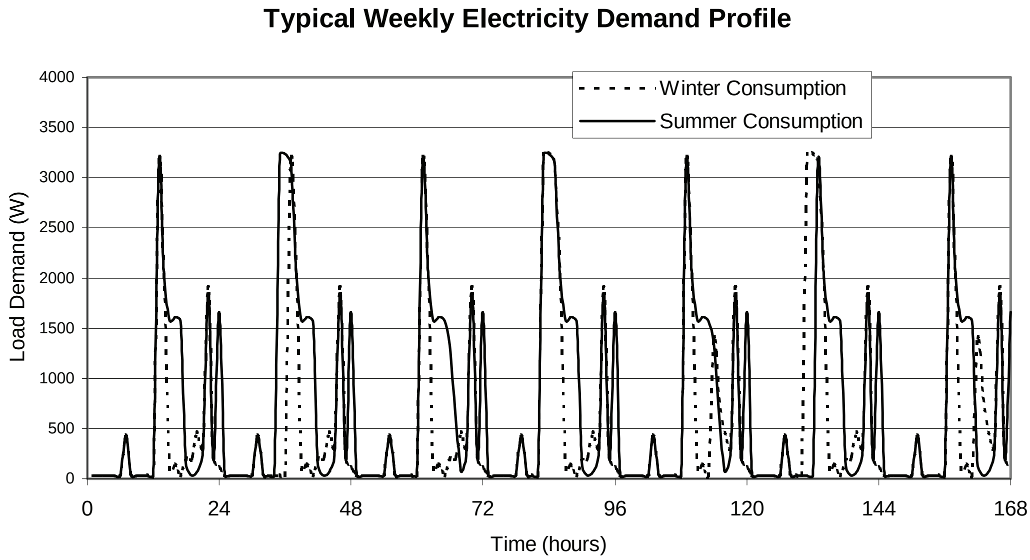


Figure 2: Typical Electricity Demand Profile of the Remote Consumer Analyzed

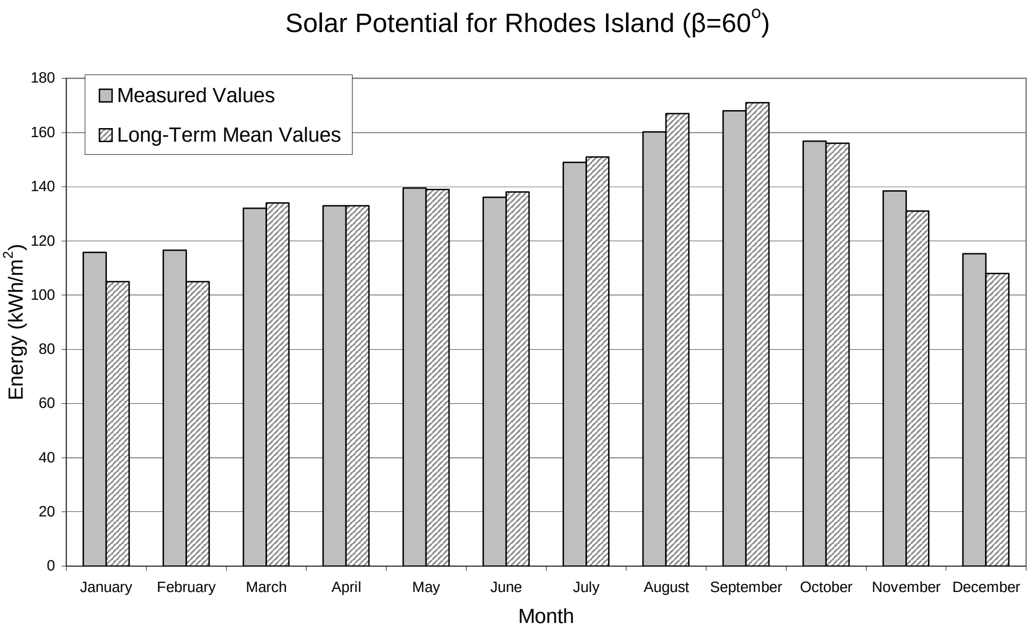
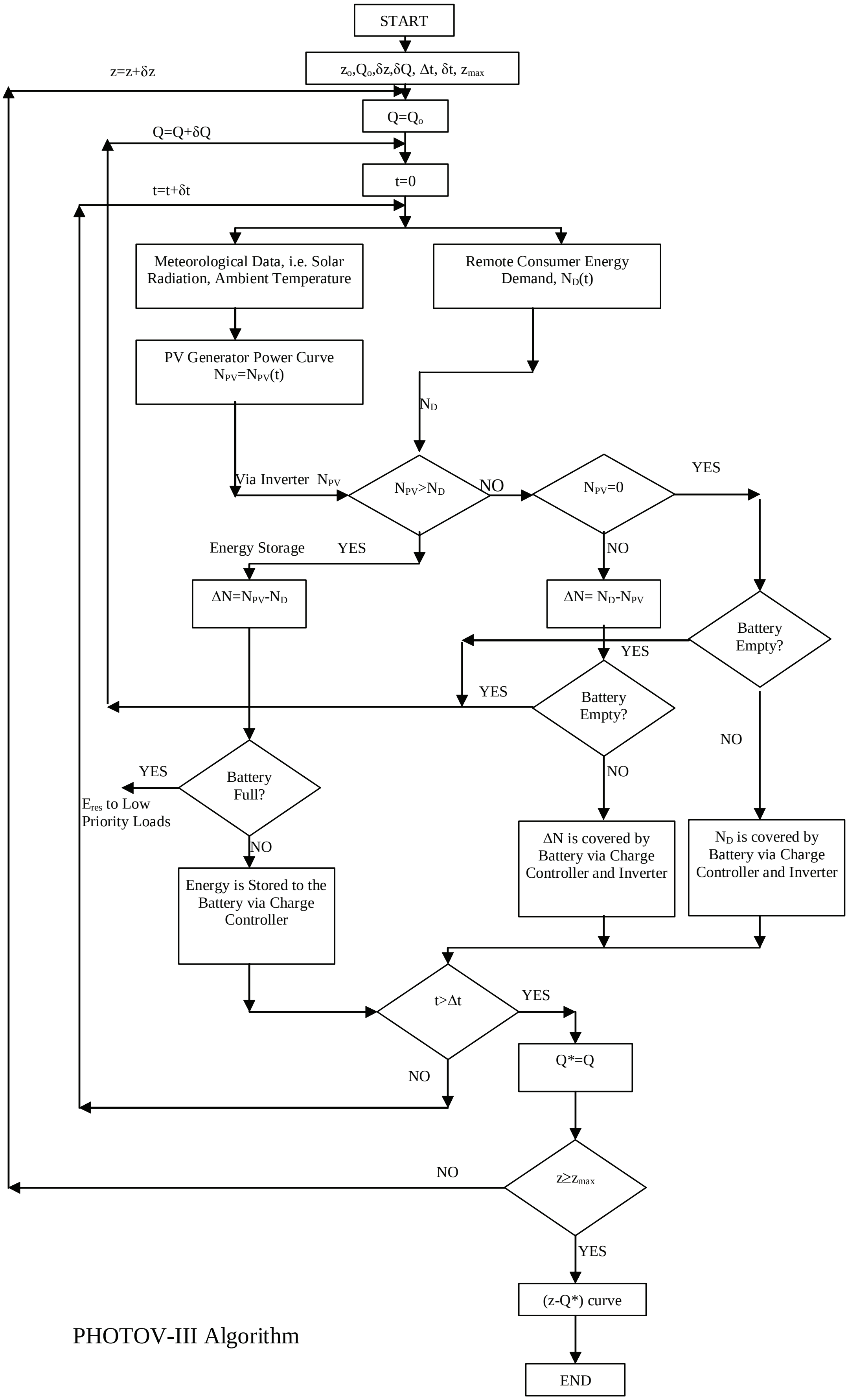


Figure 3: Measured Solar Energy Potential for Rhodes Island

As mentioned above, the first step of the present analysis is to estimate the appropriate dimensions of a stand-alone photovoltaic system (PVS) for every remote consumer examined and subsequently to evaluate the complete system energy behaviour. The two governing parameters used during the sizing procedure are the number "z" and the rated power "N_o" of each photovoltaic panel used and the battery maximum necessary capacity "Q_{max}". To confront similar problems, a computational algorithm "PHOTOV-III" is developed, figure (4). This specific numerical code is used to carry out the necessary parametrical analysis on a given time step (e.g. on an hourly) energy production-demand basis.



PHOTOV-III Algorithm

Figure 4: PHOTOV-III Algorithm

The parameters involved in the sizing procedure include the system annual electricity consumption "E_{tot}" (E_{tot}≈5MWh/year), the storage branch efficiency "η_s", used to feed the consumption (including inverter efficiency and power line loss) and the maximum permitted depth of batteries discharge "DOD_L". In the present case the battery operation voltage "U_b" is taken equal to 24Volt.

Subsequently, for each "z" and "Q_{max}" pair the "PHOTOV-III" algorithm is executed for all the time-period selected (e.g. one month, six-months, one year or more) and emphasis is laid on obtaining the desired reliability level operation. More precisely, for every time point investigated, the system energy demand is compared to the photovoltaic generator energy production, including the inverter and the power line losses. The photovoltaic generator output is defined by the solar radiation at the selected tilt angle "β", the ambient temperature and the manufacturer power curve (I-U). Thus, during the long-lasting operation of the proposed stand-alone system, the following situations may appear:

a. The power demand "N_D" is less than the power output "N_{PV}" of the photovoltaic generator, ($N_{PV}>N_D$). In this case the energy surplus ($\Delta N=N_{PV}-N_D$) is stored via the battery charge controller. If the battery is full ($Q=Q_{max}$), the residual energy is forwarded to low priority loads.

b. The power demand is greater than the photovoltaic generator power output ($N_{PV}<N_D$), which is not zero, i.e. $N_{PV}\neq 0$. In similar situations, the energy deficit ($\Delta N=N_D-N_{PV}$) is covered by the batteries via the battery charge controller and the DC/AC inverter.

c. There is no solar energy production (e.g. zero solar radiation, system not available), i.e. $N_{PV}=0$. In this case the entire energy demand is fulfilled by the battery charge controller -DC/AC inverter subsystem, under the condition that $Q>Q_{min}$.

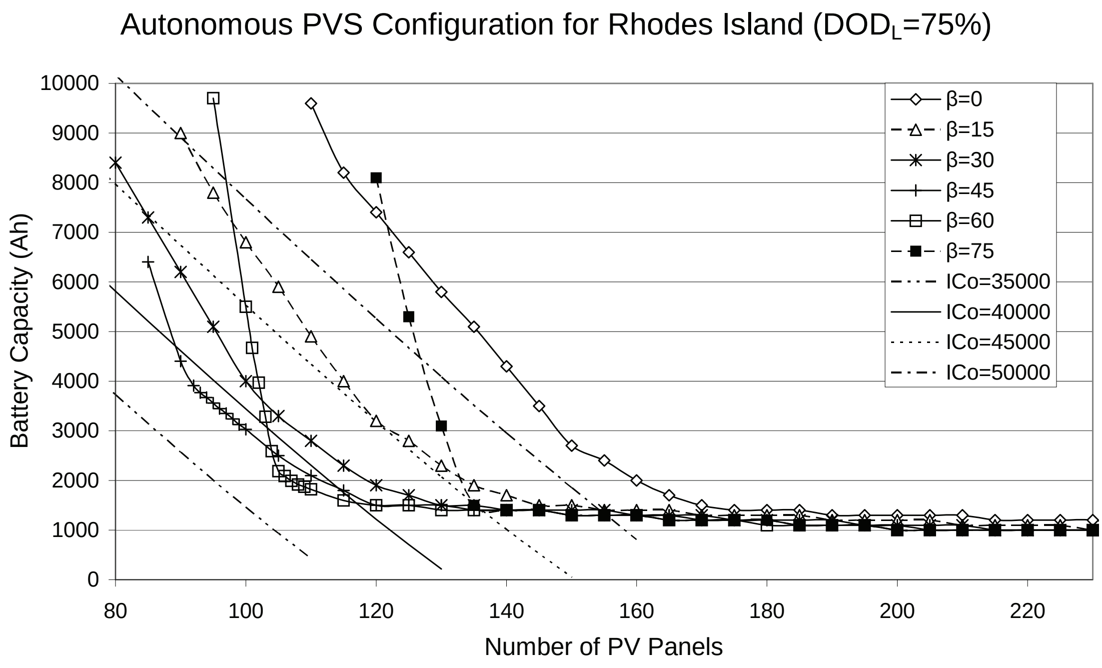


Figure 5: Optimum Autonomous PV-ESS Configuration for Rhodes Island

In cases (b) and (c) -when the battery maximum depth of discharge is exceeded- load rejection takes place, hence the battery size is increased and the calculation is re-evaluated up to the case that the desired reliability level is fulfilled for the complete time period examined. Next, the number of photovoltaic panels is increased and the calculations are repeated. Thus, after the integration of the analysis a (z-Q^*) curve is predicted (figure (5)) under a specified reliability level restriction[2][6].

Finally, for every (z-Q*) pair ensuring the energy autonomy of the remote system, a detailed energy production and demand balance is available[7] along with the corresponding time-depending battery depth of discharge, "DOD".

3. Best Configuration Choice

Using the "PHOTOV-III" numerical algorithm one may calculate the energy production of the stand-alone photovoltaic systems for a selected time period. To get an unambiguous picture, keep in mind that for every pair of (z-Q*) the stand-alone photovoltaic system is energy autonomous for the period investigated, excluding a small period of preselected "h_{max}" hours per annum. Finally, the optimum pair may be selected from every (z-Q*) curve, on the basis of the minimum first installation cost criterion, figure (5).

In this context, the initial cost "IC_o" of a photovoltaic stand-alone system includes[6] the photovoltaic modules ex works cost, the battery bank buy-cost and the cost of the major electronic devices. Finally, the BOS (balance of system) cost should also be taken into consideration, using the local market values. Recapitulating, the initial installation cost of a stand-alone photovoltaic-battery based system is a function of "z" and "Q_{max}" if "N_o" is defined. Hence, by using the initial cost data it is possible to estimate for any (z-Q*) curve the minimum initial cost solution, which guarantees a specific acceptable number "h_{max}" of hourly load rejection per annum of the remote consumer for the time-period examined. On top of this, it is important to note that the Greek State and the European Union strongly subsidize small photovoltaic systems, with the subsidization percentage "γ" varying between 40% and 70%.

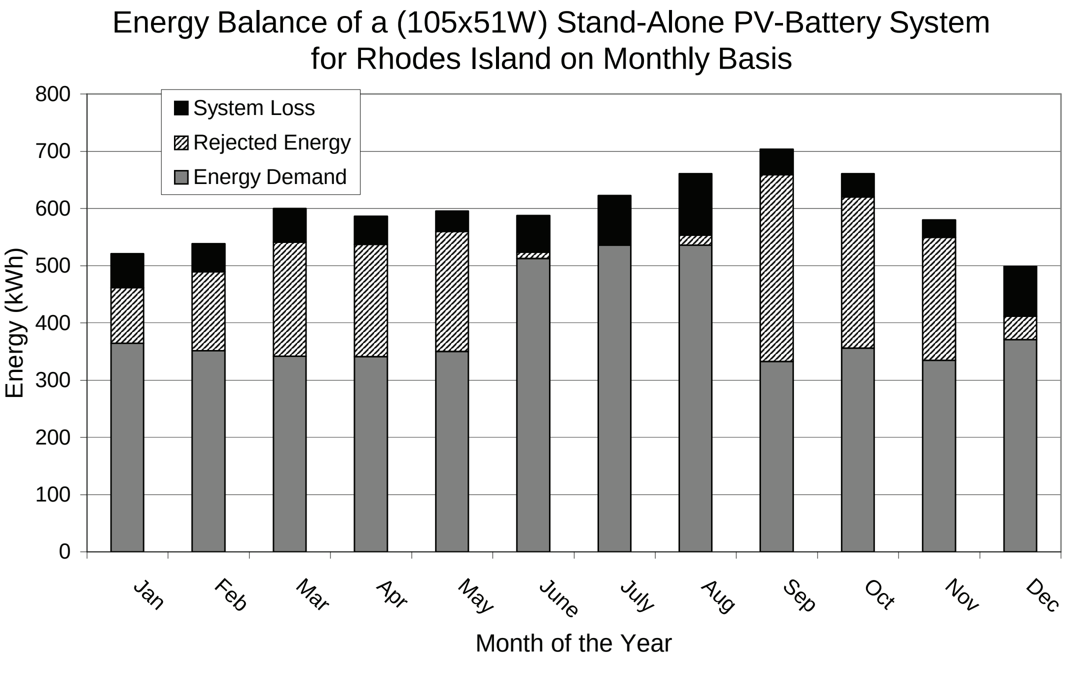


Figure 6: Monthly Energy Balance of Rhodes Island Photovoltaic Stand-Alone System

Using the above analysis one may present in figure (5) several combinations of (z-Q*) values that guarantee the remote consumer energy autonomy for a large range of PV-panels tilt angle "β". In the same figure one may also find the constant initial cost curves, based on the local market financial data. More specifically, the optimum configuration may be achieved using one hundred-five panels (z=105, N_o=51W) at a panel tilt angle of 60° and battery capacity of 2190Ah. At this point it is important to note that for almost all constant "β" energy autonomy curves, two distinct parts can be defined. In the first part the battery capacity is significantly reduced as the photovoltaic number is slightly increased. This rapid change is more evident for "β" angles greater than 50 degrees. In the second part the battery capacity remains almost constant, not depending on the photovoltaic panels number, achieving an asymptotic value of Q_{max}=1000Ah, for all "β" values examined.

Accordingly, the energy balance of the optimum PV-energy storage system (PV-ESS) configuration is presented in figure (6) on a monthly basis. According to the detailed data obtained the annual energy production of the installation is almost 7.2MWh. Taking into consideration that the total annual energy consumption of the specific remote consumer under investigation is 4.7MWh and the corresponding total system loss is 0.7MWh, there is a remarkable energy surplus of the installation (1.7MWh/year) that may be used in additional energy intensive applications (e.g. water pumping, desalination etc.).

4. Energy Included in a PV-Battery System

Managing to determine the optimum size of a PV-stand alone system in terms of both economic and energy yield performance does not allow the investigation of the system's energy performance on a life cycle basis (i.e. also considering the embodied energy of the system components). By considering the net energy yield, the feasibility of an acceptable cost/performance ratio may be more or less predicted[8].

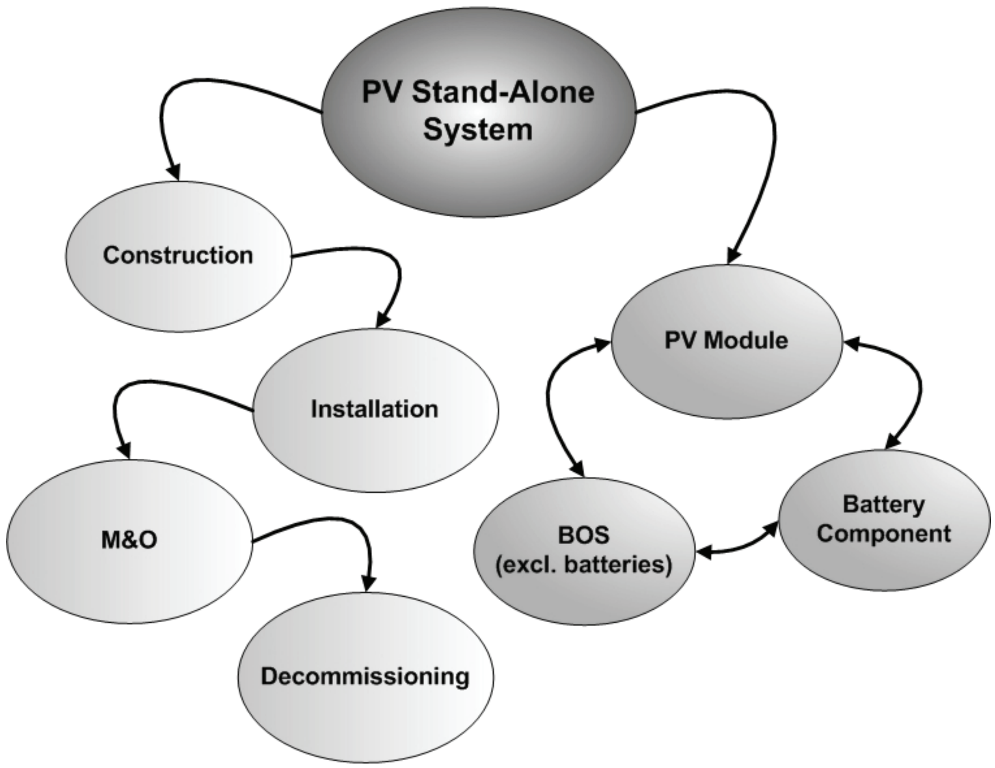


Figure 7: Energy Requirements of a PV Stand-Alone System: Stages and Components

In order to evaluate the proposed system's potential lifecycle effectiveness, an analysis regarding various combinations of photovoltaic modules and battery types will be carried out in order to designate the best solution. More specifically, the life-cycle analysis should involve the stages of construction, installation, maintenance and final decommissioning of the plant. On the other leg of the PV stand-alone requirements (figure (7)), the components comprising the system include the PV module selected, the balance of the system (BOS) parts and the battery component, currently excluded from the BOS and examined separately. A review of several studies[8-14] regarding the energy requirements met in the LCA stages for each of the under examination system's components was carried out. Note that apart from a great deal of uncertainty concerning most of the information and data gathered, even at the levels of 40%[8], the different manufacturing techniques along with the special features describing each installation's type (roof, ground, façade, etc.), also imply strong variations among the results provided. Moreover, in the majority of studies, a quantification of the decommissioning stage is not available due to the lack of trustworthy data. In this context, from the range of data collected the ones suiting the autonomous destination of the system (with special concern ascribed to the BOS parts and the installation stage) may be illustrated in Tables I-III. Accordingly, the different components (PV, BOS and batteries) and technologies presently investigated are discussed on the basis of their energy requirements.

Table I: Crystalline and thin film PV modules embodied energy[8-13]

	sc-Si	mc-Si	a-Si	CdTe
Efficiency η_{PV} (%)	14-15	12-14	5-7	7-9
Embodied Energy (MJ/m^2)	4000-4500	3000-3500	1100-1600	700-1200
Service Period (Years)	20	20	20	20

Table II: Frame's and BOS components' embodied energy[8-13]

	Frame	Array Support	Cabling, installation etc.	Charger	Inverter
MJ/m^2	300-500	600-900	90-120	-	-
MJ/W	-	-	-	0.5-1	0.5-1
Service Period (Years)	20	20	20	10	10

Table III: Energy characteristics of the battery technologies examined[14-23]

	Embodied Energy (kWh_{incl} /kg)	Energy Density (kWh_{out}/kg)	Energy Efficiency	Energy Ratio (kWh_{incl}/kWh_{PV})	Service Period (Years)
Li-ion	58-63	0.20	0.90	274.05	10
NaS	50-55	0.17	0.85	259.70	15
PbA	10-15	0.05	0.74	176.95	5,5
NiCd	35-40	0.08	0.70	324.63	10

4.1. Photovoltaics

Photovoltaic systems are gradually becoming a quite interesting investment opportunity, combining attractive financial performance and environmental protection[15]. Taking into consideration the improved energy efficiency and the significant cost reduction of PV modules in combination with the remarkable subsidization opportunities offered recently (law 3468/06) by the Greek State, numerous grid connected PV based applications are expected throughout Greece in the near future, this motivating remote consumers to adopt similar based autonomous systems. Referring to the technological advancement in the field, during the last years two new PV technologies have begun to be progressively utilized along with the traditional Si-based systems. These two technologies (i.e. cadmium telluride and copper indium diselenide) are the basis for thin film PV modules, which present increased attractiveness due to their low cost and improved applicability. However, due to the lack of a respectable amount of information concerning the CIS technology, in the current study the CdTe along with the a-Si modules will be investigated as far as the thin film production is concerned. Concerning crystalline modules, both the single-crystalline and the multicrystalline PV will be examined.

Based on the present-day production technology, the energy requirements of constructing a typical crystalline module (either sc-Si or mc-Si) involve the processes regarding the silicon winning and purification, the silicon wafer production (two major sources are recognized: the semiconductor industry off-grade silicon and the direct solar grade silicon production)[9], the cell/module processing, the module encapsulation, and additional operations and services (e.g. manufacturing of the special manufacturing equipment used). Note that the more demanding crystallization process of sc-Si wafers is the main reason for the latter increased value of embodied energy[8].

On the other hand, the philosophy of thin films production is based on the deposition of a thin semiconductor layer on a certain substrate, this being achieved by several techniques applied, also involving the deposition of contact layers (chemical vapor and evaporation methods). Overall, the manufacturing of thin film photovoltaics includes the processing of the cell material, the module encapsulation material, the cell/module processing and the additional operations and services required, similar to the crystalline modules case. What must be underlined is that during the manufacturing of a thin film PV, the latter is treated as an entire module throughout the various stages, opposite to the individual wafer processing concerning crystalline modules[8].

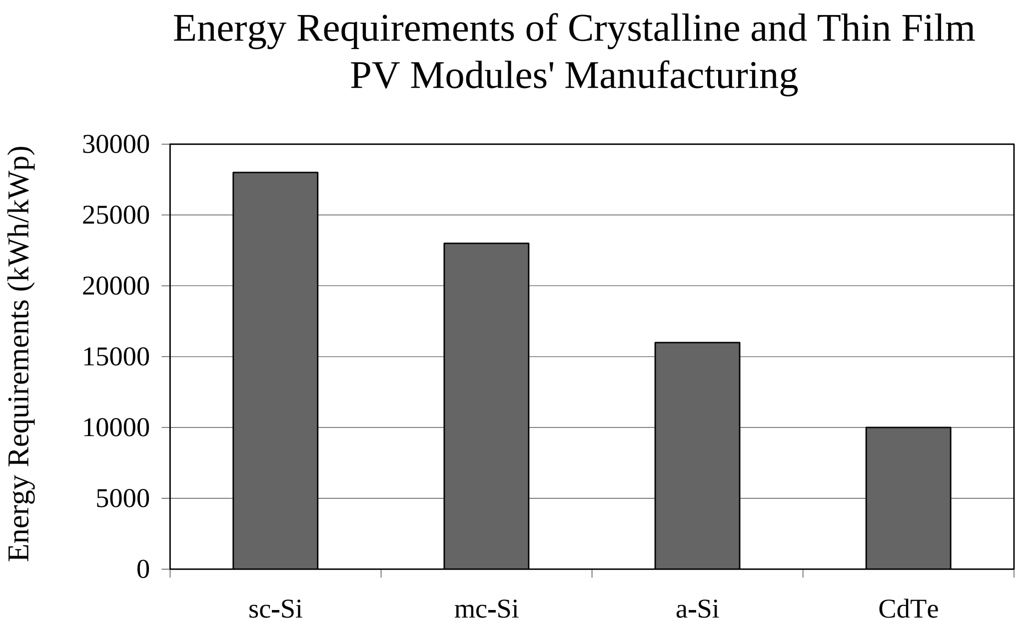


Figure 8: Energy Requirements of Crystalline and Thin-Film PV Modules

In this context, in Table I and figure (8) one may obtain two different expressions of the energy requirements for the manufacturing of crystalline and thin film PV modules presently examined, always in accordance with the autonomous destination of the PV-battery configuration. What becomes clear from figure (8) is that thin film technologies present a certain advantage not only in terms of module area (see Table I) but also in terms of power output, despite the comparatively lower efficiency rates when compared to the corresponding crystalline technologies. The specific argument is also illustrated in figures (9) and (10) where the breakdown of energy requirements for the non-refit parts of the installation is presented for the two extreme cases, i.e. the sc-Si and CdTe modules respectively.

4.2. Balance of System (excluding the batteries)

Apart from the PV modules employed, the entire PV-battery installation includes additional components -necessary for the configuration's operation- referred to as balance of the system (BOS). More specifically, the BOS includes cabling and electronic components (namely an inverter and a charge controller), foundation, array support structures, installation etc. Although batteries are also granted as a BOS component, they will be presently treated as a separate system part in order to emphasize on the latter energy footprint. Additionally, although the frame is usually incorporated in the module part it will be currently treated as a BOS component. In Table II one may obtain the embodied energy of the BOS components.

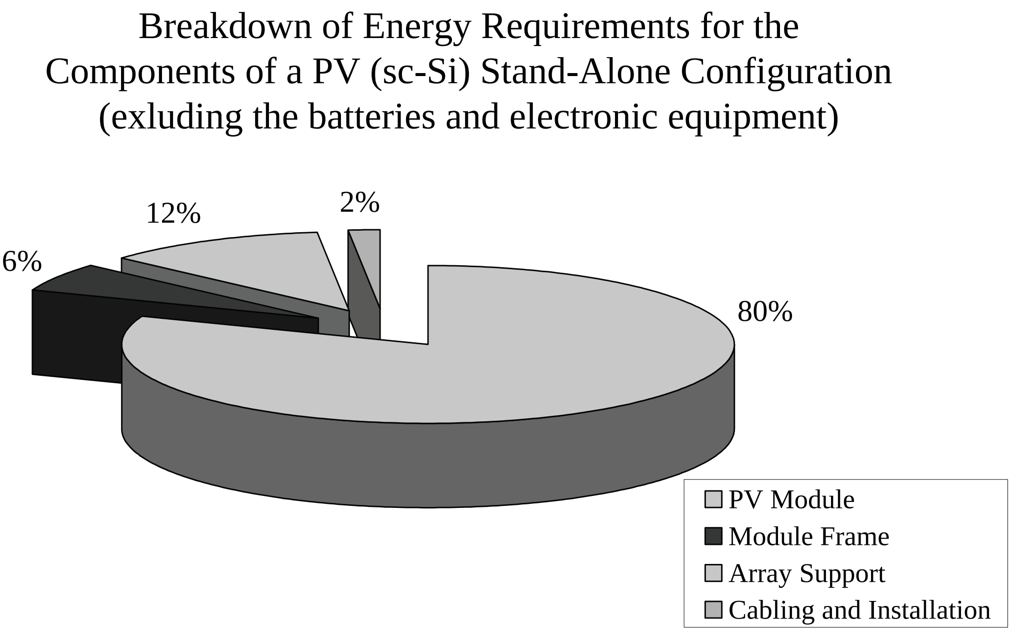


Figure 9: Energy Requirements Shares of Non-Refit Components (Module Intensive Case)

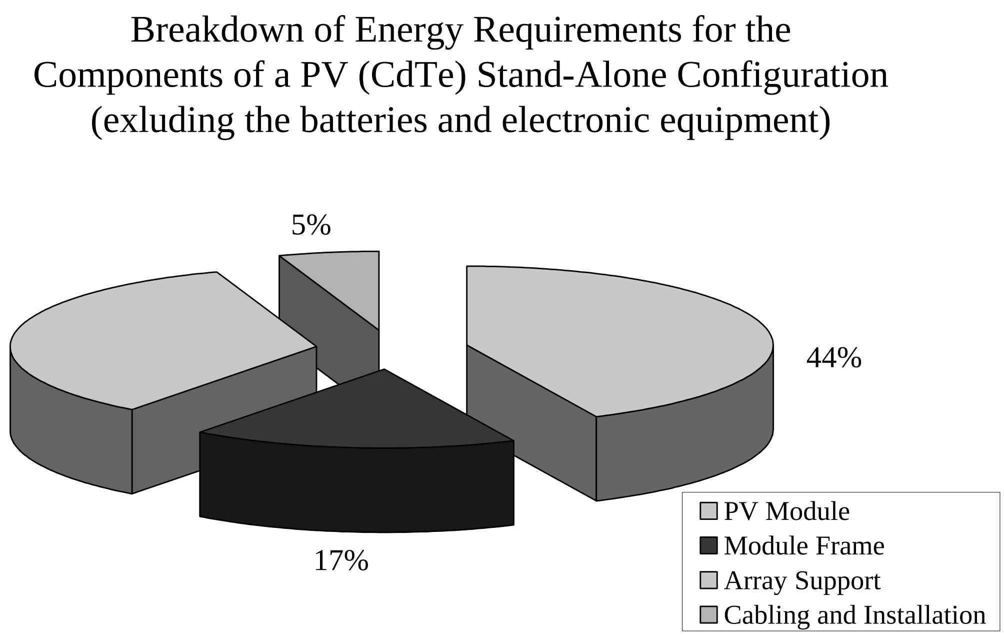


Figure 10: Energy Requirements Shares of Non-Refit Components (Faint Module Effect)

As it may be concluded, the array support comprises the most energy intensive part, even tending to higher rates for open field installations due to the need for cement, concrete, etc. On the other hand the expression of the electronic equipment energy requirements being dependent on the load demand and presenting a useful lifetime lower than the corresponding of the installation (n_{system}=20 years), does not allow for a straightforward comparison. As already mentioned, in figures (9) and (10) one may observe the contribution share of non refit components of the PV-battery configuration with special attention paid in figure (10) where the CdTe module and the array support are more or less described by an equal embodied energy share. The value range provided for the cabling and installation (between 2% and 5%) and the corresponding for the module frame (between 5% and 16%) illustrate the latter less demanding character.

4.3. Battery Energy Storage

Batteries are the most popular storage system. As far as their application range is concerned, battery energy storage systems show almost no restrictions, also serving for the operation of PV stand-alone systems[14]. The technologies currently examined (see also Table III) are the "mature" lead-acid along with the advanced sodium-sulphur, the lithium-ion batteries lately beginning to commercialize, and the nickel-cadmium type accused of the cadmium deposition environmental impacts[16].

In brief, lead-acid batteries are defined as a mature technology with known performance characteristics and a reliable market background[17][18][19]. The low self discharge value, the proven standby capability and the low maintenance requirements are some of the main advantages. On the other hand, the low energy density, the limited service period, the environmentally unfriendly content and the recommended low depth of discharge are the drawbacks of the particular technology[20].

Subsequently, NaS batteries demonstrate increased energy densities, both gravimetric and volumetric in comparison with the lead-acid ones[20]. Due to the existence of beta alumina (it has zero electron conductivity) there is no self discharge phenomenon. In addition, the energy efficiency of such batteries is kept quite high and may reach a value of 85%. At the same time the cost is thought to be low, the maintenance needs appear insignificant, and the service period is very satisfying. However, the use of Na-S may not be able to satisfy certain systems' requirements as the need to maintain the temperature high levels (320-360 ^{o}C) sets a serious obstacle.

The main advantages of lithium-ion technology are the high energy density with a potential for yet higher capacities, the high efficiency value (>90%), and the respectable lifetime combined with deep discharges[21]. Additional advantages include the low self discharge rate, the low maintenance needed, and the ability for the provision of very high currents[22]. The limitations set at present are the required protection circuits to maintain voltage and current within safety limits, the technology not yet sufficiently developed and the high cost for the batteries' manufacture.

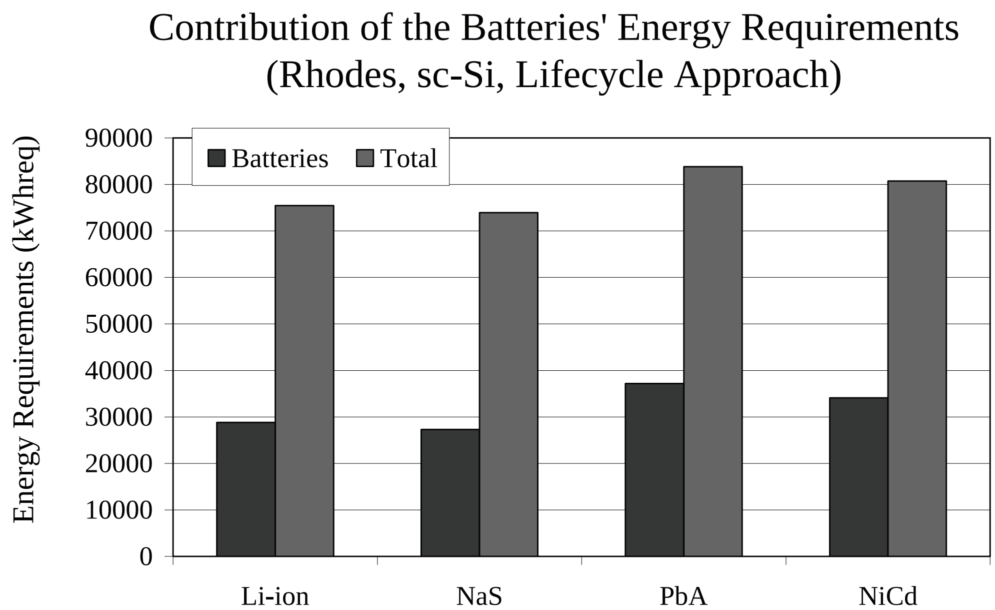


Figure 11: Battery Contribution on the LCA Energy Requirements (Module Intensive Case)

Finally, NiCd batteries although accused of their environmental impacts due to the cadmium deposition[16] comprise -along with lead acid batteries- the two most common battery technologies involved in PV applications. The specific type of batteries may be described by comparatively low rates of both energy efficiency and energy density, this opposing to the modest production energy requirements, second lowest after the PbA batteries.

To obtain the embodied energy for each type of battery, gravimetric values of the former along with the corresponding gravimetric energy density[23] and the battery energy efficiency may result to the ratio of energy included in the battery to the amount of the PV energy surplus the battery is capable of storing and providing (kWh_{incl}/kWh_{PV}). Subsequently, based on the optimum sizing of the battery component, the embodied amount of energy may be available. In this context, in figures (11) and (12) one may obtain the contribution share of each battery technology examined on the basis of the former lifecycle energy requirements. In the two extreme cases presented (sc-Si and CdTe) the contribution percentage varies from 38% to 65% of the entire plant requirements, this value being largely dependent, apart from the amount of embodied energy, on the service period of each battery (for example PbA batteries need to be changed three times over the entire configuration's life period).

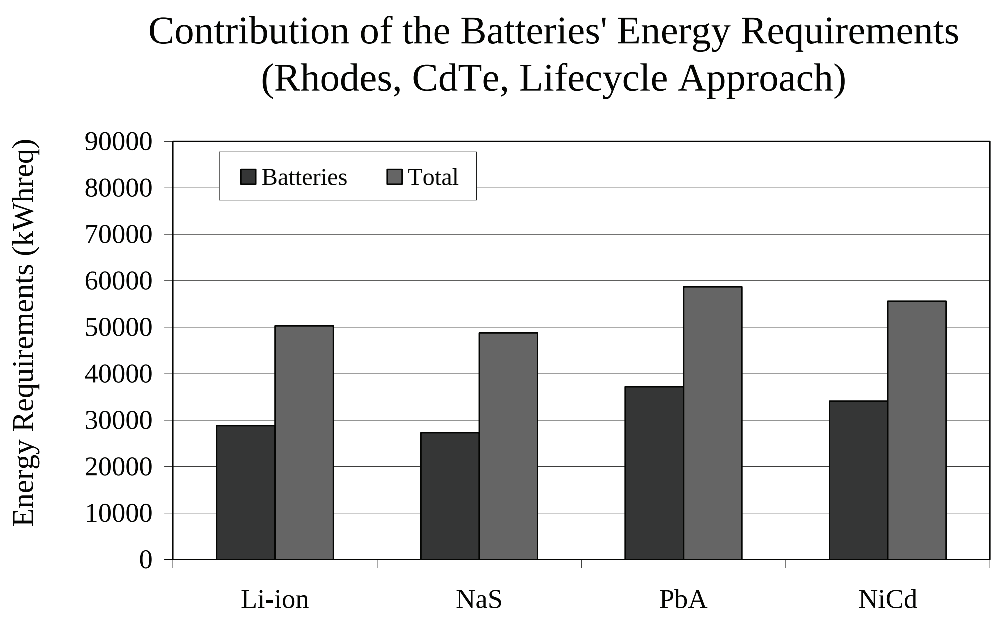


Figure 12: Battery Contribution on the LCA Energy requirements (Battery Intensive Case)

5. Energy Pay-Back Period

Provided the optimum sizing of the PV stand-alone system and having determined the energy requirements of the various components comprising the entire plant, a summation of the latter on a lifecycle basis, also accounting for each component's service period, will designate the most attractive PV-battery combination in terms of energy required during the LCA stages previously discussed. In this context, in figure (13) the final results of LCA energy requirements for the various PV-battery combinations examined are presented.

As it may be configured, sc-Si crystalline modules on the one hand and PbA batteries on the other suggest the most energy intensive solutions. Note that although described by the lowest energy ratio, PbA batteries are "injured" by their moderate service period. The opposite is valid for NaS batteries and thin film modules, especially the CdTe technology. Li-ion batteries, although defined by the highest embodied energy value (kWh_{incl}/kg) eventually comprise the second best choice that may even prevail over the NaS solution due to the latter high temperature operation. Regarding NiCd combinations, the corresponding results seem to approach the PbA rates, mainly due to their respectably high energy ratio.

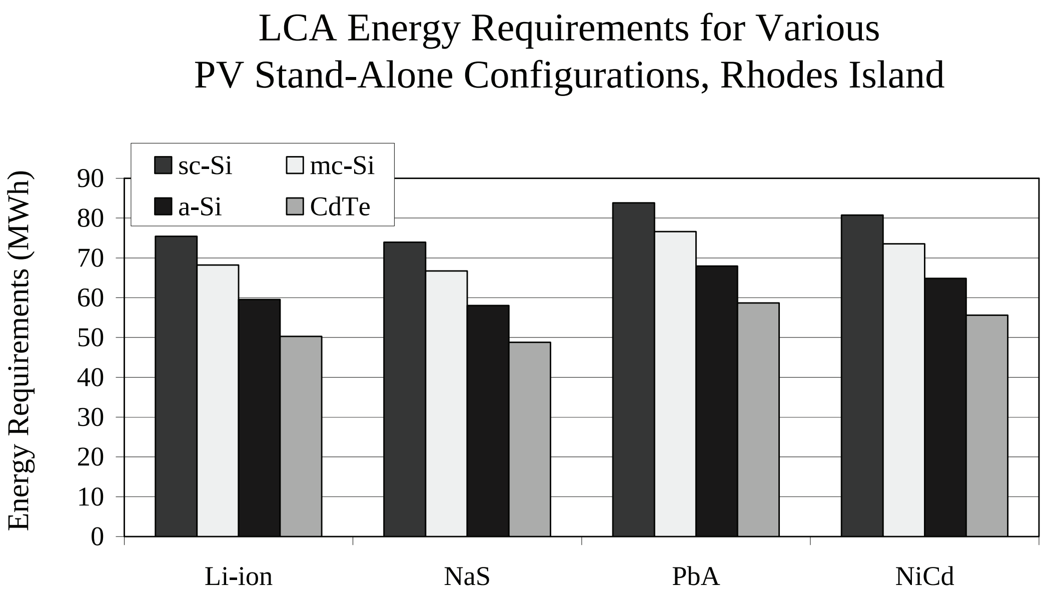


Figure 13: LCA Energy Requirements of Various PV Stand-Alone Configurations

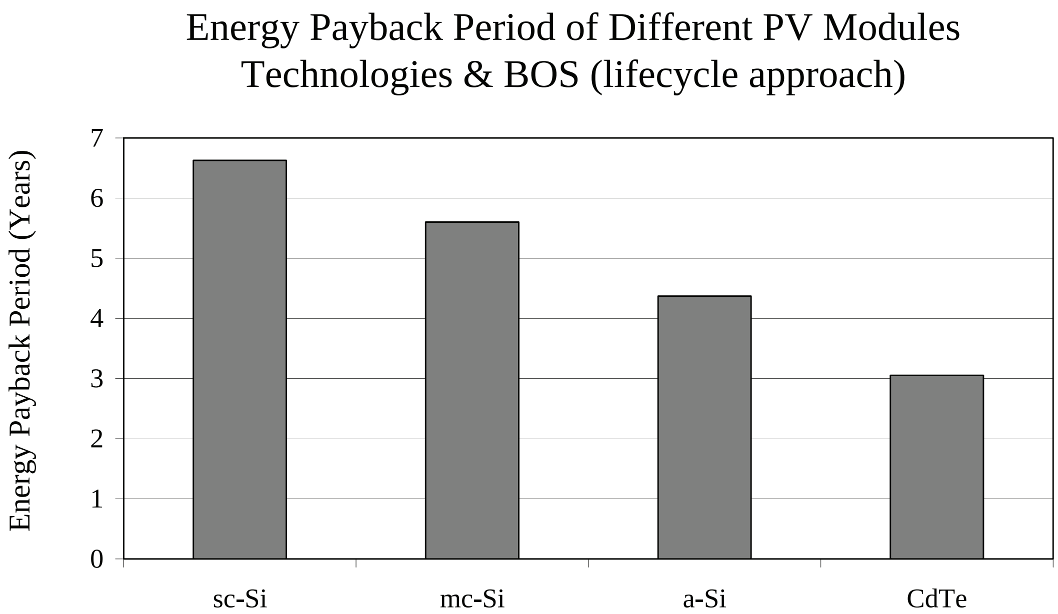


Figure 14: Energy Payback Period Excluding the Battery Part

Based on the results of figure (13) and the annual energy yield of the optimum configuration (figure (6)) the energy payback period (EPBP) for each of the examined combinations may be estimated. In order to disengage the battery part from the overall energy payback period estimated, two figures provided illustrate the results obtained with and without the battery component (figures (14) and (15)). More specifically, in figure (14), the results demonstrated refer to the PV module employed and the balance of the system (BOS) components alone, without including the battery part, while in figure (15) the entire plant EPBP is given. By comparing the two figures results, it becomes clear that depending on the combination examined the batteries add another 3.5 to 5 years in comparison with the EPBP regarding only the PV modules and the BOS components.

Following the results of figure (13) concerning the LCA energy requirements, thin film technologies demonstrate a clear advantage over the corresponding crystalline with the CdTe combinations even achieving EPBP shorter than 7 years. PbA batteries comprise the least attractive solution with EPBP reaching the maximum of approximately 12 years. However, combinations of thin film modules with PbA batteries imply EPBP rates that are shorter than the respective of crystalline modules with NiCd, or even Li-ion batteries in the case of sc-Si. It is interesting to note that for the optimum combination (CdTe and NaS) the EPBP estimated is even less than the corresponding of sc-Si and BOS alone. Finally, what must be underlined is that any case given, the EPBP remains shorter than the entire configuration lifetime (i.e. 20 years), in most cases also not exceeding the installation's half life-period (i.e. 10 years), this illustrating the sustainable character of crystalline modules as well.

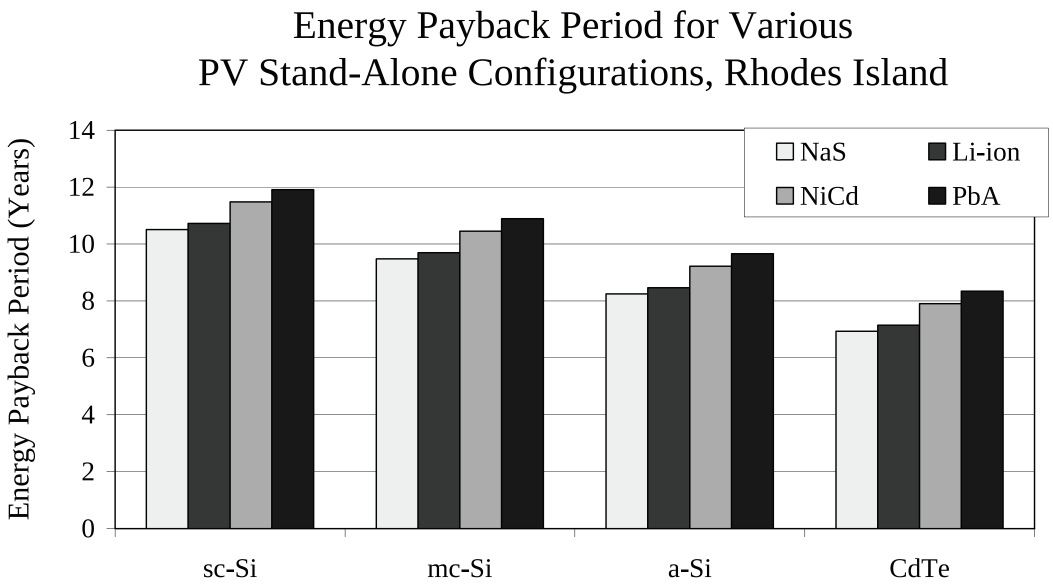


Figure 15: Energy Payback Period of Various PV Stand-Alone Configurations

6. Conclusions

Recapitulating, an integrated evaluation methodology developed in the present study is able to provide both the optimum sizing of an autonomous PV-battery configuration in terms of economic efficiency and also ensure the system's minimum energy pay-back period. In order to designate the best solution (i.e. the one implying the shortest time of energy payback) various combinations of photovoltaic technologies and battery types are investigated. From the results obtained, new thin film technologies along with NaS and Li-ion batteries suggest the most attractive solutions, although crystalline PbA and crystalline NiCd combinations comprise the most common configurations in PV stand alone systems. What is also evident is that batteries comprise a major factor influencing the final EPBP and may in certain cases suggest the main energy input of the installation energy requirements, even reaching contribution shares of 68% (in the case of CdTe).

Whatever the impact of either the battery type selected or the PV technology employed, the restriction for the EPBP to remain shorter than the entire installation lifetime is always validated. Besides, the constant research and development in the field of PV modules promising for greater output efficiencies and more energy efficient production methods implies further reduction rates of the energy pay-back period. Overall, the PV-battery stand alone configurations do not only comprise a potential cost-effective solution for remote consumers but also demonstrate satisfying periods of energy pay-back with respectable improvement opportunities in the year to come, this illustrating the latter sustainability commitment.

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BUSINESS ACTIVITIES IN THE ENVIRONMENTAL SECTOR IN GREECE: CURRENT STATUS AND PROSPECTS

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Abstract

The imperative environmental protection needs of the recent years have created significant business and professional activities in Europe and in our country. The objectives of the present work are to present the nature and magnitude of the environment related business activities in Greece today and in the near future, to make an assessment of the professional specialisations that are necessary for the above business activities, and the implied educational requirements. To that effect, the work classifies the existing environmental business activities in qualitative and quantitative terms and makes a projection of these activities in the next ten years. In its conclusions, it highlights the challenging opportunities that are emerging in the environmental field for business and professionals.

Keywords: Environmental Business Activities; Eco-Industries; Environmental Professions; Environmental Engineering Education

1. Introduction

The imperative environmental protection needs of the recent years have created very significant business and professional activities in Europe and in our country. These include the design, construction, operation and maintenance of environmental protection works (such as wastewater treatment plants, solid waste treatment units), the environmental impact assessment studies, the design, construction and trading of environmental protection equipment, the development and installation of environmental management systems. To cover these needs, during the last twenty years new business schemes have been created and new professional specializations have emerged.

As defined by the OECD, eco-industries, the term that is used for environmental business, are "activities which produce goods and services to measure, prevent, limit, minimize or correct environmental damage to water, air and soil, as well as problems related to waste, noise and eco-systems. This includes technologies, products and services that reduce environmental risk and minimize pollution and resources consumption"[1]. Eco-industries are classified into two broad categories:

- pollution management, and
- resource management.

Total EU eco-industry turnover in 2004 was €227 billion[1], from pollution management and resource management activities (figure (1)). Pollution management consists of nine eco-industry sectors referring to the “end of pipe” technology.

These nine sectors with their corresponding turnover for year 2004 are the following (figure (2)):

- Solid Waste Management & Recycling (€52.4 billion)
- Waste Water Treatment (€52.2 billion)
- Air Pollution Control (€15.9 billion)
- General Public Administration (€11.5 billion)
- Private Environmental Management (€5.8 billion)

Kondili E.M., Kaldellis J.K., 2007, *"Business Activities in the Environmental Sector in Greece: Current Status and Prospects", 1st International Conference on Environmental Management, Engineering, Planning and Economics (CEMEPE), June 2007, Skiathos, Greece.*

- Remediation & Clean Up of Soil & Groundwater (€5.2 billion)
- Noise & Vibration Control (€2 billion)
- Environmental Research & Development (€0.11 billion)
- Environmental Monitoring & Instrumentation (a supply-side estimate of turnover in the monitoring and instrumentation sector is €1 billion)

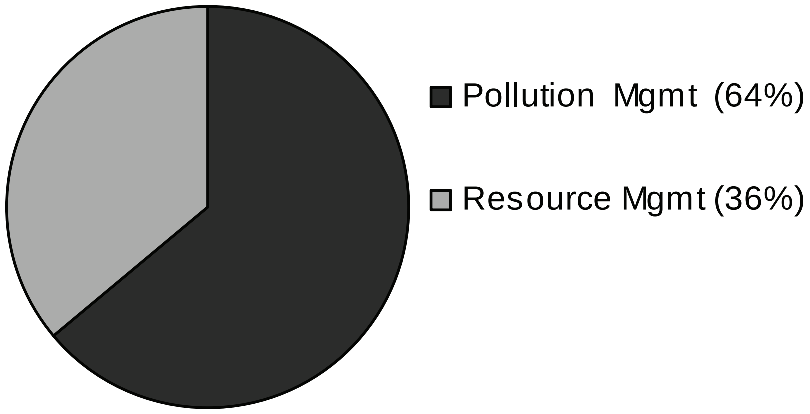

Figure 1: Distribution of total turnover by pollution management and resource management activities (million €, EU-25, 2004)[1]

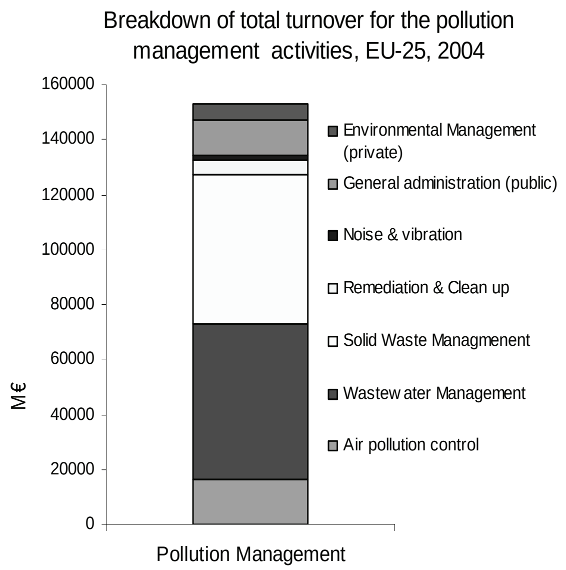

Figure 2: Breakdown of total turnover by sector for the pollution management activities, EU-25, 2004

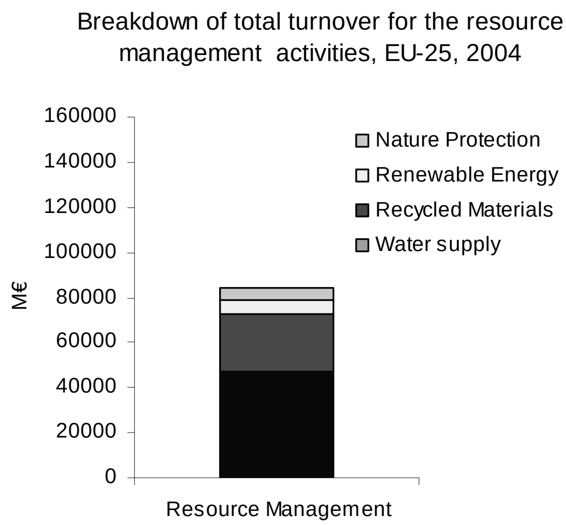

Figure 3: Breakdown of total turnover by sector for the resource management activities, EU-25, 2004[1]

Resource management includes five eco-industry sectors that take a more preventive approach (figure (3)):

- Water Supply (€45.7 billion)
- Recycled Materials (€24.3 billion)
- Renewable Energy Production (€6.1 billion)
- Nature Protection (€5.7 billion)
- Eco-construction (a supply-side estimate of eco-construction turnover is €40 billions)

Historically, the environmental business activities began with traditional, now mature, markets driven by the demand for essential commodities such as water supply and services like waste collection. There were also markets based on nationally specific requirements and opportunities such as incinerator flue gas treatment capacities in Germany.

Recent business activities are based on investment needs created by:

- new environmental legislation
- industrial intentions to improve their environmental performance
- infrastructure projects of member states.

2. Environmental Business Activities in Greece

Environmental activities in Greece started from the middle of 80's with the construction of a large number of wastewater treatment plants. Greece has strong capabilities in nature ecosystems identification and protection and in wastewater treatment; however it needs serious improvements in all other environmental areas.

According to the Greek Ministry of Environment, the Greek environmental market is estimated annually at approximately 1.5% of the GDP, thus surpassing $2.2 billion[2], (figure (4)).

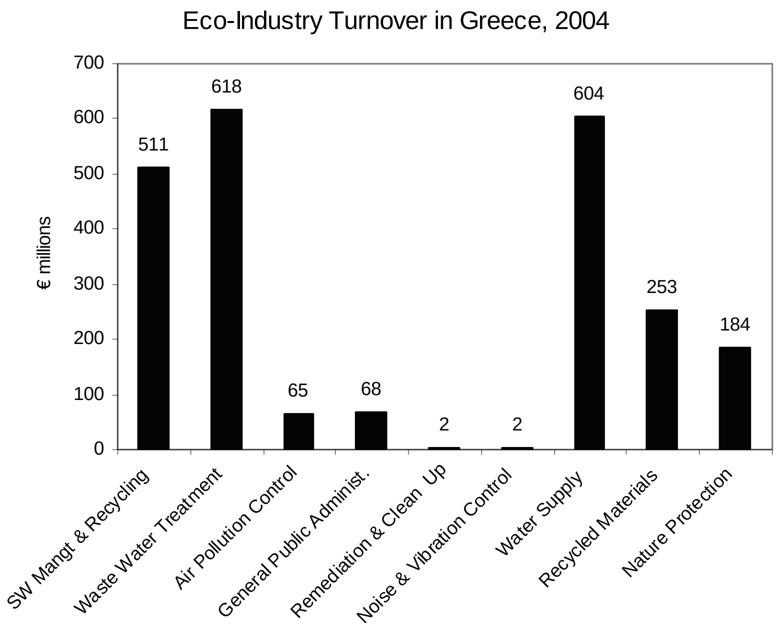

Figure 4: Eco-industry turnover by sector in Greece for 2004[1]

The current period is particularly critical for environment related business opportunities. Greece has identified its needs in detail and has developed national plans for dealing with them, always in accordance with EU directives. In particular, recycling, solid and hazardous waste treatment, and alternative energy sources in Greece fall far short of EU averages. There are significant opportunities in the air, liquid and solid waste market segments, including investment opportunities and providing new and advanced technologies. The transposition of the EU environmental legislation in national laws has also created the appropriate institutional basis for facing successfully the environmental protection challenges. As these efforts continue, the Greek market for waste management and environmental equipment and services will have excellent growth potential over the next several years.

Opportunities also include those through Greece's energy sector liberalization efforts. Greece is building power production plants and developing a regional energy network, which provides numerous opportunities for companies interested in medium- to large scale market penetration. Due to its importance and its own special features, the energy sector is not included in the scope of the present work.

Investments in environmental infrastructure through EU and national programs have been the driving forces of the environmental progress in Greece. They address major environmental problems and facilitate the financing of new environmental infrastructure around Greece, including the construction of numerous wastewater and solid waste treatment facilities as well as the building of new recycling plants, composting facilities and treatment plants for industrial and hazardous waste materials. Furthermore, operational programs encourage and support financially investments in environmental protection and / or investments in the development of new environmental companies.

With a budget that surpassed $700 million, the National Operational Program for the Environment (EPPER), funded by the Third Community Support Framework Program has been instrumental in shaping environmental policy[2].

Furthermore, changes in Greece's environmental laws will eventually create business potential for applied and proven environmental technologies. Demand for environmental technologies in Greece is primarily focused on solid waste management and wastewater treatment systems and recycling equipment. After decades of relying on inefficient landfill solutions, Greece has attempted to introduce measures and practices that conform to EU regulations and strategic policies. A significant number of solid waste treatment plants are planned in the new National Plan for Regional Development (figure (5))[3].

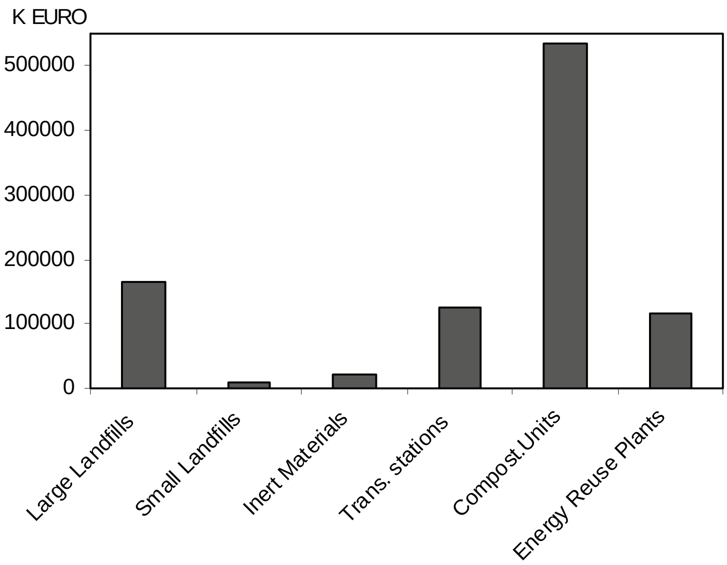

Figure 5: Budget for solid waste management projects planned in Greece[3]

As far as business activities are concerned, there is nowadays a very well established basis of environmental companies, some of them even operating since the 80's. An Association of Environmental Protection companies has been created, in order to support and promote the professional interests of the companies active in this sector.

The Association has today 82 company members[4]. Activities of the environmental companies may include one or more of the following:

- Development and implementation of integrated waste management plants
- Development, implementation and monitoring of environmental management systems

- Technoeconomic studies – feasibility studies of environmental investment solutions
- Resource allocation and cost minimization
- Environmental studies and risk assessment
- Technical studies for environmental infrastructure
- Planning, development, operation and restoration of old landfills
- Recycling and recovering
- Environmental impact assessment studies
- Participation in national and European R&D programs
- Trading of environmental materials, equipment and instrumentation
- Operation and management of waste treatment facilities

In addition to the above, it should be mentioned that many European companies are active in Greece in various environmental projects. It foreseen that, in the next years, this phenomenon will be extended and more foreign companies will be attracted in order to be involved in various emerging projects, in most cases in cooperation with domestic companies. Investors and environmental technology companies will be interested in Greece developing a pollutants trade system. There is also potential to use Greece as a starting point for business in the Balkan and Black Sea countries.

On the other hand, there are emerging opportunities for the Greek companies to expand their activities out of the country, since a lot of money will be spent in less advanced countries for the improvement of the basic water, wastewater, and pollution control infrastructure that wealthier nations have already constructed.

3. Environmental Professions and Education

In order to cover all these needs, a number of specializations and professions have emerged during the last years. Integration of different fields-science, engineering, politics, law, information technology, project management, business administration, communications, and economics-is at the heart of the new environmental professions.

On the other hand, a number of undergraduate and postgraduate environmental engineering and environmental management courses are offered in the Greek universities (see for example [5]), following the domestic needs and the international trends. There are already many graduates from these courses that work in the private and public sector. The relevant postgraduate courses are extremely popular and demanded, thus indicating the prospects of the associated professions. The qualifications that environmental professionals are required to have emerge from the changing nature of their job descriptions.

Nowadays we find in Greece professionals to be involved in various fields, such as:

- The engineering and construction sector
- Environmental impact assessment studies
- Development, implementation, monitoring and auditing of Environmental Management Systems
- Trading of equipment and instrumentation

Engineers of all kinds are at the center of the environmental careers. Environmental, civil, mechanical, chemical and process engineers with industry-specific knowledge are particularly in demand for pollution prevention projects.

The environmental projects need reliable data, especially data that can be shown visually and interactively by computer systems that demonstrate interaction between human activities and ecological systems. Geographic information systems (GIS) specialists are in demand at planning agencies, consulting firms, research centers, and in private industry. GIS, of course, relies on the existence of good data in the first place, which creates employment for sampling professionals and new technological developments in monitoring equipment and remote sensing from satellites.

Another important but rather underestimated profession is that of the operator of water and wastewater treatment plants, as well as at treatment, storage, and disposal sites. Most of these sites are under the supervision of local authorities and municipalities that do not always have the qualified personnel to operate them. Therefore, the malfunctioning of very expensive infrastructure projects is a common phenomenon. Proper education and training are of imperative need in this field.

Simultaneously, the rapid growth in environmental information creates a pressing need for professionals to stay up-to-date. Continuing education is critical for success, and this has created opportunities for educators who provide rapidly changing seminars, workshops, short courses, trainings and other learning opportunities.

Finally, it is expected that in the next years new environment related enterprises will be developed in Greece, since the private sector plays a continuously greater role. This emphasizes the need for a new kind of properly educated and experienced manager and for entrepreneurs who will start businesses that advance sustainability.

In general, the professionals being involved in environmental projects need to know and understand the relevant legislation, to be able to prepare environmental impact assessments and statements in support of projects; to have the ability to negotiate agreements with state and local authorities regarding environmental compliance, to have the ability to write sound, comprehensive environmental documents; prepare reports and briefs on environmental issues for management; communicate complex scientific and technical issues to technical and non-technical audiences.

4. Conclusions

The environmental sector offers continuously increasing opportunities for business activities in Europe and in Greece. To cover the needs of the sector, new professional specializations have been created and a significant number of scientists, engineering and other professionals are now involved in pollution management or resource management activities. In order to face the needs of these emerging professions, new departments and educational courses have been developed in the university education. In fact, because of the continuously changing nature of these new specialisations, the curricula of the corresponding courses also change frequently, in order to adapt to the real societal needs.

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