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LABORATORY

OF SOFT ENERGY APPLICATIONS & ENVIRONMENTAL PROTECTION

TEI OF PIRAEUS

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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 ″***

Research Areas

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

Published Results:

- **Kaldellis J.K., Vlachos G., 2005**, "Optimum Sizing of an Autonomous Wind-Diesel Hybrid System for Various Representative Wind-Potential Cases", *Applied Energy Journal*, vol. 83(2), pp.113-132.
- **Kaldellis J.K., Kavadias K.A., Filios A.**, **Garofallakis S., 2004**, "Income Loss due to Wind Energy Rejected by the Crete Island Electrical Network: The Present Situation", *Journal of Applied Energy*, vol.79(2), pp.127-144.
- **Kaldellis J.K., 2002**, "Parametrical Investigation of the Wind-Hydro Electricity Production Solution for Aegean Archipelago", *Journal of Energy Conversion and Management*, vol.43(16), pp.2097-2113.
- **Kaldellis J.K., Kavadias K., Christinakis E., 2001**, "Evaluation of the Wind-Hydro Energy Solution for Remote Islands", *Journal of Energy Conversion and Management*, vol.42(9), pp.1105-1120.

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

Published Results:

- **Kaldellis J.K., Vlachos G.Th., Paliatsos A.G., Kondili E., 2005**, "Detailed Examination of Greek Electricity Sector Nitrogen Oxides Emissions for the Last Decade", *Journal of Environmental Science and Policy*, vol.8(5), pp.502-514.
- **Kaldellis J.K., Kavadias K.A., Paliatsos A.G., 2003**, "Environmental Impacts of Wind Energy Applications: Myth or Reality?" *Fresenius Environmental Bulletin*, vol. 12(4), pp.326-337.
- **Kaldellis J.K., Konstantinidis P., 2001**, "Renewable Energy Sources Versus Nuclear Power Plants Face the Urgent Electricity Demand of Aegean Sea Region", presented in the First Hellenic-Turkish International Physics Conference, Kos-Alikarnassos, published also in "*Balkan Physics Letters*" Journal, SI/2001, pp.169-180.

3. "Technological Progress in Wind Energy Market"

Published Results:

- **Kaldellis J.K., 2004**, "Investigation of Greek Wind Energy Market Time-Evolution", *Energy Policy Journal*, vol.32(7), pp.865-879.
- **Kaldellis J.K., Vlachou D.S., Paliatsos A.G., 2003**, "Twelve Years Energy Production Assessment of Greek State Wind Parks", *Wind Engineering Journal*, vol.27(3), pp.215-226.
- **Kaldellis J.K., Zervos A., 2002**, "Wind Power: A Sustainable Energy Solution for the World Development", Energy-2002 International Conference, June-2002, Athens, Greece.

4. "Technological Progress in Solar Energy Market"

Published Results:

- **Kaldellis J.K., Kavadias K.A., Spyropoulos G., 2005**, "Investigating the Real Situation of Greek Solar Water heating Market", Renewable and Sustainable Energy Reviews, vol.9(5), pp.499-520.
- **Kaldellis J.K., Koronakis P., Kavadias K., 2004**, "Energy Balance Analysis of a Stand-Alone Photovoltaic System, Including Variable System Reliability Impact", *Renewable Energy Journal*, vol.29(7), pp.1161-1180.
- **Kaldellis J.K., Vlachou D.S., Koronakis P.S., Garofalakis J.E., 2001**, "Critical Evaluation of Solar Collector Market in Greece Using Long-Term Solar Intensity Measurements", presented in the First Hellenic-Turkish International Physics Conference, Kos-Alikarnassos, published also in "*Balkan Physics Letters*" Journal, SI/2001, pp.181-193.

5. "Flow Field Prediction for High Speed Turbomachines"

Published Results:

- **Kavadias K.A., Kaldellis J.K., 2003**, "An Integrated Aerodynamic Simulation Method of Wind Turbine Rotors", *Applied Research Review* Journal of the TEI of Piraeus, vol.8(1), pp.221-242.
- **Kaldellis J.K., 1998**, "Static Pressure Gradients inside the Shock-Shear Flow Interaction Region", *Technika Chronika, Scientific Journal of the Technical Chamber of Greece-IV*, vol.18(2), pp.19-33.
- **Kaldellis J., 1997**, "Aero-Thermodynamic Loss Analysis in Cases of Normal Shock Wave-Turbulent Shear Layer Interaction", published in ASME Transactions, *Journal of Fluids Engineering*, vol.119, pp.297-304.

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

Published Results:

- **Kondili E., Kaldellis J.K., 2005**, "Optimal Design of Geothermal-Solar Greenhouses for the Minimisation of Fossil Fuel Consumption", *Applied Thermal Engineering*, vol.26(8-9), pp.905-915.
- **Kaldellis J.K., El-Samani K., Koronakis P., 2005**, "Feasibility Analysis of Domestic Solar Water Heating Systems in Greece", *Renewable Energy Journal*, vol.30(5), pp.659-682.
- **Kaldellis J.K., Vlachou D.S., Korbakis G., 2005**, "Techno-Economic Evaluation of Small Hydro Power Plants in Greece: A Complete Sensitivity Analysis", *Energy Policy Journal*, vol.33(15), pp.1969-1985.
- **Kaldellis J.K., 2004**, "Optimum Techno-Economic Energy-Autonomous Photovoltaic Solution for Remote Consumers Throughout Greece", *Journal of Energy Conversion and Management*, vol.45(17), pp.2745-2760.
- **Kaldellis J.K., 2002**, "An Integrated Time-Depending Feasibility Analysis Model of Wind Energy Applications in Greece", *Energy Policy Journal* vol.30(4), pp.267-280.
- **Kaldellis J.K., Gavras T.J., 2000,** "The Economic Viability of Commercial Wind Plants in Greece. A Complete Sensitivity Analysis", *Energy Policy Journal*, vol.28, pp.509-517.

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

Published Results:

- **Kaldellis J.K., Kavadias K.A., Koronakis P.S., 2005**, "Comparing Wind and Photovoltaic Stand-Alone Power Systems Used for the Electrification of Remote Consumers", to appear in *Renewable and Sustainable Energy Reviews*, on-line available (05/03/05) in www.ScienceDirect.
- **Kaldellis J.K., 2004**, "Parametric Investigation Concerning Dimensions of a Stand-Alone Wind Power System", *Journal of Applied Energy*, vol.77(1), pp.35-50.
- **Kaldellis J.K., 2003**, "An Integrated Feasibility Analysis of a Stand-Alone Wind Power System, Including No-Energy Fulfillment Cost", *Wind Energy Journal*, vol.6(4), pp.355-364.
- **Kaldellis J.K., 2002**, "Optimum Autonomous Wind Power System Sizing for Remote Consumers, Using Long-Term Wind Speed Data", *Journal of Applied Energy*, vol.71(3), pp.215-233.

8. "Evaluation of Energy Storage Systems"

Published Results:

- **Kaldellis J.K., Kostas P., Filios A., 2005**, "Minimization of the Energy Storage Requirements of a Stand-Alone Wind Power Installation by Means of Photovoltaic Panels", *Wind Energy International Journal*, on-line available in http://www3.interscience.wiley.com.
- **Kaldellis J.K., Tsesmelis M., 2002**, "Integrated Energy Balance Analysis of a Stand-Alone Wind Power System, for Various Typical Aegean Sea Regions", *Wind Energy* Journal, vol.5(1), pp.1-17.
- **Kaldellis J.K., Kavadias K.A., 2001**, "Optimal Wind-Hydro Solution for Aegean Sea Islands Electricity Demand Fulfillment", *Journal of Applied Energy*, vol.70, pp.333-354.
- **K.A. Kavadia**s, **J.K. Kaldellis, 2000**, "Storage System Evaluation for Wind Power Installations", International Conference "Wind Power for the 21st Century", Paper OR7.3, Kassel, Germany.

9. "Air Pollution Analysis"

Published Results:

- **Paliatsos A.G., Koronakis P.S., Kaldellis J.K., 2005**, "Effect of Surface Ozone Exposure on Vegetation in the Rural Area of Aliartos, Greece", 13th International Symposium of MESAEP, Thessaloniki-Greece.
- **Kaldellis J.K., Spyropoulos G., Chalvatzis K.J., 2004**, "The Impact of Greek Electricity Generation Sector on the National Air Pollution Problem", *Fresenius Environmental Bulletin*, vol. 13(7), pp.647-656.
- **Paliatsos A.G., Kaldellis J.K., Koronakis P.S., Garofalakis J.E., 2002**, "Fifteen Year Air Quality Trends Associated with the Vehicle Traffic in Athens, Greece" *Fresenius Environmental Bulletin*, vol.11(12b), pp.1119-1126.
- **Kaldellis J.K., Paliatsos A.G., Toumbaniaris P., Kavadias K., 2001**, "The Impact of Fossil Fuel Consumption on Air Pollution Problem in Greece", presented in the First Hellenic-Turkish International Physics Conference, Kos-Alikarnassos, published also in "*Balkan Physics Letters*" Journal, SI/2001, pp.194-205.

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

Published Results:

- **Nastos P.T., Paliatsos A.G., Priftis K.N., Kaldellis J.K., Panagiotopoulou-Gartagani P., Tapratzi-Potamianou P., Zachariadi-Xypolita A., Kotsonis K., Kassiou K., Saxoni-Papageorgiou P., 2005**, "The Effect of Weather Types on the Frequency of Childhood Asthma Admissions in Athens, Greece", 13th International Symposium of MESAEP, Thessaloniki-Greece.
- **Kaldellis J.K., M. Voutsinas, A.G. Paliatsos, P.S. Koronakis, 2004**, "Temporal Evolution of the Sulfur Oxides Emissions from Greek Electricity Generation Sector", *Journal of Environmental Technology*, vol.25, pp.1371-1384.
- **Paliatsos Ath., Kaldellis J.K., Halvatzis K., 2003**, "The Seasonal and Diurnal Variation of Surface Ozone at the EMEP Station in Greece", "Ecological Protection of the Planet Earth II", Conference Proceedings, pp. 591-596, Sofia, Bulgaria.
- **Koronakis P.S., Sfantos G.K., Paliatsos A.G., Kaldellis J.K., Garofalakis J.E., Koronaki I.P., 2002**, "Interrelations of UV-global/global/diffuse Solar Irradiance Components and UV-global Attenuation on Air Pollution Episode Days in Athens, Greece", *Atmospheric Environment*, vol.36(19), pp. 3173-3181, July.

11."Autocats Standardization and Recycling"

Published Results:

- **Paliatsos A.G., Kaldellis J.K., Viras L.G., 2001**, "The Management of Devaluated Autocats and Air Quality Variation in Athens", 7th International Conference on "Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes", Conference Proceedings, vol.A, pp.474-478, Belgirate-Italy.
- **Kaldellis J. K., Konstantinidis** P., **Charalambidis P., 2001,** "The Impact of Automobile Catalytic Converters Degradation on Air Quality" International Conference on "Ecological Protection of the Planet Earth I", vol.II, pp.633-641, Xanthi, Greece.
- **Kaldellis J.K., Charalambidis P., Konstantinidis P., 2000,** "Feasibility Study Concerning the Future of Devaluated Autocats, Social-Environmental Cost Included", International Conference, Protection and Restoration of the Environment V, pp.879-886, Thassos Island, Greece.

12."RES Based Desalination"

Published Results:

- **Kaldellis J.K., Kondili E., Kavadias K.A., 2005**, "Energy and Clean Water Co-production in Remote Islands to Face the Intermittent Character of Wind Energy", *International Journal of Global Energy Issues*, vol.25(3-4), pp.298-312.
- **Kaldellis J.K., Kavadias K.A., Kondili E., 2004**, "Renewable Energy Desalination Plants for the Greek Islands, Technical and Economic Considerations", *Desalination Journal*, vol.170(2), pp.187-203.
- **Vlachos G., Kaldellis J.K., 2004**, "Application of a Gas-Turbine Exhausted Gases to Brackish Water Desalination. A Techno-Economic Evaluation", Applied Thermal Engineering, vol.24(17-18), pp.2487-2500.

13."Waste Management and Recycling Techniques"

Published Results:

- **Konstantinidis P., Giarikis Ath., Kaldellis J.K., 2003**, "Evaluation of Domestic-Waste Collection System of Nikaia Municipality. Improvement Proposals", 8th International Conference on Environmental Science and Technology, Conference Proceedings, University of Aegean, Global-NEST, Lemnos, Greece.
- **Konstantinidis P., Skordilis A., Kaldellis J.K., 2001**, "Recycling of Electric and Electronic Waste in Greece: Possibilities and Prospects", 7th International Conference on Environmental Science and Technology, Conference Proceedings, vol.A, pp.460-469, University of Aegean, Global-NEST, Syros, Greece.
- **Sakkas Th., Kaldellis J. K., 2001,** "Environmental Behavior of a Charcoal Gasification System. Experimental and Theoretical Investigation", International Conference on "Ecological Protection of the Planet Earth I", vol.II, pp.625-632, Xanthi, Greece.
- **Konstantinidis P., Spiropoulos V., Vamvakis A., Kaldellis J.K., 2000,** "Energy Savings and Cost Reduction by Recycling the Demolition-Construction Debris", International Conference, Protection & Restoration of the Environment V, pp.869-878, Thassos, Greece.

14."Waste Water Treatment Applications"

Published Results:

- **Kondili E., Kaldellis J.K., 2005**, "Water Use Planning with Environmental Considerations for Aegean Islands", 13th International Symposium of MESAEP, Thessaloniki-Greece.
- **Kondili E., Kaldellis J.K., 2002**, "Waste Minimization and Pollution Prevention by the Use of Production Planning Systems", International Conference, Protection and Restoration of the Environment VI, Conference Proceedings, pp. 1277-1284, Skiathos Island, Greece.
- **Sigalas J.S., Kavadias K.A., Kaldellis J.K., 2000,** "An Autonomous Anaerobic Wastewater Treatment Plant Based on R.E.S. Theoretical and Experimental Approach", International Conference, Protection and Restoration of the Environment V, pp.735-743, Thassos Island, Greece.
- **Kaldellis J.K., Vlachou D., Konstantinidis P., 1999**, "Sea Pollution by Oil Products. A Comparative Study of Combating Oil Spills in the Aegean Sea", 6th International Conference on Environmental Science and Technology, Conference Proceedings, vol.C, pp. 729-737, University of Aegean, Pythagorion, Samos, Greece.

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

Published Results:

- **Kaldellis J.K., 2005**, "Social Attitude Towards Wind Energy Applications in Greece", *Energy Policy Journal*, vol.33(5), pp.595-602.
- **Kaldellis J.K., Kavadias K.A., 2004**, "Evaluation of Greek Wind Parks Visual Impact: "The Public Attitude" *Fresenius Environmental Bulletin*, vol.13(5), pp.413-423.
- **Kaldellis J. K., 2001**, "The Nimby Syndrome in the Wind Energy Application Sector", International Conference on "Ecological Protection of the Planet Earth I", vol.II, pp.719-727, Xanthi, Greece.

Research Projects under Development *(1/2)*

Participation in Research Programs (2002-2005)

1. "***Overview of Incentive Programmes on Alternative Motor Fuels and Review of their Impact on the Market Introduction of Alternative Motor Fuels***", PREMIA Project, sponsored by DG TREN

2. "***Optimum Micrositing of Selected Wind Parks in Peloponnesus***", supported by the Centre for Technological Research of Piraeus and Islands.

3. "***Maximum Energy Autonomy of Greek Islands on the Basis of Renewable Energy Sources***" Research Program "Archimedes-I" supported by the Greek Ministry of Education

4. "***Advanced Control Systems in the Water Supply Networks***" Research Program "Archimedes-I" supported by the Greek Ministry of Education

5. "***Transformation of a Typical Vapor Compression Air-Conditioning System to a Combined Air Conditioning System Based on Solar Energy***", Research Program "Archimedes-I" supported by the Greek Ministry of Education

6. "***Feasibility Study Concerning the Parameters of Ecological Behavior of Buildings in Natural and Urban Environment***", Research Program "Archimedes-I" supported by the Greek Ministry of Education

7. "***VISION: A New Vision for Engineering Economy***" (TEMPUS, 2004, in collaboration with Italy, Egypt and UK)

8. "***Integrated Study and Prediction of Electricity Related Air Pollution (NO_x, SO_2, CO_2) in Greece in View of the European Efforts for Improving the Air Quality***", Research Program "Archimedes-II" supported by the Greek Ministry of Education

9. "***Simulation-Study of the Energy Behavior of Buildings using Economically Acceptable Passive and Hybrid Solar Systems and Construction Materials in order to Improve the Thermal Behavior of Greek Buildings***", Research Program "Archimedes-II" supported by the Greek Ministry of Education

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

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

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PART ONE

EDUCATION

- Renewable Energy Applications
- Environmental Protection

EDUCATION AND RESEARCH ON RENEWABLE ENERGY SOURCES (RES): THE SOFT ENERGY APPLICATIONS LABORATORY OF TEI OF PIRAEUS

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Abstract

Renewable Energy Sources (RES) have an excellent potential in Greece, however various legal, social and technical obstacles have limited their applications. In this article the present status and future prospects of RES applications in Greece are presented. The importance of well educated professionals in the field is emphasized. In addition, the main educational and research activities of the Soft Energy Applications Laboratory of TEI of Piraeus are described in brief. More specifically, emphasis is laid on illustrating the mission, the infrastructure, the research areas as well as the syllabus of the courses offered, along with the future plans of the Lab.

Keywords: Renewable Energy Sources; Education; Applied Research; TEI of Piraeus; Wind Power; Solar Energy; Biomass; Geothermal Energy; Hydropower; Techno-economic Evaluation; Environmental Impacts

1. Introduction

During the last 25 years that have followed the Greece incorporation in the European Union, there is a continuous increase in the primary and electric energy consumption, covered by oil and natural gas imports, as well as low quality local lignite, with obvious economic and environmental impacts in the national economy and society in general. In order to present some indicative magnitudes, the national energy balance for year 2002 is shown in figure (1)[1,2].

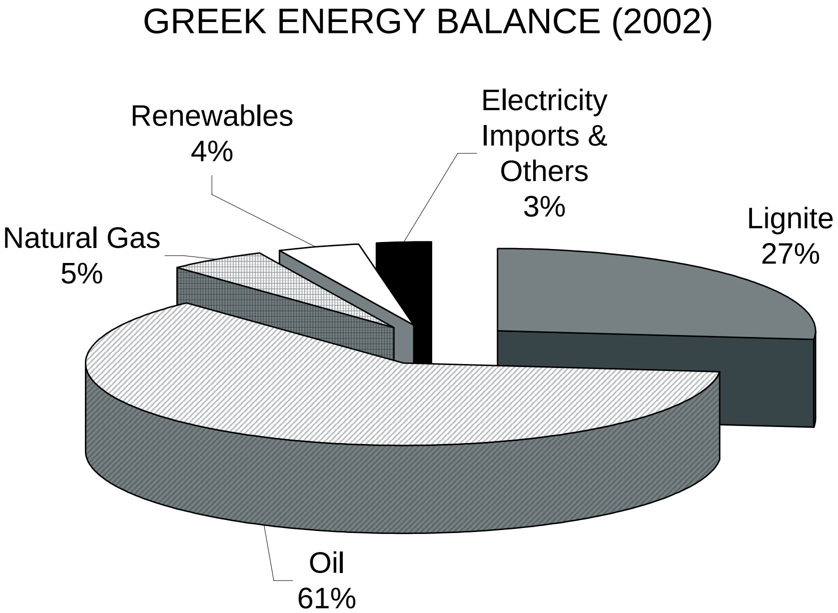


Figure 1: Greek Primary Energy Consumption Analysis

Kaldellis J.K., Kavadias K., Kondili E., Spyropoulos G., 2005, "Education and Research on Renewable Energy Sources (RES): The Soft Energy Applications Laboratory of TEI of Piraeus", International Conference on "Integration of RES into Buildings", July 2005, Patras, Greece

Similarly, Greece, since 1950, has based its electricity production system on locally mined lignite and imported heavy-oil. In fact, lignite and heavy oil fired stations generated during the last 25 years almost 80% of the national electricity production, figure (2), while the contribution of renewable energy sources (mainly wind) and large hydropower units rated less than 10%. In this context, Table I shows the contribution of each RES for year 2000 (the most recent year that official data exist) and Table II compares the energy balances of years 1991, 2002[3].

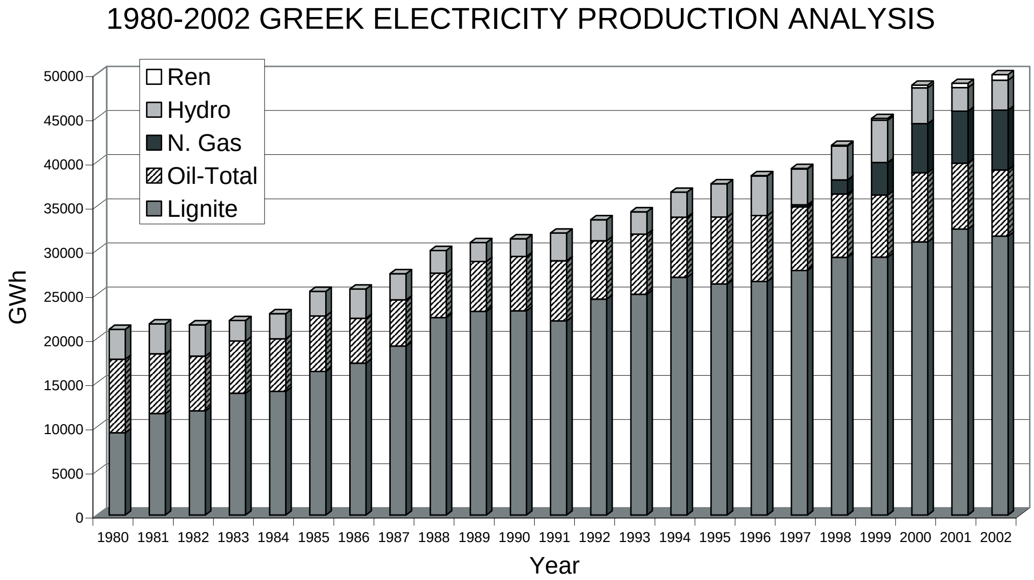


Figure 2: Greek Electricity Sector Time-Evolution

Table I: RES Energy Production Analysis (2000)

SOURCE	ktoe
Biomass	946
Wind Energy	38.8
Small Hydro	14.28
Large Hydro	303.5
Photovoltaics	0.024
Solar-Thermal	99
Geothermal Heat	1.61
TOTAL	**1,403**

Table II: National Energy Balance (%)

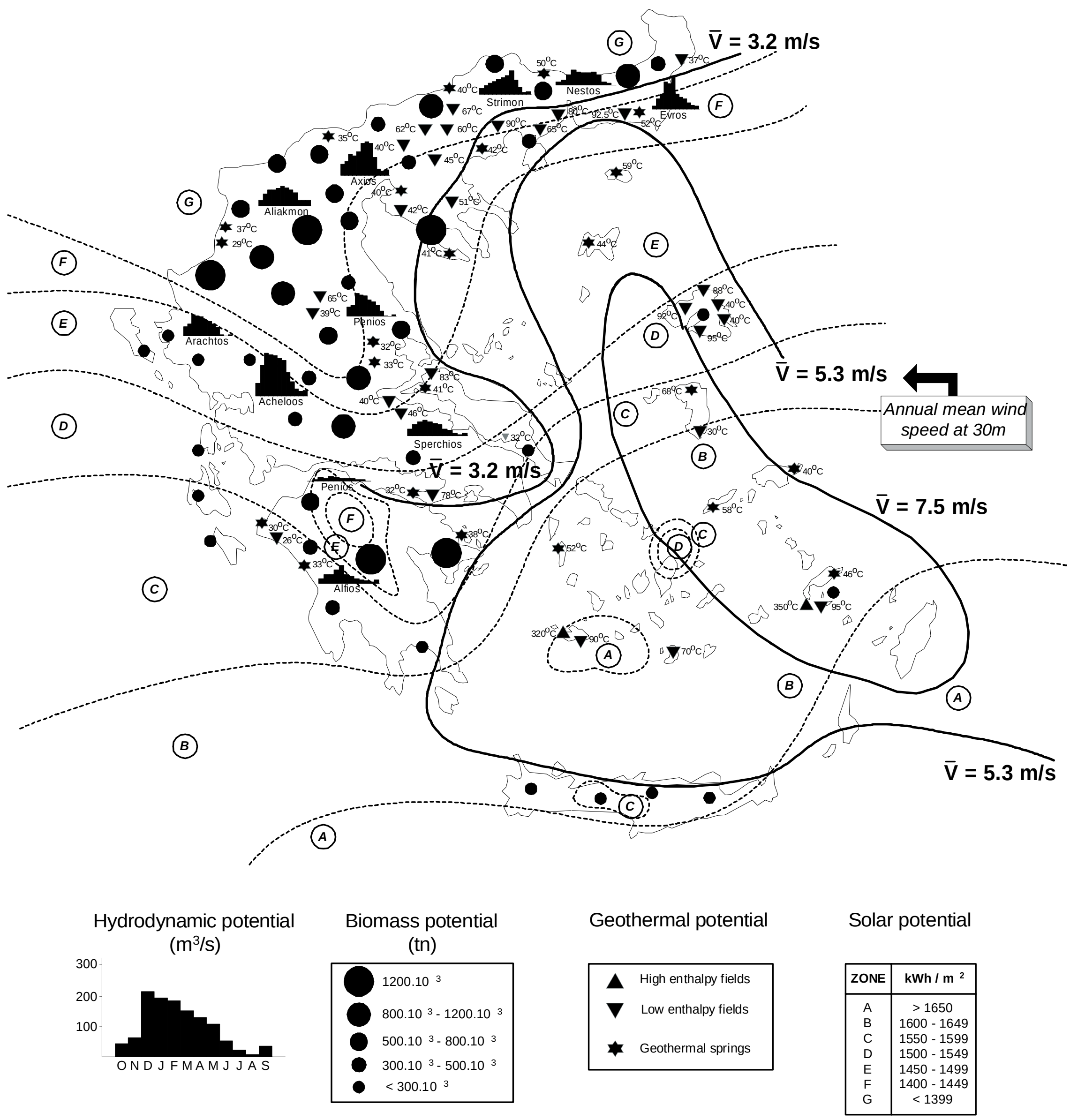
ENERGY SOURCE	1991	2002
Lignite-Charcoal	28.9	26.6
Oil	61.7	61.4
Natural Gas	0.6	5.2
Renewable Energy Sources	5.2	4.2
Electric Energy Imports	3.6	2.7
TOTAL	**100**	**100**

However, serious efforts are made for the rational use of energy and energy conservation, including cogeneration projects and, mainly, the exploitation of local Renewable Energy Sources. Greece has excellent RES potential[4]. The island and mountain areas of the country have very good wind potential[5], while the whole country possesses excellent solar radiation[6]. In addition, most of Nothern and Western areas have very good hydropower potential[7] supported by the local geomorphology and many areas of Central and Eastern Greece have abundant high, average and low enthalpy geothermal fields[8], while remarkable biomass reserves are also mentioned[9], see also figure (3). Finally, figure (4) shows the last ten year evolution of the existing RES based power generation stations[10].

From the above described situation it becomes obvious that the current contribution of RES in the national energy balance is rather low, compared to their excellent potential. However, the exploitation of local energy sources, and, especially, RES and cogeneration may have a very significant contribution to the safety of energy supply[11] and the environmental protection[12].

In addition, it is well known that RES development and the implementation of energy conservation measures contribute to the regional development and create new employment opportunities in remote areas.

THE POTENTIAL OF RENEWABLE ENERGY SOURCES IN GREECE



ZONE	kWh / m 2
A	> 1650
B	1600 - 1649
C	1550 - 1599
D	1500 - 1549
E	1450 - 1499
F	1400 - 1449
G	< 1399

Figure 3: RES Potential in Greece

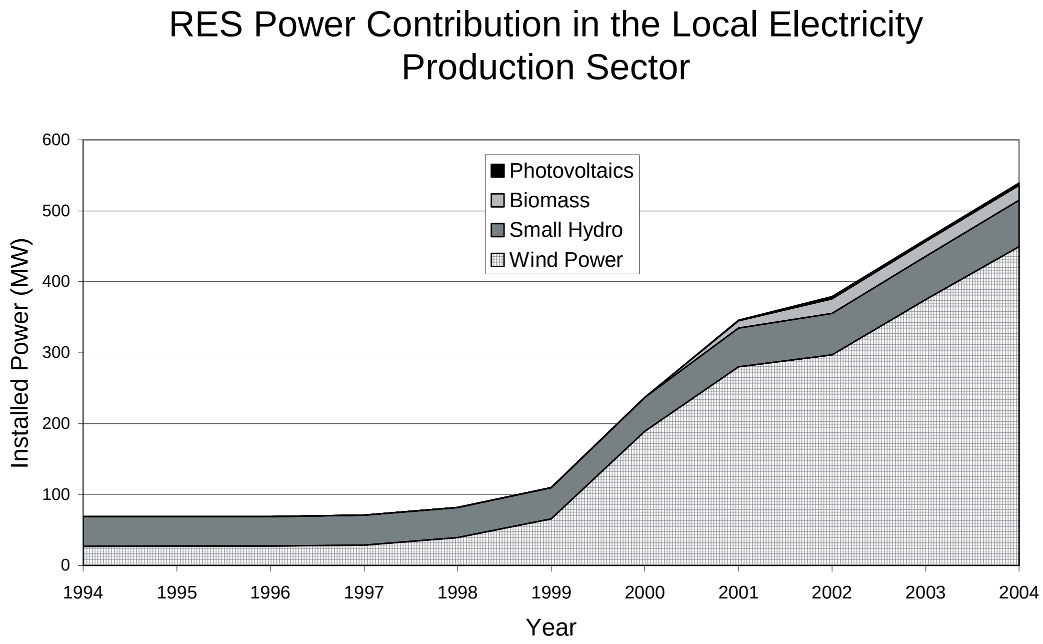


Figure 4: RES Applications in the Last Decade

On the other hand, there is a number of driving forces that will definitely enhance the role and contribution of RES in our national energy balance for the next five to ten years. More specifically, these driving forces are:

- ✓ The European and international attitude against the environmental impacts caused by the conventional power generation stations and the national legislation that sets severe constraints on the greenhouse gases emissions.
- ✓ The European legislation, (Directive 2001/77/EC) that defines the Greek RES contribution in the National Energy Balance to the percentage of 20.1% (including the large hydro-plants).
- ✓ The New Development Law (3299/2004), as the previous ones (2601/1998, etc.) that supports RES investments with 40% subsidy all over the country.
- ✓ The Operation Program "Competitiveness", (Ministry of Development) supporting energy efficient and environmentally friendly investments. A significant number of proposals for RES applications has already been approved and will be implemented in the next years.

2. The SEALAB of TEI of Piraeus

Despite of the previously described slowly moving present situation, the Renewable Energy Business sector exhibits good prospects, since the European governments have made a commitment to increase the contribution of the RES in the energy balance of the member states. There is no doubt that the RE industry will flourish with many job opportunities being realized over the next five to ten years[13]. As it happens in all business sectors, this industry needs professionals who are technically proficient, socially responsive and highly motivated[14].

The Soft Energy Applications and Environmental Protection Laboratory (SEALAB[15]) has been created in 1991 in the Mechanical Engineering Department of TEI of Piraeus. Exploiting it's significant and over a decade accumulated experience, the SEALAB goals extend to three main directions:

- ➢ To offer high quality and modern undergraduate and postgraduate educational courses in its fields of specialization,

- To develop and maintain a remarkable infrastructure, in order to support its educational and research activities, and,
- To continue and develop its research activities and be recognized as a highly specialized partner in Greek and European research teams.

In the rest of the present paper, these three main axes of activity are described in detail and the future directions are highlighted.

3. Educational Activities

The courses being offered[15,16] provide theoretical knowledge and practical experience in a wide range of renewable energy options such as wind, solar, geothermy, biomass, hydro, along with a contextual understanding of the social, political, economic and environmental motivations present in their development and application. More specifically, in addition to the purely technical content of the various courses, great efforts are made to transfer integrated knowledge by tackling issues like the criteria for a rational energy source selection[17,18], assessment of the environmental consequences of the various energy sources[19,20], feasibility studies of energy investments[21,22], social cost-benefit analysis[23] of energy and environmental projects, etc. The Soft Energy Applications & Environmental Protection Lab offers the courses of Table III.

Table III: Courses Offered by the SEALAB

Course	**Semester**
Introduction to Renewable Energy Sources	5th
Lab of Renewable Energy Sources	5th
Applications of Renewable Energy Sources (Lab & Theory)	6th
Energy Engineering & Management of Natural Resources	4th
Environment & Industrial Development	2nd
Basic Principles of Ecology	2nd
Air Pollution-Pollution Prevention Technologies	5th
Environmental Measurements Technology	5th
Waste Management Systems (Lab & Theory)	7th
Design & Optimisation of Energy Systems	7th

The syllabus of each course is described below:

a. Introduction to Renewable Energy Sources

- ✓ Introduction to the Wind Energy Technology
- ✓ Introduction to the Solar Energy Technology
- ✓ Introduction to the Biomass Systems
- ✓ Introduction to the Hydroelectric Energy Systems
- ✓ Introduction to the Geothermal Energy
- ✓ Innovative Applications of RES
- ✓ Cost-Benefit Analysis & RES Applications
- ✓ Impact of External Cost on RES Investment Options

b. Applications of RES

- ✓ Integrated Wind Energy Applications
- ✓ Stand-Alone Systems
- ✓ Geothermal-Solar Greenhouse Design and Energy Balance Analysis
- ✓ Wind–Hydro Systems
- ✓ Photovoltaic Applications
- ✓ RES Based Desalination

- ✓ Energy Storage Systems for RES Applications
- ✓ Integrated Feasibility Studies & RES Applications

c. Energy Engineering and Management of Natural Resources
- ✓ Introduction in the Energy Demand Problem
- ✓ Analysis of Local Energy Consumption Problem
- ✓ Energy Quality –Exergy Analysis
- ✓ Cogeneration Systems
- ✓ Energy Conversion Technologies
- ✓ Energy Saving Technologies
- ✓ Introduction to Fuel Cell Technology
- ✓ Rational Management of Natural Resources
- ✓ Introduction to Energy Economics

d. Environment & Industrial Development
- ✓ Development Constraints and Sustainability
- ✓ Basic Elements of Air Pollution
- ✓ Greenhouse Phenomenon
- ✓ Ozone Depletion
- ✓ Acid Rain
- ✓ Sea Pollution
- ✓ Waste Water Management
- ✓ Toxic Waste Management
- ✓ Solid Waste Management
- ✓ Devastation
- ✓ Nuclear Energy and Environmental Pollution

e. Basic Principles of Ecology
- ✓ Ecosystems and Environmental Balance
- ✓ Planetary Ecosystems and Environmental Problems
- ✓ Human Effect in Planetary Ecosystems
- ✓ Ecosystems Simulation Models
- ✓ Moral and Technological Problems of Development
- ✓ Life Cycle Assessment
- ✓ Environmental Impact Assessment
- ✓ Introduction to Risk Assessment

f. Air Pollution–Pollution Prevention Technologies
- ✓ Air Pollution Prevention in the Power Industry
- ✓ Pollution Prevention in the Transportation Sector
- ✓ Pollution Prevention in the Industrial Sector
- ✓ Pollution Prevention in the Services Sector
- ✓ Automobile Catalytic Converters
- ✓ Air Pollution Data Banks
- ✓ Air Pollution Measurement Methods and Techniques

g. Environmental Measurements Technology
- ✓ Introduction to Measurements Strategy
- ✓ Experimental Data Assessment
- ✓ Wind Speed Measurements
- ✓ Solar Radiation Measurements
- ✓ Pressure, Temperature and Humidity Measurements
- ✓ Noise and Visual Impact Assessment
- ✓ Measurements of Water Parameters
- ✓ Integrated Systems for Air Pollution Measurements

- ✓ Steady and Moving Pollution Sources Analysis
- ✓ National and International Pollution Data Bases

h. Waste Management Systems

This course is implemented in collaboration with the Optimisation of Production Systems Lab[16] of Mechanical Engineering Department and it includes the following:

- ✓ Physical, Chemical and Toxic Characteristics of Waste Water
- ✓ Greek and European Union Legislation for Waste Disposal
- ✓ Solid Waste Characteristics
- ✓ Main technologies for Solid Waste Management
- ✓ Municipal Waste Water Management
- ✓ Industrial Waste Water Management
- ✓ Waste Water Treatment Systems
- ✓ Sea Pollution Prevention Technologies
- ✓ Toxic Waste Management Technologies
- ✓ Design, Implementation and Management of Environmental Projects
- ✓ Cost Estimation of Major Environmental Technologies and Projects

i. Design & Optimisation of Energy Systems

This course covers the design and optimisation aspects of various energy systems and is implemented with the cooperation of three labs of the Mechanical Engineering Department (Steamboilers-Steamturbines Lab, Optimisation of Production Systems Lab, SEALAB). The topics covered by the SEALAB are:

- ✓ Energy systems optimisation with the use of hybrid systems
- ✓ Integrated Energy and Fresh Water Solutions for Remote Consumers
- ✓ Cost Benefit Assessment of Integrated Energy Systems
- ✓ Social Attitude & Environmental Cost Impact on Optimising Energy Production Systems
- ✓ Reliability Impact on Energy Systems

4. Lab Infrastructure

The SEALAB of TEI of Piraeus has developed an infrastructure available for education, training and research activities. Various lab exercises[4] of the courses being offered are carried out in the equipment and measurement instruments of the Lab, thus providing practical experience to the students and consolidating their theoretical knowledge.

The main equipment of the Lab related with the Energy Production Sector is the following:

- Windgenerator BW-1-KAS, an experimental wind turbine with fixed pitch of 2.5kW on the campus, figure (5).
- A small wind turbine of variable pitch of 200W, operating in combination with an existing low speed wind tunnel, figure (6).
- Equipment for measuring wind speed, e.g. figure (7).

Figure 5: Experimental Wind Turbine

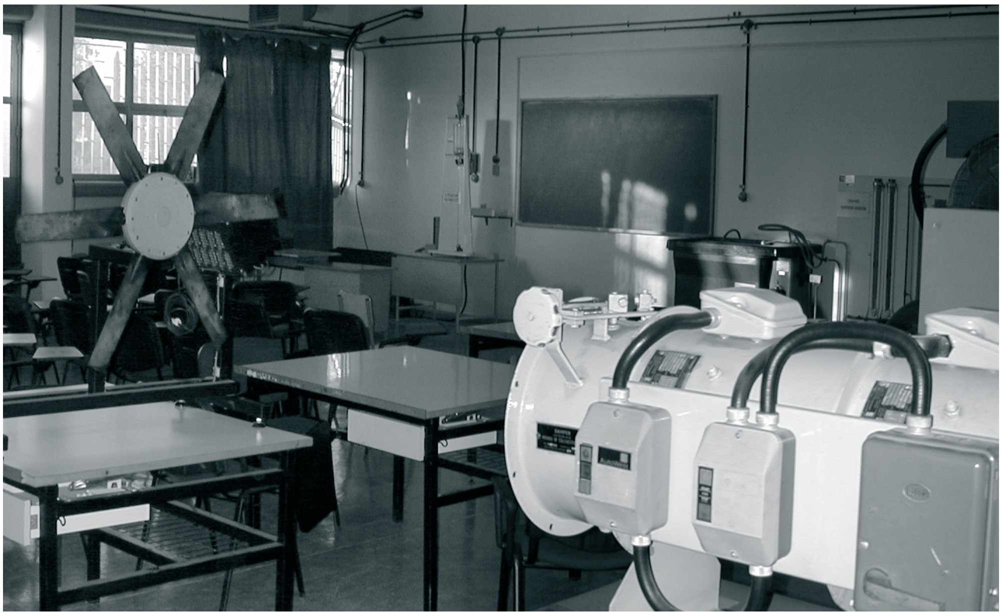


Figure 6: Small Wind Turbine-Existing Low Speed Wind Tunnel

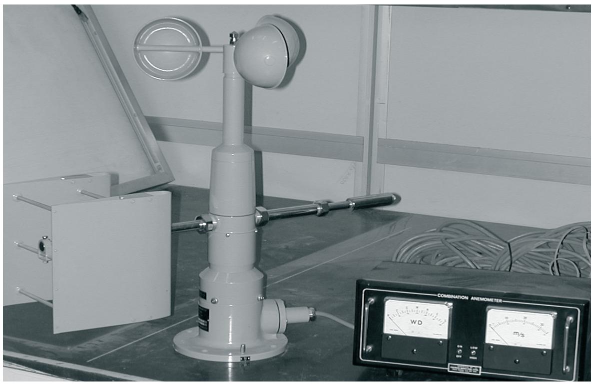


Figure 7: Remote Anemometer

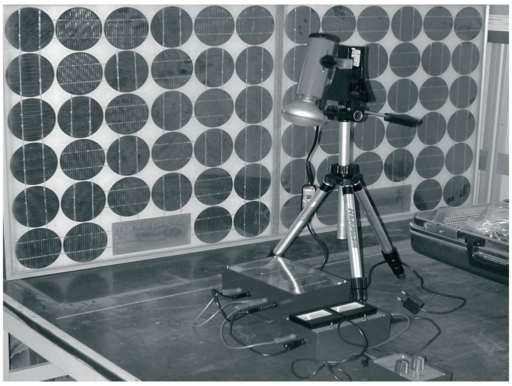


Figure 8: PV Experimental Configuration

- Photovoltaic (stand-alone systems, grid integrated applications), figure (8).
- Solar Collectors (Active Solar Systems: flat plate and evacuated heat pipe solar collectors, e.g. figure (9).
- Biogas & Biomass Production Installation, figure (10).
- Experimental system based on a small anaerobic bioreactor-thickener device, figure (10), used to simulate an integrated Waste Water Treatment Plant.
- BOD Measuring Apparatus
- Various Instruments

5. Research Activities

The SEALAB of TEI of Piraeus has been working for the last ten years in the areas of Renewable Energy Sources and Environmental Technology[24]. More specifically, the SEALAB has been working in the following ***energy related*** areas:

✓ Wind and Solar Energy Applications[25-28]
✓ Feasibility Studies on Energy Investments[29,30]

- ✓ Hybrid Energy Systems[31-34]
- ✓ Energy Storage Systems[35,36]
- ✓ Energy Saving[37]
- ✓ Cogeneration Systems[38]
- ✓ RES based Desalination[39]
- ✓ Environmental Impact of Power Stations[40,41]

Figure 9: Evacuated Heat Pipe Solar Collector

Figure 10: Experimental Bioreactor

The SEALAB is also carrying extensive research in the area of Environmental Protection Technologies. In fact SEALAB has participated in the following projects:

- ➢ Hellenic-French Collaboration Research Program "Platon" entitled "Advanced Techniques of Automation in Wastewater Treatment Plants"
- ➢ Development of an Experimental Hybrid Plant based on a Wind Turbine-PV Station Collaboration, supported by T.E.I. of Piraeus
- ➢ Reorganization of Mechanical Engineering Department, supported by EPEAEK-Greek Ministry of Education
- ➢ Program "RENES-Unet", for the Diffusion of Renewable/Soft Energy Applications in Greece and European Union
- ➢ Techno-economic Study of Small Hydro Power Stations, supported by the private company EMPEDOS SA
- ➢ Water Pumping Storage Systems for Crete Island, in collaboration with the Technical University of Crete and the Enercon Hellas SA
- ➢ Desalination System Based on Gas-Turbines Exhausted Gases, supported by PPC and Crete Municipalities Union
- ➢ NATURA-2000, supported by the Greek Ministry of Environment, Physical Planning and Public Works
- ➢ Natural Gas Cogeneration Opportunities in Urban Areas, in collaboration with the Municipality of Nikaia
- ➢ Energy Saving in TEI Buildings, supported by TEI of Piraeus

The Lab is currently active in the following research areas:

- Improving the Hybrid Power Stations Viability for the Region of Aegean Archipelago
- Estimation of Social-Environmental Cost in the Energy Production Sector
- Technological Progress in Wind Energy-Solar Energy Market
- Flow Field Prediction for High Speed Turbomachines
- Social Attitude Towards Wind Energy Applications in Greece
- Combined Wind-Photovoltaic Stand-Alone Applications

- Evaluation of Energy Storage Systems
- Air Pollution Analysis
- Air Pollution Impact on Children and other Delicate Social Groups
- Autocats Standardization and Recycling
- RES Based Desalination
- Waste Management and Recycling Techniques
- Waste Water Treatment Applications

The Laboratory has been contributing to the following research projects supported by National or European funds:

- ✓ Maximization of the Energy Autonomy of Greek Islands with the Use of Hybrid Energy Systems (ARCHIMEDES I, 2004)
- ✓ Advanced Control Systems in the Water Supply Networks (ARCHIMEDES I, 2004; in collaboration with the Lab of Intelligent Systems of TEI of Piraeus)
- ✓ Transformation of a Typical Vapor Compression Air-Conditioning System to a Combined Air Conditioning System Based on Solar Energy (ARCHIMEDES I, 2004; in collaboration with the Lab of Steamboilers-Steamturbines of TEI of Piraeus)
- ✓ Feasibility Study Concerning the Parameters of Ecological Behavior of Buildings in Natural and Urban Environment (ARCHIMEDES I, 2004; in collaboration with the TEI of Chalkida)
- ✓ VISION: A New Vision for Engineering Economy (TEMPUS, 2004, with Italy, Egypt and UK)
- ✓ 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 (ARCHIMEDES II, 2005)
- ✓ 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 (ARCHIMEDES II, 2005; in collaboration with the Lab of Fluids of TEI of Piraeus)

Finally, the Lab has recently started being active in the area of water management systems, especially in the area of the combined exploitation of RES for energy and fresh water production. To that effect, the Lab participates in the recently approved research project: "Optimisation of Water Systems in Islands with Limited Water Resources" (ARCHIMEDES II, 2005), in collaboration with the Optimisation of Production Systems Lab of Mechanical Engineering Department.

6. Conclusions-Futures Prospects

The Soft Energy Applications & Environmental Protection Lab, in addition to its educational task, makes continuous efforts to contribute significantly in the development of new, affordable and operational tools, methods and technologies for the promotion and the application of RES and Environmental Protection in Greece, by its research activities and the continuous improvement of the education being offered.

The laboratory’s research efficiency during the last decade has resulted into the development of innovative methods and technologies in the area of RES applications and environmental technology. The application of those technologies appear to have a special interest in our country. In addition, some of the research results have a wide academic recognition.

Despite the infrastructure difficulties being faced, the SEALAB invests in the development of small and flexible research groups, and collaborates with scientific teams from the same institution and other universities and companies.

Following up the career path of its former students, the Lab has realised that many graduates actually follow a profession in these subjects.

Finally, the Lab intends to integrate its existing and significant experience in the fields of Energy and Environmental Engineering with the design, development and implementation of a high quality Postgraduate Course in the filed of Renewable Energy Applications and Environmental Technology. The course scope will be to educate Engineering graduates in the design, construction, operation and maintenance of RES applications. The course also intends to focus its attention to strategic issues in the above areas, such as the evaluation of the economic and environmental consequences of the operation of these plants.

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UNDERSTANDING THE QUANTIFIED PERFORMANCE OF ENGINEERING STUDENTS IN ENVIRONMENTAL CLASSES

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Abstract

The environmental education is considered to be a vital element for every level of the modern formal education. Despite this fact, numerous scientific disciplines including the various engineering fields have been resisting in the introduction of environmental courses, considering them as irrelevant to the core engineering interests. However, the growing importance of the environmental aspects in the education of engineers has significantly contributed in changing this attitude, giving them the ability to adapt more efficiently with environmental legislation and certification needs as well as to improve their general environmental sensitivity in designing and constructing procedures.

In this scope the Mechanical Engineering Department of the Technological Educational Institute of Piraeus is offering to the students a wide variety of environmental related courses. The Laboratory of Soft Energy Applications and Environmental Protection is playing a key role in supporting the environmental educational and research activities of the engineering students both in undergraduate and postgraduate level. While there are mandatory environmental courses available in the engineering syllabus, the present paper focuses on the most popular optional environmental course offered by the Mechanical Engineering department entitled "Basic Principles of Ecology". Special emphasis is placed apart from the educational procedure and the evaluating methods, on the better understanding of the quantified performance of the engineering students. Not only is the latter considered to be part of the students' evaluation but also a useful feedback for improving the course syllabus and presentation.

Although the teaching procedure of the course in question is based on lectures and not on laboratory experiments, the evaluation method may optionally consist of multiple parameters at the students' choice. More precisely apart from the final exams the students can choose from weekly, short length tests on the taught material and the preparation of three application essays. The current study utilizes the data concerning the quantified performance of the students, through the evaluation process in the aforementioned assignments. Valuable results regarding the week after week teaching procedure as well as the evolution of numerous proposed indicators and indexes are being extracted.

It is well recognized that there is a growing demand for broader and deeper environmental education for the engineers. The in depth discussion of the statistical analysis held out is, according to the authors, a tool of crucial importance for the comprehensive auditing and improvement of the class work being done. Moreover the results are considered to be beneficial for the students who can improve their studying efficiency by choosing the most suitable path in order to gain the best results and knowledge.

Keywords: Environmental Education; Environmental Engineering; Industrial Ecology; Students' Performance

1. Introduction

The education for the environment and sustainable development has been mainly approached through separate departments specialized in environmental studies[1]. However, nowadays the environmental

Chalvatzis K.J., Skanavis C., Kaldellis J.K., 2005, *"Understanding the Quantified Performance of Engineering Students in Environmental Classes", 9th Conference on Environmental Education in Europe, CEEE-2005, Klaipeda, Lithuania.*

education is considered to be a vital element for every level of the modern formal education. Despite this fact, numerous scientific disciplines, including the various engineering fields, have been resisting in the introduction of environmental courses considering them as irrelevant to the core engineering interests[2]

Even in the case that environmental classes are finally approved in the engineering departments these tend to be included in the optional courses bank, away from the mandatory curriculum[3] Nevertheless, the growing importance of the environmental aspects in the education of engineers has significantly contributed in changing this attitude, giving them the ability to adopt more efficiently with a number of tasks.

As such may be considered the adoption to the increasing environmental legislation as well as the various environmental performance certifications for operational management or specific constructions[4]. Moreover it is in the very core of the engineering profession to interfere with the environment and burden it in some respects[5]. However, although the expertise level in anti-pollution and conventional technology is relatively high, a spherical consideration of the environment is what seems to be the missing element of the environmental education for engineers[6].

2. Brief Description of the Case Studied

The Technological Educational Institute of Piraeus is divided into two major Schools. The School of Technological Applications and the School of Management & Economics which consist of seven and two departments respectively. While the latter presents very limited interest for the current paper, the former successfully features a wealth of technology-related departments including those of Mechanical Engineering, Electrical Engineering, Systems Automation, Electronics Engineering, Information Technology, Textile Engineering and Civil Engineering.

Although most of the aforementioned Departments have done noteworthy steps towards the implementation of Environmental Education, the Mechanical Engineering Department in particular is offering to the students a wide variety of environment-related courses. The Laboratory of Soft Energy Applications & Environmental Protection is playing a key role in supporting the educational and research activities of the engineering students both in undergraduate and postgraduate level[1].

More specifically the undergraduate program[7] of the Mechanical Engineering Department includes mandatory and optional courses with environmental and energy context. These are the: "Environments' Industrial Development", "Introduction to Renewable Energy Sources", "Lab of Renewable Energy Sources", "Applications of Renewable Energy Sources", "Energy Mechanics and Management of Natural Resources", "Basic Principles of Ecology", "Atmospheric Pollution – Antipollution Technologies", "Environmental Measurements Technologies", "Waste Management Systems", "Design and Optimization of Energy Systems". Finally, the postgraduate course concerns the remarkable "MSc in Energy" offered in collaboration with the University Herriot-Watt of Scotland.

The course examined in the present paper is the "Basic Principles of Ecology", which is offered on an optional basis. It has been chosen among the other optional courses due to its high popularity. The week after week syllabus of the course can be mainly separated into three parts. First comes the Descriptive Ecology which discusses issues regarding the natural ecosystems and describes the relations and factors influencing their balance. Second follows the Quantitative Ecology, dealing with aspects of population evolution and dynamics not only for the natural but also for the manmade ecosystems. Finally, the course stresses the topic of Industrial Ecology in terms of a deeper understanding of input and output flows, constantly in the light of the most environmentally friendly procedures.

While the syllabus of the course in question can be considered as extensive the evaluation methodology consists of various options on the choice of the students. These include weekly brief tests on the taught material offered as well as essays on the three aforementioned parts of the course. One may not disregard the final written exams as the core evaluation methodology. However, it is noteworthy that the students who will gain sufficient credit from the weekly tests and the written assignments are exempted from the final written exams. Regarding the students who will try unsuccessfully to be released from the final exams, they will still have their papers marked with a bonus depending on the credit they managed to gather during the semester.

3. Evaluation of the Results

As already mentioned the "Basic Principles of Ecology" course, is the most popular among the optional environment-related courses offered. More precisely the students enrolled in the course initially have been more than 240 (figure (1)).

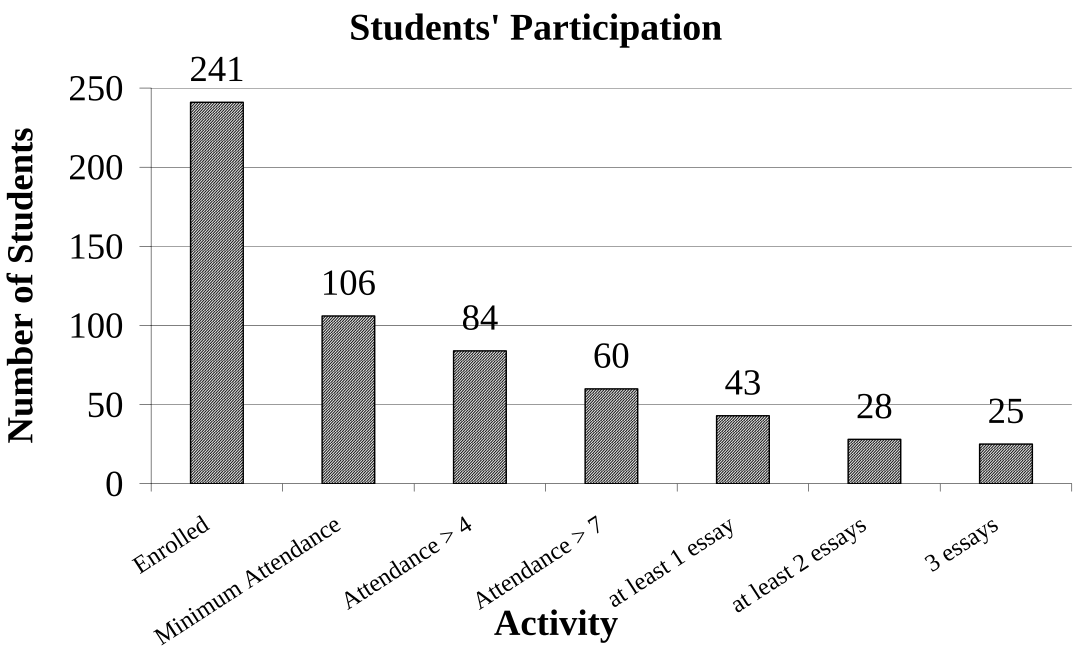

Figure 1: Students' Participation

Although this number might be considered as enormously high it is a common practice that students are registered in more courses than what they will finally be able to attend. Therefore the number of students who have appeared in the classroom for at least once throughout the semester was only 106. Nevertheless not more than 84 and 60 have been the students who attended the class for more than 4 and 7 times respectively. Regarding the written assignments, that the students can optionally prepare, one may notice in figure (1) that while 43 essays have been delivered during the first session of the semester, only 28 and 25 students worked on the second and third essay accordingly.

Concerning the observed decrease in the number of students decided to study for the second and third assignment one may suppose that after being informed for the mark of the first one many realized that it would not be of interest to continue with the forthcoming essays. The same picture is reflected in figure (2), where the evolution of the number of students attending every week is presented. After the third week and the completion of the first session ten students decided to drop out.

The same happens after the sixth week and the completion of the second session. The rise of the students which occurs in the ninth week can be connected to the common practice of the course in question to present revision exercises helping those students who will sit the final exams.

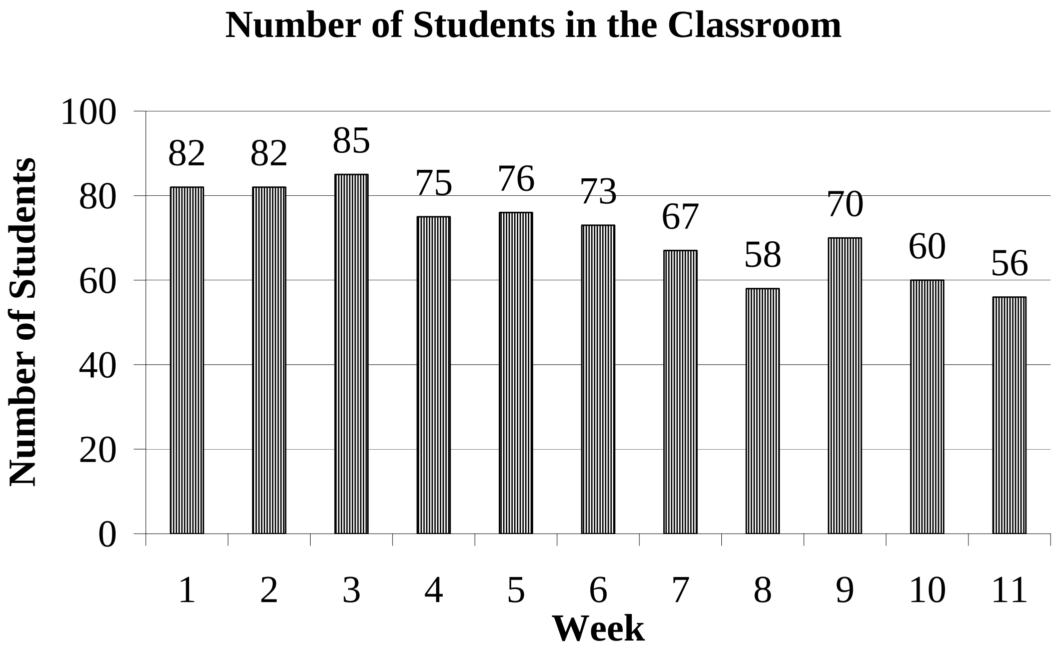

Figure 2: Number of Students in the Classroom

4. Discussion of the Results

Observing the final results after having finished the semester and the written exams some interesting points should be highlighted. To begin with, only 21 of the students finally succeed to avoid the final written exams. However, the number of students who attended more than 7 classes and delivered all the 3 requested assignments was 25. Therefore one may notice that 84% have been successful.

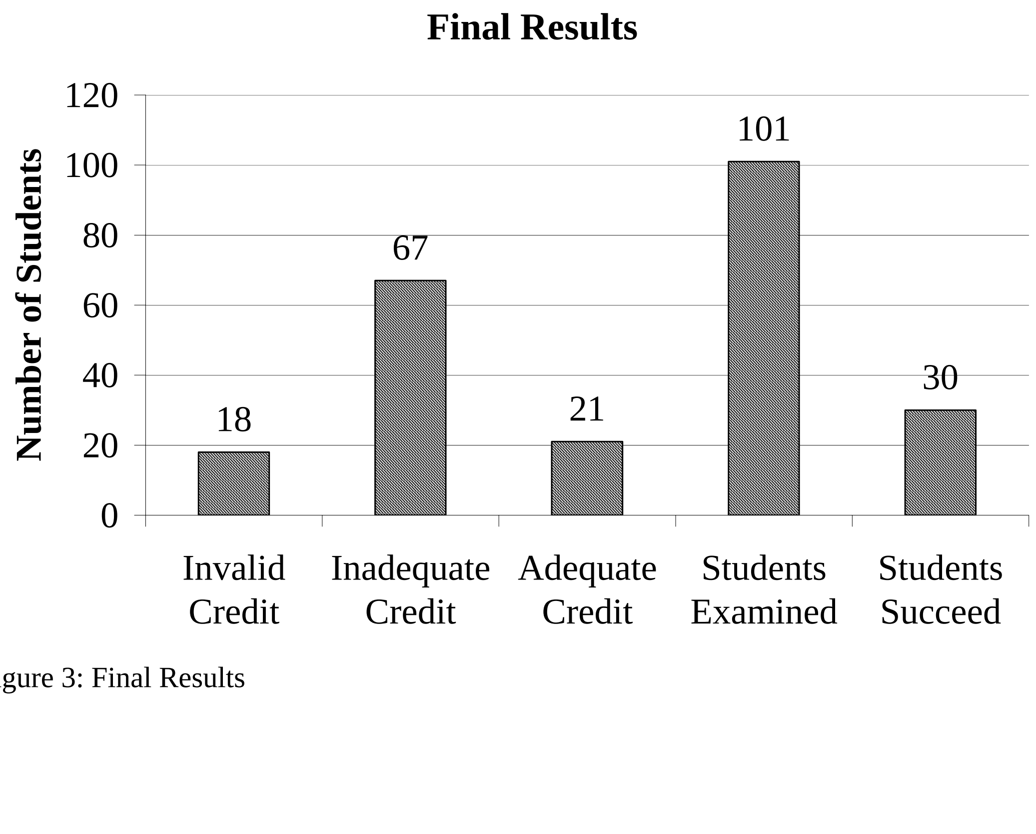

Figure 3: Final Results

While 21 students have managed to avoid the final written exams the 80% (85 pupils) of the students who attended at least one class did not manage to gain an adequate credit. Therefore 67 of them will be able to sit the exams being benefited by a significant bonus in their mark. Finally only 18 students collected a credit of insignificant value that will be of no importance in their exams.

Concerning the final written exams one may notice in figure (3) that 101 students are taking part and only 30% achieve a sufficient mark. Needless to say that the vast majority of the successfully examined students is coming from the group of the 67 ones who had collected a credit due to their class work. Not only was the credit of particular help but also the fact that these students have been attending rather regularly the lectures and working at least for some of the written assignments contributed in a better understanding of the course's syllabus.

A final consideration should be placed on the comparative assessment among the different sessions presented throughout the semester concerning separate aspects of the science of Ecology. Data show that the session of industrial ecology is the one marked higher. While in no case, industrial ecology can be considered as a comparatively easier session, the authors believe that the mechanical engineering students simply tend to find it more interesting. In an attempt to explain the higher marks observed in the last session (industrial ecology) one may not disregard the fact that the students taking part are the best qualified ones, having already completed successfully the two previous sessions.

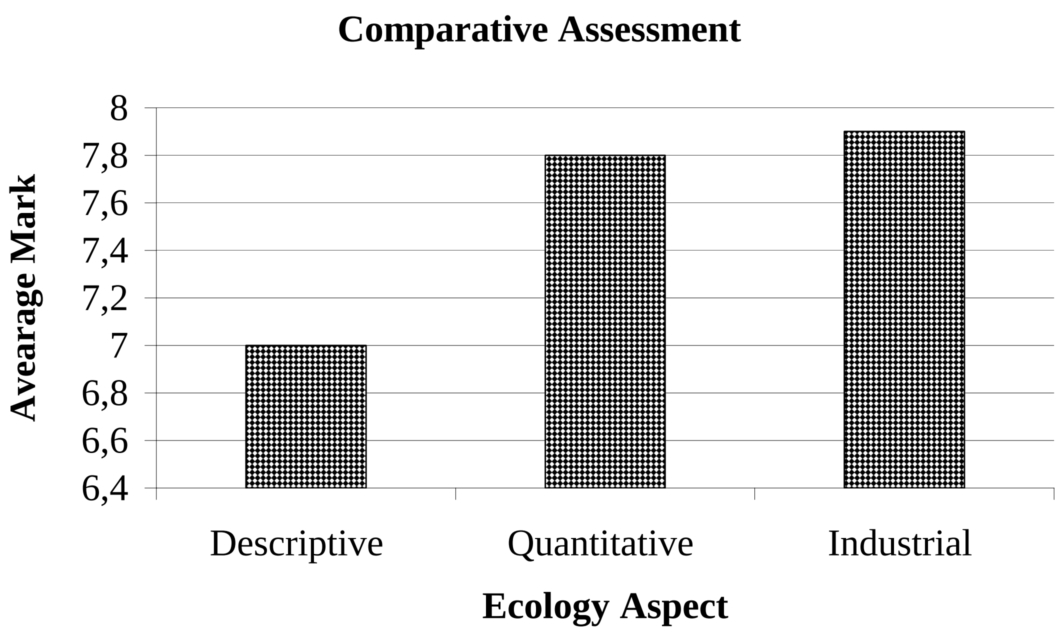

Figure 4: Comparative Assessment

5. Conclusion

While the quantified performance of the students in the course in question has been presented, the authors believe that some useful results can be extracted. As such would be to the need to encourage students to participate actively during the semester in order to maximize their benefit both in terms of knowledge and credit gained. Moreover it is of significant importance to emphasize on the Descriptive Ecology in order to help the students familiarize with the relevant lectures' demands. Finally, the in depth preparation of the students who will sit the final exams would be considered as more than welcome.

Concerning the Environmental Education for Engineers it is obvious that narrowing it down to the improvement of skills on green production is simply an insufficient approach[1]. A wider, inter-disciplinary approach can only meet the demands for a holistic integration[8] of the values of the environmental awareness and responsibility. The analysis carried out can be of use not only for the interested teachers but also for the keen students who can improve their studying efficiency by choosing the most suitable path in order to gain the best marks and knowledge.

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PART TWO

RES APPLICATIONS

- Stand Alone Systems
- Geothermal Applications
- Photovoltaic in Buildings
- Clean Water Production

COMPARING WIND AND PHOTOVOLTAIC STAND-ALONE POWER SYSTEMS USED FOR THE ELECTRIFICATION OF REMOTE CONSUMERS

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Abstract

Wind power and photovoltaic driven stand-alone systems have turned into one of the most promising ways to handle the electrification requirements of numerous isolated consumers worldwide. In this context, the primary target of the present work is to estimate the appropriate dimensions of either a wind power or a photovoltaic stand-alone system that guarantees the energy autonomy of several typical remote consumers located in representative Greek territories. For all regions examined, long-term wind speed and solar radiation measurements as well as formal meteorological data are utilized. Accordingly, special emphasis is put on the detailed energy balance analysis of the proposed systems on an hourly basis, including also the battery bank depth of discharge time evolution. Finally, comparison is made between the wind and the solar based systems investigated, proving that in most Greek regions either a wind or photovoltaic driven stand-alone system is able to cover the electrification needs of remote consumers, at a moderate first installation cost, without any additional energy input.

Keywords: Wind Power Stand-alone System; Photovoltaic Stand-alone System; Energy Balance; Battery Capacity; System Comparison

1. Introduction

Greece, being located in the SE European edge, possess excellent wind and abundant solar potential, since in several areas the wind speed exceeds the 10m/s at 30m height, while the annual solar energy approaches the 1900kWh per square meter[1]. On the other hand, the country is strongly depended on imported oil and natural gas, which represent almost the 75% of the domestic energy consumption[2].

Besides, in Greece, due to its geographical distribution, exist several thousands of remote consumers[3,4], located on the numerous small and medium-sized islands scattered throughout the Aegean and Ionian Archipelagos, as well as in rural areas of mainland, i.e. country houses, shelters, telecommunication stations etc. All these isolated consumers have no direct access to reliable electrical networks, covering their electrification needs using small diesel-generator sets.

In this frame, the present study investigates the possibility of using either a wind power[3,5,6] or a photovoltaic[7,8,9] driven stand-alone system to meet the electricity demand of all these remote consumers. Thus, the primary target of the present study is to estimate the dimensions of either a wind power or a photovoltaic stand-alone system that guarantees the energy autonomy of a typical remote consumer. Accordingly, special emphasis is put on the detailed energy balance analysis of these systems on an hourly basis, including also the battery bank depth of discharge time evolution. Finally, comparison is made between the wind and the solar based systems for various representative wind and solar potential profiles, proving that in most Greek regions a wind or solar driven stand-alone system is able to cover the electrification needs of remote consumers at a moderate first installation cost.

Kaldellis J.K., Kavadias K.A., Koronakis P.S., 2005, *"Comparing Wind and Photovoltaic Stand-Alone Power Systems Used for the Electrification of Remote Consumers", to appear in Renewable and Sustainable Energy Reviews, on-line available (05/03/05) in www.ScienceDirect.*

2. Description of the Wind/Solar Stand-Alone System

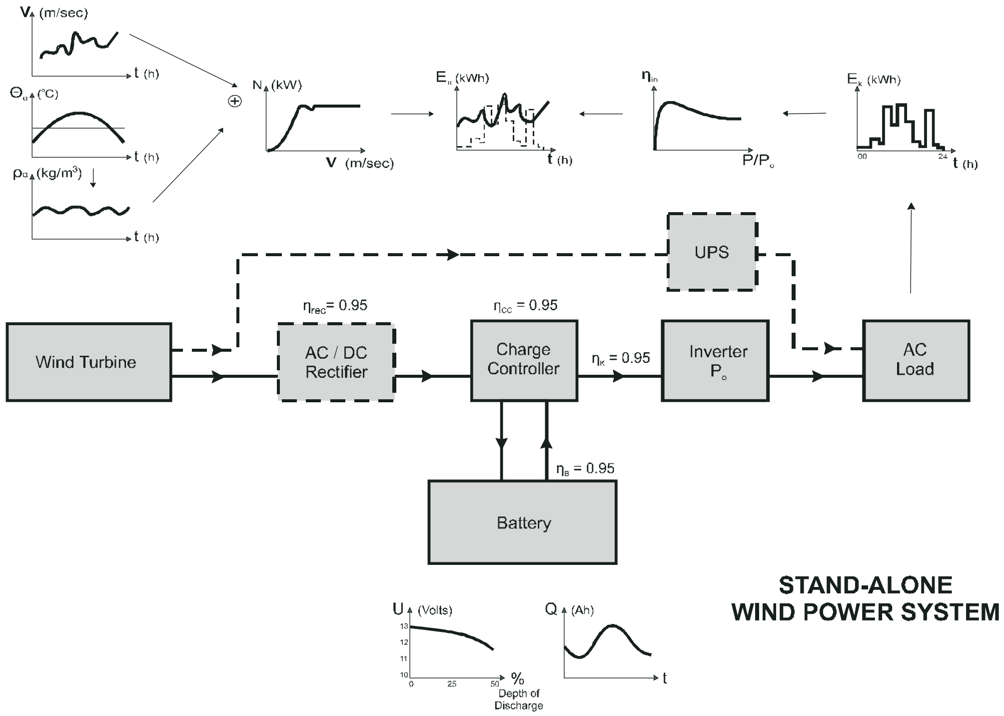


Figure 1: Proposed Stand-Alone Wind Power System

The proposed by the authors[3,7] stand-alone system (figures (1) and (2)) comprises either a small wind converter feeding -via a UPS of similar nominal power- the AC load of the system or a small photovoltaic generator of "z" panels properly connected to meet via a charge controller and an inverter the consumption load demand. In case that the electricity demand is inferior to the corresponding wind turbine or photovoltaic generator production, the energy surplus is stored to a battery row via the battery charge controller. Finally, in cases that the wind or the solar energy production cannot fulfill the load demand, a DC/AC inverter is used to transform the battery output in order to meet the system's power requirements. More precisely the proposed stand-alone systems are described as follows.

2.1 Wind Power System

As shown in figure (1) the wind power system is based on:

i. A small wind converter of rated power "N_o" kW (i.e. $N_o \leq 20$kW) and specific power curve "$N_{WT}=N(V)$" for standard day conditions[3]
ii. A lead-acid battery with cell capacity of "Q_{max}", maximum depth of discharge "DOD_L" ensuring a long term operation and output voltage "U_b"
iii. An AC/DC rectifier of "N_o" kW and U_{AC}/U_{DC} operation voltage values
iv. A charge controller of "N_o" kW, maximum 8h charge rate "R_{ch}" and outlet voltage "U_{CC}"
v. A UPS of "N_p" kW, frequency of 50Hz, autonomy time "$\delta t \approx 2$min" and operational voltage 220/380Volt
vi. A DC/AC inverter of "N_p" kW, frequency of 50Hz and operational voltage 220/380Volt[3]

The main system dimensions are the wind turbine rated power "N_o" and battery size "Q_{max}", while the inverter maximum power is directly related to the consumption peak load demand "N_p", see also[10].

2.2 Photovoltaic Power System

Accordingly, the proposed stand-alone photovoltaic system (figure (2)) consists of:

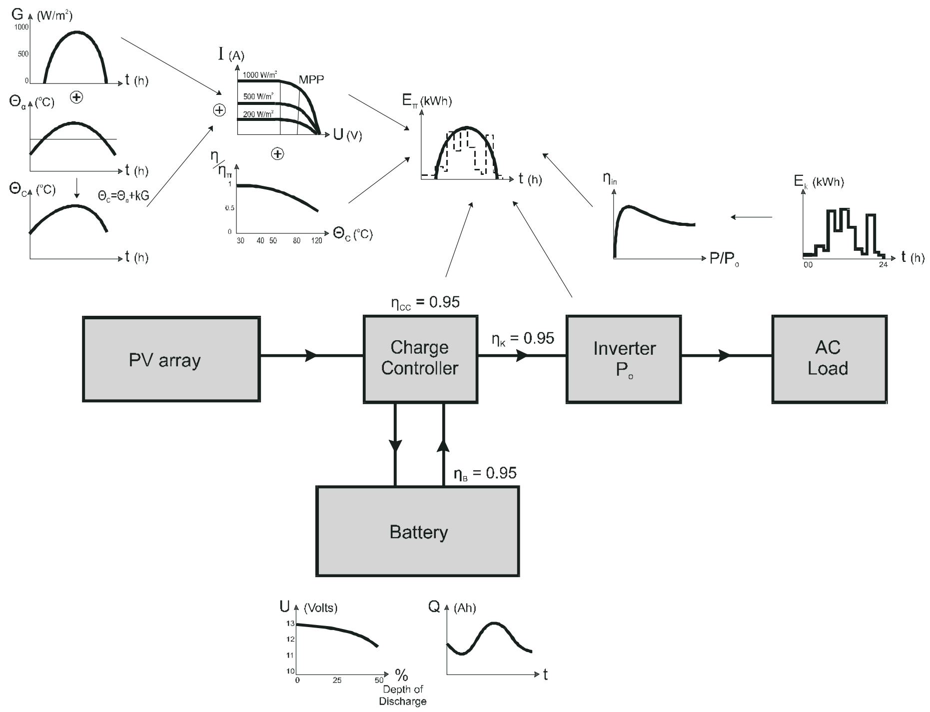


Figure 2: Proposed Photovoltaic Stand-Alone System for Isolated Consumers

i. A photovoltaic system of "z" panels ("N_+" maximum power of every panel, N_{PV}=z.N_+) properly connected (z_1 in parallel and z_2 in series) to feed the charge controller to the voltage required[11]

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, maximum 8h charge rate "R_{ch}" and charging voltage "U_{CC}"

iv. A DC/AC inverter of maximum power "N_p" able to meet the consumption peak load demand, frequency of 50Hz and operational voltage 220/380Volt

where "N_p" is the maximum load demand of the consumption, including a future increase margin (e.g. 30%). Taking into account that the proposed system has an operational life of at least twenty years, it is assumed reasonable to take into consideration a five-year forecast of the expected electricity consumption. The two governing parameters of the proposed installation are the number "z" and the rated power "N_+" of each photovoltaic panel used along with the battery maximum necessary capacity "Q_{max}".

Both stand-alone systems include also the non-active part of the installation, including supporting structures, power conditioning devices and wiring.

2.3 Stand-Alone Systems Operational Modes

During the long-lasting service period of the proposed stand-alone system (20-30 years is assumed to be realistic), the following operational modes may appear:

a. The power demand "N_D" is less than the power output of renewable energy station "N_{RES}" (where $N_{RES}=N_{WT}$ or $N_{RES}=N_{PV}$), i.e. ($N_{RES}>N_D$). In this case the energy surplus ($\Delta N=N_{RES}-N_D$) is stored via the rectifier (only for wind power systems producing AC) and the battery charge controller. If the battery is full ($Q=Q_{max}$), the residual energy is forwarded to low priority loads.

b. The power demand is greater than the renewable energy station power output ($N_{RES}<N_D$), which is not zero, i.e. $N_{RES}\neq 0$. In similar situations, the energy deficit ($\Delta N=N_D-N_{RES}$) is covered by the batteries via the battery charge controller and the DC/AC inverter.

c. There is no renewable energy production (e.g. low wind speed or zero solar radiation, system not available), i.e. $N_{RES}=0$. In this case the entire energy demand is covered by the battery charge controller-DC/AC inverter subsystem, under the condition that $Q>Q_{min}$.

In cases (b) and (c) -when the battery maximum depth of discharge is exceeded- an electricity management plan should be applied; otherwise the load would be rejected. In this context, a system-monitoring device may encourage operators to remarkably improve the efficiency operation of the autonomous wind/solar power station. Finally, for practical reasons, in an attempt to preserve the stand-alone system energy autonomy, an emergency energy consumption management plan is also necessary, in order to face unexpected energy production problems related to "Force Majeure" events.

3. Computational Algorithms Presentation

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

- Detailed meteorological data, including either wind speed "V" or solar radiation "G" measurements for a given time period (e.g. one year minimum)
- Ambient temperature "θ" and pressure "p" data for the entire period analysed
- Operational characteristics of the wind turbine (i.e. specific power curve "$N_{WT}=N(V)$" for standard day conditions) or of the photovoltaic modules (current, voltage) selected, i.e. I=I(U,G) and "N_+"
- Operational characteristics of all the other electronic devices of the installation, i.e. inverter efficiency, AC/DC rectifier performance (only for wind driven systems), battery cell (Q-U;θ) curve etc.
- The electricity consumption profile, based on information provided by the Hellenic National Statistical Agency[3,7], on an hourly basis (see figure (3)), being also dependent[12,13,14] upon the selected period of analysis (winter, summer, other).

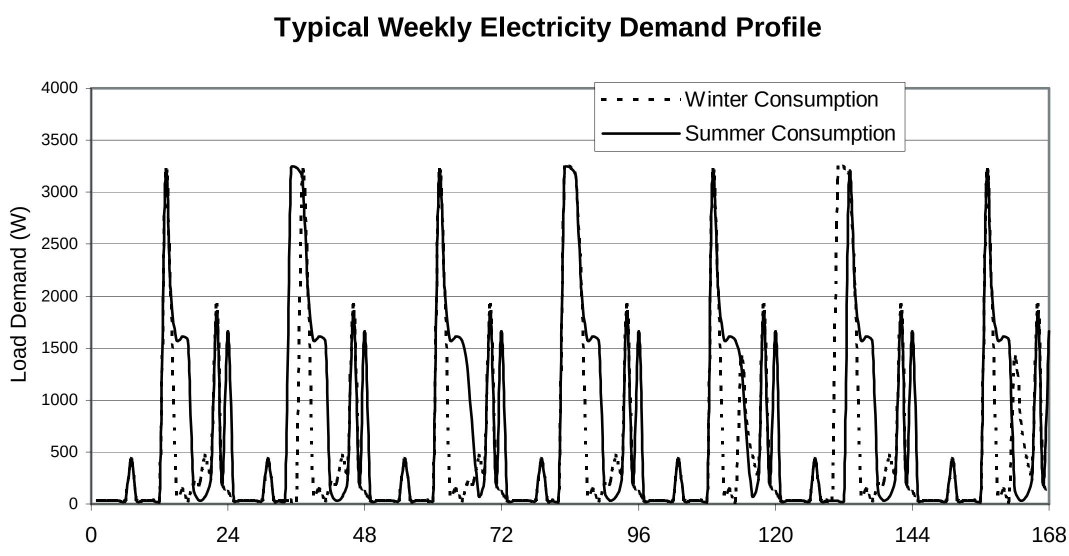


Figure 3: Typical Electricity Demand Profile of the Remote Consumer Analyzed

Accordingly, for the estimation of the appropriate configuration of a wind or solar stand-alone system able to guarantee the energy autonomy of an isolated consumer two fast and reliable numerical algorithms (i.e. WINDREMOTE-II and FOTOV-III, respectively) have been created [3,11], able to analyze in detail the energy behaviour of the above described installation for a selected time period. The main steps of the two algorithms (see also figures (4) and (5)) are as follows:

a. For every region analysed, select a (N_o-Q_{max}) or (z-Q_{max}) pair, respectively.
b. For every time point of a given time period (with a specific time step) estimate the energy produced by the renewable energy station, i.e. "N_{WT}" by the wind turbine or "N_{PV}" by the photovoltaic generator, taking into account the existing meteorological parameters (i.e. wind speed or solar radiation, the ambient temperature and pressure) and the selected wind turbine or photovoltaic panel power curve.
c. Compare the renewable energy production "N_{RES}" with the isolated consumer energy demand "N_D". If any energy surplus occurs (N_{RES}>N_D), this energy is stored to the battery bank and a new time point is examined (i.e. proceed to step b). Otherwise, proceed to step (d).
d. The energy deficit (N_D-N_{RES}) is covered by the energy storage system, if the battery is not near the lower limit ($Q>Q_{min}$). Accordingly proceed to step (b). In cases that the battery is practically empty ($Q \le Q_{min}$), the load is rejected for an hour period and the complete analysis is repeated, starting from step (a), up to the case that the no-load rejection condition is fulfilled for the complete time period examined. If the desired energy autonomy is obtained define $Q^*=\min\{Q_{max}\}$.
e. Next, the wind turbine rated power or the number of photovoltaic panels is increased and the calculations are repeated. Thus, after the integration of the analysis a (N_o-Q^*) or a (z-Q^*) curve is predicted which guarantees the isolated consumer energy autonomy for the investigated period.

At this point it is important to mention that for every (N_o-Q^*) or (z-Q^*) pair ensuring the energy autonomy of the remote system, a detailed energy production and demand balance time-distribution is available along with the corresponding time-series of battery depth of discharge.

4. Application Results

The present analysis should be applied for several typical Greek territories possessing representative wind and solar potential, see figure (6). For the regions selected long-term wind speed and solar irradiance measurements[15] exist, as well as formal meteorological data. More specifically, for the installation of wind power stand-alone systems the cases analyzed (see Table I) include:

Table I: Annual Wind Potential Characteristics of the Areas Analyzed

Island	Annual Mean Wind Speed (m/s)	Max. Calm Spell Duration (h)
Andros	9.56	41
Naxos	7.54	94
Skiros	7.01	112
Kithnos	6.58	178
Kea	6.09	210

- a very high wind potential area (Andros island, mean wind speed 9.5m/s),
- a high wind potential area (Naxos island, mean wind speed 7.5m/s),
- a medium-high wind potential area (Skiros island, mean wind speed 7.0m/s),
- a medium wind potential area (Kithnos island, mean wind speed 6.5m/s) and
- a medium-low wind potential area (Kea island, mean wind speed 5.8m/s)

To get a clear-cut picture of the wind potential difference, figure (7) demonstrates the daily average wind speed time series for the best and the worst wind potential cases examined, for an entire year. There is a remarkable wind speed value difference for almost every day of the year between Andros and Kea islands. Hence, applying the WINDREMOTE-II algorithm to the above islands we get the

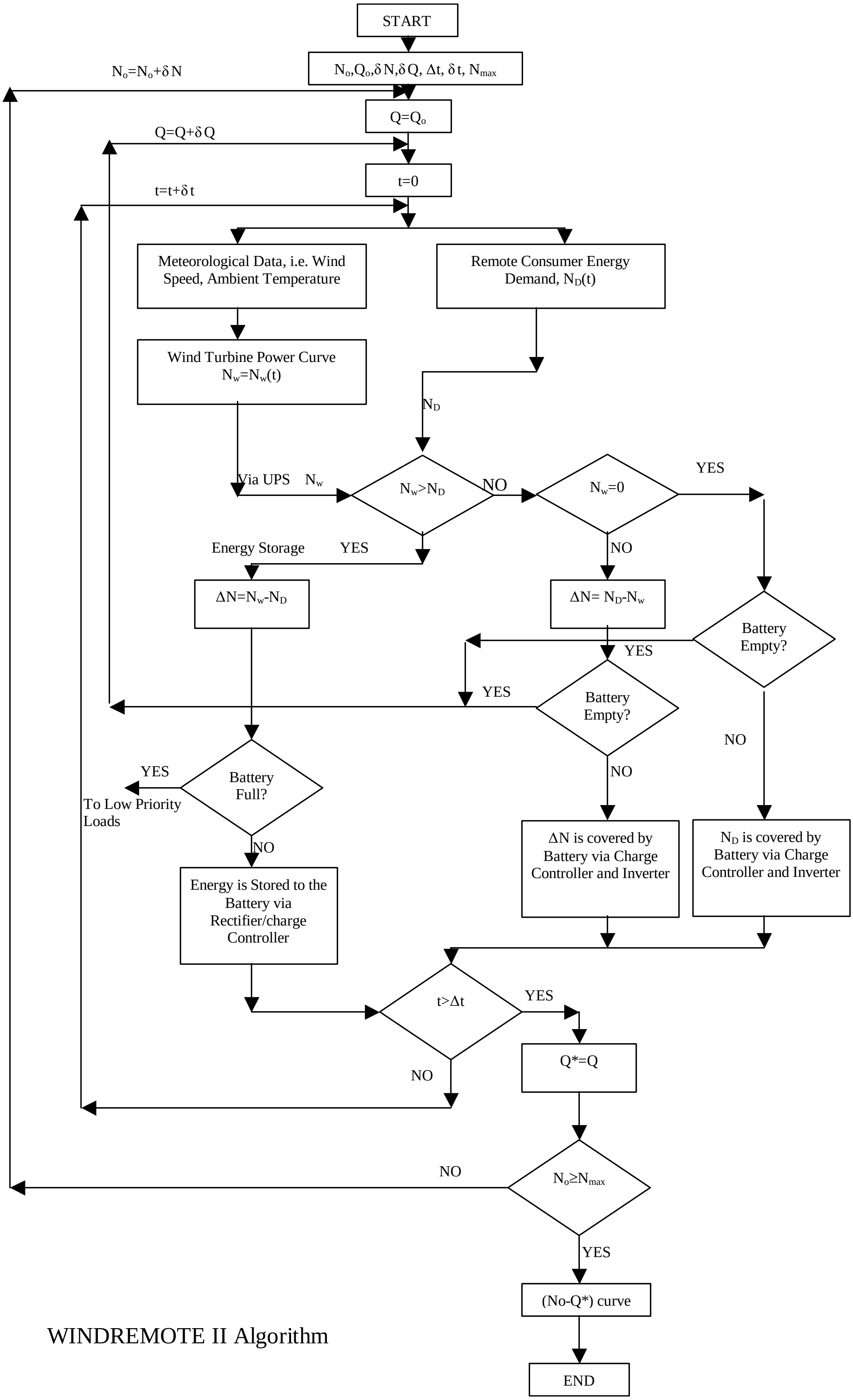


Figure 4: WINDREMOTE-II Algorithm

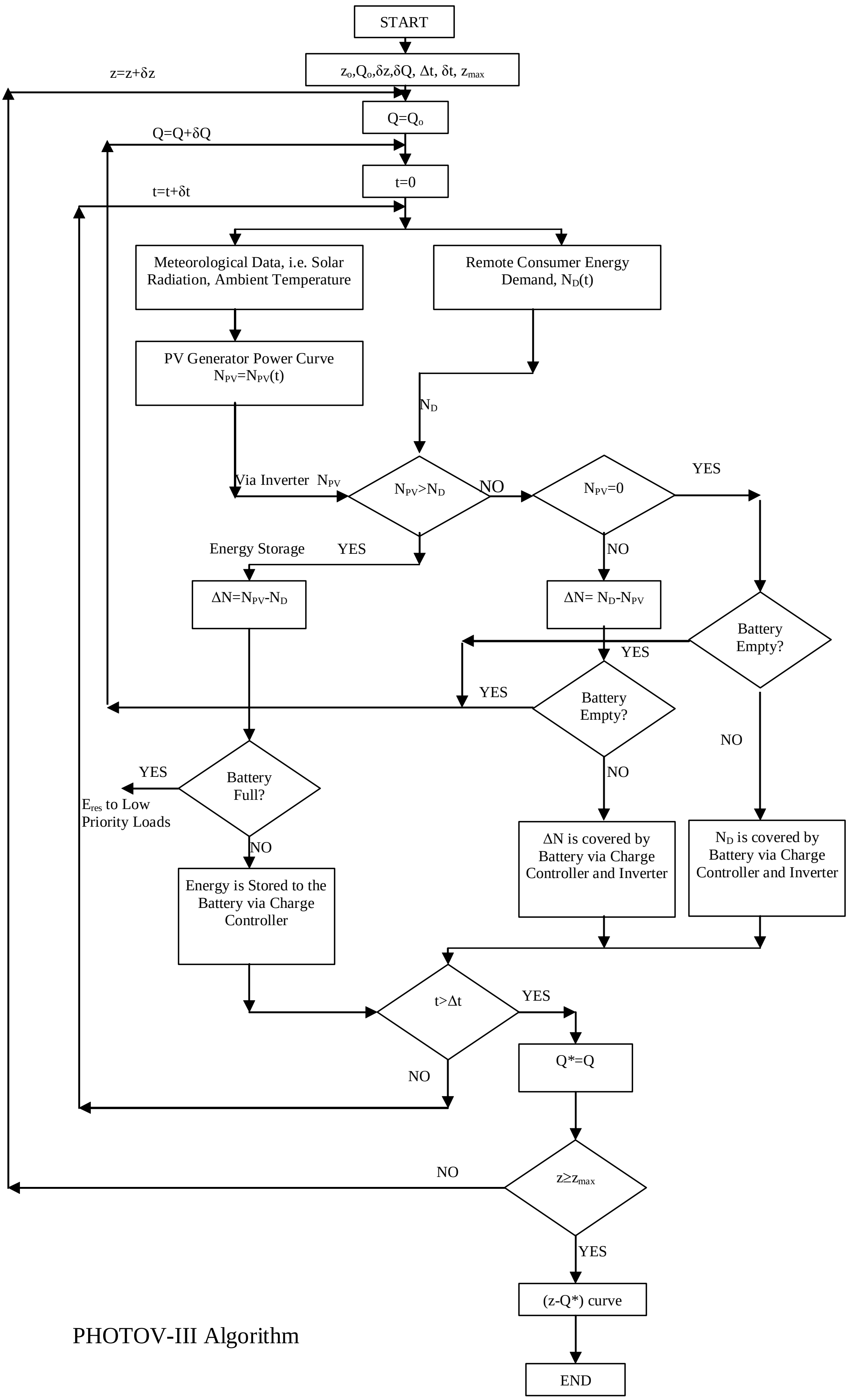
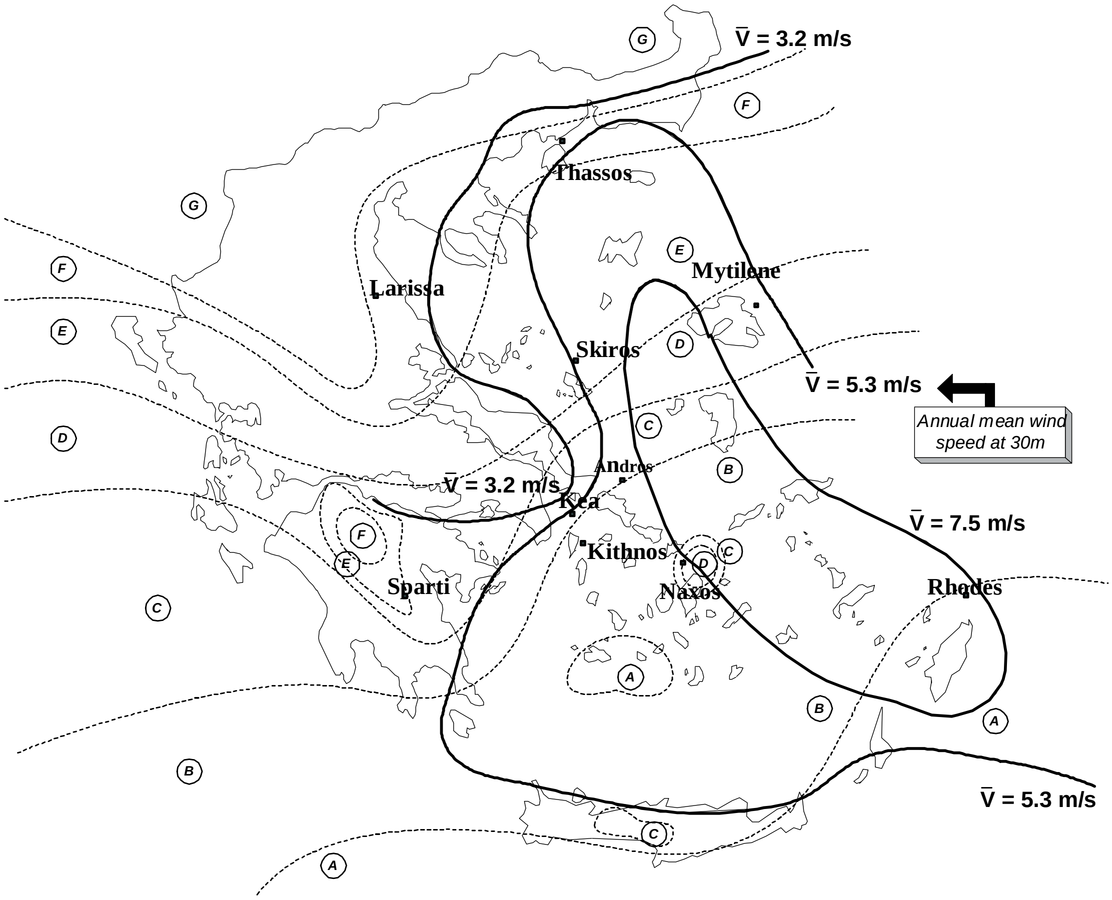


Figure 5: PHOTOV-III Algorithm

WIND & SOLAR ENERGY IN GREECE



Solar potential

ZONE	kWh / m ^{2}
A	> 1650
B	1600 - 1649
C	1550 - 1599
D	1500 - 1549
E	1450 - 1499
F	1400 - 1449
G	< 1399

Figure 6: Wind-Solar Potential in Greece

results of figure (8). In this figure one may find the corresponding wind turbine rated power and battery bank capacity combinations that guarantee one year energy autonomy without any external energy input. According to the results obtained, there is a significant battery capacity reduction as the wind turbine rated power increases. This increase is more abrupt for the high wind potential areas, while the medium wind potential areas present milder distribution. Besides, for all regions examined, the battery size tends to an asymptotic value as the wind turbine size surpasses a specific value, which is depending on the wind potential quality. Finally, it is important to note that for the relatively low wind potential areas the battery size is significantly bigger than for the medium or high wind potential case. In fact, Naxos and Andros islands tend to almost the same asymptotic battery capacity value, despite their remarkable wind potential difference, see also Table I. On the contrary, the battery capacity difference between Kea and Kithnos islands is quite large, although for these two islands the annual mean wind speed difference is less than 1m/s. Kithnos and Skiros islands distributions are rather similar, although Skiros island possesses a slightly higher annual mean wind speed.

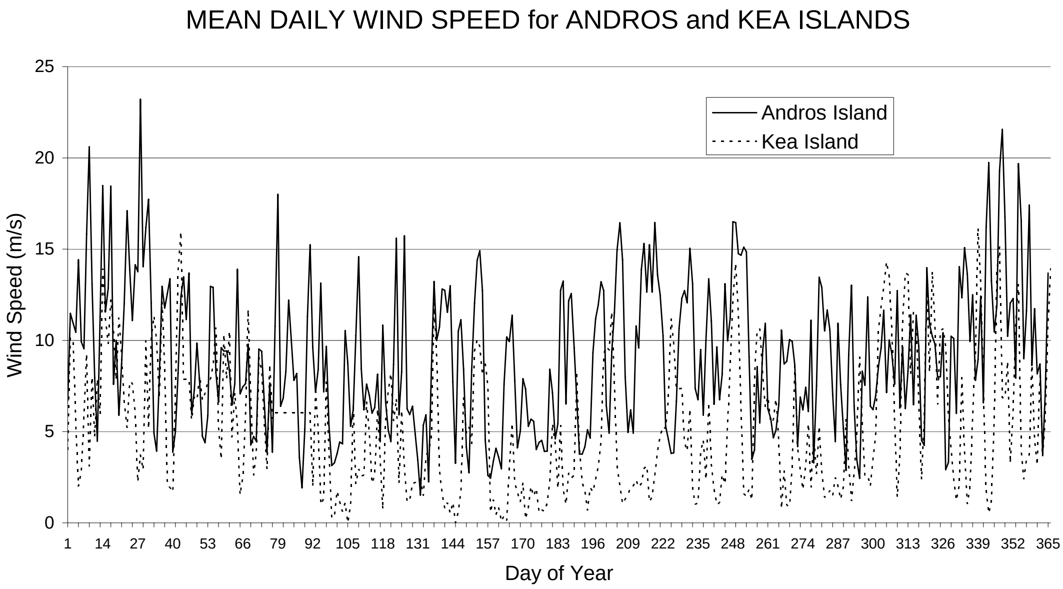


Figure 7: Comparison of Wind Speed Time Series for the Two Extreme Cases Analyzed

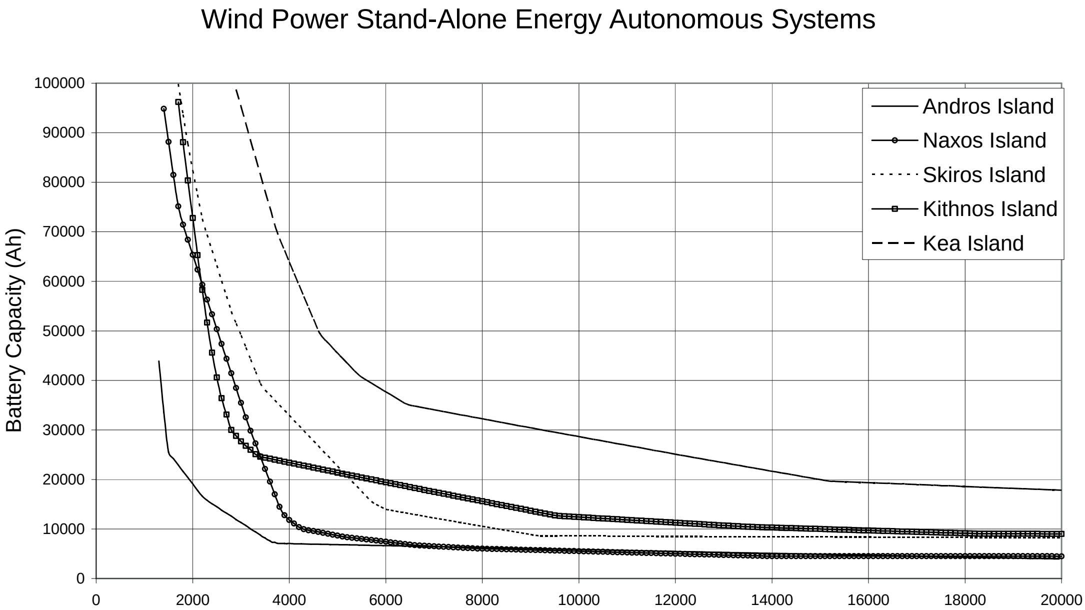


Figure 8: Comparison of Wind Power Stand-Alone System Configurations for Selected Greek Islands

Subsequently, for the installation of photovoltaic power stand-alone systems the cases analyzed (see Table II) include:

- a high solar potential island of Aegean Sea (Rhodes island, annual solar energy 1843kWh/(m^2.year) at horizontal plane),
- a S. Greece medium-high solar potential area (town of Sparti in Peloponnesus, annual solar energy 1731kWh/(m^2.year)),

- a medium-high solar potential island of N.E. Aegean Sea (town of Mytilene in Lesvos island, annual solar energy 1680kWh/(m^2.year)),
- a medium solar potential area of Central Greece (Larissa town, annual solar energy 1565kWh/(m^2.year)) and
- a medium-low solar potential island of N. Aegean Sea (Thassos island, annual solar energy 1547kWh/(m^2.year))

Table II: Solar Potential Characteristics (at Horizontal Plane) of the Areas Analyzed

Region	**Annual Specific Solar Energy (kWh/(m^2.year))**	**Geographical Latitude**	**Geographical Longitude**
Rhodes	1843	36°22'	28°13'
Sparti	1731	37°04'	22°26'
Mytilene	1680	39°06'	26°33'
Larissa	1565	39°38'	22°25'
Thassos	1547	40°56'	24°25'

Using the available experimental data (e.g. figure (9) for the worst solar potential month) and applying the PHOTOV-III numerical algorithm, the calculation results concerning the autonomous photovoltaic panel and battery capacity combination for the examined areas are summarized in figure (10). All the calculations are carried out using panel tilt angles equal to 60° [7,16]. For almost all energy autonomy curves, two distinct parts can be defined. In the first part of these curves the battery capacity is significantly reduced as the photovoltaic panels' number is slightly increased. This rapid change is more evident for high solar potential areas. In the second part, the battery capacity remains almost constant, not depending on the photovoltaic panels' number, achieving an asymptotic value depending mostly upon the local solar potential. It is also interesting to mention that the battery capacity of the stand-alone systems decreases remarkably as the available solar potential is improved. In any case, the differences encountered between the best and the worst solar potential cases are quite smaller than the ones of figure (8).

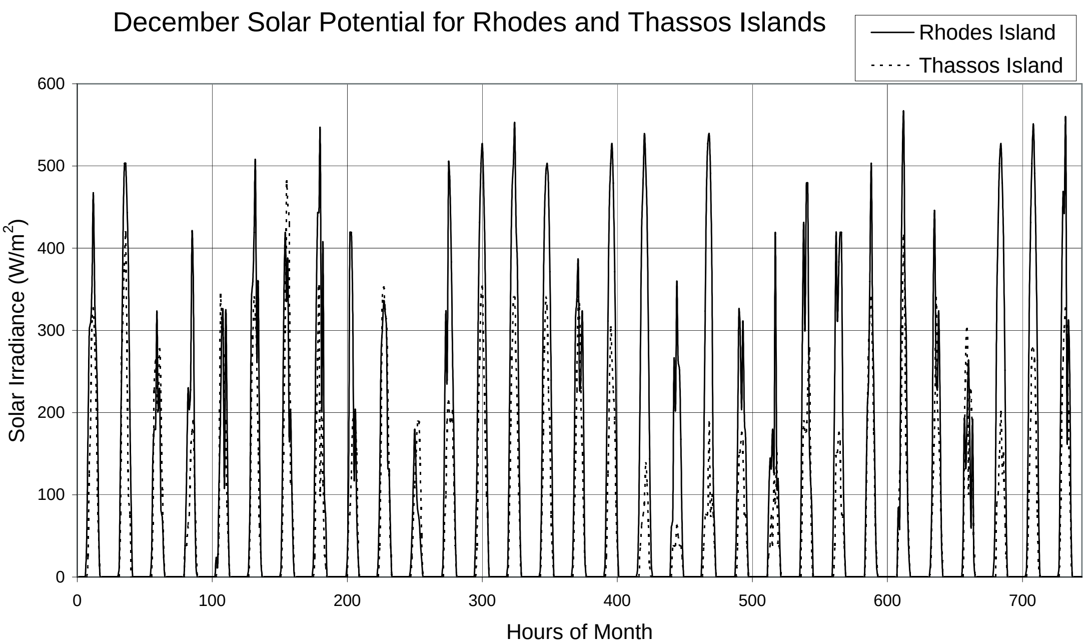


Figure 9: Comparison of Solar Irradiance for the Two Extreme Cases Investigated

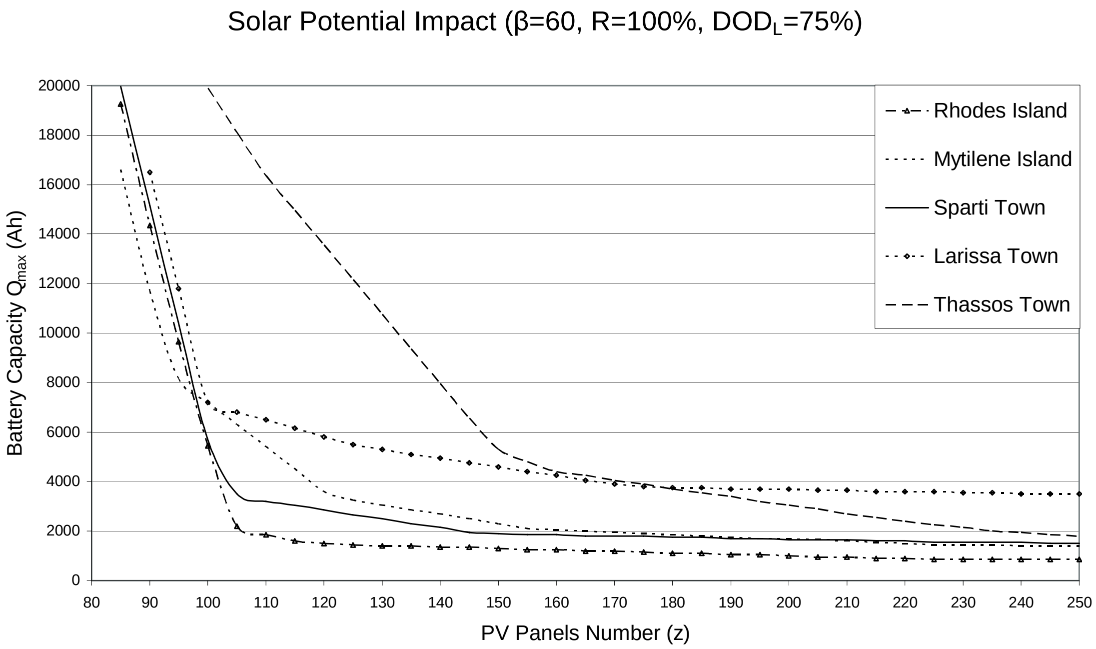


Figure 10: Comparison of Photovoltaic Stand-Alone Systems Configuration, for Selected Greek Regions

In an attempt to directly compare the wind and solar stand-alone power system configurations we present together in figure (11) three representative configurations of each category that guarantee, on an annual basis, energy autonomy to the isolated consumer of figure (3). After a careful inspection of figure (11) data, covering the vast majority of Greek territory, one may state the following:

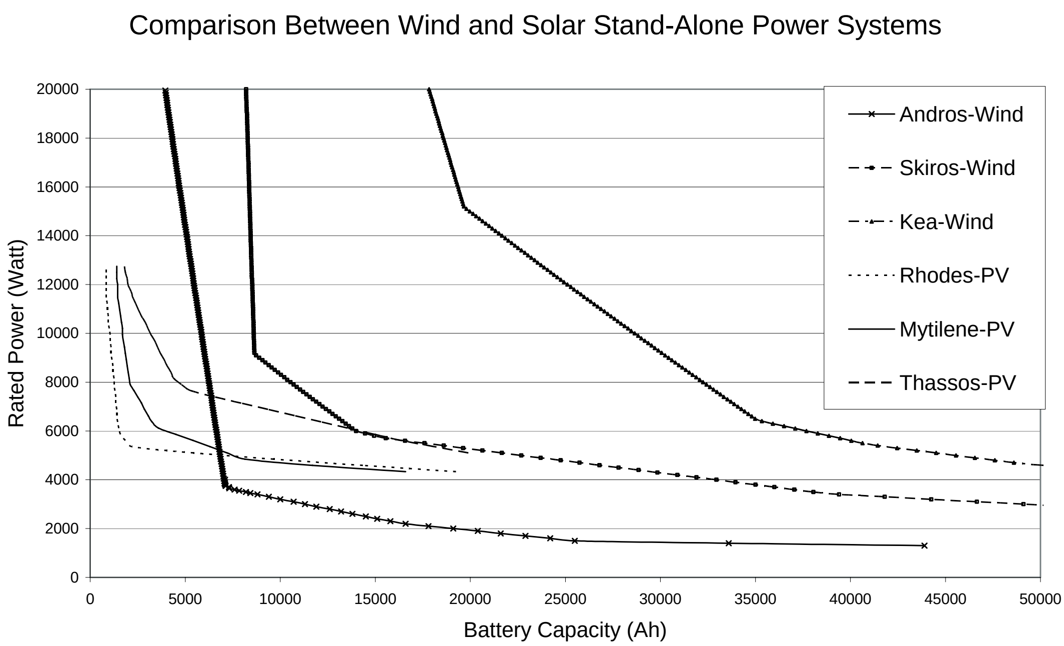


Figure 11: Size Comparison between Wind and Solar Driven Stand-Alone Systems Located in Greece

- The best wind potential areas need quite smaller stand-alone system configuration than the best solar potential case.
- On the other hand, medium-low wind potential areas need extremely huge configurations to guarantee energy autonomy.
- The necessary battery capacity of photovoltaic stand-alone systems is quite smaller than the minimum battery size required by wind-driven stand-alone systems. This may be explained by the fact that considerable calm spell periods may appear (Table I) even in the best wind potential areas (stochastic behaviour of wind), while there is almost no possibility for a place in Greece, for two successive days, not to experience a fair solar energy gain; see for example figures (7) and (9).
- On the contrary the rated power of the wind turbines used are lower than the corresponding photovoltaic generator peak power, especially for medium-high wind potential cases. This fact can be attributed to the different available wind-solar energy density (i.e. kWh/m^2), as well as by the rather high efficiency discrepancy between the contemporary wind turbines (up to 45%) and the commercial photovoltaic panels (≈13%)[17,18].

As a general conclusion one may state that -taking into consideration the ex-works cost difference between wind turbines and solar panels of the same rated power- wind based stand-alone systems present a relative size-advantage for high or medium-high wind potential cases. On the other hand, photovoltaic based stand-alone installations are using quite smaller batteries and need less maintenance for almost every area in Greece. Of course, a detailed cost-benefit analysis is necessary on long-term basis in order to reach final conclusions, under the current socio-economic environment.

5. Energy Balance Analysis of Wind/Solar Stand-Alone Systems

As already mentioned, one of the main targets of the present study is to analyze and compare the energy behaviour of wind and solar based stand-alone systems located throughout Greece. In order to select a representative stand-alone configuration among the pairs of figures (8) and (10), the minimum initial cost combination is selected -using the analysis presented by the authors[11,19], for every region examined. Thus, the resulting outcomes are based on wind power and photovoltaic stand-alone

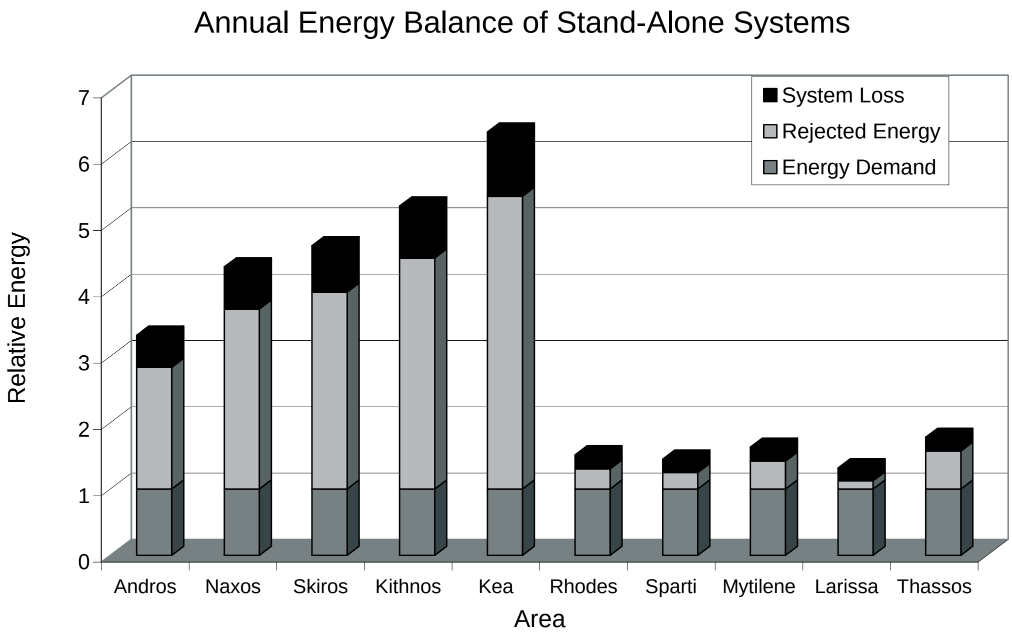


Figure 12: Annual Energy Balance of Wind and Solar Stand-Alone Systems

systems that guarantee the remote consumers energy autonomy under the minimum first installation cost restriction.

To get an integrated picture of the proposed system energy balance, figure (12) demonstrates the annual energy balance of several wind power and photovoltaic stand-alone systems. Taking into consideration that energy demand is the same for every stand-alone system, it is interesting to note that the energy production of wind power systems is three to six times higher than the demanded energy, while the corresponding energy production of the photovoltaic installations is not greater than 1.5 the remote consumer energy demand. As a result, all wind power systems present quite higher losses than the photovoltaic ones, while their corresponding energy surplus is very high, exceeding the 150% of the energy consumption. This is not the case for the photovoltaic systems, since even in Thassos island case presenting the lowest solar potential, the energy rejection is slightly over 30% of the energy consumption.

Another interesting point related to the monthly energy analysis of the stand-alone systems investigated (figures (13) and (16)) is the big differences between Andros and Kea islands energy distribution, where the Kea wind turbine is almost 15kW, while the corresponding engine for Andros island is less than 4kW. Despite this considerable size difference, during low wind speed periods (e.g. May to July) the wind energy production of these power stations is similar, due to the quite different wind potential of the areas. In fact, comparing the detailed energy balance profile of these two islands during June (figures (14) and (15)) one may state the following:

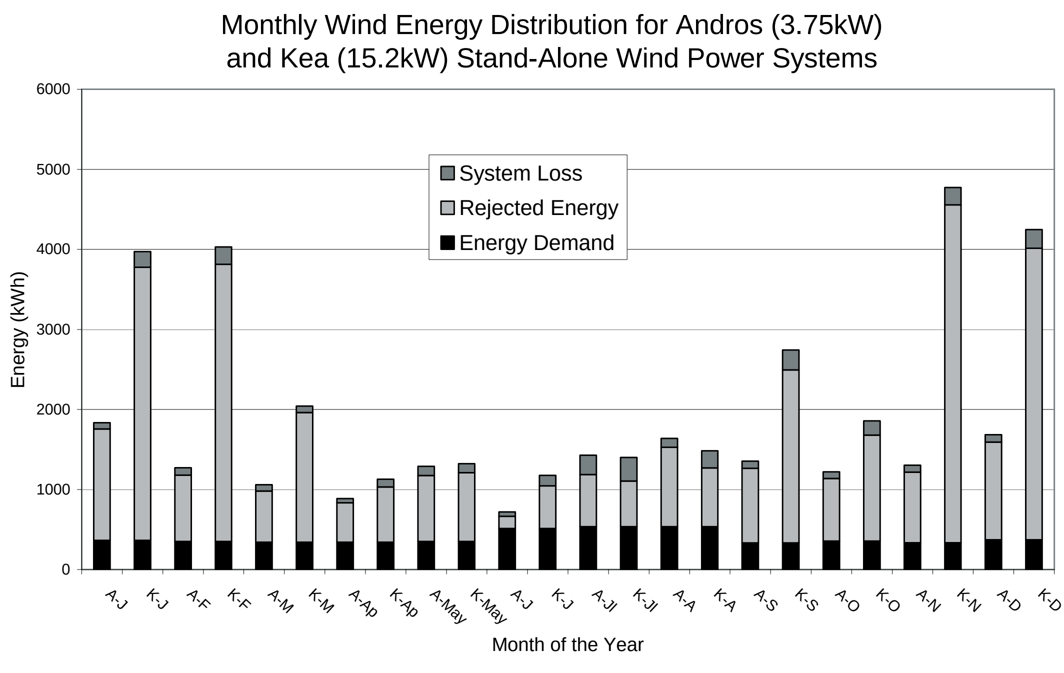


Figure 13: Monthly Energy Balance of Selected Wind Power Stand-Alone Systems

- The wind energy production in Andros (4kW) is bigger than the one of Kea (15kW)
- The calm spell periods of Kea island is much longer than Andros island
- In both cases there are two relatively long low wind speed periods leading to considerable battery energy storage decrease.
- Due to quite higher battery bank size, the first minimum battery discharging limit of Kea island is not very low, while in Andros island both minima are very near to the maximum battery DOD limit.
- Due to the relative smaller wind turbine used, the instantaneous wind energy production in Andros island is comparable with the energy demand, which is not the case for Kea island.

- Unfortunately, the excessive wind power of Kea stand-alone system during the first week of June is practically lost, since the system batteries are completely full.

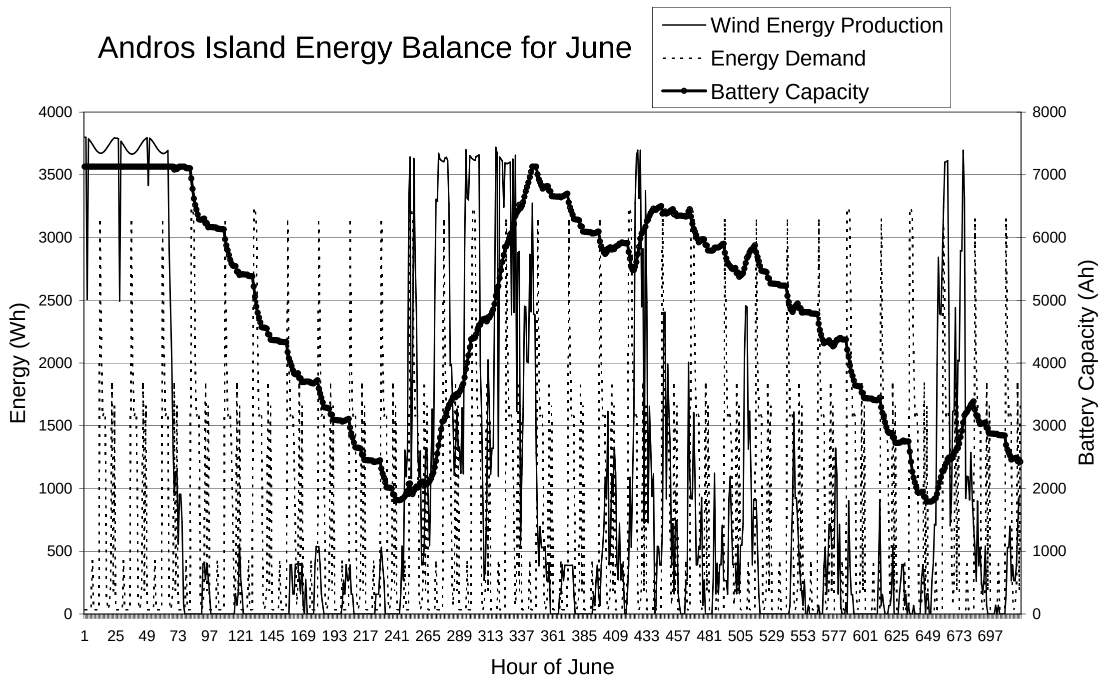


Figure 14: Energy-Battery Capacity Distributions of a Wind Power Stand-Alone System Located in Andros Island

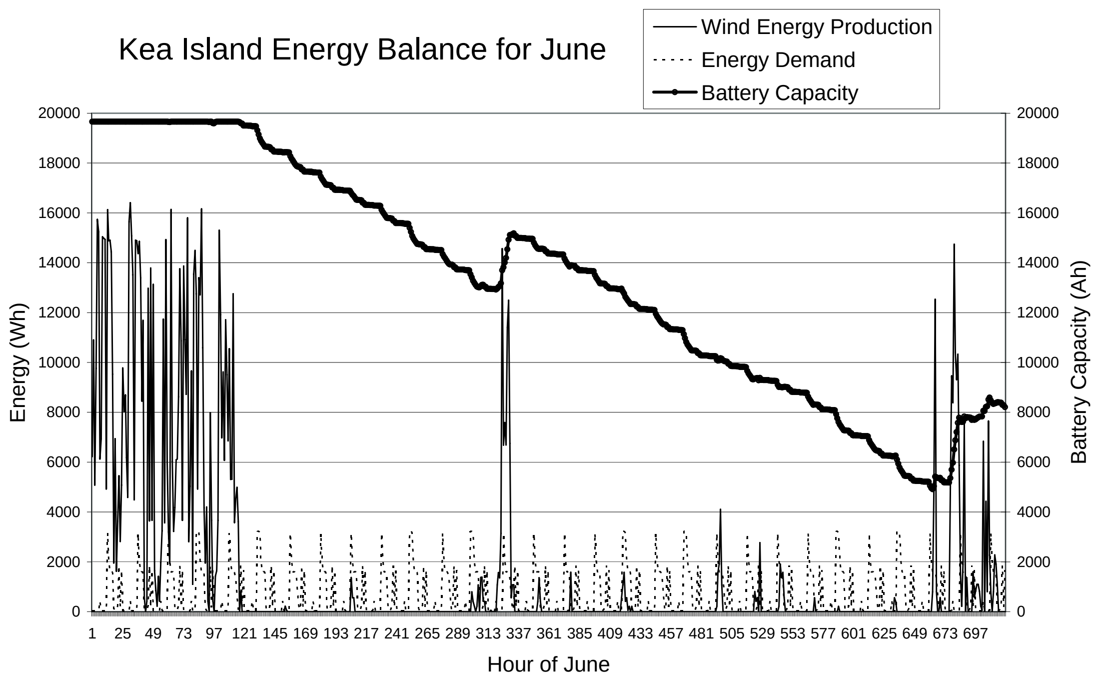


Figure 15: Energy-Battery Capacity Distributions of a Wind Power Stand-Alone System Located in Kea Island

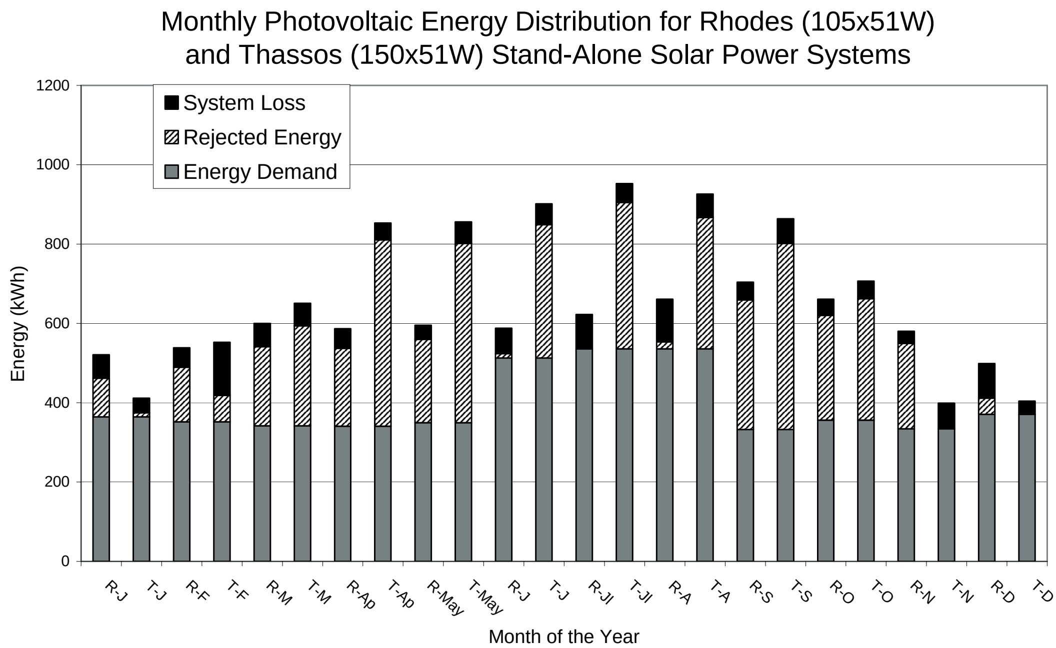


Figure 16: Monthly Energy Balance of Selected Photovoltaic Stand-Alone Systems

Similarly, one may analyze the monthly energy profile of the photovoltaic stand-alone systems situated in the two extreme Greek solar potential regions, i.e. Rhodes and Thassos islands, keeping in mind that the Thassos stand alone system uses 50% more solar panels than the corresponding Rhodes one. As mentioned in figure (12), the photovoltaic energy production is primarily used to meet the energy consumption, while only a small portion of the energy production is finally rejected. This energy rejection takes place primarily during the hot months of the year and is more obvious for Thassos system. More specifically, the most difficult energy balance situation for this N. Aegean island is during December and January, where the photovoltaic generator hardly covers the installation load. On the contrary, for S. Greece installation the limited energy balance takes place during June and July, where the selected photovoltaic generator faces quite higher power demand, see also figure (3). In any case, the energy disposal by the photovoltaic generator is quite better than the one produced by wind turbines, a fact that may support the idea that photovoltaic panels are more convenient than micro wind converters, disregarding the first installation cost matter.

Finally, in figures (17) and (18) one may find the energy balance time evolution along with the corresponding battery energy content for the two most difficult months of Rhodes and Thassos photovoltaic stand-alone systems, i.e. June and December respectively. On the basis of these two figures one may conclude that:

- Energy production in Rhodes island is comparable with the increased energy consumption of the installation, hence the problem is not due to the low solar irradiance in June but mainly due to the small system battery bank (only 2200Ah). In fact, this means that the selected photovoltaic stand-alone system is almost perfectly adapted to the local conditions.
- On the other hand, there is a remarkable low energy production period during the 3rd week of December for Thassos island, which endangers the energy autonomy of the proposed stand-alone system.
- Even during this low solar potential period (December) the Thassos stand-alone system produces relatively high energy.
- The energy production of Rhodes island during June is almost constant, excluding a few cloudy days during the first week of the month.

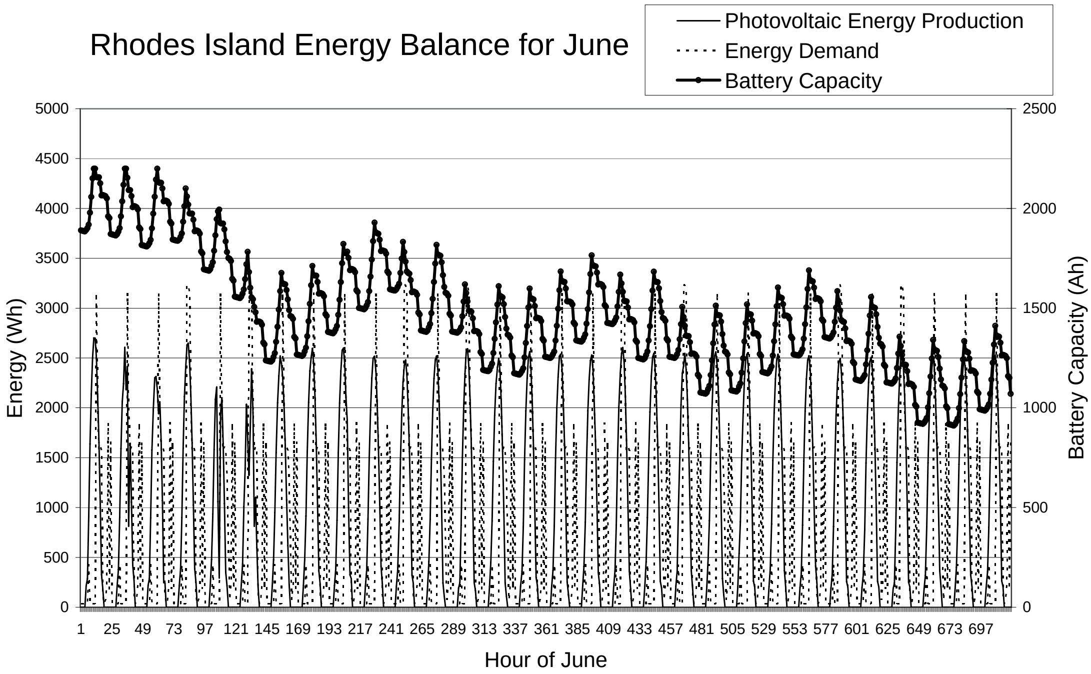


Figure 17: Energy-Battery Capacity Distributions of a Photovoltaic Stand-Alone System Located in Rhodes Island

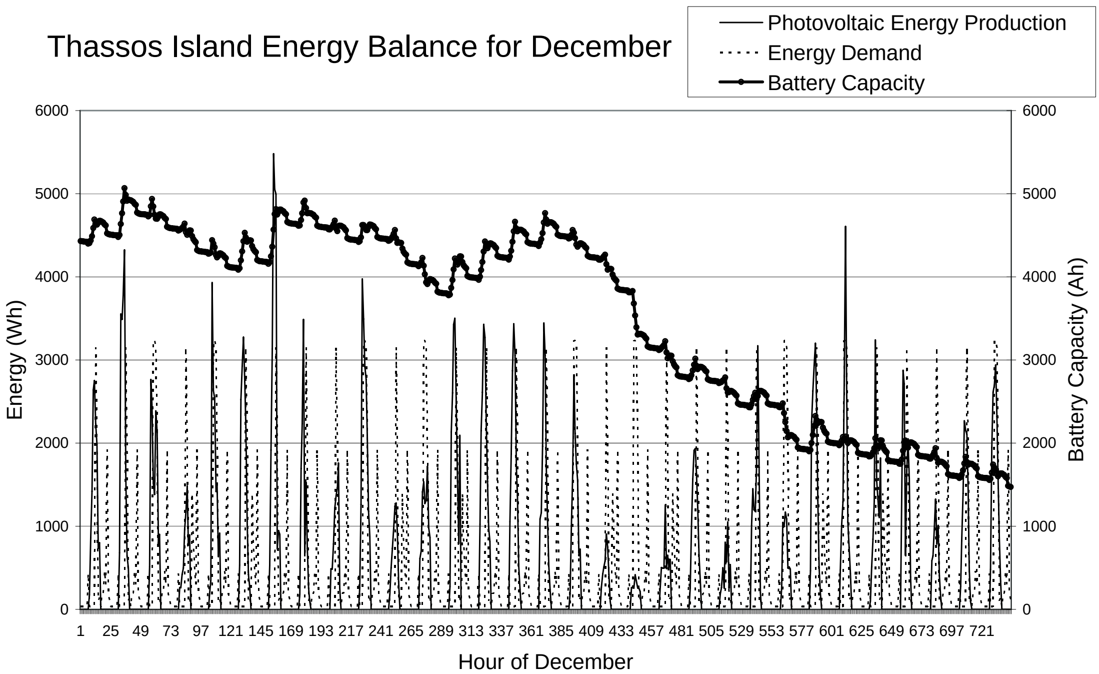


Figure 18: Energy-Battery Capacity Distributions of a Photovoltaic Stand-Alone System Located in Thassos Island

Therefore, according to the information presented, both wind and solar based stand-alone systems can face the energy demand of the isolated consumer. To be more precise, the photovoltaic systems seem to be more adaptable to the specific energy consumption profile, although high wind potential areas may use smaller and less expensive configurations than the corresponding photovoltaic ones. On the other hand, wind driven stand-alone systems may be more attractive when supporting supplementary second priority electrical loads, like small desalination plants[20], water pumps for irrigation purposes[21], small ice-making machines etc.

6. Conclusions

The possibility of using either a wind power or a photovoltaic driven stand-alone system to meet the electricity demand of typical remote consumers located in different places in Greece is investigated. For this purpose two independent stand-alone configurations are used, based respectively on a small wind converter or a small photovoltaic generator.

Applying the proposed methodology, one has the opportunity to estimate the two systems dimensions that guarantee energy autonomy of the installation for the entire period analyzed. For all regions examined, long-term wind speed and solar irradiance measurements, as well as other meteorological data are needed.

According to the results presented both wind or photovoltaic driven systems have the ability to cover the corresponding load demand. More specifically, for most regions analyzed the rated power of the wind turbine used is lower than the corresponding photovoltaic generator peak power. On the other hand the necessary battery capacity of the photovoltaic based systems is quite smaller than the one of the wind based installation. A long-term cost-benefit evaluation may be used, for each region separately, in order to reach to final estimates and conclusions.

Finally, a detailed energy analysis for both wind and solar driven stand-alone systems is presented, including also the system battery depth of discharge time-evolution. Generally speaking, the energy production of the wind power stand-alone systems is much higher than the corresponding power demand, while photovoltaic installations seem to be more adaptable to the power demand profile of the specific consumer. In this context, wind driven systems may be more appropriate to cover additional second-priority loads, especially during high wind speed periods.

Summarizing, on the basis of the above presented information, one may definitely state that both stand-alone configurations can significantly contribute to the energy requirements of numerous isolated consumers all around Greece. More precisely, in regions of high or medium-high wind potential wind driven systems are definitely the best solution, including preliminary cost aspects. On the other hand, in most other situations photovoltaic driven installations use quite smaller batteries and may present even a remarkable initial cost advantage.

In any case, every one of the proposed configurations is able to guarantee the remote consumer energy autonomy without any additional energy input, while protecting the corresponding system batteries from deep discharge. For all these regions, wind or photovoltaic based stand-alone systems are possibly the best alternatives to meet the electrification requirements of isolated communities, improving also their life quality.

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OPTIMAL DESIGN OF GEOTHERMAL-SOLAR GREENHOUSES FOR THE MINIMISATION OF FOSSIL FUEL CONSUMPTION

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Abstract

Greece has a significant geothermal potential with high enthalpy fields in the Aegean Sea region and low enthalpy fields scattered in specific locations of the country that has not been sufficiently exploited yet. One promising application would be the use of geothermal energy for greenhouse heating. The present work proposes an integrated and analytical methodology for the design of a geothermal-solar greenhouse that minimises the fossil fuels consumption and replaces it with geothermal energy. To that effect, the system modules are modelled analytically and the energy balances of all the system components are formulated. The resulting model is solved and the main design parameters are determined, in order to minimise the entire installation heat losses and the electric energy consumption. A case study is presented where the proposed methodology has been applied with interesting results concerning the technical and financial efficiency of the system.

Keywords: Geothermal Energy; Greenhouse heating; Renewable Energy Sources; Low Enthalpy Geothermal Field; Energy System Modelling

1. Introduction

Greece has a remarkable geothermal potential[1,2], taking into account that the Aegean microplate is strongly influenced by the collision between the European and African tectonic plates. As a result of this evolution, some high enthalpy geothermal fields exist in the central Aegean Sea (Milos, Kimolos, Santorini). At the same time, several low enthalpy fields are located throughout central and northern Greece. All these geothermal fields have a significant energy potential[3], not sufficiently exploited yet.

More specifically, despite the remarkable geothermal potential, only few applications are reported over the last years concerning the exploitation of the energy content of the local geothermal reservoirs, while the most promoted direct geothermal use is the balneology[4]. One of the basic obstacles concerning the geothermal energy applications in Greece is the absence of the appropriate legislation. However, it is expected that with the recently voted geothermal law 3175/2003, the main problems related with the geothermal applications will be resolved and geothermal energy development will speed up in the country.

One of the main disadvantages of the low enthalpy geothermal fields is the relatively low temperature of the corresponding fluid. However, even these relatively low temperatures are quite appropriate to satisfy -in combination with the available solar radiation- the energy requirements of typical greenhouses, thus displaying the imported fossil fuels. On top of this, geothermal energy is a clean energy source, i.e. it does not have a negative impact on the environment when used correctly.

In this context, the proposed work presents an integrated methodology for the optimal design of a geothermal solar greenhouse. For this purpose the necessary analytical model is presented, while special emphasis is laid on estimating the appropriate dimensions of the geothermal fluid transportation network, in order to minimize the entire installation heat loss and the corresponding electrical energy consumption. Finally, the developed methodology is applied to a representative low enthalpy geothermal field with interesting results.

Kondili E., Kaldellis J.K., 2005, *"Optimal Design of Geothermal-Solar Greenhouses for the Minimisation of Fossil Fuel Consumption", Applied Thermal Engineering, Vol.26/8-9, pp.905-915.*

2. Geothermal Greenhouse System Components

In an attempt to satisfy the energy demand requirements of the operating greenhouses, taking into account the advantage of the existence of low enthalpy geothermal fields[5,6], the following hybrid geothermal-solar configuration is proposed, see also figure (1). In particular the proposed system comprises of the following components:

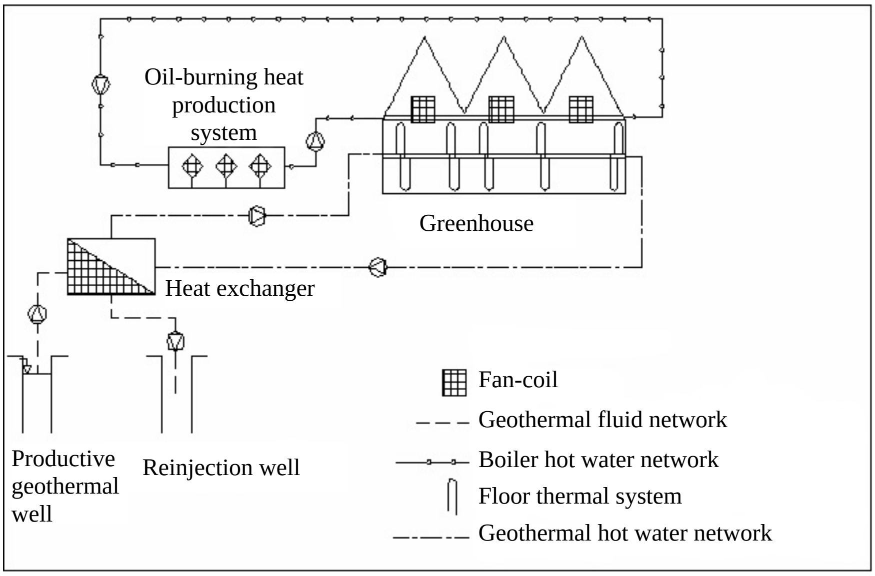

Figure 1: Proposed Geothermal-Solar Based Solution

i. *A typical solar-greenhouse*: The proposed greenhouse consists[7,8] of a metal frame, the cover material, an irrigation network, an artificial light installation, a heating system and an air-circulation and ventilation mechanism.

ii. *A low enthalpy geothermal well or spring*: The geothermal fluid is available from the existing scattered throughout Greece geothermal springs and productive boreholes.

iii. *The geothermal fluid transportation network*: This network, based usually on polyethylene tubes properly insulated to reduce heat loss, transfers the geothermal fluid from the geothermal well to the greenhouse heat exchanger.

iv. *The geothermal fluid transportation pump and the corresponding electrical motor*: This heavy duty water transportation pump[9] is used to pump the geothermal fluid to the geothermal wellhead, and accordingly to feed the greenhouse heat exchanger with the appropriate hot geothermal fluid quantity to meet the consumption thermal needs.

v. *The main heat exchanger*: Usually a steel plate heat exchanger is used between the geothermal water and the greenhouse heating system.

vi. *An auxiliary oil-burning installation (optional)*: This oil-burning heat production system is used to satisfy the greenhouse heating requirements only during some very cold periods or to operate as a back up system in case of maintenance or malfunction of the main geothermal based heating system.

During the long-lasting service period of the installation (10-15 years is assumed to be a realistic value), the following operational modes may appear:

a. The thermal demand of the greenhouse "$\dot{Q}_d$" is less or equal than the solar energy "$\dot{Q}_s$" available, i.e.:

$$\Delta\dot{Q} = \dot{Q}_s - \dot{Q}_d \geq 0 \tag{1}$$

In this case, the energy surplus "$\Delta\dot{Q}$" should either be stored in order to be used during low (zero) solar radiation periods or to be transferred away by the air-conditioning system in order to avoid very high temperatures inside the greenhouse[7,8].

b. The thermal energy demand of the greenhouse "$\dot{Q}_d$" is greater than the solar energy "$\dot{Q}_s$" and the greenhouse temperature is near the low temperature limit "θ_{min}", dictated by the type of the cultivation. In these situations the energy deficit "$\Delta\dot{Q}$" is covered by the geothermal fluid with the use of a transportation pump and the corresponding heat exchanger.

c. The thermal energy needs of the greenhouse "$\dot{Q}_d$" cannot be satisfied by the solar and the geothermal potential of the installation (e.g. unusual cold weather, cloudy days, system malfunction etc.). In this occasion, if the greenhouse temperature approaches the low temperature limit "θ_{min}", all the energy deficit should be covered by the oil-based back up heating system; otherwise the greenhouse production is in danger.

3. Solar Greenhouse Energy Analysis

In order to formulate the energy balance of a typical solar greenhouse, the following heat losses sources should be taken into account[10]:

a. The heat loss "$\dot{Q}_l$", resulting from the thermal conductivity of the cover material and the soil as well as the cover material heat loss through radiation "$\dot{Q}_r$", expressed as:

$$\dot{Q}_l = \sum_{1}^{i_{max}} A_i \cdot k_i \cdot [\theta(t) - \theta_a(t)] + A_{soil} \cdot k_s \cdot [\theta(t) - \theta_s(t)] + \dot{Q}_r \tag{2}$$

where "A_i" the surface areas of the cover material, including sides and roof and "A_{soil}" the greenhouse covered area. Accordingly, "k_i" and "k_s" are the thermal conductivity coefficients of the greenhouse surface areas ($i=1,i_{max}$) and of the soil, respectively. Finally, "$\theta_a(t)$" and "$\theta_s(t)$" are the ambient and soil temperatures in course of time "t", while "$\theta(t)$" is the greenhouse interior temperature profile, which should follow the requirements of the selected cultivation. Finally, the cover material heat loss through radiation depends on various parameters, like surface area and inclination angle, material type, indoor and ambient temperature etc. Due to the complexity of the involved calculations, approximations are normally applied, suggesting that the maximum contribution of "$\dot{Q}_r$" in "$\dot{Q}_l$" is less than 20%[11].

b. Subsequently, one should take into consideration the heat loss "$\dot{Q}_v$" caused by the inflow of cold (clean) air into the greenhouse and replacing the existing air quantity, in order to maintain the basic development processes of the plants. In this context, the following equation may be used:

$$\dot{Q}_v = z(t) \cdot \rho_a(t) \cdot V^* \cdot C_p \cdot [\theta(t) - \theta_a(t)] \tag{3}$$

where "z(t)" expresses the air circulations per time unit (usually per hour), depending on the crop cultivated, the day period and the year season, "ρ_a" and "C_p" are the air density and specific heat coefficient and "V*" is the greenhouse volume.

c. Accordingly, one should take also into account the latent heat "$\dot{Q}_h$" depending on the biological operations of the plants and the humidity variation of the greenhouse air due to the water absorption or evaporation by the plants. Using the above presented analysis, one has the ability to estimate the total greenhouse energy demand "$\dot{Q}_d$" as follows:

$$\dot{Q}_d(t) = \dot{Q}_l(t) + \dot{Q}_v(t) + \dot{Q}_h(t) + \delta\dot{Q}(t) \tag{4}$$

Note that the term "$\delta\dot{Q}$" in equation (4) is used to simulate the existence of any passive solar energy storage systems (water bags, black painted material etc.). In the absence of any additional information, "$\delta\dot{Q}$" is taken equal to zero.

On the other hand, the main heat input of the greenhouse is due to the solar energy gains "$\dot{Q}_s$", resulting by the solar radiation[12,13] entering the greenhouse area and absorbed/captured by the system. In this context one may use the following simplified relationship:

$$\dot{Q}_s = \sum_{i=1}^{i_{max}} A_i \cdot (F_{D_i} \cdot I_{D_i} + F_{d_i} \cdot I_{d_i}) \cdot (1 - \Gamma) \tag{5}$$

where "I_D" and "I_d" are the direct and diffused solar radiation in each greenhouse surface location ($i=1,i_{max}$; mainly at horizontal or normal plane), while "F_D", "F_d" describe the corresponding cover material transmissivity. Lastly, "Γ" is the coefficient of reflectivity of the greenhouse ground.

By comparing the greenhouse thermal demand "$\dot{Q}_d$" (equation (4)) and the corresponding solar gains (equation (5)), we get the already introduced equation (1), which along with the entire installation thermal inertia defines the greenhouse temperature profile "$\theta(t)$". Depending on the proposed cultivation type and the crop development phase, attention should be paid in order to ensure that the effective conditions follow the specifications, i.e.:

i. The greenhouse interior temperature should not violate the minimum and maximum plant survival temperatures (θ_{min}, θ_{max}), i.e.:

$$\theta_{min} \le \theta(t) \le \theta_{max} \tag{6}$$

This is for the protection of the investment.

ii. The greenhouse interior temperature profile follows the optimum (desired-maximum production criterion) production temperature (and humidity) distribution "θ_d", i.e.:

$$\theta(t) \rightarrow \theta_d(t) \tag{7}$$

4. Low Enthalpy Geothermal System Sizing

Utilizing the desired capacity of the low enthalpy geothermal field "$\dot{V}_w$" (with $\dot{V}_w \le \dot{V}_g$, where "$\dot{V}_g$" is maximum flow rate of the geothermal field), the following heat load "Q_G" for a specific time interval "Δt" may be covered, i.e.:

$$Q_G = \int_0^{\Delta t} \eta_{ex} \cdot \rho_w \cdot \dot{V}_w \cdot C_w \cdot \left(\theta_0 - \Delta\theta - \theta_2\right) \cdot dt \qquad (8)$$

where "ρ_w" and "C_w" are the geothermal fluid density and specific heat coefficient, "$\dot{V}_w$" is the utilized geothermal fluid flow rate ($\dot{V}_w \le \dot{V}_g$), "θ_2" the heat exchanger outlet (discharge) temperature, "η_{ex}" the heat exchanger efficiency and "$\Delta\theta$" the temperature drop during the geothermal fluid transportation process.

At this point it is important to mention that the temperature drop of the geothermal fluid is a very important parameter of the problem and it depends on the heat loss caused during the fluid's transportation. More specifically, the temperature drop is a function of:

- the geothermal fluid temperature at the wellhead "θ_o"
- the ambient temperature "θ_a"
- the transportation network length "L"
- the network pipes' diameter, material and thickness
- the geothermal fluid mass flow rate (or velocity) and thermodynamic characteristics
- the system insulation type selected

For the heat transfer analysis, see also figure (2), the transportation network heat loss "$\Delta\dot{Q}_G$" can be estimated[14]:

$$\Delta\dot{Q}_G = \pi \cdot (d + 2\delta + 2t) \cdot L \cdot U \cdot \frac{\Delta\theta}{\ln\left(1 + \frac{\Delta\theta}{\theta_1 - \theta_a - \Delta\theta}\right)} \qquad (9)$$

where "U" is the overall heat transfer coefficient, expressed as:

$$U = \frac{1}{\left(1 + \frac{2\delta}{d} + \frac{2t}{d}\right) \cdot \frac{1}{h_i} + \left(\frac{d}{2} + \delta + t\right) \cdot \left(\frac{\ln\left(1 + \frac{2\delta}{d}\right)}{k_p} + \frac{\ln\left(1 + \frac{2t}{d + 2\delta}\right)}{k_{in}} \right) + \frac{1}{h_o}} \qquad (10)$$

with:

"d"	the polyethylene pipes diameter
"L"	the polyethylene pipes length
"δ"	the polyethylene pipes wall thickness
"k_p"	the corresponding thermal conductivity coefficient of polyethylene pipes
"t"	the external insulation thickness
"k_{in}"	the external insulation thermal conductivity coefficient)
"h_i,h_o"	the thermal conductance (or convection heat transfer coefficients) of the geothermal fluid flow throughout the transportation network and that of the atmospheric air outside the network, respectively.

At the same time, the network heat loss is associated with the temperature drop and the geothermal fluid mass flow rate via the following relationship:

$$\Delta\dot{Q}_G = \rho_w \cdot \dot{V}_w \cdot C_w \cdot \Delta\theta \qquad (11)$$

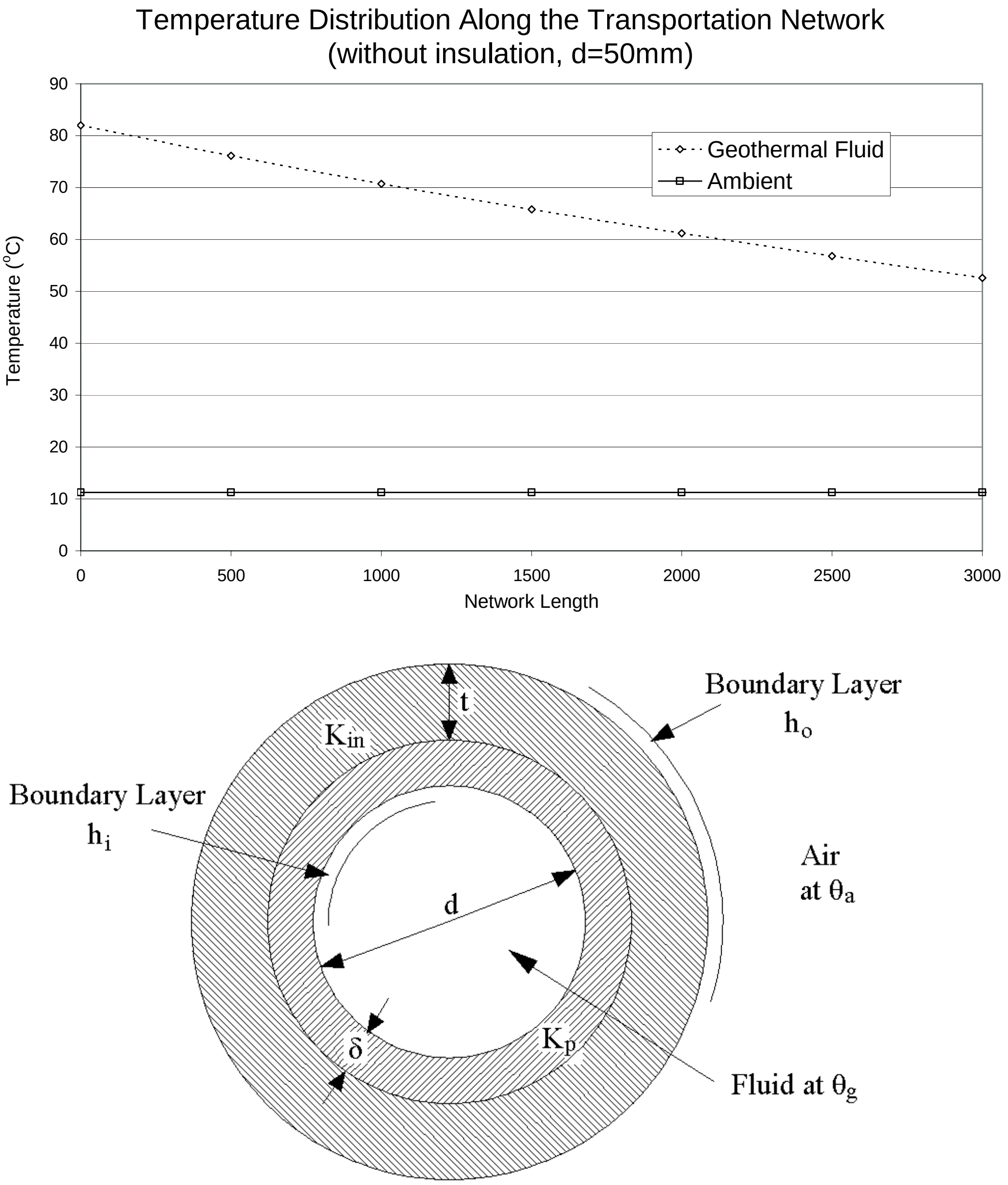

Figure 2: Temperature Distribution in the Transportation Network

Hence, comparing equations (9) and (11), "$\Delta\theta$" and "$\Delta\dot{Q}_G$" can be calculated.

In this context, one may also estimate the fossil fuel (oil or natural gas) consumption "m_f", used by the backup heating system of the installation during the time period "Δt", i.e.:

$$m_f = \int_o^{\Delta t} \frac{\left|\Delta\dot{Q}_o\right|}{\eta \cdot H_u} \cdot dt \qquad \text{only if } \Delta Q_o \prec 0 \tag{12}$$

where "η" is the efficiency of the backup heating system and "H_u" the specific calorific heat of the fuel used. Also, "$\Delta\dot{Q}_o$" is the total energy deficit defined as:

$$\Delta\dot{Q}_o = \Delta\dot{Q} + \dot{Q}_G \tag{13}$$

At the same time one should calculate the main characteristics of the geothermal pump of the installation along with the corresponding electricity consumption. More precisely, the power "N" of the geothermal pump is given[9] as:

$$N = \frac{\rho_w \cdot \dot{V}_w \cdot g(\delta h + \delta z + \delta H_f)}{\eta_p \cdot \eta_{el}} \tag{14}$$

with:

- g: the acceleration gravity
- δh: the well depth
- δz: the hydrostatic head, i.e. the elevation difference between the top of the geothermal borehole (wellhead) and the greenhouse level
- η_p: the efficiency of the water pump
- η_{el}: the efficiency of the electrical motor driven the pump, and
- δH_f: the total hydraulic losses of the geothermal fluid transportation network, both lengthwise and locally.

The following relationship applies for the estimation of the hydraulic losses[15]:

$$\delta H_f = \lambda \cdot \frac{L}{d} \cdot (1+\xi) \cdot \frac{8\dot{V}_w^{\,2}}{g \cdot \pi^2 \cdot d^4} \tag{15}$$

where "λ" is the friction coefficient of the network pipes, "d" is the corresponding internal diameter and "ξ" is the local pressure loss coefficient of the entire transportation network. The electrical energy "E" consumed by the geothermal pump during a time period "Δt" is given as:

$$E = \int_0^{\Delta t} N \cdot dt \tag{16}$$

5. Main Advantages and Critical Issues of the Proposed Solution

The proposed integrated system has numerous advantages, such as:

- ✓ The system uses existing local renewable energy sources, minimizing the oil (or natural gas) consumption
- ✓ The operational cost of the installation is rather low, thus an improved financial efficiency of the installation is expected
- ✓ The environmental benefits of the proposed hybrid greenhouse are obvious, since clean energy resources replace heavy pollutant oil
- ✓ There is increased energy system reliability, due to the presence of three different energy sources (solar, geothermal, oil based boiler)

At the same time some critical factors related to the proposed solution should not be ignored, such as:

- The initial investment cost is increased, in comparison with a simple solar greenhouse, using an oil-heating system
- The proposed solution is rather complex, due to the utilization of water pumps, the existence of the geothermal fluid transportation network, etc.
- There is a possibility that legal issues will be raised, related to the geothermal field ownership. Fortunately, the basic legal issues are resolved by the recently voted law (3175/2003) concerning the exploitation of the existing geothermal fields in Greece.

6. Application Results

For the implementation of the proposed methodology, the interesting geothermal field of Polichnitos in Lesvos area is chosen. Lesvos island is one of the largest Greek islands (area $1600km^2$, population 98,000), located in the northeastern part of the Aegean Sea. Due to the intense geological history[16] of the island, several geothermal reservoirs are spread throughout it. The major Polichnitos area is located at the east side of the gulf of Kalloni and includes several thermal springs with gas (δh=0). One of the most interesting geothermal fields has geothermal surface water temperatures around 82°C and yields a flowrate over $30m^3/h$.

The complete area around the geothermal field is almost flat, used mainly for agricultural purposes and stock raising. Taking also into consideration that the area climate is mild (minimum temperature of the area 2°-3°C) and the corresponding solar radiation is adequately high (approximately $1680kWh/m^2/year$), it is evident that the region under discussion may provide an excellent opportunity for development of geothermal-solar greenhouses.

In this context, the present work is concentrated on the analysis of a $10,000m^2$ polyethylene even-span solar greenhouse, used to cultivate tomatoes for the local island community. The additional energy requirements of the greenhouse under consideration are fulfilled by the exploitation of the nearby (L≈1000m) geothermal field. Applying the analysis of section 3 concerning the greenhouse energy balance, the energy deficit of the installation for the entire year is estimated, see for example figure (3). According to the results obtained the mean daily energy deficit during winter approaches the 5MWh/day. Equivalently, 600kg of oil (0.6toe) per day are needed to cover the heat demand on the basis of an oil-burning heating system, with a total efficiency of 80%. It is noted that normally there is no tomato cultivation in the greenhouses during the hot months of the year, i.e. from May to September.

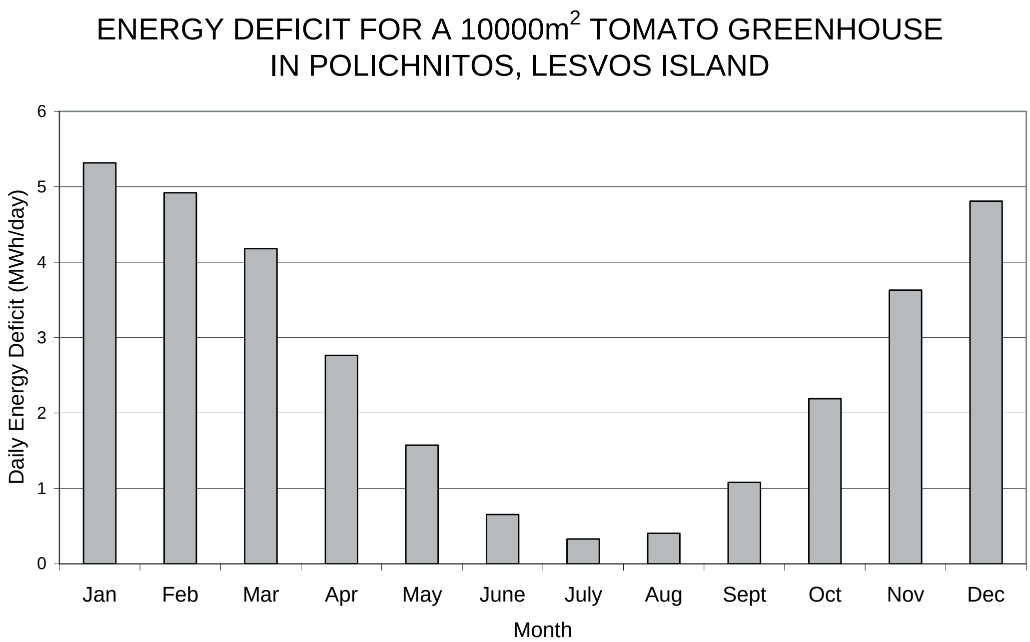

Figure 3: Energy Balance for a Typical Greenhouse in Polichnitos, Lesvos Island

The maximum energy deficit during the winter nights is 300kWh/hour, hence the corresponding oil-burning heating system rated power should be 350,000Kcal/h. For comparison purposes one should mention that the necessary oil quantity (H_u=40,000kJ/kg) to face the annual (in fact from October to

April) energy deficit of the installation is approximately 110tn or equivalently 130,000lt. Using the current oil prices in the local market[17], the fuel cost per year ranges between 60,000€ and 75,000€.

Taking now into consideration the proposed alternative solution based on the existing low enthalpy geothermal field, one has the opportunity to estimate the necessary parameters of the geothermal fluid in order to achieve the desired temperature profile (indicated by equation (7)), see for example figure (4). As it results from the solar-greenhouse energy balance the indoor temperature during January is slightly higher than the ambient temperature (low solar radiation, high energy loss due to low cost plastic covering used) and far lower than the temperature required by the crop cultivated. For this purpose one should cover the energy deficit of approximate 220kWh per hour by transferring 5.2m^3/h of the geothermal fluid. Bear in mind that the quantity needed is less than 20% of the available capacity of the geothermal field.

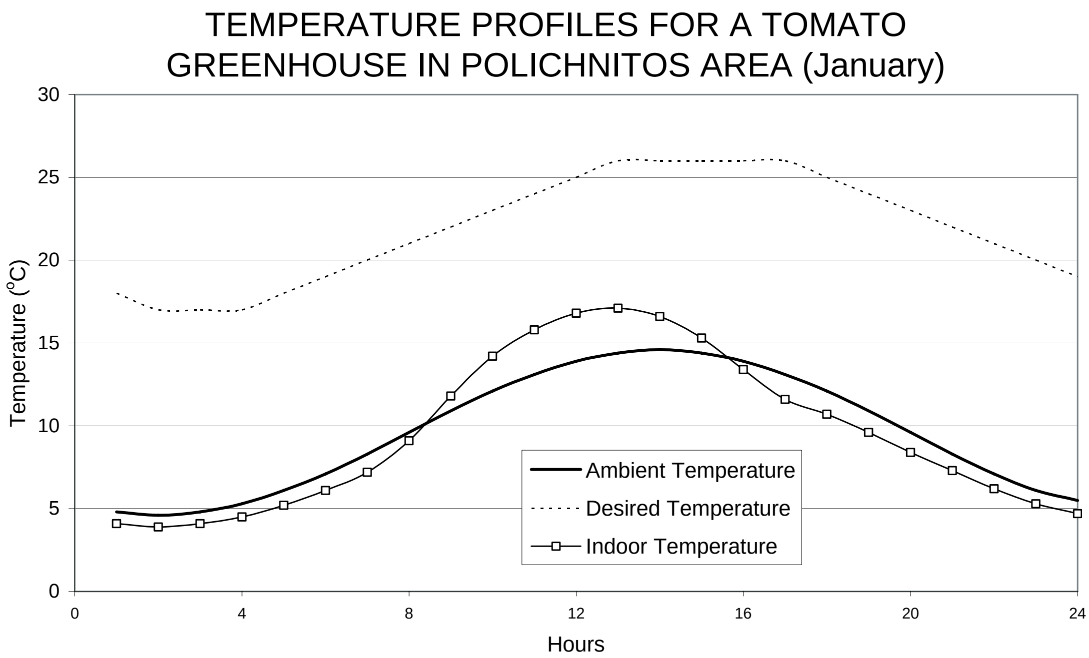

Figure 4: Temperature Profiles for a Typical Greenhouse in Polichnitos, Lesvos Island

Similarly, in figure (5) one may find the geothermal fluid volume needed to cover the energy deficit of the specific greenhouse for the entire year. In this context, almost 25,000m^3 of geothermal fluid are needed per year. In the same figure the geothermal fluid exploitation efficiency (defined as the energy transferred to the greenhouse "Q_G" divided by the geothermic energy at the wellhead) is demonstrated, indicating a value slightly above 50% for the entire operational period, i.e. excluding the summer season. In order to understand the above mentioned efficiency value, one should take into account the temperature drop of 10 to 15 degrees along the transportation network as well as a 20% energy loss in the geothermal heat exchanger (efficiency 80%).

Accordingly, in figure (6) the corresponding geothermal fluid daily average velocity (for d=50mm) is demonstrated. The velocity values achieved are less than 1m/s, limiting thus the corresponding friction losses. In addition, the electricity consumption of the geothermal pump (3kW or 4HP) is given in figure (6). According to the calculation results the annual electricity consumption is less than 5800kWh, representing an average cost of 300€ or 0.5% of the corresponding oil purchase value.

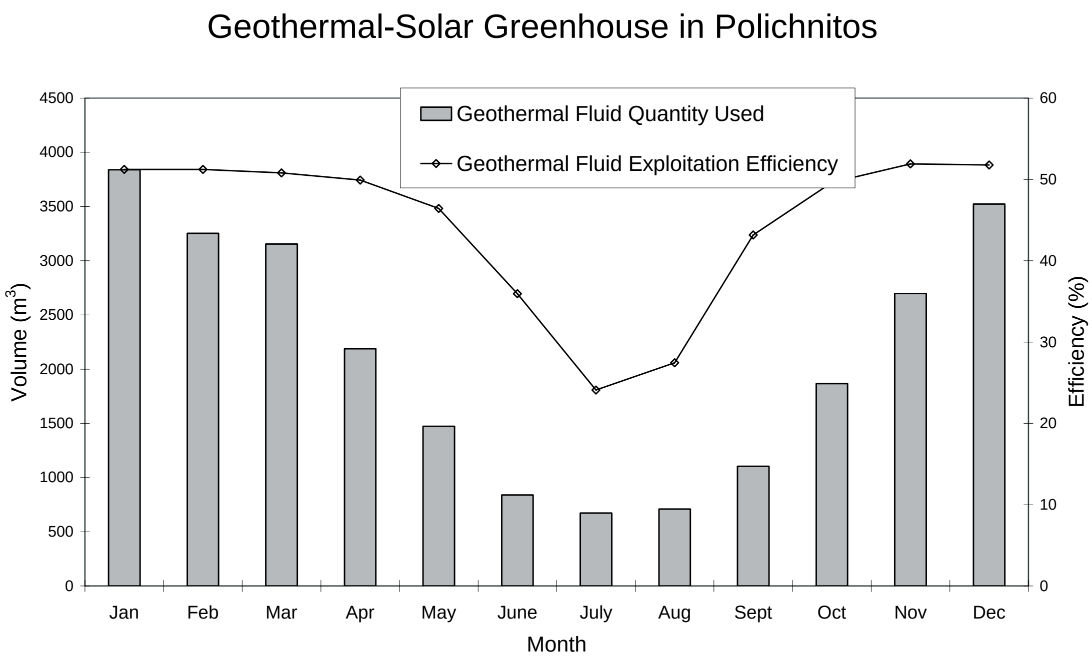

Figure 5: Main Parameters of the Geothermal Fluid Used for a Typical Greenhouse

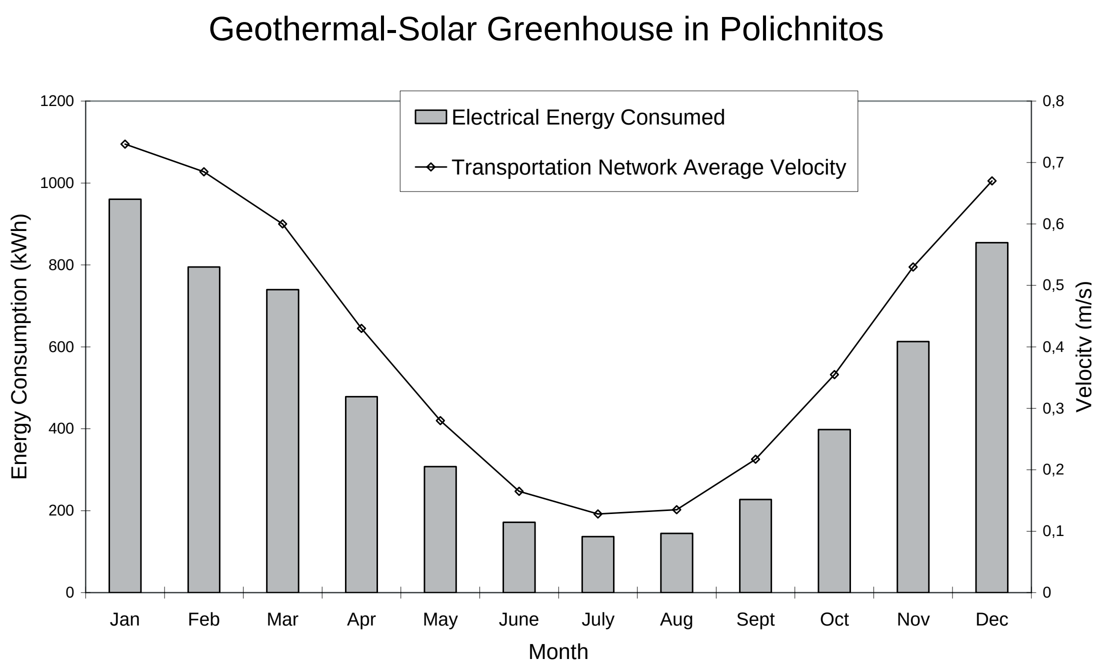

Figure 6: Energy Consumption and Velocity of the Geothermal Fluid Used

6.1 Optimal Selection of the Network Diameter

Subsequently, the network diameter should be chosen in order to minimize the geothermal fluid transportation heat and pressure loss. For this purpose four typical polyethylene pipe diameters are tested with values ranging between 30mm and 100mm. The simulation results are summarized in figures (7) to (9). As it can be observed in figure (7), the geothermal fluid quantity needed is reduced (lower heat loss) as the network diameter is decreased. On the other hand, by reducing the network

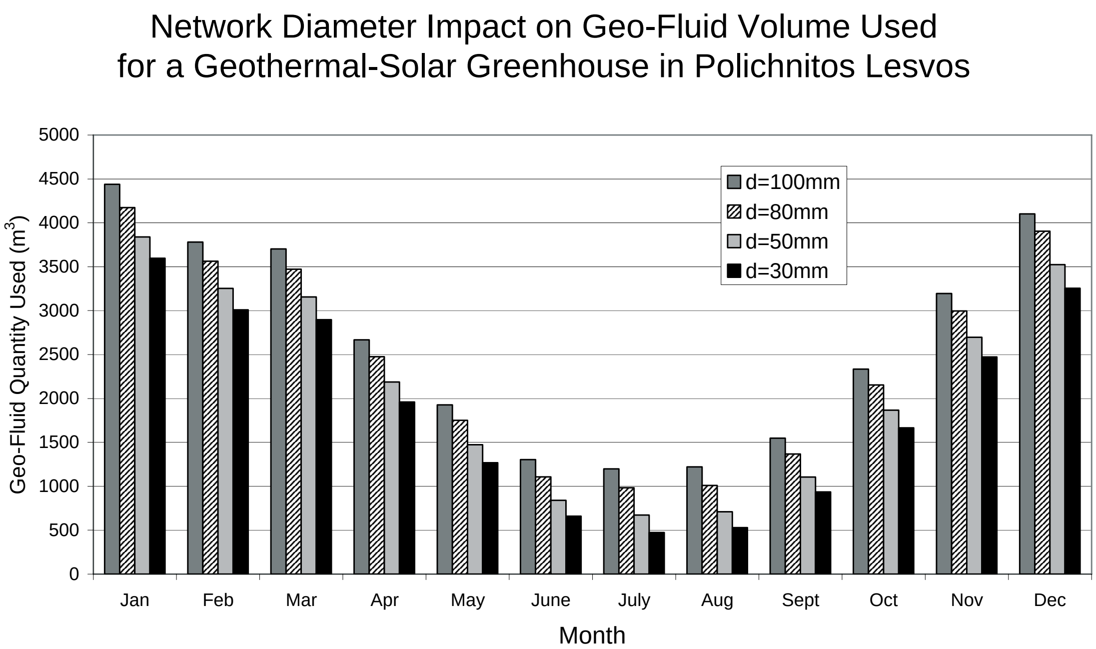

Figure 7: The Impact of Network Tubes Diameter on the Volume of Geothermal Fluid Used

diameter the corresponding electricity consumption (absorbed by the system pump) is substantially amplified, especially for d=30mm, due to the system velocity and the corresponding pressure loss increase, figure (8). In order to get a clear cut picture, the annual electricity consumption and the geothermal fluid quantity used as a function of the transportation network diameter are presented in figure (9). Taking into consideration that the geothermal fluid quantity required represents only a small portion (≤ 20%) of the available geothermal potential, the optimum network diameter should be equal to d_o=50mm, in order to minimize the electricity consumption of the installation.

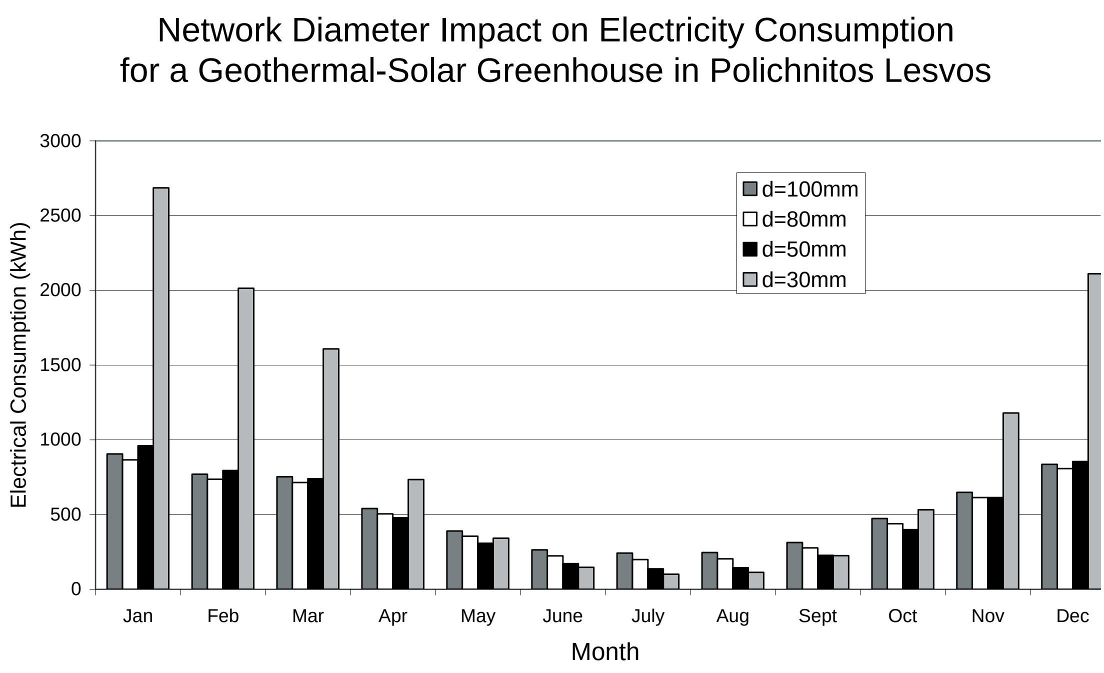

Figure 8: The Impact of Network Tubes Diameter on the Electricity Consumption for the Transportation of the Geothermal Fluid Required

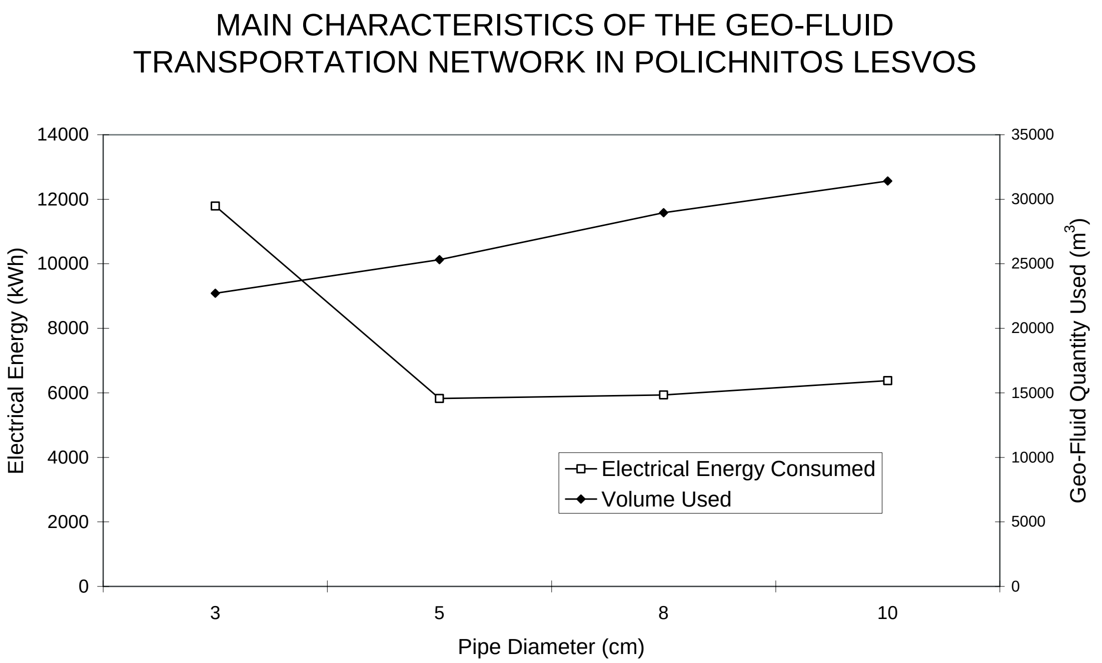

Figure 9: Annual Electrical Energy Required and Geothermal Fluid Quantity Used

6.2 The Impact of the Network Length on the System Energy Balance

The second parameter to be analyzed is the distance "L" between the geothermal wellhead and the corresponding greenhouse. As it is expected, the heat loss of the transportation network is remarkably increased with the distance "L", hence additional geothermal fluid is needed, figure (10). Similarly, the electricity consumption of the installation pump is also increasing, especially from L=2km to L=3km, figure (11). This fact may be explained not only by the increased length-depended friction loss but also due to the increased transportation velocity (higher volume rate, constant diameter). Finally, in figure (12) one may observe the annual electrical energy required and the corresponding geothermal fluid quantity needed as a function of the distance between the geothermal wellhead and the application location.

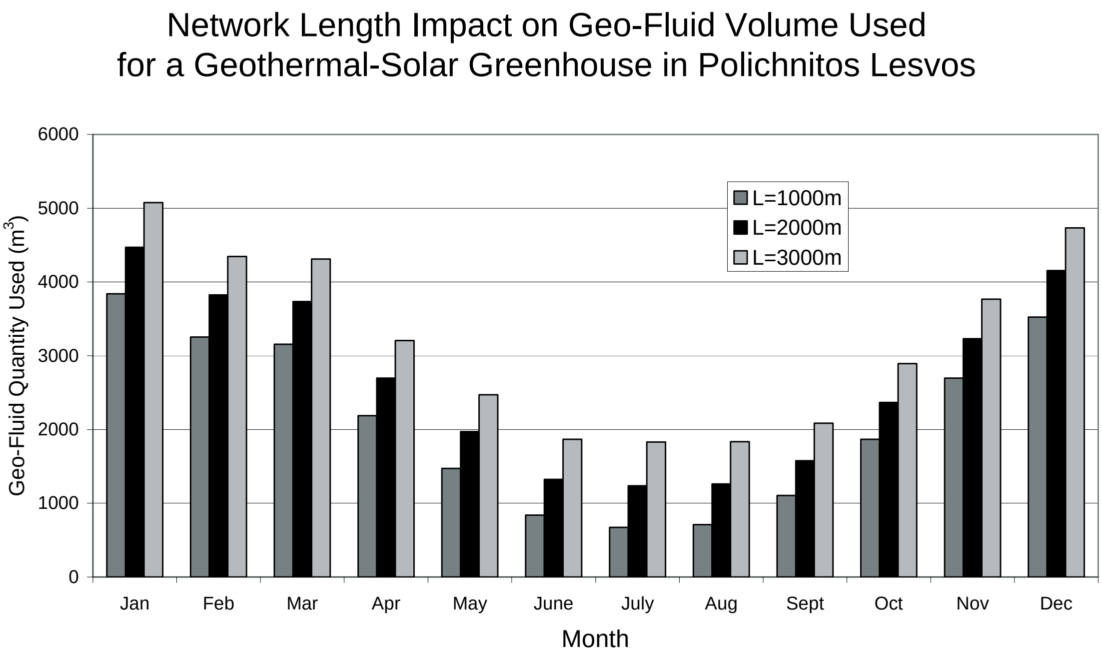

Figure 10: The Impact of Transportation Network Length on the Volume of Geothermal Fluid Used

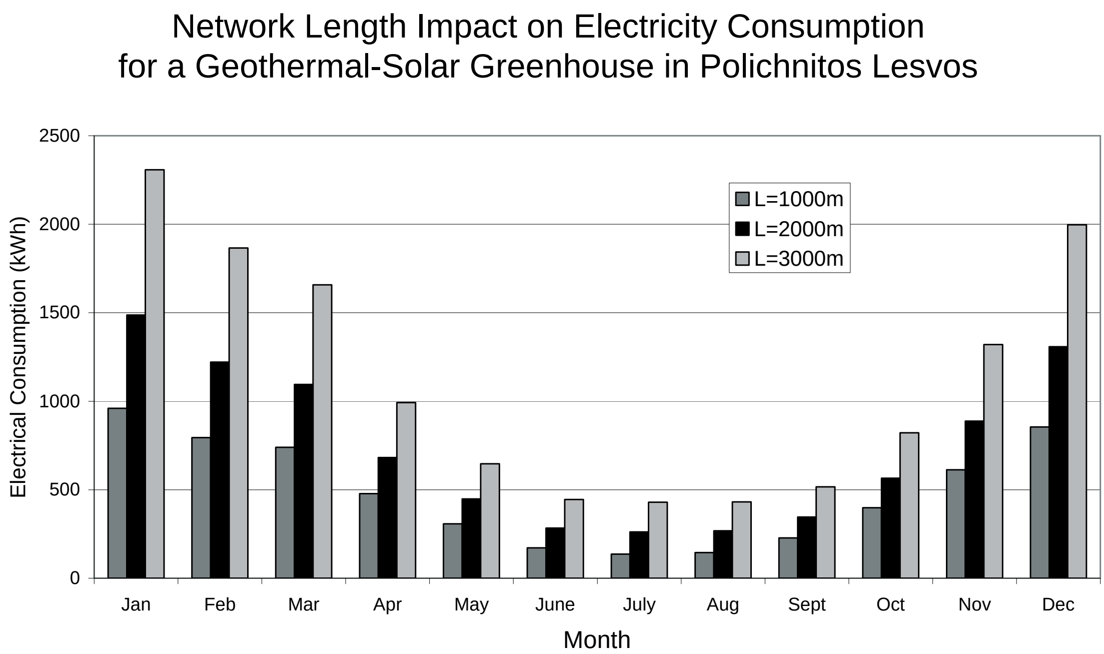

Figure 11: The Impact of Transportation Network Length on the Electricity Consumption for the Transportation of the Geothermal Fluid Required

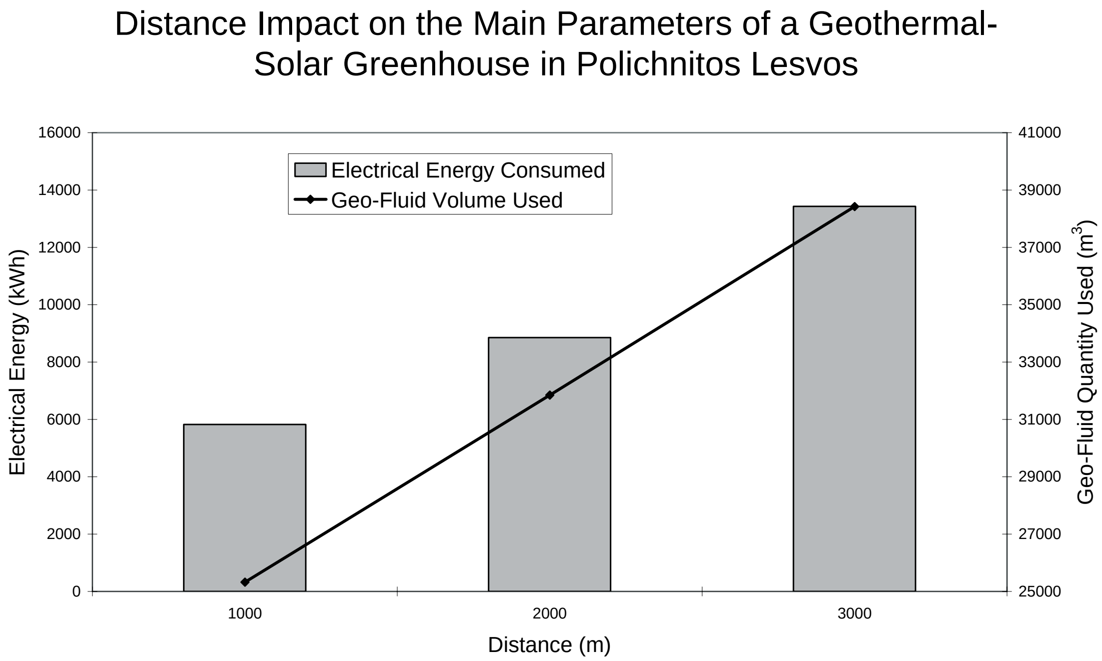

Figure 12: The Impact of Transportation Network Length on the Annual Electrical Energy Required and Geothermal Fluid Quantity Used

In conclusion, one may definitely support that for "L" values up to 3km the usage of the geothermal fluid is a much more cost effective solution (annual electricity cost less than 700€) than the utilization of an oil burning heating system (annual oil cost ≈70000€).

Additionally, the entire geothermal fluid transportation network cost (including the water pump and the geothermal heat exchanger) varies between 60,000€ and 100,000€ (1km ≤ L ≤ 3km). Disregarding any State subsidization the entire geothermal installation cost has a Payback Period (PBP) between 1 and 1.5 operational years, while the service period of the proposed solution is five (5) years minimum. At this point, it is assumed that the income of the investment practically reflects the money saved from not using the diesel oil.

7. Conclusions

The low enthalpy geothermal energy exploitation prospects for the greenhouse energy needs satisfaction are analyzed in the present work. To that effect, an integrated solution for the energy system configuration and design has been proposed.

The main idea is to display as much as possible the fossil fuels with low enthalpy geothermal energy and to optimally design the system so that the conventional energy needs are minimized. The design parameters that are determined with the proposed methodology are the location of the greenhouse (as far as the maximum acceptable distance from the geothermal field is concerned) and the geothermal fluid transportation network dimensions. In parallel, the main parameters of other system components (pumps, heat exchanger) are also suggested.

The methodology has been implemented in a selected agricultural area with remarkable geothermal potential. The results of the application have indicated that the financial efficiency of the proposed system configuration is also attractive. In conclusion, the proposed analytical solution exploits local clean energy sources, and more specifically geothermal and solar energy, achieving promising technical and financial efficiency in the energy use of a greenhouse.

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TECHNO-ECONOMIC EVALUATION OF AUTONOMOUS BUILDING INTEGRATED PHOTOVOLTAIC SYSTEMS IN GREECE

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Abstract

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

Keywords: Autonomous Photovoltaic System; Optimum System Sizing; Remote Consumers; Building Integrated Photovoltaic Systems; Techno-economic evaluation

1. Introduction

In Greece -especially in the Aegean and Ionian Archipelago areas- there exist several isolated consumers (such as private farms, tiny villages, shelters, lighthouses, telecommunication stations, etc.), which have no access to an electrical grid[1-3]. So far, in an attempt to cover their urgent electrification needs, they consider small oil-fired electrical generators to be their only alternative[4]. Besides, due to the geographical position of Greece, most Greek territories possess an abundant and reliable solar supply[5] all year round; figure (1).

Hence, to face the urgent electrification problem of remote consumers spread throughout Greece, the present study is focused on investigating the possibility of creating an integrated photovoltaic station (PVS), based on a small photovoltaic generator and an energy (battery) storage device, along with the corresponding electronic equipment[6-8]. This analysis is mainly planning to evaluate the techno-economic viability of a stand-alone PVS[9,10] able to satisfy the electricity demand of a representative remote consumer under the restriction of minimum installation cost, for several representative Greek areas, figure (1). The areas selected are located either in mainland or in the Aegean Archipelago.

2. Proposed Solution

In an attempt to simulate the energy balance profile of a remote consumer, a joint effort is made to settle the electricity demand difficulty of a typical isolated consumer (e.g. a four to six member family), using a properly sized stand-alone photovoltaic system. After an extensive localmarket survey[11,12] a representative weekly electricity consumption profile is adopted, being also depended on the year period analysed (i.e. winter, summer, other). The load profile used (see figure (2)) is basically

Kaldelli El., Xirakis Ef., Kavadias K., Kaldellis J.K., 2005, *"Techno-Economic Evaluation of Autonomous Building Integrated Photovoltaic Systems in Greece", International Conference on "Integration of RES into Buildings", July 2005, Patras, Greece.*

a rural household profile (not an average load taken from typical users) selected[13,14] among several profiles provided by the Hellenic Statistical Agency. More precisely, the numerical load values vary between 30W (refrigerator load) and 3300W.

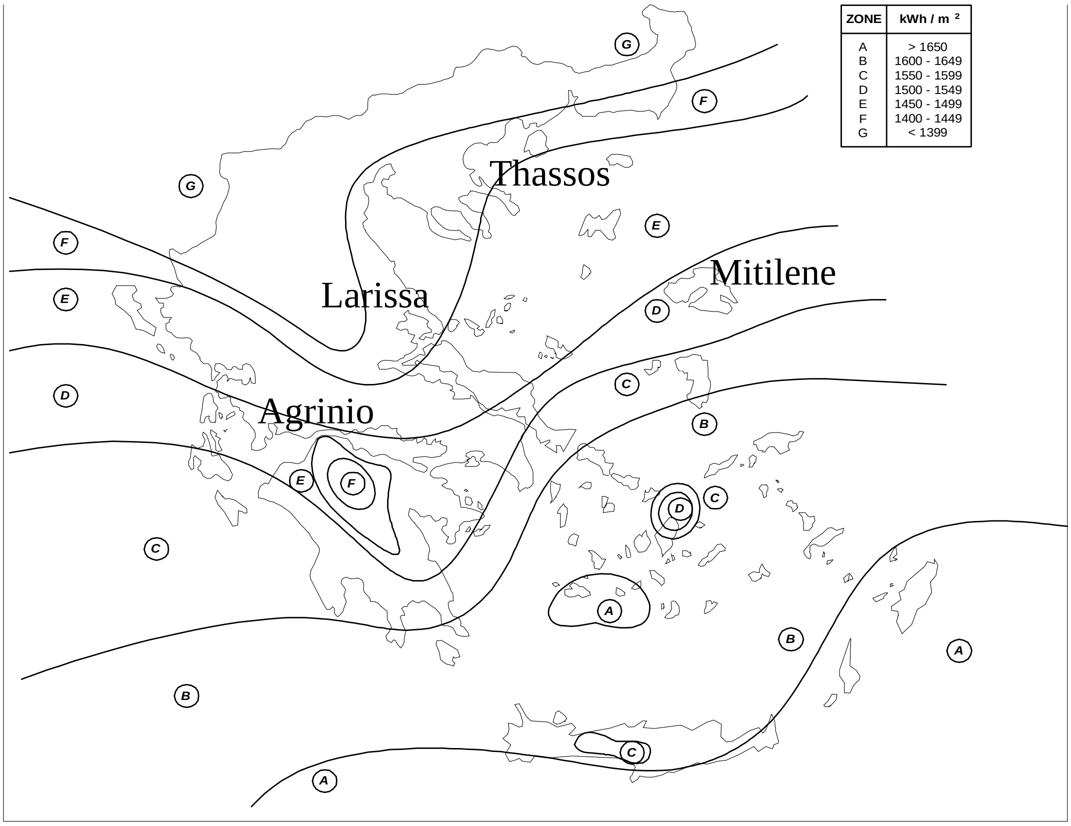

Figure 1: Solar Potential of Greece

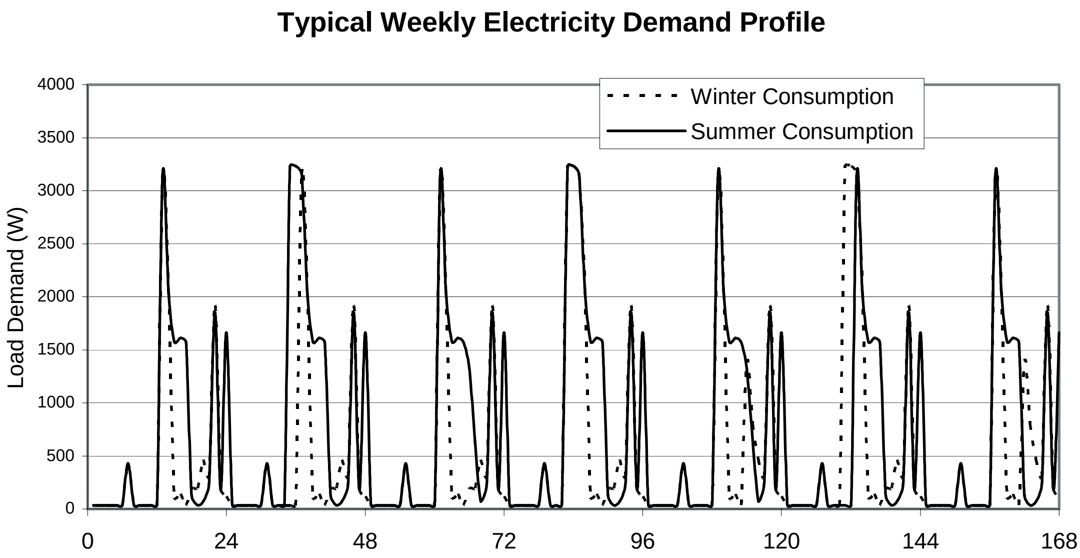

Figure 2: Typical Electricity Demand Profile of the Remote Consumer Analyzed

Thus, the annual electricity consumption -on an hourly basis- is the first input of the present analysis. Additionally, the corresponding solar radiation and ambient temperature are also necessary to integrate the calculation of the proposed system dimensions[15,16]. Finally, 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 are also required.

In this context, the proposed stand-alone PVS comprises (see figure (3)) an array of photovoltaic (PV) modules connected to a battery via a battery charge controller or to a DC/AC inverter. Keep in mind that the battery charge controller switches the PV array off when the battery is fully charged and switches (rejects) the load off before the battery gets completely discharged. The energy storage system (a lead acid battery is found[17] to be the most appropriate solution, given the present technological status) should be adequate to store the energy production during sunlight hours for use at night or bad weather conditions. Finally, since most applications are based on alternative current, a DC/AC inverter is also required.

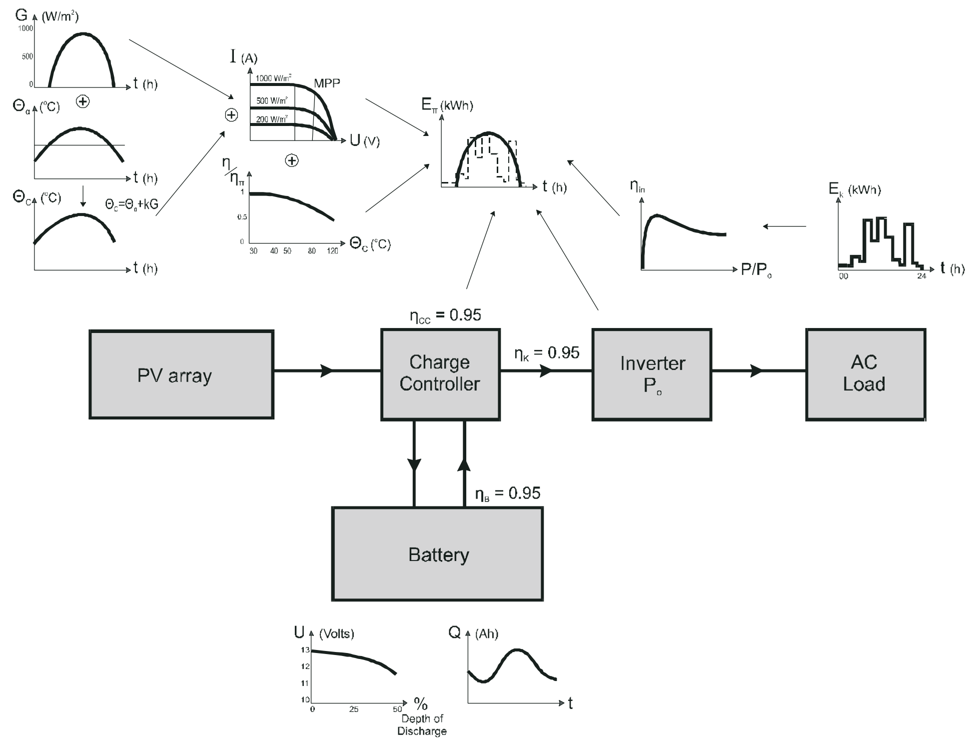

Figure 3: Proposed Autonomous PVS Configuration for Remote Consumers

More precisely, the proposed (figure (3)) 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/AC inverter of maximum power "N_p" able to meet the consumption peak load demand

where "N_p" is the current maximum load demand of the consumption, including a future increase margin (e.g. 30%).

3. PVS Sizing Analytical Model

For the estimation of the main dimensions of a building integrated PVS, a fast and reliable numerical algorithm "PHOTOV-III" has been created during the last years[18,19]. This algorithm is able to calculate the energy behaviour of stand-alone photovoltaic systems for a selected time period (e.g. one or more years). The main steps of this algorithm (see also figure (4)) are:

a. For every region analysed, select a "z" and "Q_{max}" pair.
b. For every time point of a given time period (with a specific time step) estimate the energy produced "N_{PV}" by the photovoltaic generator, taking into account the existing solar radiation, the ambient temperature and the selected photovoltaic panel power curve.
c. Compare the energy production with the isolated consumer energy demand "N_D". If any energy surplus occurs (N_{PV}>N_D), the energy is stored to the battery bank and a new time point is examined (i.e. proceed to step a). Otherwise, proceed to step (d).

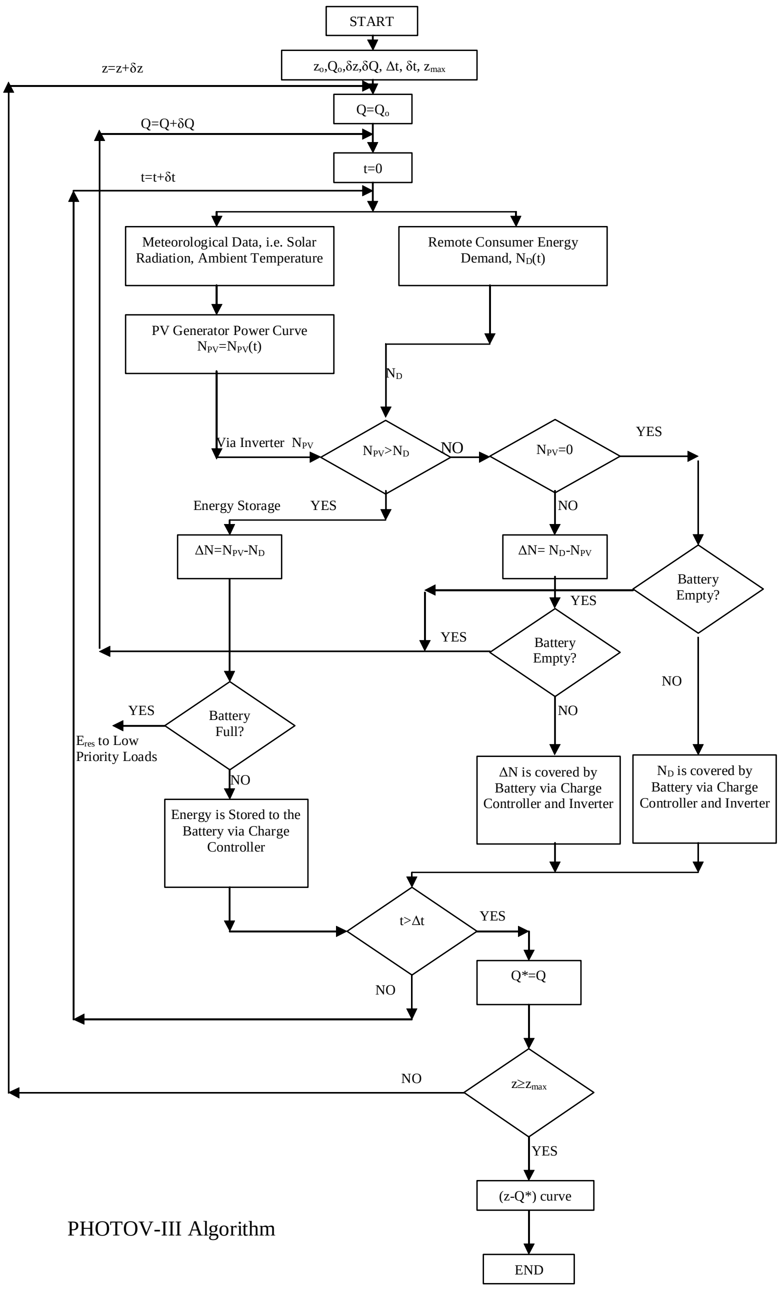

Figure 4: PHOTOV-III Algorithm

d. The energy deficit (N_D-N_{PV}) is covered by the energy storage system, if the battery is not near the lower limit ($Q>Q_{min}$). Accordingly proceed to step (d). In cases that the battery is practically empty ($Q \leq Q_{min}$), the load is rejected for an hour period. If the load rejection number "h" exceeds a pre-described limit "h_{max}" (e.g. $h_{max}=0$, for the no-load rejection case) the battery size is increased (by a given quantity) and the complete analysis is repeated, starting from step (a).

After the integration of the PVS energy analysis, a (z-Q^*) curve is predicted. 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 desired small period of "h_{max}" hours per annum. Finally, the optimum pair may be selected from the predicted (z-Q^*) curve, on the basis of a specific installation cost criterion.

4. PVS Cost Analysis

The initial cost "IC_o" of a photovoltaic stand-alone system (PVS) can be approximated[20] as:

$$IC_o = C_{PV} + C_{bat} + C_{elec} + f \cdot C_{PV} \tag{1}$$

where "C_{PV}" is the photovoltaic modules ex works cost, "C_{bat}" is the battery bank buy-cost and "C_{elec}" the cost of the major electronic devices. Finally, the BOS (balance of system) cost is expressed via the first installation cost coefficient "f" (excluding the cost of electronic equipment). Using previous analysis by the authors[14,19], one may finally get:

$$IC_o = \zeta \cdot z \cdot Pr \cdot N_o \cdot (1+f) + c_b \cdot Q_{max} + a + b \cdot z \cdot N_o \tag{2}$$

where "ζ" is a function of "z" (i.e. $\zeta=\zeta(z)$), expressing the scale economies[21] for increased number of photovoltaic panels utilized. In the present case ($z \approx 100$), thus ζ is taken equal to one. Subsequently "P_r" is the specific buy-cost of a photovoltaic panel (generally $P_r=P_r(N_o)$) expressed[22] in Euro/kW_p. Similarly, "c_b" is slightly dependent (Euro/Ah) on battery capacity[23]. Thus for the local market -after a market survey concerning lead-acid batteries of 24V- the following semi-empirical relation may be used:

$$c_b = \frac{5.0377}{Q_{max}^{0.0784}} \tag{3}$$

Additionally, parameters "a" (in Euro) and "b" (in Euro/kW) describe the cost of the major electronic devices, being generally a function of the peak load demand (e.g. inverter) and the photovoltaic modules rated power (e.g. charge controller).

Recapitulating, the initial installation cost of a stand-alone photovoltaic system is a function of"z" and "Q_{max}" if the peak power "N_o" of the modules selected is defined, thus one may write:

$$IC_o = IC_o(z, Q_{max}) \tag{4}$$

Hence, by using the initial cost function (equation (4)) it is possible to estimate, using the above predicted (z-Q^*) curve, the minimum initial cost solution, which guarantees energy autonomy excluding a specific acceptable number "h_{max}" of hourly load rejection per annum of the remote consumer for the time-period examined.

On top of that, it is important to note that Greek State and European Union strongly subsidy small photovoltaic systems, while the subsidization percentage "γ" varies between 40% and 70%. More precisely one may write:

$$IC_{IN} = (1-\gamma)\cdot IC_o \tag{5}$$

5. Applications Results

Table I: Main Characteristics of Regions Tested

Region	Geographical Latitude	Geographical Longitude	Zone of figure (1)
Agrinio	38º37′	21º24′	E
Mitilene	39º6′	26º33′	D
Larissa	39º38′	22º25′	F
Thassos	40º56′	24º25′	G

The present analysis is focused on selected representative locations throughout Greece (Table I). More specifically in the following we investigate autonomous building integrated PVS located in Agrinio of West Greece, Mitilene of Lesvos island, Larissa of Central Greece and Thassos island, see also figure (1). For all these regions long-term solar radiation and ambient temperature measurements are existent. For example, the long-term average solar potential of all these areas is demonstrated in figure (5). According to the available measurements, Mitilene and Agrinio possess the highest solar potential, while the lowest solar radiation values are given for Thassos island (N. Greece).

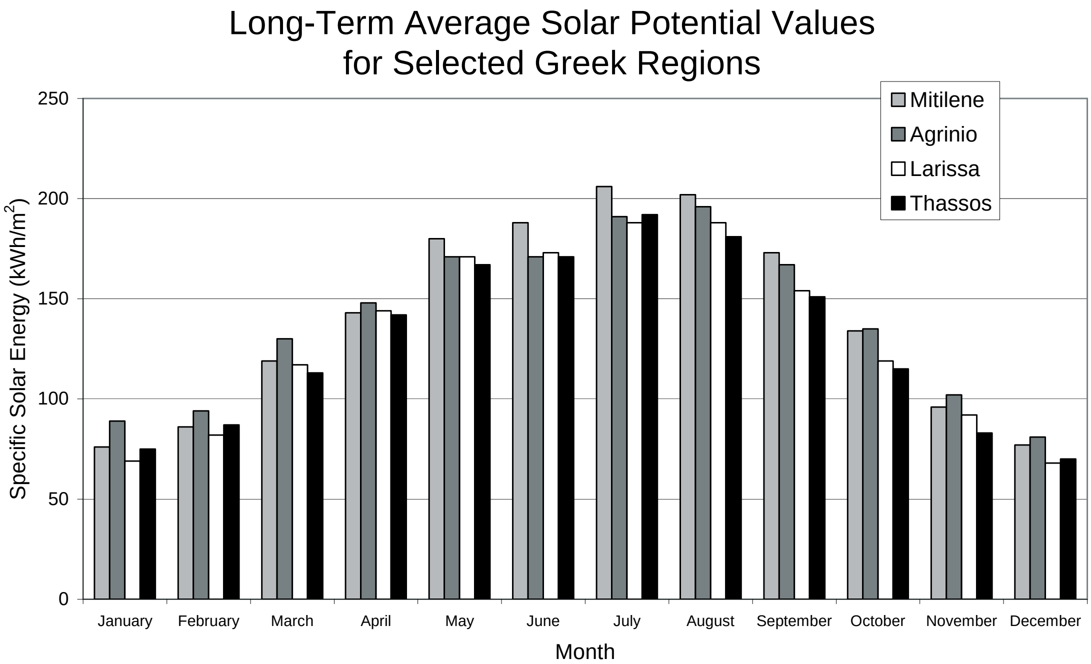

Figure 5: Measured Solar Energy Potential

For the specific case of building integrated PVS one should mainly examine installations placed either in horizontal or in normal plane. In the first case the photovoltaic panels' tilt angle is zero (i.e. β=0°) and the PV panels are used to cover horizontal surfaces (e.g. building roof). Applying the above-described model for the four areas under investigation, we get the results of figure (6). According to these results, the most cost effective installation is the one located in Agrinio, based on approximately 140 PV panels of 51W and lead-acid batteries of 6700Ah (DOD=75%). The corresponding minimum initial cost value is 29000Euro, including also a 50% State subsidization. For comparison purposes, it is interesting to remind that the grid connection cost exceeds 10000Euro/km, in regions with existing local electrical network.

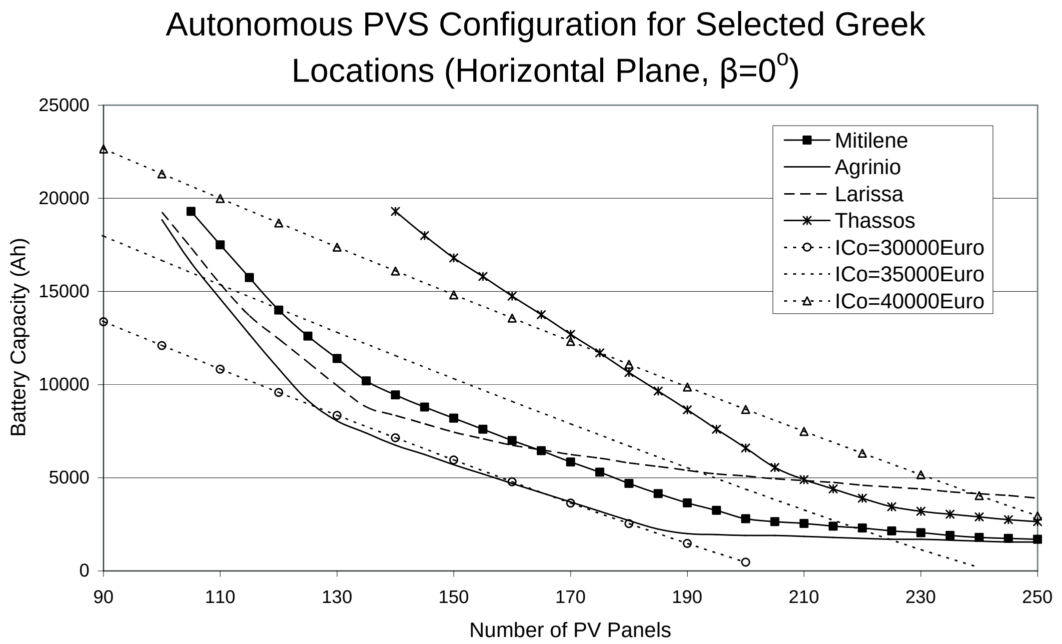

Figure 6: Optimum Autonomous PVS Configuration (Horizontal Plane, β=0°)

Subsequently, Larissa and Mitilene present a slightly most expensive solution, while the optimum PV panels number is almost the same. It is interesting to note that for low PV panels number the Larissa PVS presents lower cost, while the system battery capacity for Mitilene case is substantially lower compared with the one of Larissa, as the PV panels number is increasing. On top of this, for high photovoltaic power solutions Mitilene and Agrinio configurations almost coincide. Finally, the PVS of Thassos island is more expensive than the other three and it is based on remarkably higher PV panels number. On the other hand, the energy storage requirements are quite lower than those of Larissa installation.

For the second case, the photovoltaic panels' tilt angle is ninety degrees (i.e. β=90°) and the PV panels are used to cover normal surfaces (e.g. building walls). Applying again the proposed model for the areas under investigation, we get the results of figure (7). According to the results obtained in this specific tilt angle both installations (i.e. in Mitilene and in Agrinio) present almost the same initial cost, which is equal to 27000Euro, State 50% subsidization included. Besides the energy autonomy PVS is based on 160 PV panels (51W), while the corresponding battery capacity is less than 2500Ah. It is also interesting to note that the minimum initial cost solution for the Larissa installation presents quite similar initial cost (i.e. 28000Euro), although the energy storage requirements are almost 100% higher. Finally, the PVS of Thassos island is the most expensive one, based on higher PV panels' number than the other installations.

Taking into consideration previous works by the authors[14,24], the most cost effective panels' tilt angle is near sixty degrees (β≈56°). Thus, one may investigate -for comparison purposes- the corresponding autonomous PVS configuration for the selected areas, figure (8). In fact, by using β=60° the number of PV panels and the corresponding energy storage requirements are remarkably decreased, in comparison with the β=0° and β=90° installations. As a direct result of this evolution, the first installation cost drops to 21500Euro for Agrinio, 23000Euro for Mitilene and 24000Euro for Larissa. At the same time, the number of PV panels is only 100 for Agrinio and 120 for Mitilene, while the corresponding battery capacity varies between 4900 and 3600Ah.

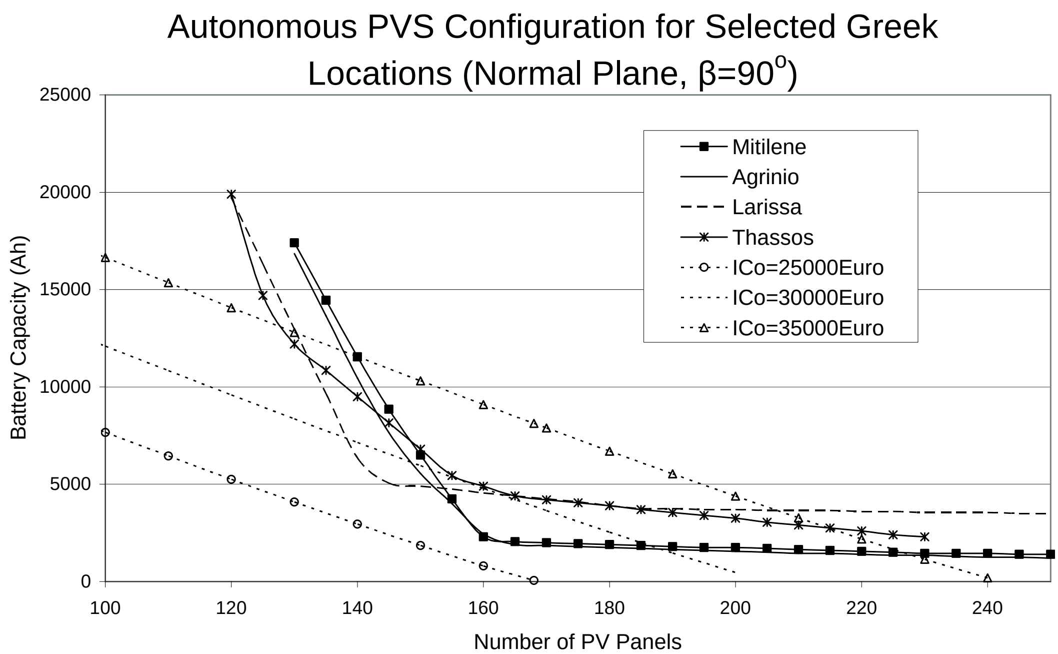

Figure 7: Optimum Autonomous PVS Configuration (Normal Plane, β=90°)

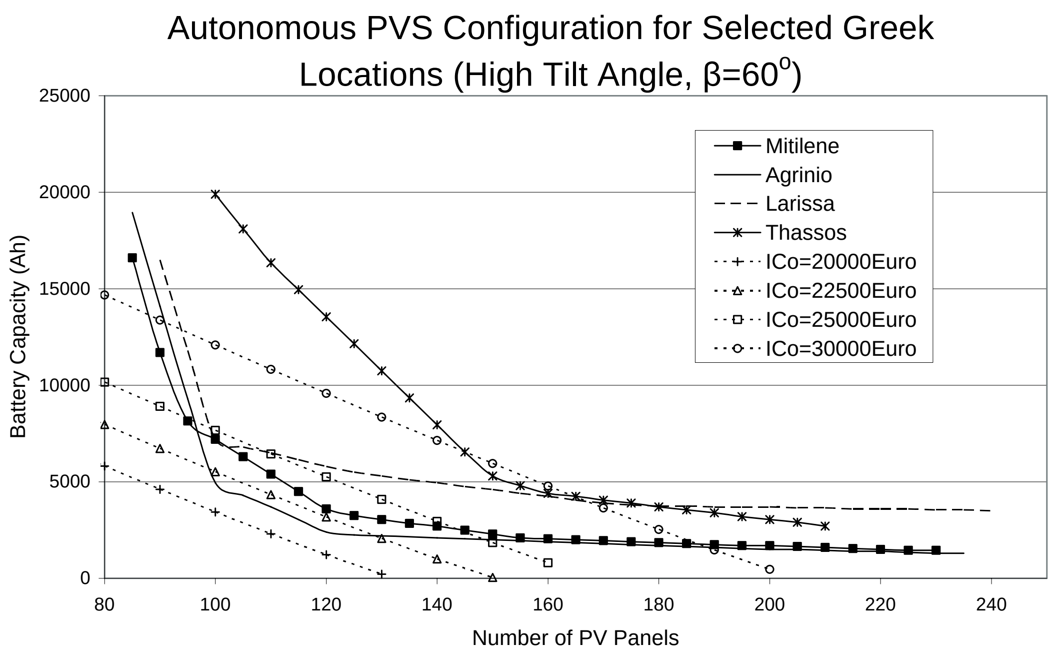

Figure 8: Optimum Autonomous PVS Configuration (Optimum Tilt Angle, β=60°)

Lastly, one may examine the case that the PV panels are set at thirty degrees tilt angle (i.e. β=30°). This choice has several practical advantages, since it is better adapted to existing roofs, while the configurations required are not very different that the optimum ones (β≈56°), see also figure (9). In this last case, the minimum initial cost configurations are based on 110 PV panels and 5000Ah for Agrinio and on 135 PV panels and 3600Ah for Mitilene regions. The corresponding minimum first installation cost is 23500Euro and 25000Euro respectively. At the same time the PVS of Larissa and

Thassos island are based on 100 and 150 PV panels while the corresponding battery capacity ranges between 8300Ah and 4900Ah.

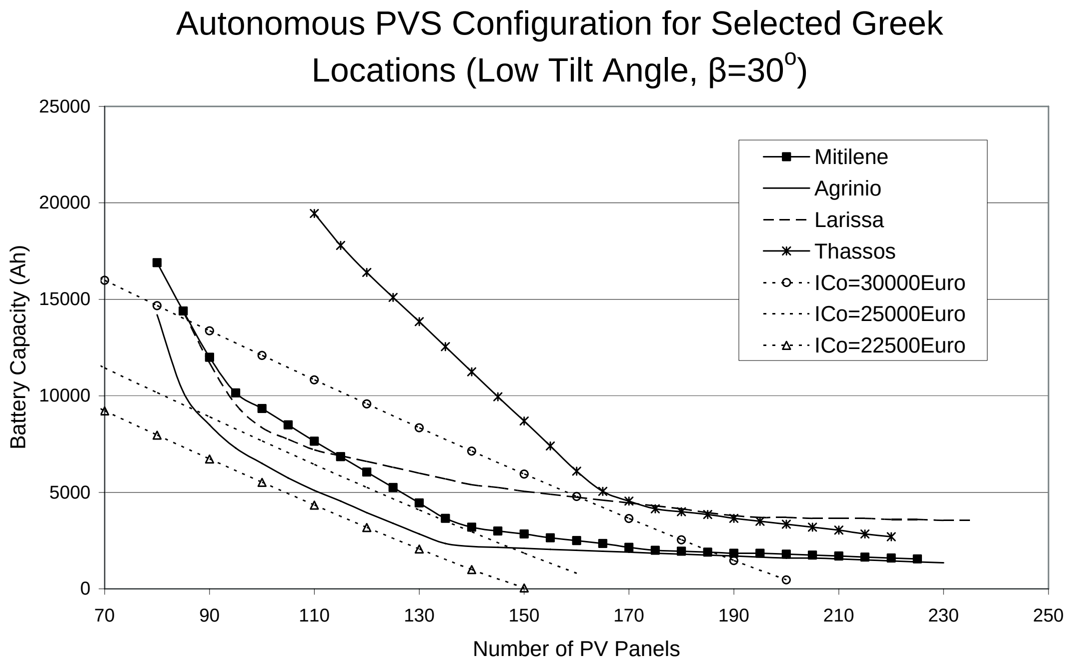

Figure 9: Optimum Autonomous PVS Configuration (Low Tilt Angle, β=30°)

Summarizing, Table II gathers the calculation results concerning the main characteristics of an autonomous photovoltaic system situated in four representative Greek territories. For comparison purposes, Table II also portrays the initial cost variation for all regions analysed and for the same time period as a function of the panel tilt angle. According to the information presented, the optimum tilt angle is around sixty degrees for all cases analysed, while the dimensions and the initial cost of an autonomous photovoltaic system are strongly depended on the exact location or more accurately on the solar potential of the installation. Keep in mind that even the horizontal and the normal cases demonstrate comparable configurations to the optimum tilt angle solution.

Table II: Basic Parameters of Proposed Solutions

Region		Agrinio	Mitilene	Larissa	Thassos
PV Panels Number	β=0°	140	190	135	210
	β=30°	110	135	100	165
	β=60°	100	120	100	150
	β=90°	160	160	145	160
Battery Capacity (Ah)	β=0°	6700	3600	8800	4900
	β=30°	5000	3600	8300	5000
	β=60°	4900	3600	7200	5300
	β=90°	2450	2300	5000	4900
Initial Cost (€)	β=0°	29000	32500	31500	37000
	β=30°	23500	25000	26000	31500
	β=60°	21500	23000	24000	29000
	β=90°	27000	27000	28000	30000

Besides, it is quite amazing to remark that between regions of the same country, quite different PVS configurations are needed to meet the electricity requirements of the same consumer. In any case, the first installation cost is not prohibitive, even for the less advantageous region, considering the significant amount of almost 10000-12000Euro per kilometre required for the electrical grid extension.

6. Conclusions

The optimum dimensions of an autonomous building integrated photovoltaic system are defined for typical regions of Greece, using representative solar potential data. The results obtained are based on experimental measurements and on operational characteristics provided by the autonomous system components' manufacturers. For the system simulation a reliable and fast numerical code "PHOTOV-III" has been applied, in order to estimate the energy-autonomy photovoltaic panel number and battery bank capacity combinations, for every region and time period analysed. Besides, the developed algorithm finds the optimum panel tilt angle that minimizes the first installation cost of the proposed PVS.

Among the most interesting findings of the present research it is the impact of panel tilt angle on the PVS configurations and initial cost. Accordingly, one may underline the remarkable autonomous PVS size difference between the locations examined. However, in all cases analysed the capital to be invested -considering the 50% State subsidization- varies between 20000 and 30000Euro, being equivalent to 1.5 to 3km of electrical grid extension, if obtainable.

Recapitulating, the proposed photovoltaic energy autonomous system turns to be one of the most appropriate solutions for the electricity demand of numerous remote consumers. On top of this, for high solar radiation areas small PVS are characterized as economically attractive investments, especially if the subsidization opportunities by local authorities are taken into consideration. Thus, according to the results obtained the authors believe than an autonomous photovoltaic system can definitely contribute on solving the urgent electrification problem of remote buildings spread throughout Greece, also improving the life quality level of their habitants.

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ENERGY AND CLEAN WATER CO-PRODUCTION IN REMOTE ISLANDS TO FACE THE INTERMITTENT CHARACTER OF WIND ENERGY

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Abstract

In many small or medium-sized remote islands 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. Wind energy can definitely contribute on solving these problems at a rational investment and operational cost. To face the intermittent and stochastic wind behaviour, a combined wind-hydro configuration is proposed in collaboration with an appropriate desalination plant. The proposed solution leads to high wind energy penetration rates and bounds the operational hours of the existing internal combustion engines, additionally contributing to the air pollution reduction. Besides, significant water quantities can be produced, remarkably reinforcing the water reserves of the local community with fresh water of desired quality. Consequently, the configuration investigated can efficiently fulfil the electrical energy and the clean water requirements of numerous remote communities on the basis of clean and low cost wind energy, overcoming the intermittent and stochastic behaviour of wind.

Keywords: Wind Energy; Remote Islands; Wind-hydro; Desalination; Stochastic Behaviour

1. Introduction

Aegean Archipelago is a remote Hellenic area on the east side of the mainland including a complex of several scattered islands; figure (1). Unfortunately, due to their relatively long distance from the mainland and the difficult access of their habitants to the decision centres, most islands face serious infrastructure problems. In this context, the electricity production cost is extremely high, while extended electrical black outs -due to the insufficient power supply- arise all over the year. On top of this, the water resources are quite restricted for the vast majority of the islands, therefore almost 80% of the fresh-water required is imported. This unfavourable situation results in the low development rates encountered[1] for the entire Aegean Sea area and in the continuous decrease of population during the last forty years.

More precisely, during the last 25 years a significant electrical power increase has been recorded in the majority of the large and small islands, on several occasions approaching 500% in relation to 1980; see Table I[2]. Up to now, the electricity requirement has been hardly fulfilled -at very high fuel consumption values- by the existing outdated autonomous power stations (APS) based on highly polluting internal combustion engines and low efficiency gas turbines. This choice results in an APS electricity production cost exceeding the 200,000,000€, the fuel cost sharing more than 50%; figure (2).

Additionally, the existing data analysis indicates[2] a seasonal electricity demand fluctuation, since the power demand is maximum during summer (e.g. August), while it decreases during November to March; see also figure (3). This seasonal electricity demand pattern, combined with the strong daily electrical load fluctuation, results in a relatively low wind power penetration in the local electrical grids, due to limited wind energy absorbance during the low demand periods.

Kaldellis J.K., Kondili E., Kavadias K.A., 2006, *"Energy and Clean Water Co-production in Remote Islands to Face the Intermittent Character of Wind Energy", International Journal of Global Energy Issues, vol.25(3-4), pp.298-312.*

Table I: Peak Electrical Power Demand (kW) of Selected Aegean Sea Islands[2]

Year	1982	1992	2002
Lesvos	19300	33000	55500
Andros	5550	10900	21570
Thira	2600	11800	27570
Ikaria	1400	3280	6100
Kalimnos-Kos	12200	32600	66100
Karpathos	1510	4000	8050
Milos	1950	3170	8270
Paros	7000	19900	48330
Samos	9000	16700	27000
Siros	8900	11000	16770
Chios	14000	24600	38500

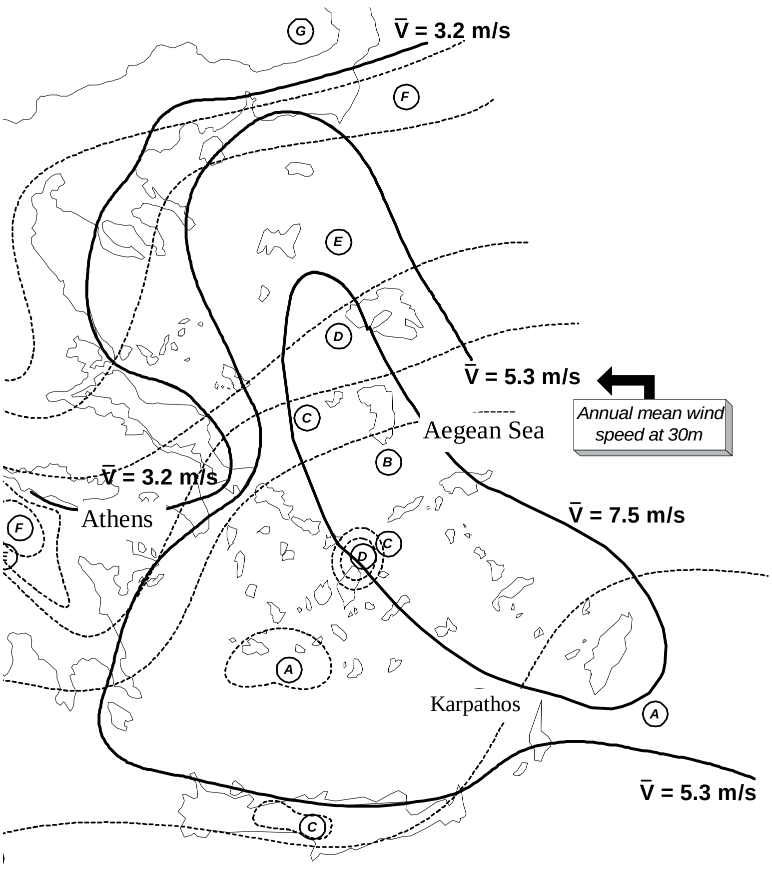

Figure 1: Wind Potential in Aegean Archipelago

On the other hand, for the majority of the Aegean Sea islands the water resources are quite restricted, deteriorating thus the habitants' standard of living. Besides, in several islands salt water intrusion into the aquifers is observed. In fact, the water reserves are not adequate to cover the needs of the islands, especially during summer, when the population is occasionally even ten times above the normal. For all these reasons, the majority of small and medium-sized Aegean Archipelago islands have a significant clean water deficit, especially during the summer, while in several cases almost between 50% and 80% of the fresh-water required is transferred at a very high cost[3,4]. Using the available data one may observe a continuous and sharp increase of water quantities transferred, figure (4), since in specific cases the daily water quantity required per permanent capita exceeds the 150lt.

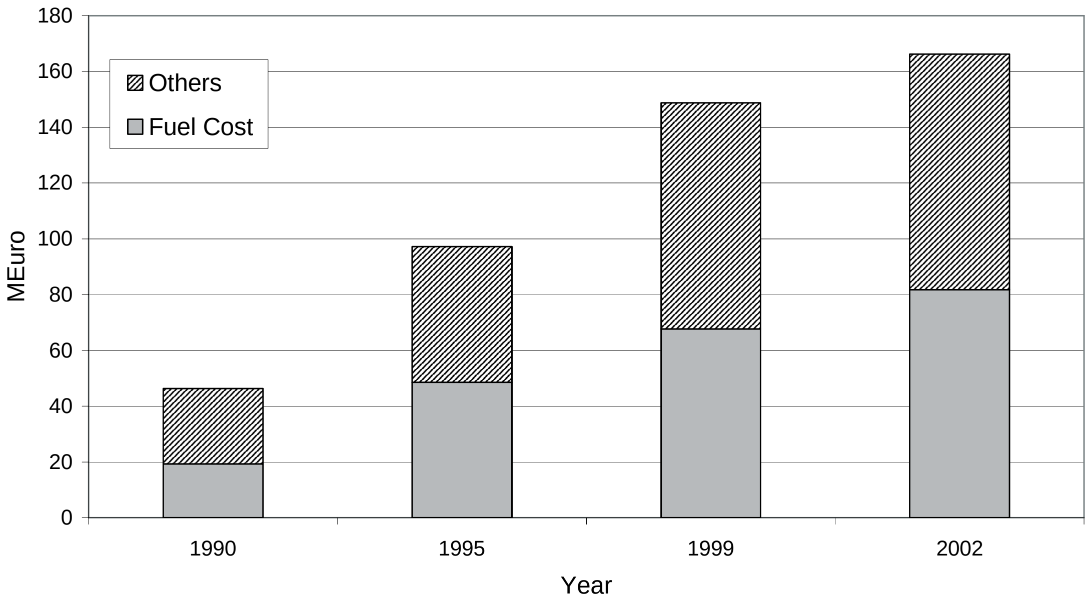

Figure 2: Electricity Production Cost of Greek APS[2]

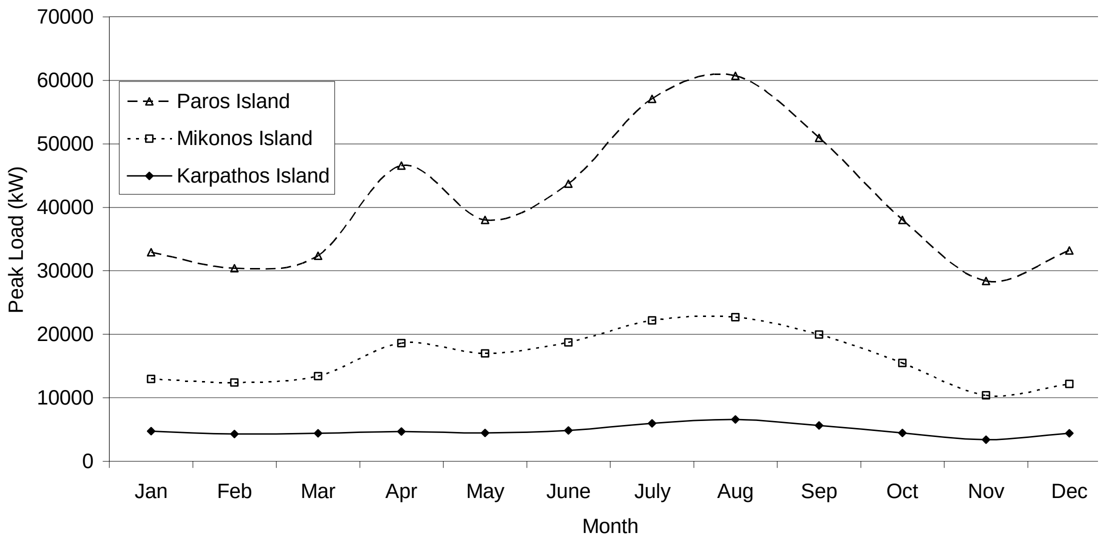

Figure 3: Electrical Peak Load Variation for Selected Islands

2. Wind Potential Exploitation Limits in the Aegean Sea Islands

During the last twenty-five years wind energy has been proven[5,6] to be a mature electricity production technology, constituting not only an economically attractive option for the worldwide constantly increasing energy demand, but also a sustainable energy solution for global development with very limited environmental impact[7]. In this context, most Aegean Sea islands have an excellent (annual mean wind speed higher than 8m/s) wind potential, figure (1), providing them with the capacity to meet their needs by producing plenty of "cheap" electricity based on wind power plants.

More specifically, in many of these isolated regions a high quality wind potential subsists all over the year, mainly characterized by remarkable annual mean wind speeds and relatively limited calm spells. However, the fluctuations of daily and seasonal electricity demand in almost all island grids result to a serious limitation of the wind park's size, since the local grid stability should be maintained. Additional barriers against the penetration of the wind energy[8,9,10] in these autonomous grids also result, due to the intermittency and the stochastic availability of the wind speed, leading to important disharmony between the wind energy production and the electricity demand.

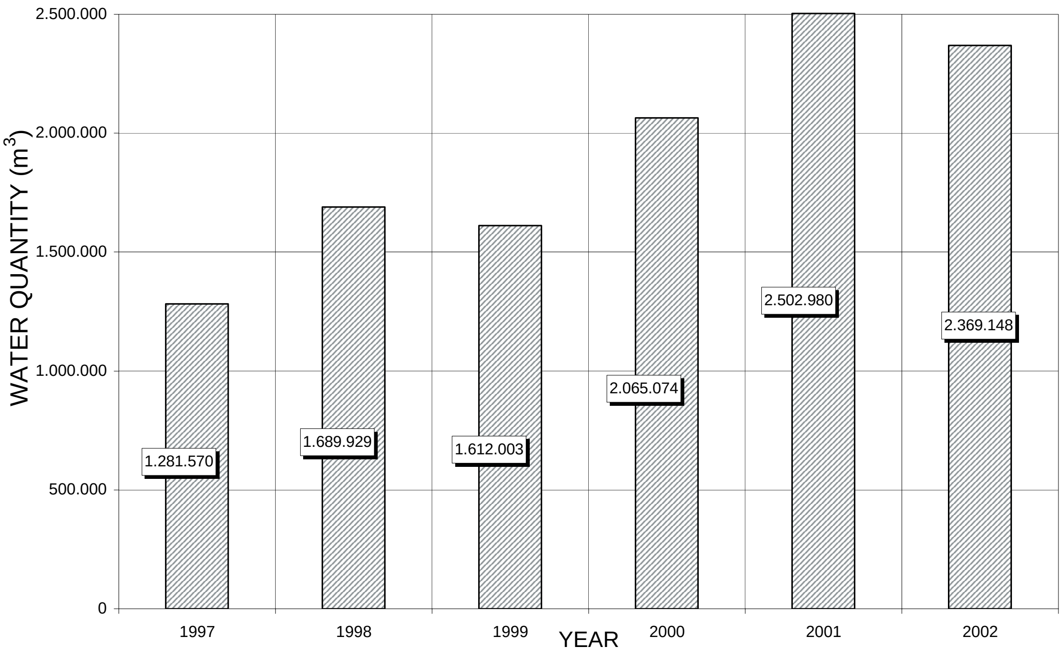

Figure 4: Water Quantities Transferred Annually to the Aegean Sea Islands

In fact, the last six years a substantial wind energy penetration has been noticed in Greece after a long period of idleness[11]. It is important to mention that, this significant wind power addition is mainly realized in the mainland, where the wind parks erected have to compete with the low cost lignite and natural gas-fired big thermal power stations. On the other hand, new size-limited wind parks have been erected in the numerous Greek islands (even in big ones), although their wind potential is clearly better than the one of the mainland and their wind energy generation is used to replace expensively operating outmoded internal combustion engines. This negative -for the Greek islands communities' evolution- policy was mentioned (1993) by the authors in their early-published work[12], underlining the inability of the local weak autonomous electrical networks to absorb the increasing but intermittent wind generated electrical energy production. As a result, a sizeable wind energy rejection has been encountered during the last years in most Greek autonomous electrical networks, leading the wind park owners to remarkable financial losses[13].

In the present study special attention is paid to investigate the possibility to stimulate the wind energy applications in remote islands by using the energy surplus to cover the water shortage problems of local communities. In this case, additional revenues may be expected from the desalinated water production, while the energy storage capacity required is remarkably decreasing.

The analysis uses extensive time series data and measurements[14] concerning the area wind speed, the local network load demand[2] and the clean water consumption[15], while special emphasis is laid on realistically estimating the corresponding wind energy and clean water production. The numerical application case study refers to the island of Karpathos, which belongs to the Dodecanese Complex. However, even in this relatively sizeable island with a continuously increasing electricity demand and an excellent wind potential, the opportunity to operate a properly sized desalination plant, on the basis of the wind energy surplus, remarkably improves the wind power installation financial efficiency.

3. Proposed Solution

In order to face the above-described problems, the possibility to create a combined Wind-Hydro Energy Station in collaboration with a Desalination Plant is investigated on a techno-economic basis, figure (5). According to the present study results, see also[16,17,18], the proposed project is the best possible method to cover the local electricity demand and the clean water shortage for the majority of the Aegean Archipelago islands, with rational installation, maintenance and operation cost, minimizing thus the dependence of the Greek economy on imported and heavy polluting fuel.

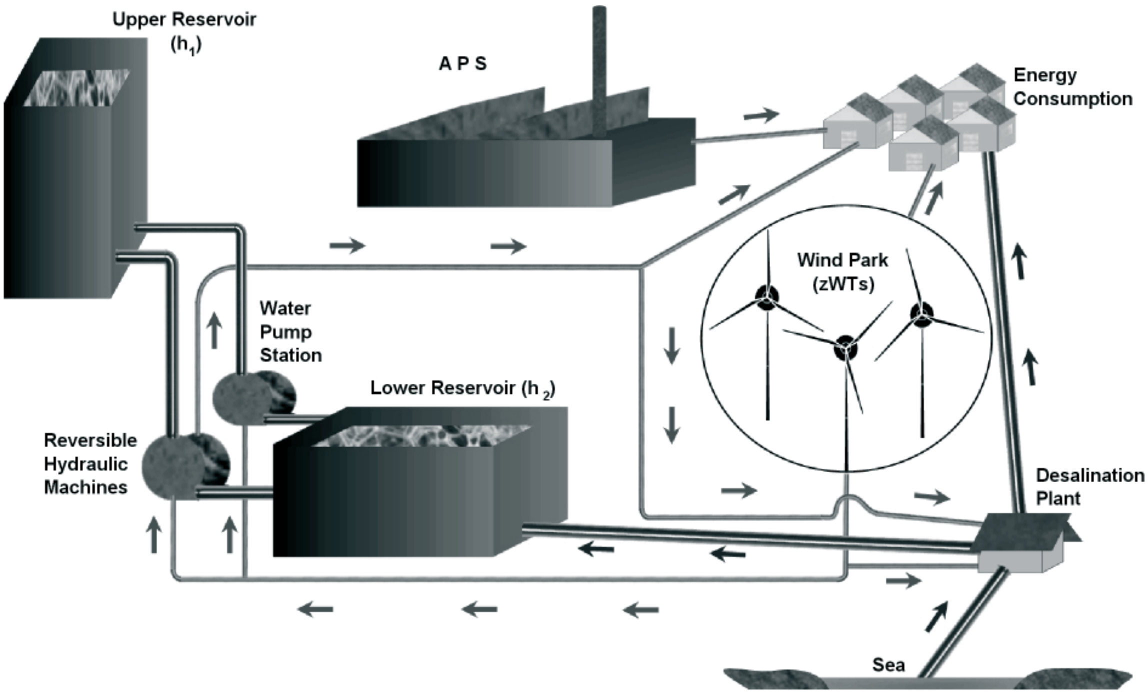

Figure 5: Combined Electricity and Clean Water Production System for Remote Islands

More precisely, the most appropriate wind-hydro configuration -capable of facing both energy and clean water requirement problems of remote islands- is based, see figure (5), on:

a. One or more wind parks of "z" wind turbines; total rated power "N^*_{wp}"
b. A small hydroelectric power plant based on reversible water turbines; rated power "N^*_H"
c. A water pump station able to absorb the system's wind power surplus, in combination with the reversible water turbines (operating as water pumps; rated power "$N^{*/}_H$"); rated power "N^*_p"
d. At least two water reservoirs at bottom elevations "h_1" and "h_2", working in closed circuit, along with the corresponding pipelines. The water reservoir size is characterized by the days of autonomy "d_o" of the local society provided.
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 covering local community's electricity requirements "N_D" and water demand "V_w" on a regular basis, minimizing thus the fuel-oil consumption.

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

a. The wind park feeds the local electrical network. Any energy surplus is forwarded according to the existing needs:

i In an appropriate water pumping station in order to transfer water from the low to the high water reservoirs.
ii In an existing modular water desalination unit, usually based on reverse osmosis, in order to produce desalinated water of desired quality.

b. The wind energy is not absorbed by the local electrical system, while the energy surplus is bigger than the water pumping capacity of the installation or the upper reservoir is full. In this case the energy surplus is transferred to the water desalination unit to increase the water reserves of the local community.

c. The wind energy production is lower than the electricity demand. In this case the energy reserves of the upper water reservoir are used via the existing small hydro turbines 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 wind energy is forwarded directly to the desalination plant. If the available wind energy is not enough one may use the water stored in the upper reservoirs.

4. Calculation Results

Accordingly, the proposed solution is applied to a typical small-medium sized island in order to prove the capability of the combined electricity-clean water production system not only to overcome the intermittent character of the wind but also to meet the requirements of a remote community with rational cost.

Karpathos is a medium-sized island (population 6000 habitants, area of 301km^2) of South-East Aegean Sea, belonging to the Dodekanesa complex (the second biggest after Rhodes). Its major town is Pigadia with 1750 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 -1050 habitants) was 31,500MWh for 2004. The peak load demand - approximately 8000kW- appears during summer, while the corresponding minimum value is 1400kW. The APS of Karpathos consists of eight internal combustion engines of total rated power 9000kW.

The evolution of the local APS production cost presents a mean annual increase of 5.1%, while the contribution of fuel cost is almost 50%. More specifically, the operational cost of the local APS currently exceeds the 0.23€/kWh, while the corresponding average price of electricity is 0.085€/kWh. This fact leads to annual operational loss of almost 4,300,000€ for 2003.

On the other hand the island has a very high wind potential, since the long-term annual mean wind speed approaches 9.6m/s, at 10m height, see also figure (6). 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. Unfortunately, due to the existing grid-related operational constraints and the intermittent character of wind, in the island there exists (since 1991) only a very small wind park of Greek Public Power Corporation (PPC) based on five (5x55kW) outdated WM-15S wind turbines, rated power 275kW.

Using the analysis presented, one may build a new wind-hydro power plant in collaboration with an appropriate water desalination station in order to cover the requirements of Karpathos and the nearby islands. In this case one may install the following configuration:

- A wind park based on 13 to 27 wind converters of rated power of 300kW each. The wind turbine type was selected on the basis of the island infrastructure, their annual energy production and their purchase and maintenance cost[19]. The exact number of the wind turbines is to be defined according to the desired wind penetration rate and the corresponding amount to be invested.

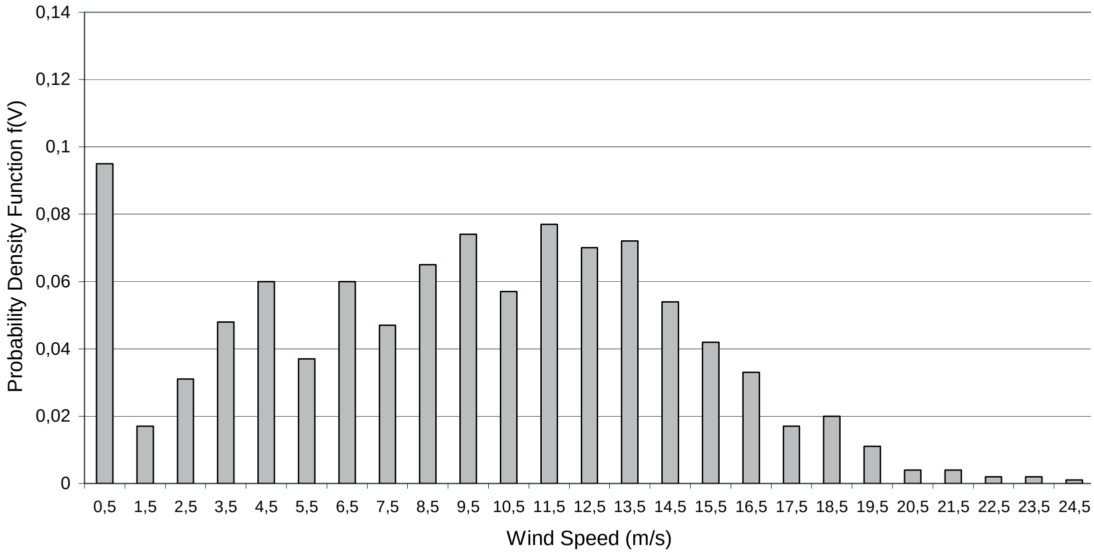

Figure 6: Wind Potential of Karpathos Island

- Three reversible hyrdo turbines (3x3000kW) of total rated power equal to the island peak load demand, increased by a safety margin to include any future changes[20].
- A water pumping installation, able to operate under the selected elevation difference between the upper and the lower water reservoirs (e.g. 200m static head). The nominal power of the water pumps is defined as the difference of the rated power of the wind park and the reversible hydro turbines, in order to absorb every wind energy surplus.
- Two or more water reservoirs at different elevation working in closed circuit in order to eliminate the water loss, able to store enough water quantities to meet via the hydro turbines the electricity requirements of the local network for "d_o" days. The exact volume of the water reservoirs is to be predicted on the basis of a parametrical analysis.
- A modular water desalination station based on modern reverse osmosis technology. The daily water capacity of the installation is set between 500 and 1000m^3/day, while the corresponding electricity consumption varies between 7 and 15 kWh/m^3 [21].

For the simulation of the proposed system one may use the "OPTIMANAG-III" numerical algorithm (figure (7)) developed by the authors' research team since 1998, see also[18,22].

The calculation results of the proposed installation's parametrical analysis are summarized in figures (8) and (9). According to figure (8) one may observe that even with the utilization of 13 wind turbines, the proposed system covers the 66% of the annual energy consumption of the island, while the water production by the desalination plant can cover the 15% of the local community needs, figure (9). As the number of wind turbines increases the autonomous (without fossil fuel consumption) operation of the local network increases also linearly, up to the installation of 17 wind turbines. At the same time the desalinated water production remains practically constant. When the wind turbine number approaches 27 the contribution of the proposed configuration to the fulfilment of annual electricity demand tends asymptotically to 95%, while the production of the desalination plant increases over-linearly, exceeding the water requirements of the local community.

At this point it is also interesting to investigate the operational hours of the existing thermal power station (APS) as a function of the wind turbines used and the water reservoirs storage capacity. According to the results of figure (10) the proposed configuration can meet the local needs without the operation of the local APS for 4150 up to 8300 hours per year. In fact, this means that for the case of 27 wind turbines used the existing heavy-polluting internal combustion engines should operate for less than 450 hours annually. Finally, in all three figures included -figures (8) to (10)- the impact of the water reservoir storage capacity is limited up to 17 wind turbines. Subsequently, as the number of wind turbines increases the impact of the water volume stored becomes more evident.

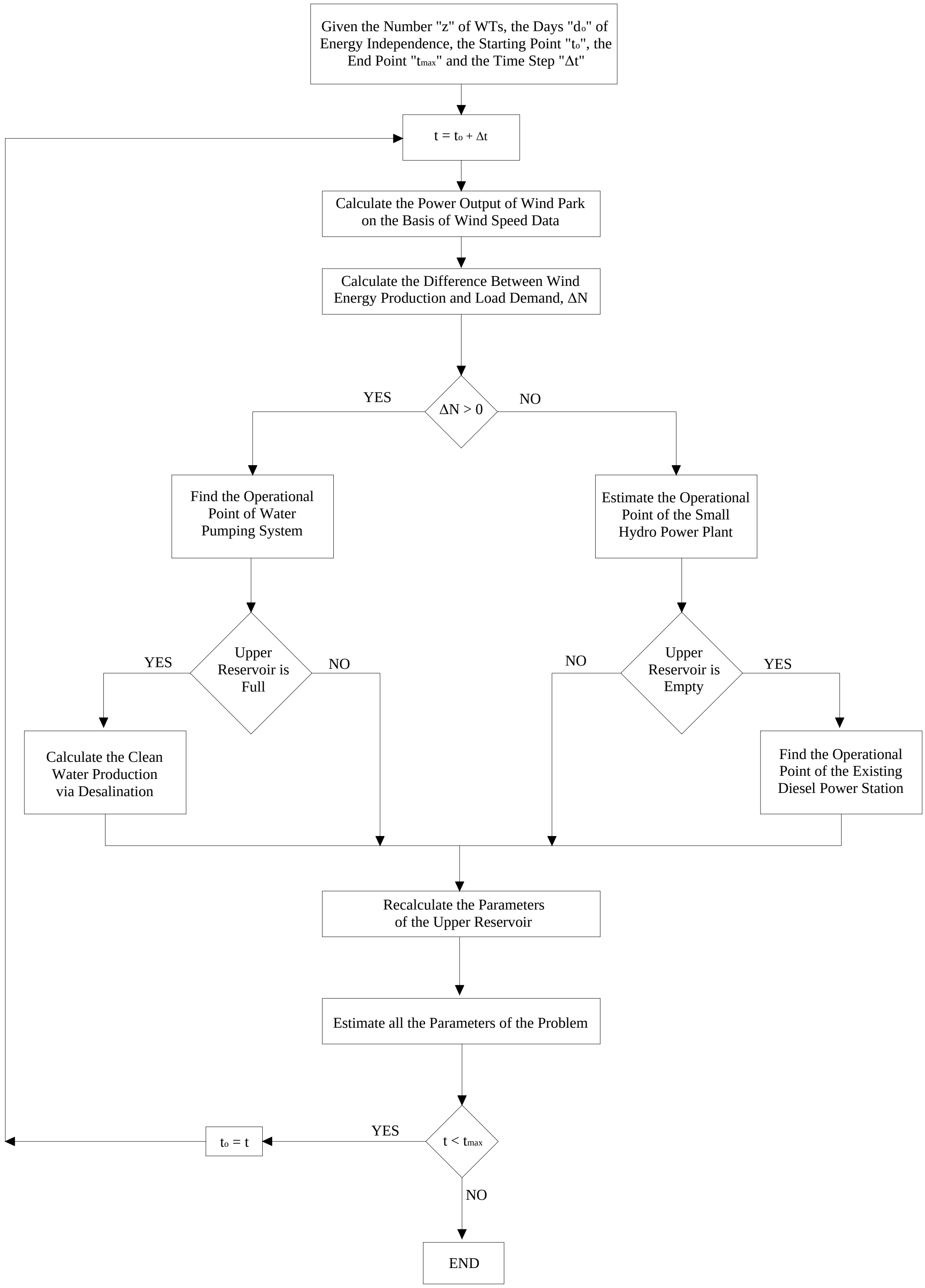

Figure 7: OPTIMANAG-III Numerical Algorithm

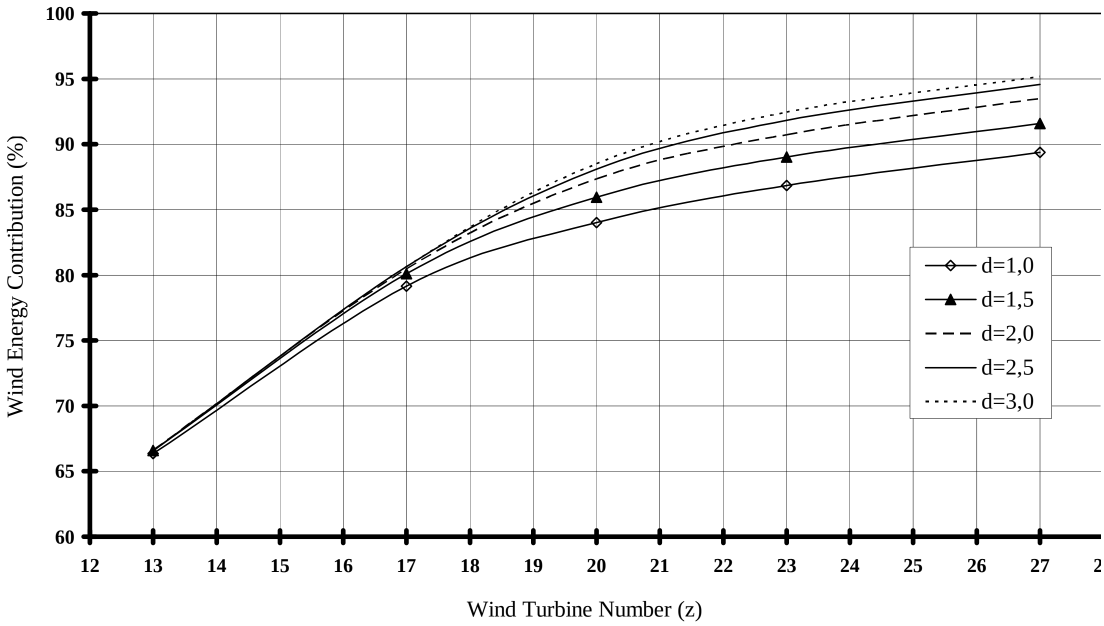

Figure 8: Contribution of the Proposed Installation on the Fulfilment of Karpathos Island Electricity Requirements

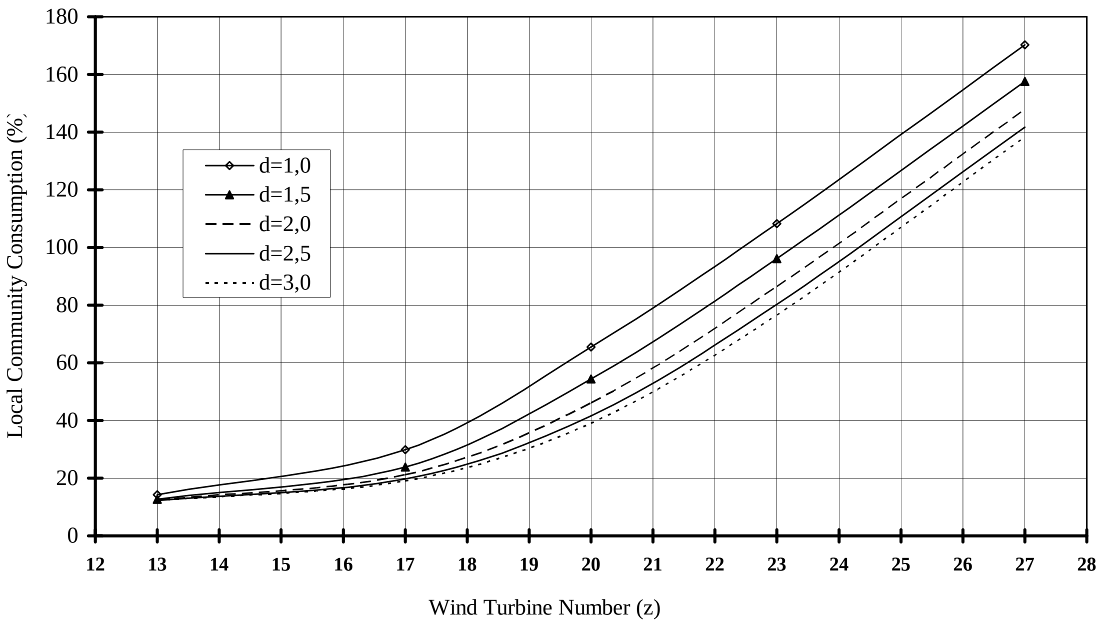

Figure 9: Contribution of the Proposed Installation on the Fulfilment of Karpathos Island Clean Water Needs

Accordingly we examine the wind energy disposal for three selected wind park configurations (utilization of 13, 20 and 27 wind turbines) concerning the Karpathos island. More precisely in figures (11) to (13) we demonstrate the contribution of wind energy in the local system electricity production as a function of the water reservoir storage capacity expressed in days of energy autonomy. In the first case, figure (11), the contribution of wind energy approaches 66.6% and is practically unaffected bythe water reservoir storage capacity. In the same figure one may observe that the energy consumed in the desalination plant is quite small (less than 2% of the annual wind park production). In the second case, figure (12), the contribution of wind energy exceeds 88.5% of the annual electricity consumption, remarkably increasing with the water reservoir storage capacity. In this case almost 25% of the wind energy production cannot be absorbed by the local system.

Hence, the operation of the desalination plant utilizes 15% to 20% of the annual wind energy production, increasing the financial viability of the proposed installation. Finally, in the last case, figure (13), the wind energy penetration achieves 95%, although almost 40% of the annual wind energy production is characterized as energy surplus by the local electrical network[13]. In fact, the vast

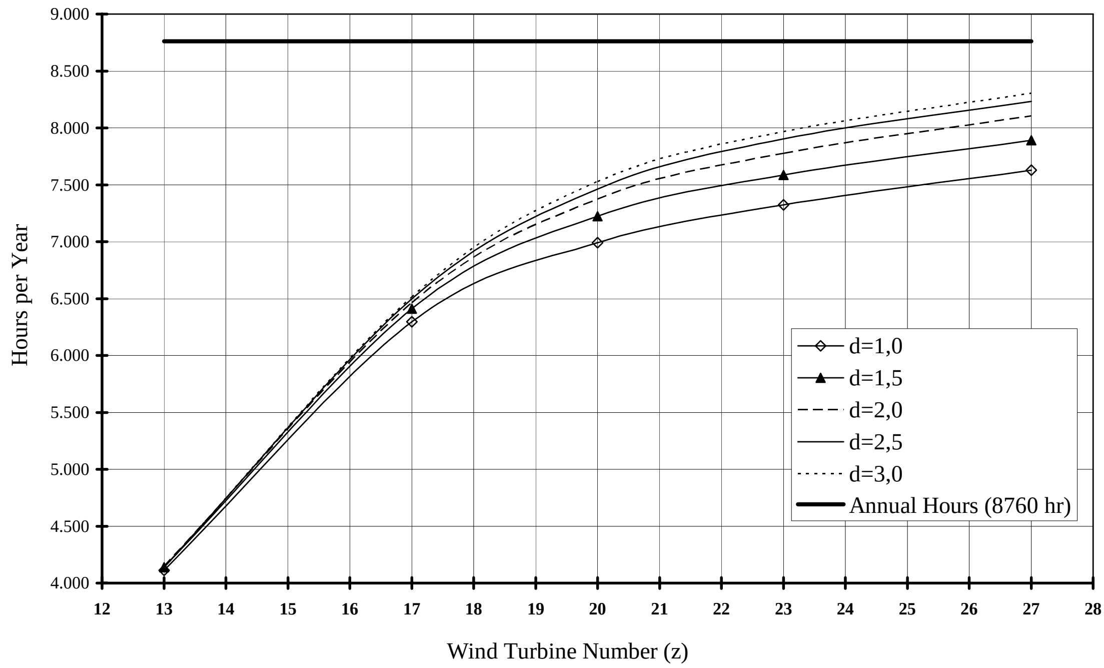

Figure 10: Contribution of Proposed Installation on Limiting the Local APS Operation Hours, Karpathos Island

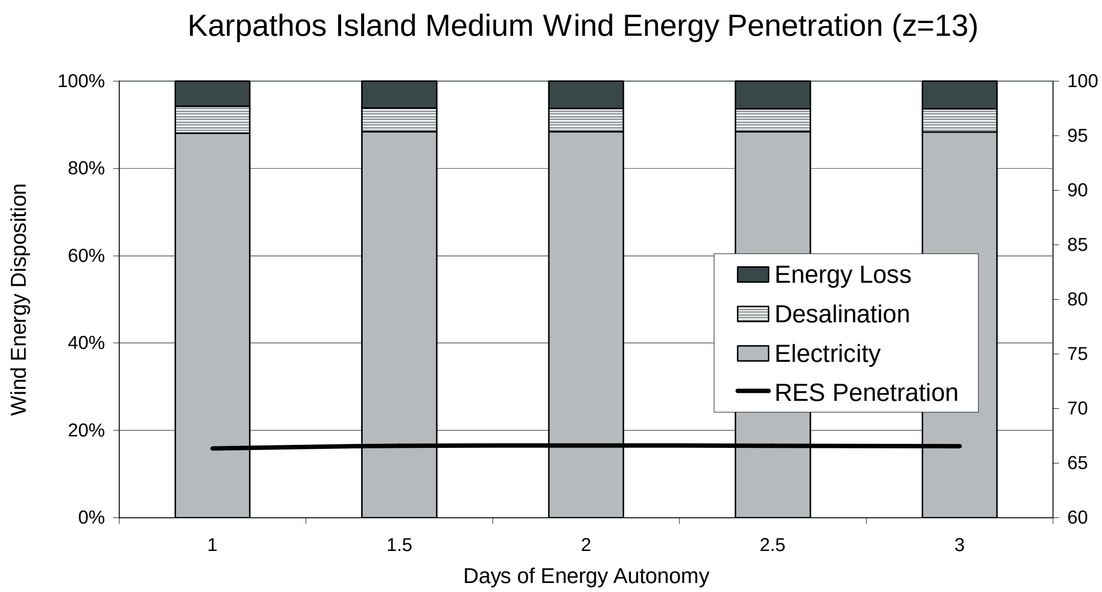

Figure 11: Proposed Installation Wind Energy Utilization (z=13) on Meeting the Local Community Electrical and Clean Water Needs, Karpathos Island

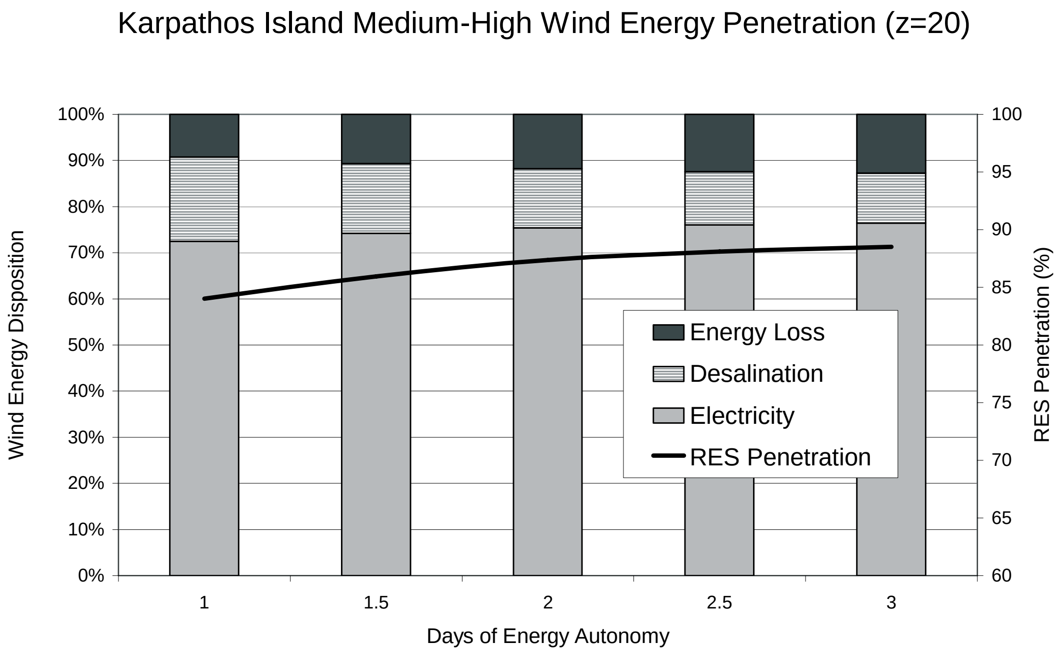

Figure 12: Proposed Installation Wind Energy Utilization (z=20) on Meeting the Local Community Electrical and Clean Water Needs, Karpathos Island

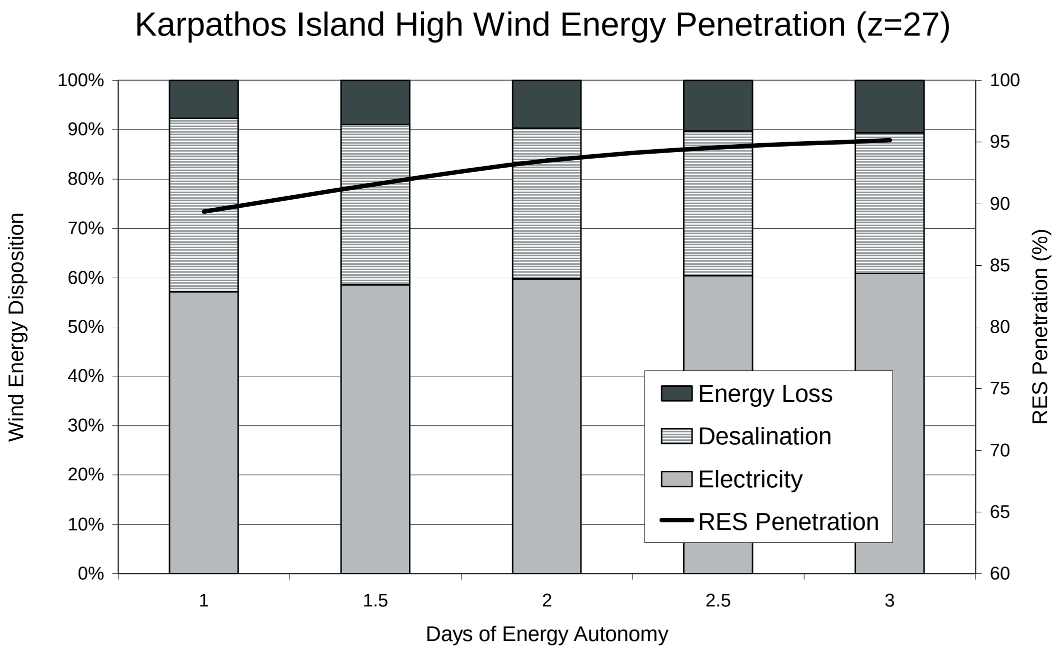

Figure 13: Proposed Installation Wind Energy Utilization (z=27) on Meeting the Local Community Electrical and Clean Water Needs, Karpathos Island

majority of this energy surplus is absorbed by the proposed desalination plant, contributing in this way to the clean water needs fulfilment of the local community.

Summarizing, one may state that by using the proposed configuration for energy and clean water production, one may fulfil the corresponding needs of local communities, reaching to significant wind energy penetration rates (up to 95%) even in remote weak autonomous electrical networks.

5. Conclusions

The present work is concentrated on presenting a complete configuration to face the intermittent character of wind power. Accordingly, the proposed system can be used to meet the electricity and water needs of a medium-small sized remote island at a rational cost.

According to the results obtained, only by co-producing electrical energy and clean water via an appropriate desalination plant it is possible to achieve at high wind energy penetration rates and minimize the system energy surplus. On top of this, the proposed configuration significantly bounds the operational hours of the existing internal combustion engines, contributing thus to the air pollution reduction. Finally, as the wind park size is amplified, significant water quantities can be produced, remarkably reinforcing the water reserves of the local community with fresh water of desired quality.

Recapitulating, according to the analysis presented, the proposed wind-hydro configuration in combination with an appropriate desalinated plant can efficiently fulfil the electrical energy and clean water requirements of numerous remote communities on the basis of clean and low cost wind energy, overcoming the intermittent and stochastic nature of the wind.

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PART THREE

HYBRID STATIONS

- Wind-Diesel System
- Combined Wind-PV System
- Electricity Production Cost

OPTIMUM SIZING OF AN AUTONOMOUS WIND-DIESEL HYBRID SYSTEM FOR VARIOUS REPRESENTATIVE WIND-POTENTIAL CASES

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Abstract

Official statistics estimate that almost two billion people worldwide have no direct access to electrical networks. Afar from decision centers and having limited political influence, isolated consumers are often abandoned, facing a dramatically insufficient infrastructure situation. In this context one may support that a wind-diesel-battery hybrid system is one of the best alternative solutions to meet the electricity demand of numerous remote consumers, with rational first installation and operational cost, even at medium wind potential areas. The basic idea of this effort, in comparison with previous works rejecting oil usage, is to use the minimum possible diesel-oil quantity and limit the battery bank dimensions. For the prediction of the optimum hybrid system configuration an integrated numerical algorithm is developed, based on experimental measurements and operational characteristics by the hybrid system components manufacturers. During the calculations a detailed energy balance analysis is carried out for the entire time period examined, while the battery depth of discharge time evolution is also investigated. The developed model is successfully applied for three representative wind potential types. The results obtained are quite encouraging supporting the applicability of the proposed solution.

Keywords: Hybrid Energy System; Optimum System Sizing; Wind-Diesel; Energy Balance; Remote Consumer

1. Introduction

Official statistics estimate[1] that almost two billion people worldwide have no direct access to electrical networks, 500,000 of them living in European Union and more than one tenth of the latter in Greece[2]. Afar from decision centers and having limited political influence, isolated consumers are usually abandoned, facing a dramatically insufficient infrastructure situation[3]. An autonomous wind power system has been proven to be one of the most interesting and environmental friendly technological solutions for the electrification of remote consumers, especially in presence of high wind potential[4,5].

On the other hand, in medium or low wind potential cases the dimensions of a wind only stand-alone system are quite large[4], thus the corresponding first installation cost is almost prohibitive, despite the existence of remarkable subsidization[5]. For these reasons, most remote consumers cover their electricity demand using small oil-fired diesel-electrical generators, with minimal first installation cost and very high operational cost. In an attempt to obtain a realistic and environmental friendly solution, the idea of using a hybrid wind-diesel-battery system is hereby examined[6,7,8]. The basic idea of this effort, in comparison with previous works by the authors insisting on no oil usage, is to minimize the oil quantity used and limit the battery bank dimensions. Keep in mind that the lead-acid batteries used should be replaced approximately every 1200 operational cycles, in no case being free of environmental impacts.

Analyzing the pro and cons of a wind-diesel and a wind-only system, one should mention that the first system presents increased reliability[9] to cover the load demand normally using smaller batteries than the second alternative, while a wind-only system consumes no fuel, having low environmental impacts. In any case the proposed improved analytical model, used to estimate the optimum size of a wind-diesel hybrid system, takes also into consideration the opportunity of zero oil-consumption.

2. Proposed Solution

In an attempt to simulate the energy consumption profile of a remote consumer, a joint effort is made to settle the electricity demand difficulty of a typical isolated consumer (e.g. a four to six member family), using a properly sized stand-alone wind-diesel system. After an extensive local market survey a representative weekly electricity consumption profile[10,11,12] is adopted, being also depended on the year period analyzed (i.e. winter, summer, other). The load profile used is basically a rural household profile (not an average load taken from typical users) selected among several profiles provided by the Hellenic Statistical Agency[4,5]. More precisely, the numerical load values vary between 30W (refrigerator load) and 3300W. According to the consumption profile approved, the annual peak load "N_p" does not exceed 3.5kW, while the annual energy consumption "E_y" is almost 4750kWh. Thus, the annual electricity consumption -on an hourly basis- is the first input of the present analysis, see also figure (1).

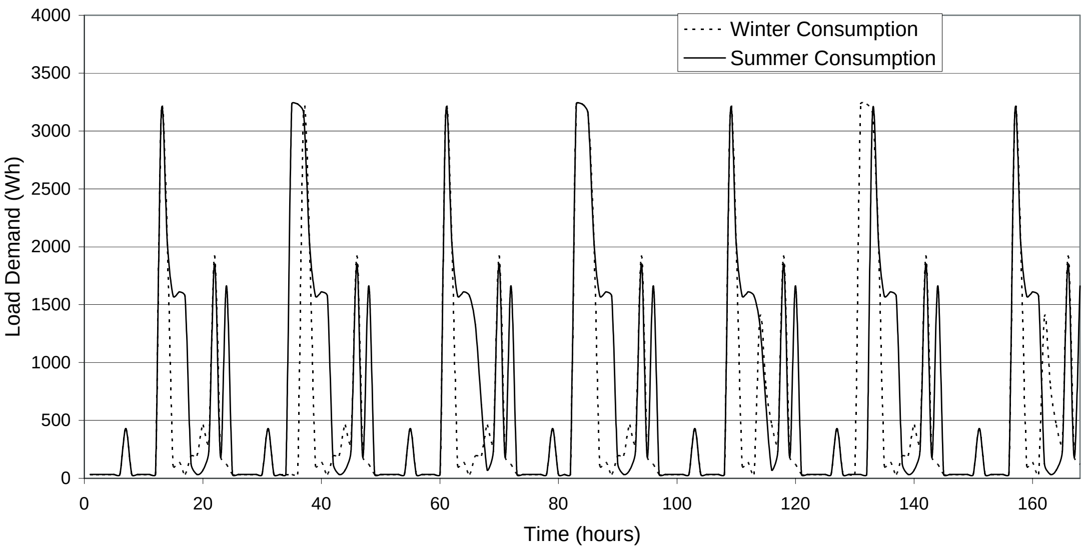


Figure 1: Typical Weekly Electricity Demand Profile of the Remote Consumer Analyzed

In order to meet the electricity demand of isolated consumers, an integrated energy production system is devised, similar to the one of figure (2). Hence, the proposed system comprises:

a. A micro wind converter of rated power "N_o" and given power curve N=N(V) for standard day conditions
b. A small internal combustion engine of "N^*" kW, able to meet the consumption peak load demand "N_p" (i.e. $N^* \geq N_p$), presenting a typical specific fuel consumption curve versus partial loading of the engine, i.e. ($SFC=SFC(N/N^*)$)
c. 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")
d. An AC/DC rectifier of "N_o" kW and U_{AC}/U_{DC} operation voltage values
e. A DC/DC charge controller of "N_o" rated power, charge rate "R_{ch}" and charging voltage "U_{CC}"

f. A UPS (uninterruptible power supply) of "N_p" kW, frequency of 50Hz, autonomy time "δt" and operation voltage 220/380V
g. A DC/AC inverter of maximum power "N_p" able to meet the consumption peak load demand, frequency of 50Hz and operational voltage 220/380V

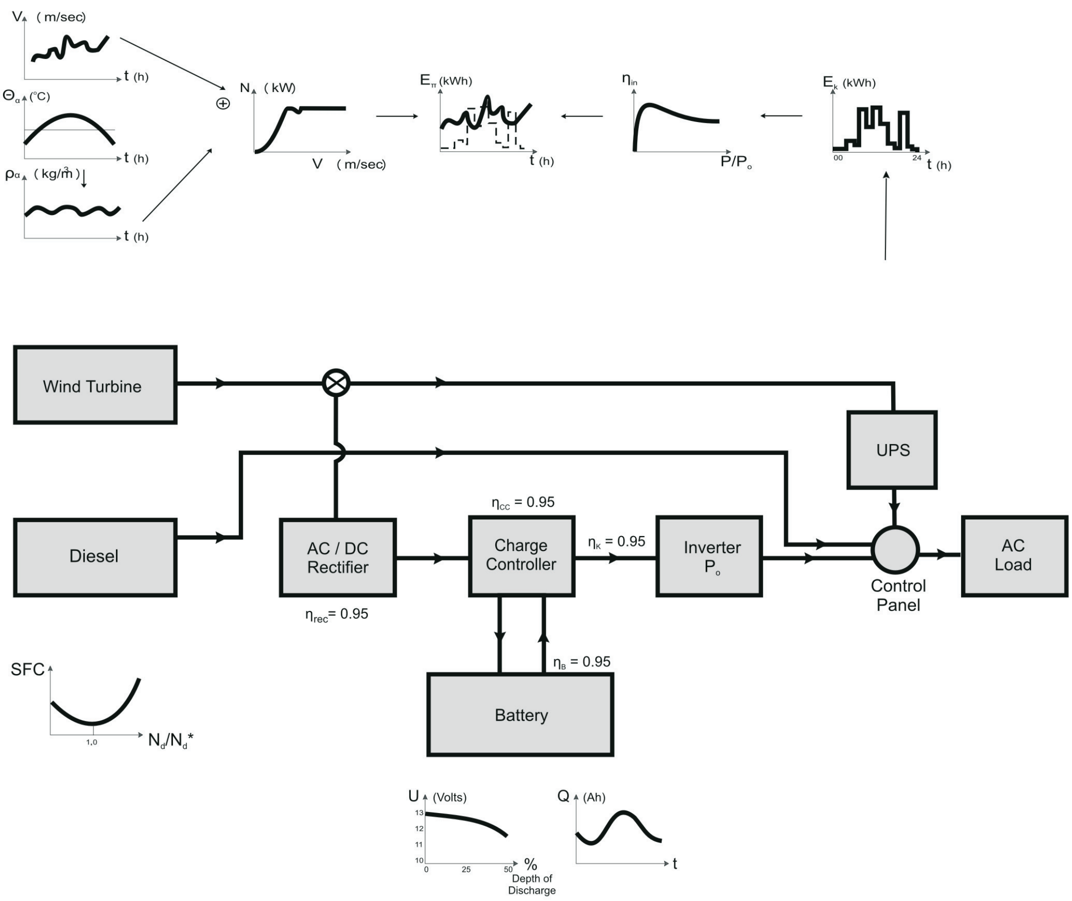


Figure 2: Proposed Autonomous Wind-Diesel Hybrid System

As it results from figure (2), the corresponding wind potential and ambient temperature and pressure are also necessary to integrate the system sizing calculations. Finally, the operational characteristics of all components (e.g. wind power curve at standard day conditions, diesel generator specific fuel consumption, inverter efficiency, battery bank characteristic etc.) composing the hybrid system under investigation are also required.

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

- ✓ Energy (AC current) is produced by the micro wind converter, sent directly to consumption via the UPS
- ✓ Energy (AC current) is produced by the small diesel generator and forwarded to consumption
- ✓ The energy output of the wind turbine (not absorbed by the consumption-energy surplus) is transformed to DC current (via an AC/DC rectifier), subsequently charging the batteries via the charge controller
- ✓ The battery is used to cover the energy deficit via the charge controller and the DC/AC inverter

In the present analysis, the diesel generator will not be used to charge the batteries via the AC/DC rectifier and the charge controller, as in any serious energy deficit case the diesel generator may directly cover the load demand, without the energy storage losses.

Recapitulating, using the above-described configuration it is possible to determine the appropriate system dimensions in order to fulfill the maximum load demand of the consumption, including a safety coefficient. At the present analysis the optimum system dimensions are defined using the relation between the battery capacity reduction and the annual diesel oil consumption, i.e. (dQ_{max}/dM_f).

3. System Sizing Model

3.1 Proposed Numerical Algorithm

As mentioned above, the main scope of the present work is primarily to estimate the appropriate dimensions of a stand-alone wind-diesel system for every remote consumer examined, under given annual diesel-oil consumption of the system. Accordingly, an effort is made to select the optimum combination of the stand-alone system dimensions and the annual diesel-oil consumption. The three governing parameters used during the optimization procedure are the rated power "N_o" of the wind turbine used, the battery maximum necessary capacity "Q_{max}" and the annual mass fuel flow consumption "M_f".

During the long-lasting operation of the proposed wind-diesel hybrid system, the following situations may appear:

a. The power demand "N_D" is less than the power output "N_w" of the wind turbine, ($N_w>N_D$). In this case the energy surplus ($\Delta N=N_w-N_D$) is stored via the rectifier and the battery charge controller. If the battery is full ($Q=Q_{max}$), the residual energy is forwarded to low priority loads.

b. The power demand is greater than the wind turbine power output ($N_w<N_D$), e.g. low wind speed, machine non-available etc. In similar situations, the energy deficit ($\Delta N=N_D-N_w$) is covered by the batteries via the battery charge controller and the DC/AC inverter, under the precondition that the corresponding battery depth of discharge "DOD(t)" is lower than a given limit "DOD_1", i.e. $DOD(t)< DOD_1$.

c. If this precondition is not fulfilled (i.e. $DOD(t)\approx DOD_1$), then the energy deficit is covered by the diesel generator in expense of the existing oil reserves.

d. In case of no further oil reserves the energy deficit ($\Delta N=N_D-N_w$) is covered by the batteries via the battery charge controller and the DC/AC inverter, violating the first degree battery protection precondition, i.e. accepting DOD(t) values greater than "DOD_1". However, if the battery maximum depth of discharge "DOD_L" is exceeded, a load rejection takes place, underlining the necessity to increase the wind turbine rated power or the battery bank capacity or both of them.

In the real world, when the fuel reserves are zeroed and the battery is almost empty, an emergency energy consumption management plan is applied, also capable of facing unexpected energy production problems related to "Force Majeure" events.

Under the above-described operational situations, the already presented[13] computational algorithm "WINDREMOTE-II" is substantially modified in order to take into account the existence of a small diesel generator. This new numerical code "WIND-DIESEL I" is used to carry out the necessary parametrical analysis on an hourly energy production-demand basis, targeting to estimate the wind turbine rated power "N_o" and the corresponding battery capacity "Q_{max}" given the annual permitted oil consumption "M_f", see also figure (3).

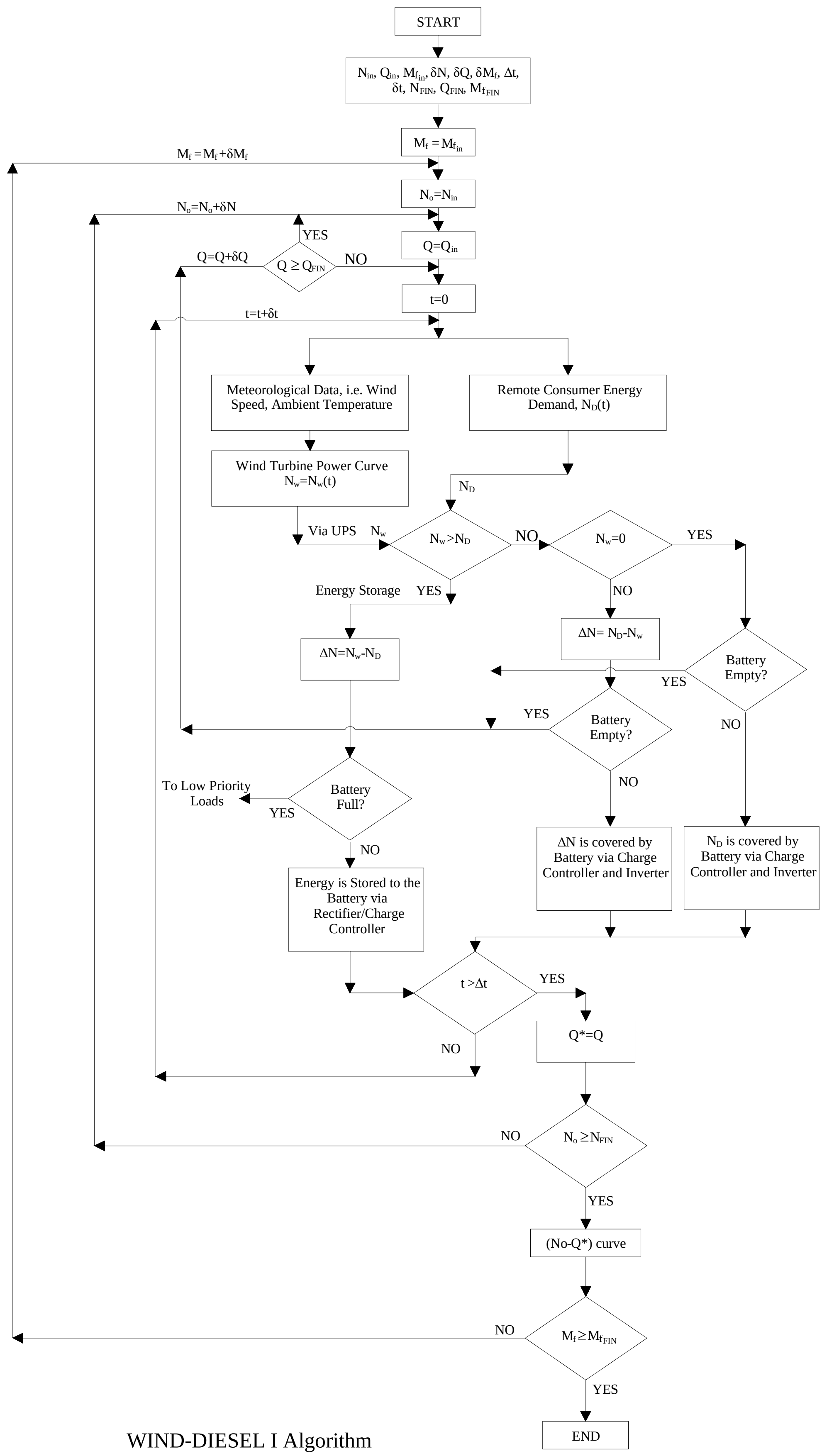


Figure 3: WIND-DIESEL-I Algorithm

More specifically, given the "M_f" value and for each "N_o" and "Q_{max}" pair the "WIND-DIESEL I" algorithm is executed for all the time-period selected (e.g. for one month, six-months, one year or even for three years), while emphasis is laid on obtaining a zero-load rejection operation. More precisely, for every time point analyzed, the system energy demand is compared with the wind turbine energy production. The wind-turbine output is defined by the wind speed, the ambient density and the manufacturer's power curve.

In case (c), the energy deficit is covered by the diesel generator, if the corresponding oil reserves are not zero.

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

$$N_{exit}(t) \geq N_D(t) \qquad \forall t \tag{1}$$

Next, another wind turbine size is selected and the calculations are repeated. Thus, after the integration of the analysis a (N_o-Q^*) curve is predicted under the no-load rejection restriction and a specific given annual mass fuel consumption value "M_f". The calculations can be repeated for various "M_f" values in an attempt to estimate the optimum system configuration and the minimum oil consumption.

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

$$DOD(t) = 1 - \frac{Q(t)}{Q_{max}} \leq DOD_L \qquad \forall t \tag{2}$$

3.2 Governing Parameters' Initial Values

Before the application of the above-presented analysis, in order to estimate the appropriate configuration of a wind-diesel system, one may give some details concerning the variation limits of the problem's main parameters. In this context, the minimum wind turbine rated power results in the totally hypothetical situation of an absolute coincidence between the consumption load demand and the stochastic wind energy production. In such a situation one may write:

$$N_o \geq \frac{E_y}{8760 \cdot CF \cdot \eta_{ups}} \tag{3}$$

where "E_y" ($E_y \approx 4750$kWh) is the annual energy consumption, "CF" is the mean annual capacity factor of the installation[14] and "η_{ups}" is the efficiency ($\eta_{ups} \approx 95\%$) of the UPS.

Similarly, the maximum annual fuel consumption of the installation results in the theoretical case that the energy consumption is fulfilled only by the diesel generator; hence the corresponding annual fuel consumption is limited by:

$$M_f \leq \frac{E_y}{\eta_d \cdot H_u} \tag{4}$$

where "η_d" is the diesel generator electrical efficiency ($\eta_d \approx 20\%$-30%) and "H_u" is the oil used lower specific calorific value ($H_u \approx 40000$kJ/kg).

Finally, the battery bank capacity depends mainly on the hours of system energy autonomy "h_o", thus the expected mean battery capacity is estimated as:

$$\overline{Q}_{max} = h_o \cdot \frac{E_y}{8760} \cdot \frac{1}{\eta_s \cdot DOD_L \cdot U_b} \quad (5)$$

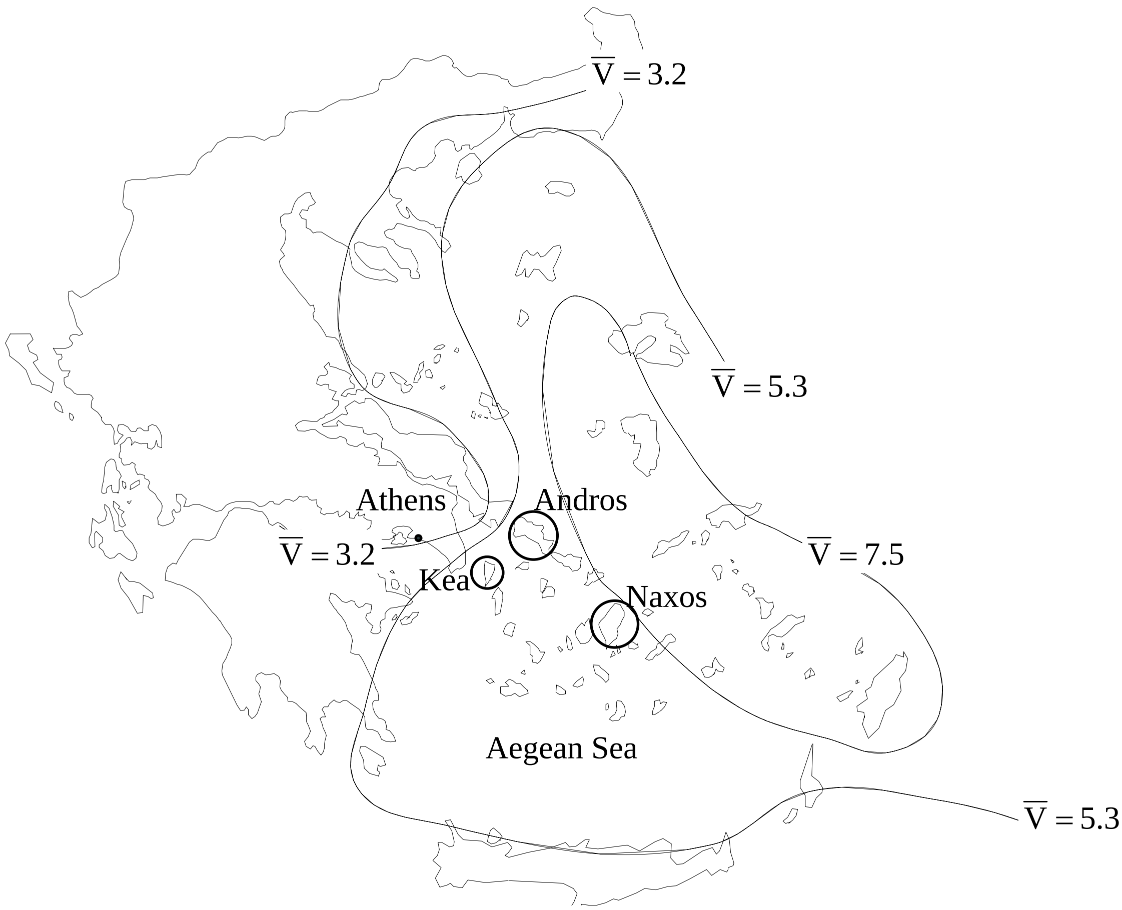
where "η_s" is the efficiency ($\eta_s \approx 75\%$) of the energy production branch (including battery discharge loss, line loss, inverter loss etc.) and "DOD_L" and "U_b" are described in section two.

4. Application Results

Using the above information, we proceed to analyze representative wind-diesel hybrid systems located throughout Greece. The areas selected (Table I) represent a high wind potential area (Andros island) a medium-high one (Naxos island) as well as a low wind potential case, island of Kea; see also figure (4).

Table I: Main Characteristics of the Regions Investigated

Region	**Area (km^2)**	**Population (cap)**	**Annual mean wind speed (m/s)**	**Max calm spells (h)**
Andros	384	12000	9.5	36
Naxos	428	18000	7.4	104
Kea	103	2300	5.6	158



h=30m

Figure 4: Wind Potential Map for Aegean Sea Area at 30m Height

Andros is a small medium-sized island (the second biggest one) of the Cyclades complex (population 12000 habitants, area of 384km^2), located in the middle of the Aegean Sea. The local terrain is very intense, including several rocky mountains with relatively sharp slopes. The island has one of the best wind-potential in Greece ($\overline{V} \approx 10$m/s), as the minimum monthly average wind speed exceeds the 6.5m/s, figure (5). At the same time, the number of days with a daily average wind speed below 4.0m/s (no wind production) is minimum, see also figure (6), validating the fact that the maximum calm spell period of the island is 37 hours.

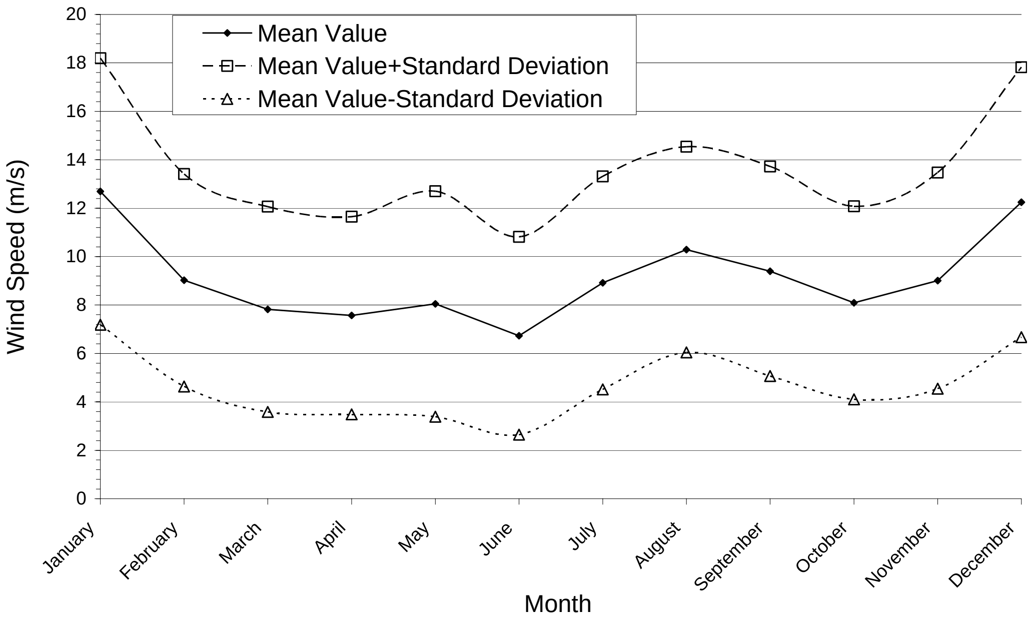


Figure 5: Monthly Averaged Wind Speed Values at Andros Island

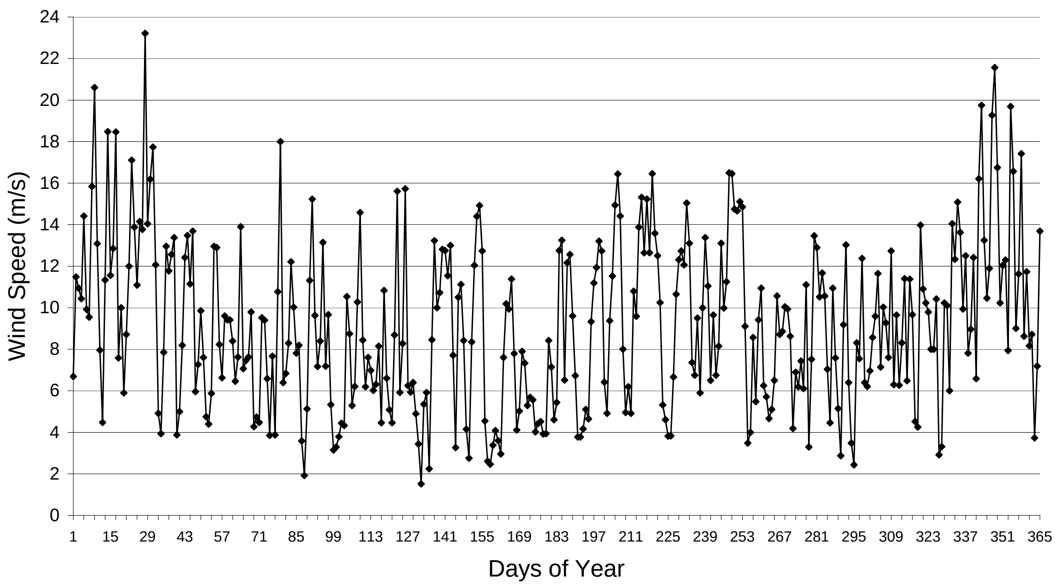


Figure 6: Daily Mean Wind Speed at Andros Island

The results of the "WIND-DIESEL I" algorithm application to the Andros island case are demonstrated in figure (7) for various annual diesel-oil consumption levels. More precisely, each curve drawn corresponds to a given diesel-oil quantity (e.g. M_f=100kg/y), while the x-axis describes the wind turbine rated power and the y-axis the corresponding battery capacity. In the same figure, the zero-diesel solution is also included. According to the results obtained, there is a considerable battery capacity diminution by accepting minimum (25kg/y) diesel-oil consumption, representing approximately 1% of the annual diesel-only system fuel consumption, see eq.(4). A significant battery capacity decrease is also encountered by accepting 100kg/y diesel-oil consumption. For bigger diesel-oil quantities the battery capacity is fairly reduced, excluding the configurations based on very small wind turbines, i.e. rated power below 3kW.

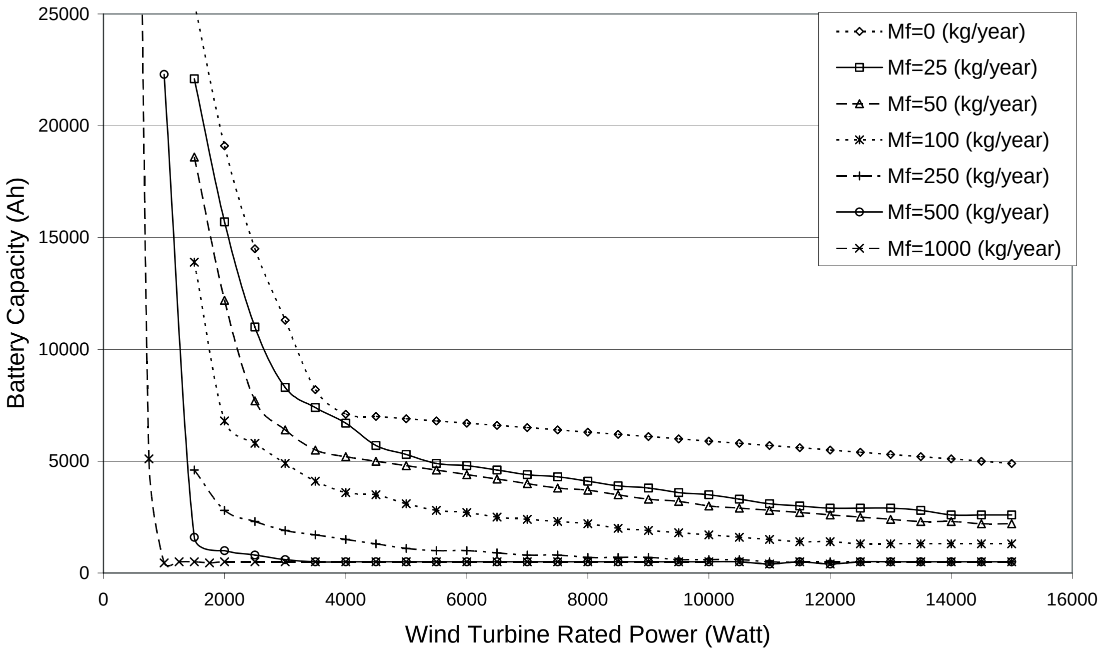


Figure 7: Energy Autonomous Configuration for a Wind-Diesel Hybrid System, Andros Island

Accordingly, Kea is a small island (2300 habitants, area 103km^2) close to Athens. The topography of the island is typically Aegean, i.e. gentle slopes, absence of flat fields, low mountains and sparse vegetation, while the main economic activities of the local society are agriculture, cattle breeding, beekeeping and tourism. The corresponding wind potential, although quite lower than the one of Andros, is good enough (annual mean wind speed ≈5.6m/s, figure (8)) to feed contemporary wind turbines for electricity production.

In figure (9) one may see the calculation results concerning this relatively low wind potential area. Using the information of figure (9) one may easily conclude that, even by using remarkable diesel oil quantities, the system dimensions (mainly battery capacity) are much larger than the Andros ones. On top of this, only by using significant annual diesel oil quantities (e.g. M_f=250kg/y) it is possible to obtain a considerable battery capacity reduction. Finally, one should use almost 1000kg/y of diesel-oil in order to guarantee system autonomy exploiting a relatively small wind turbine (i.e. below 3kW). This fact is clearly explained by comparing the wind potential of Andros and Kea islands, e.g. figures (5) and (8).

Finally, Naxos is also a medium-sized island (18000 habitants, area of 428km^2) of central Aegean Sea, also belonging to the Cyclades complex and presenting similar topography with the Andros island. The island has an outstanding wind potential, as in several locations the annual mean wind speed approaches 7.5m/s, at 10m height, figure (10).

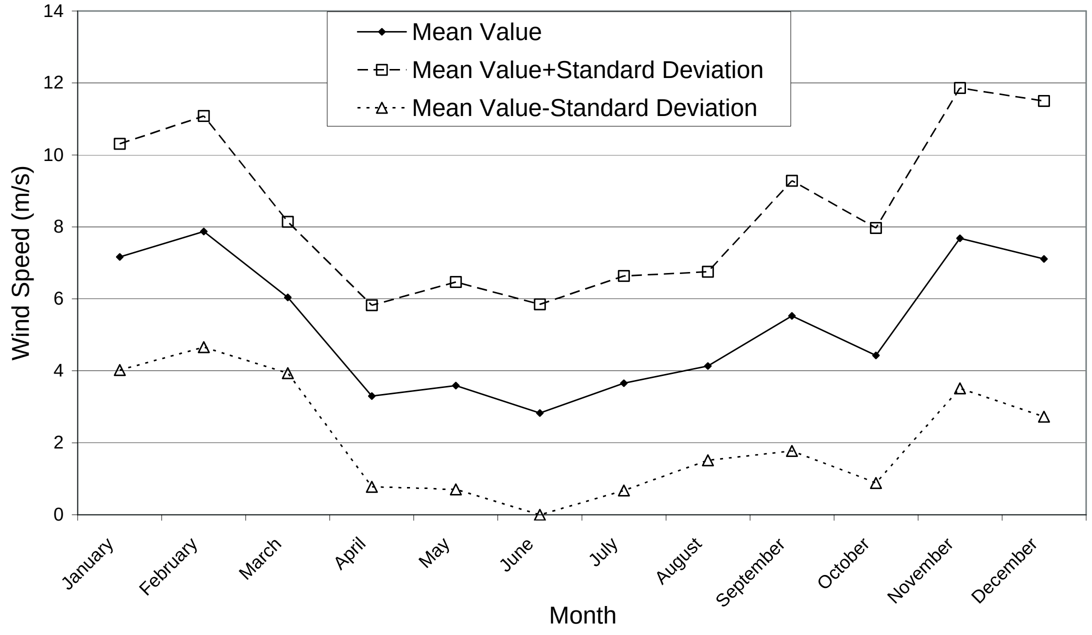


Figure 8: Monthly Averaged Wind Speed Values at Kea Island

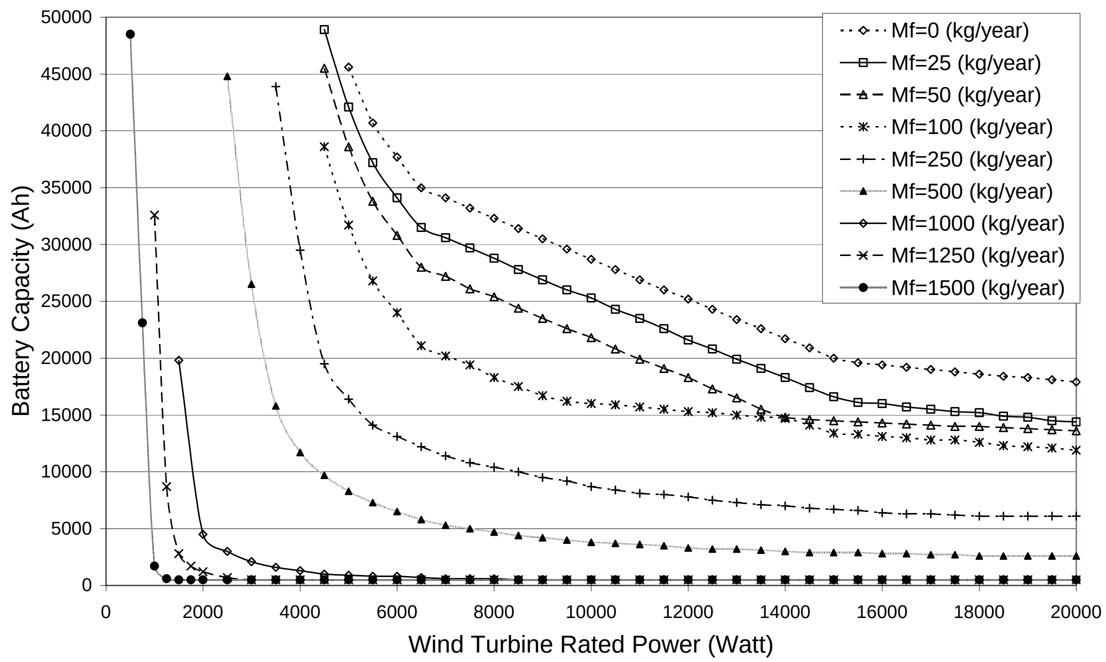


Figure 9: Energy Autonomous Configuration for a Wind-Diesel Hybrid System, Kea Island

In figure (11) one may see the calculation results concerning this relatively medium-high wind potential area. According to the results of figure (11) one may state that, as in the Kea island case, one should use noteworthy diesel oil quantities in order to remarkably decrease the system dimensions (mainly battery capacity). Of course the hybrid system dimensions are much smaller than the Kea ones. Besides, almost 250kg/y of oil should guarantee system energy autonomy using a reasonably small wind turbine (i.e. less than 3kW). A rational explanation concerning the configuration of the above investigated cases may be evident by comparing the wind potential of Andros, Kea and Naxos islands, i.e. figures (5), (8) and (10).

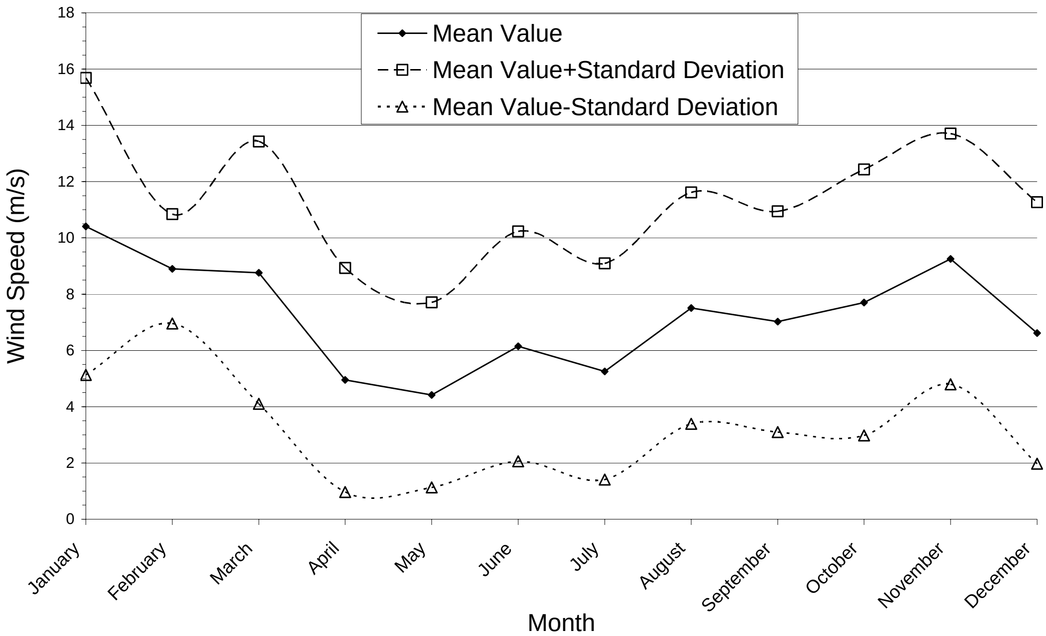


Figure 10: Monthly Averaged Wind Speed Values at Naxos Island

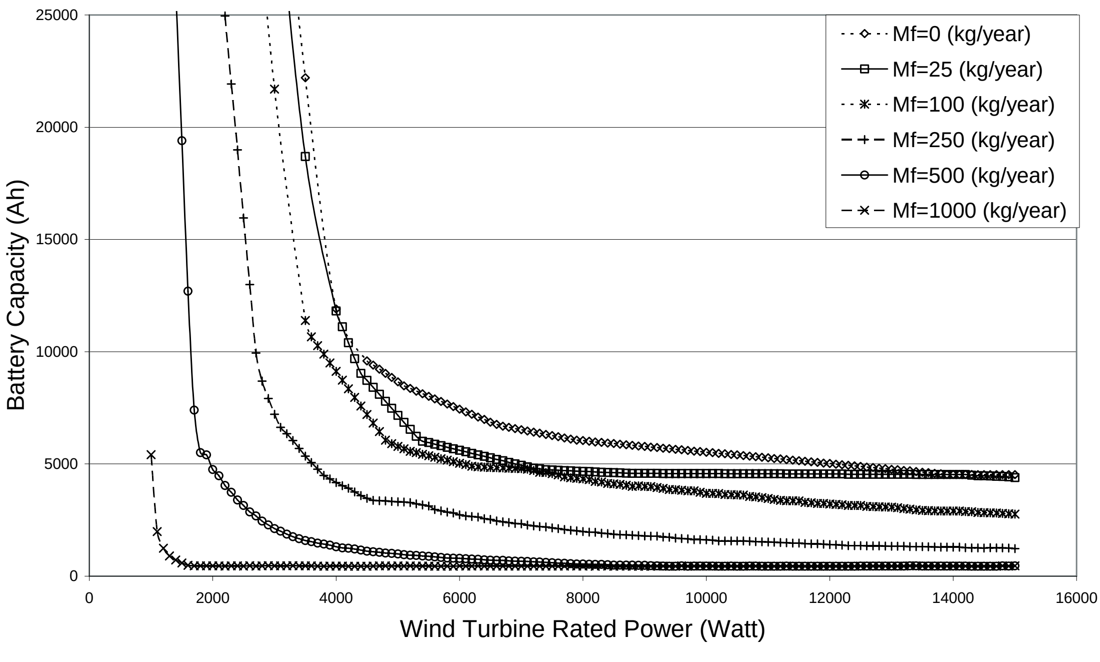


Figure 11: Energy Autonomous Configuration for a Wind-Diesel Hybrid System, Naxos Island

5. Discussion of the Results

5.1 Selection of the Solution

In order to select the best system configuration for each case investigated, the maximum battery capacity diminution rate versus the given annual oil consumption should be taken into consideration. For this purpose figure (12) presents the battery capacity variation versus the annual diesel oil consumption, for a given wind turbine rated power, regarding Andros island. According to the results obtained, there is a considerable battery size diminution when passing from a diesel-free to a wind-diesel hybrid system. This diminution is quite big in cases of relatively low diesel oil contribution to the system energy consumption (i.e. up to 100-200kg/y or 5% to 10% of the diesel-only system annual consumption (approx. 2000kg/y)). For larger diesel oil consumptions the battery capacity decrease is decelerated, since the battery capacity versus annual diesel-oil consumption distribution tends to an asymptotic value.

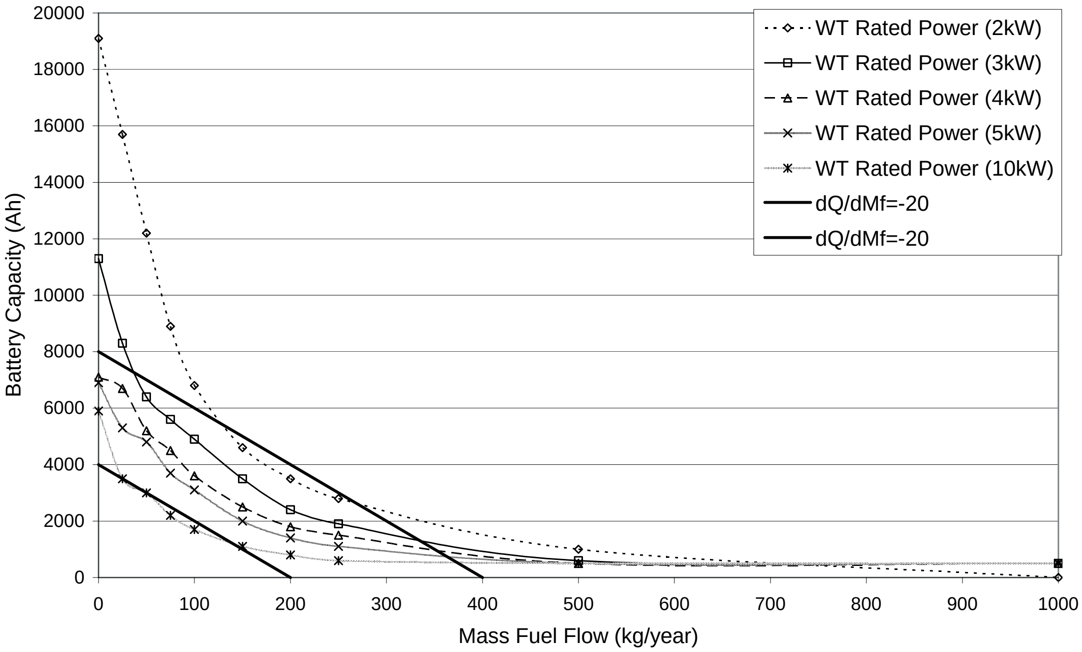


Figure 12: Battery Capacity Decrease Versus Diesel Oil Annual Consumption, Andros Island

In this context, by setting the minimum acceptable (dQ_{max} / dM_f) value equal to (-20), see also figure (12), one may estimate the maximum necessary annual oil consumption that minimizes the corresponding battery capacity contribution to the hybrid system under investigation. Bear in mind that the "dQ/dM_f=-20" value has been selected using the current oil market price at the specific isolated location (i.e. 1.5€/kg of diesel oil) and the corresponding specific purchase cost (0.5€/Ah; U=24Volt) of a lead-acid heavy-duty battery bank. According to the data of figure (12), once the wind turbine rated power of the hybrid system located in Andros island is equal to 3kW, the optimum system configuration is obtained by using approximately 150kg/y of diesel oil. In this case the corresponding battery capacity is 3500Ah, see also figure (7). On the other hand, when the wind turbine rated power is 10kW, the maximum necessary annual oil consumption may be equal to 50kg/y, leading to a battery bank capacity equal to 3000Ah.

Using the same methodology, the corresponding hybrid system dimensions for the Naxos and Kea islands may be estimated, along with the maximum annual oil quantity required; see Table II. As expected, given the annual mass fuel consumption, the battery capacity reduction is in inverse proportion to the wind potential of the installation area; see also figures (13) and (14). Besides, larger annual oil quantity is required in cases of small wind turbines than in cases of relatively big ones. An integrated cost-benefit analysis on a ten or twenty-year operational period of the system may be used in order to obtain a most accurate long-term solution of the problem.

Table II: Proposed Optimum Configurations

Region	**Wind turbine rated power (kW)**	**Battery Capacity (Ah)**	**Annual Diesel-oil consumption (kg/y)**
Andros	3	3500	150
	5	3700	75
	10	3000	50
Naxos	3	7210	250
	5	5780	100
	10	4150	50
Kea	5	8300	500
	10	8700	250
	15	13400	100

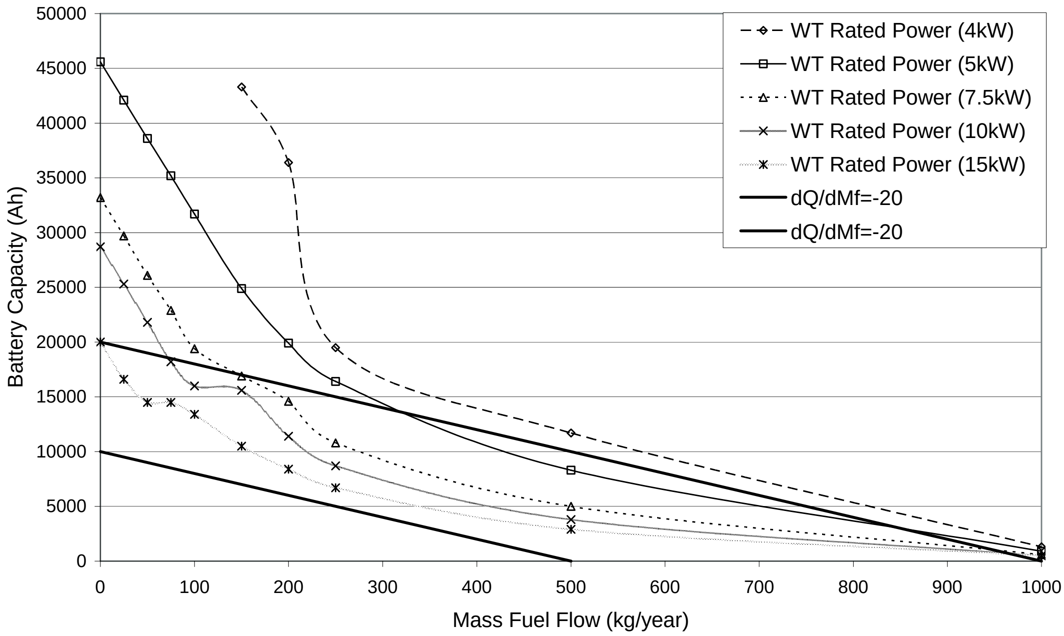


Figure 13: Battery Capacity Decrease Versus Diesel Oil Annual Consumption, Kea Island

5.2 Energy Balance

Another target of the present study is to extensively analyze the energy balance of the proposed wind-diesel hybrid system for the complete time period investigated. To get a representative picture of the proposed system behavior, figure (15) presents the annual energy production of typical energy autonomous hybrid configurations located in Andros island. As it is obvious from the results sited, the energy production is quite higher than the energy demand (≈4750kWh) especially for low diesel oil contribution. This might be the cost of reducing the battery size; hence one cannot store the entire wind energy surplus. Only at high diesel-oil penetration cases the energy production is fairly comparable with the energy demand and there is no extra wind energy production.

This fact is also validated by figure (16), where the system energy disposal is demonstrated. As it is clear from the data presented, a significant part of the energy production is finally rejected, being the direct result of wind energy production and consumption demand incompatibility, along with limited energy storage capacity. In any case, the diesel generator production represents a small part of the total system output, while the energy excess may be forwarded to additional energy consumption, like water pumping for irrigation purposes[15] or small autonomous desalination installations[16].

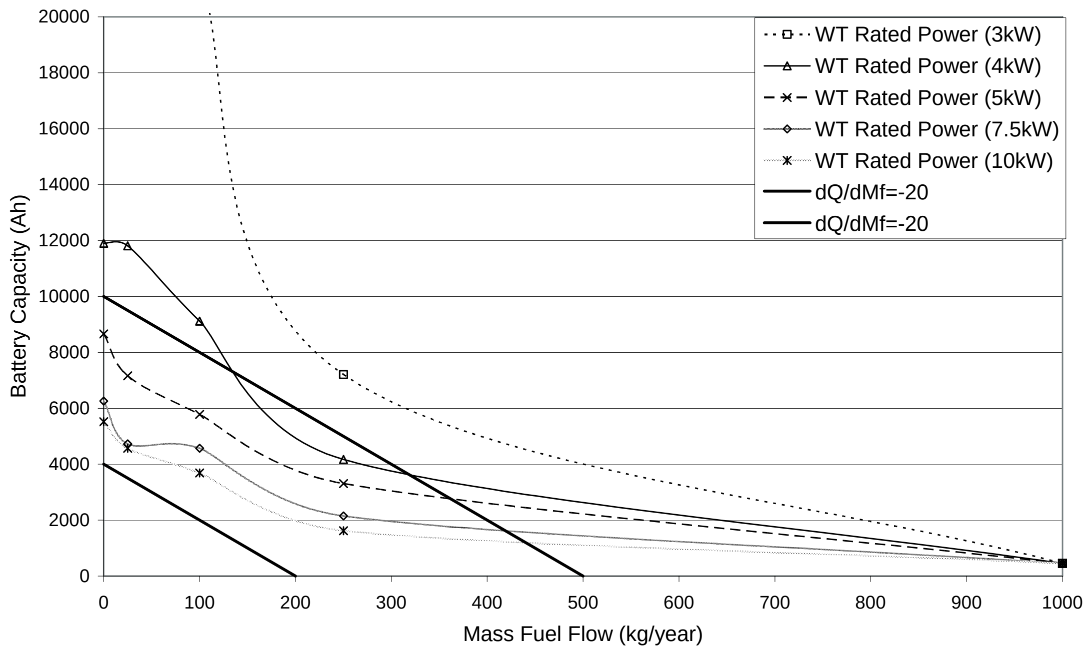


Figure 14: Battery Capacity Decrease Versus Diesel Oil Annual Consumption, Naxos Island

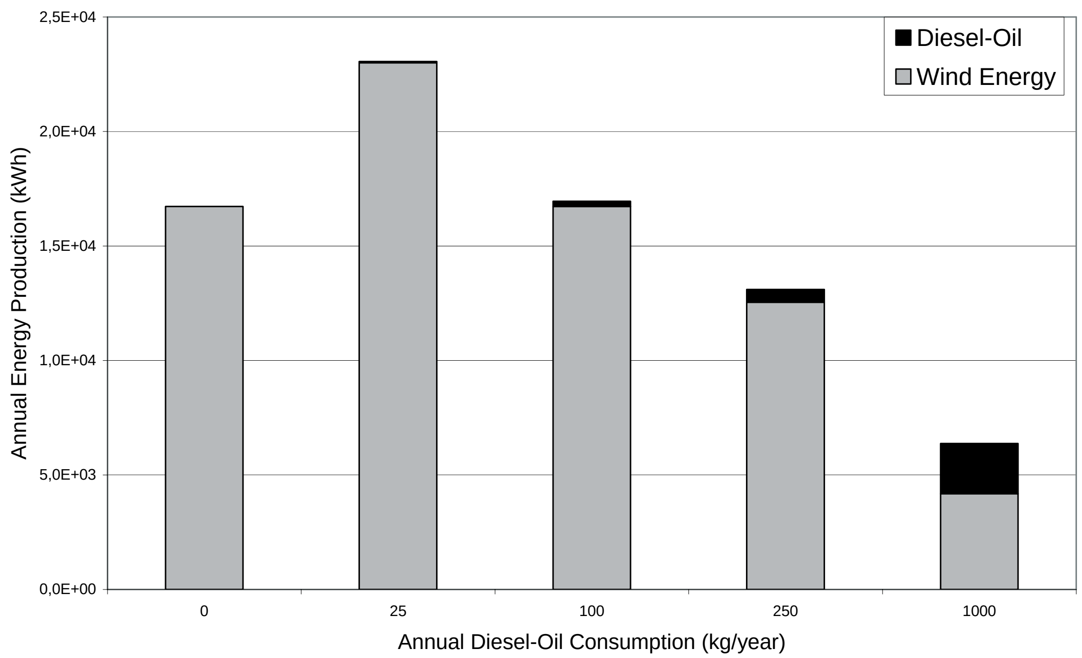


Figure 15: Annual Energy Production Analysis for Andros Wind-Diesel Hybrid System

This conclusion is clearly supported by inspecting figures (17a) to (17c) and figures (17d) to (17f), where the distribution of the wind energy production of the wind-diesel hybrid system is demonstrated for zero, low and high diesel oil penetration and for the two extreme wind potential cases examined, i.e. Andros and Kea islands. As already mentioned at low diesel-oil penetration a large portion of the wind turbine production is finally rejected, while the internal system loss (i.e. rectifier and charge controller losses, standing losses owing to the battery self-discharge, losses of the lines connecting the installation apparatus, UPS and inverter loss) represents 14% of the wind energy production for the Andros case. On the other hand, the wind energy rejection for Kea island is quite lower, while the internal system loss represents approximately one third of the wind turbine production. Bear in mind that by increasing the diesel-oil consumption, the wind energy contribution is reduced to meet the consumption requirements, representing only 50% of the total annual consumption in case of figures (17c) and (17f).

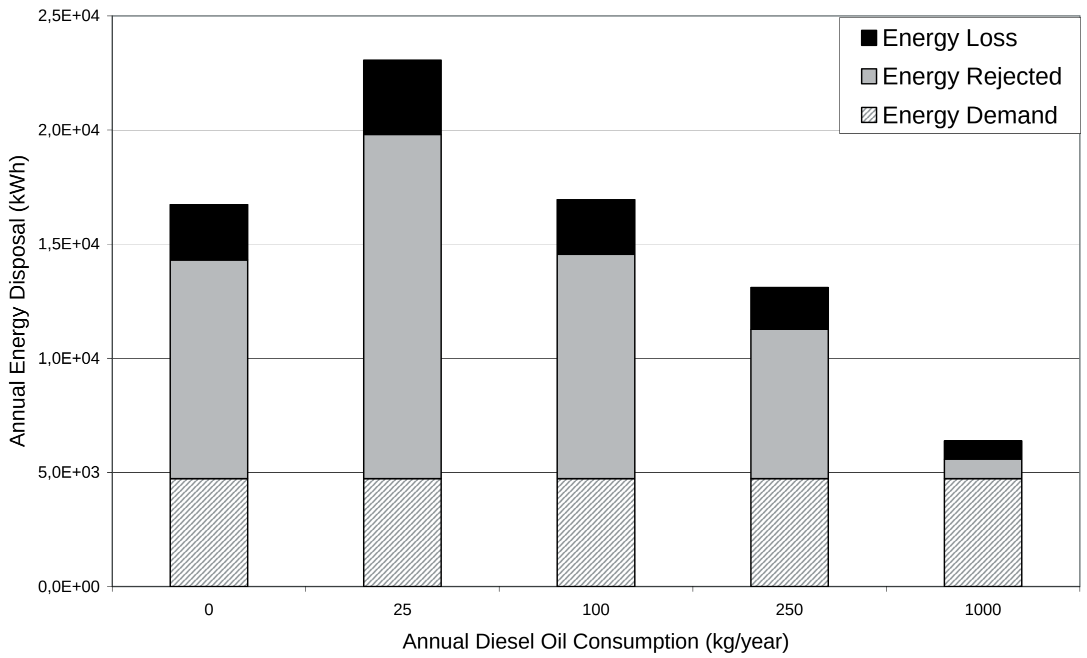


Figure 16: Annual Energy Production Disposal for Andros Wind-Diesel Hybrid System

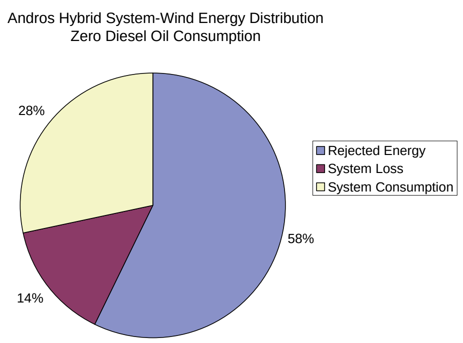


Figure 17a: Andros Island, Zero Oil Penetration

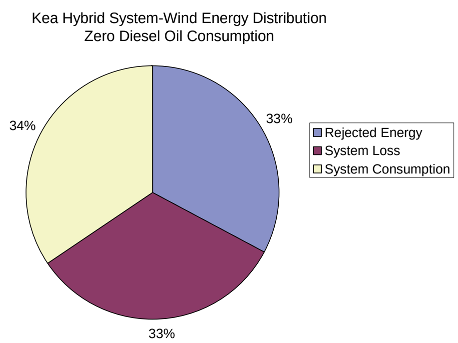


Figure 17d: Kea Island, Zero Oil Penetration

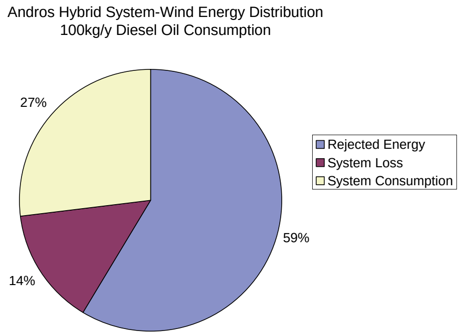


Figure 17b: Andros Island, Low Oil Penetration

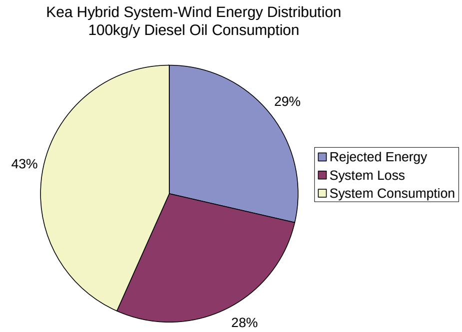


Figure 17e: Kea Island, Low Oil Penetration

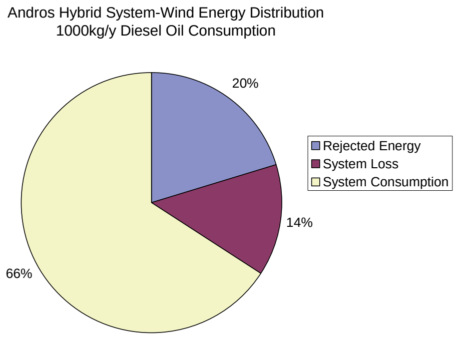


Figure 17c: Andros Island, High Oil Penetration

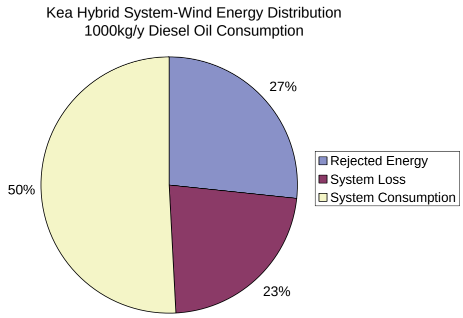


Figure 17f: Kea Island, High Oil Penetration

6. Conclusions

The central target of the present study is to estimate the optimum dimensions of a stand-alone wind-diesel hybrid system with energy storage, able to fulfill the energy requirements of a representative remote consumer. Thus, the optimum dimensions of a stand-alone hybrid system are defined for three representative wind potential types, using long-term meteorological data. It is important to mention that the first case analyzed concerns a high wind potential area, while the other two cases represent a medium-high and a medium-low quality wind potential region.

The proposed hybrid system presents a first installation cost inferior to a stand-alone wind power system and a considerably lower operational cost from a diesel-only installation. In addition the existence of three independent power sources increases the system reliability, while the usage of limited diesel-oil quantity remarkably diminishes the corresponding battery size.

For the prediction of the optimum hybrid system configuration, an integrated numerical algorithm is developed, based on experimental measurements and the operational characteristics by the hybrid system components manufacturers. During the calculations a detailed energy balance analysis is carried out for the entire time period examined, in order to verify that -for every time point- the electricity requirement of the remote consumer is fulfilled by the proposed solution. Similarly, the battery depth of discharge (battery capacity) time evolution is also investigated, to ensure that the corresponding "DOD" values do not exceed the existing limiting value.

Finally, although no financial data are included in the present analysis, it is obvious that a wind-diesel-battery hybrid system is among the best alternative solutions facilitating the electricity demand of numerous remote consumers with a rational first installation and operational cost, even at medium wind potential areas. On top of this, subsidization possibilities -either by local authorities or via

European funds- should greatly increase the economic attractiveness of similar stand-alone hybrid applications.

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MINIMIZATION OF THE ENERGY STORAGE REQUIREMENTS OF A STAND-ALONE WIND POWER INSTALLATION BY MEANS OF PHOTOVOLTAIC PANELS

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Abstract

Autonomous wind power systems are among the most interesting and environmental friendly technological solutions for the electrification of remote consumers. In many cases, however, the battery contribution to the initial or the total operational cost is found to be dominant, discouraging further penetration of the available wind resource. This is basically the case for areas possessing a medium-low wind potential. On the other hand, several isolated consumers are located in regions having the regular benefit of an abundant and reliable solar energy supply. In this context, the present study investigates the possibility of reducing the battery size of a stand-alone wind power installation by incorporating a small photovoltaic generator. For this purpose an integrated energy production installation -based exclusively on renewable energy resources- is hereby proposed. Subsequently, a new numerical algorithm is developed, able to estimate the appropriate dimensions of a similar system. According to the results obtained by long-term experimental measurements, the introduction of the photovoltaic panels considerably improves the operational and financial behaviour of the complete installation, due to the imposed significant battery capacity diminution.

Keywords: Wind Power Stand-Alone System; Photovoltaic Generator; Battery Capacity Reduction; Wind Potential

1. Introduction

Autonomous wind power systems are among the most interesting and environmental friendly technological solutions[1-3] for the electrification of remote consumers. However, the expected system operational cost is quite high, especially in case of no-load rejection[4,5], i.e. in the case where all of the load must be met. One of the most expensive components of a stand-alone system is the battery pack -necessary to guarantee the required system reliability. Thus, in cases of increased system autonomy, the battery contribution to the initial or the total operational cost is found to be dominant[5,6]. In addition, batteries should be replaced every 4 to 7 years[7,8], thus mounting up the operational cost of the system.

On the other hand, Greek islands are located in regions having the regular benefit of an abundant and reliable solar energy supply. Hence, the introduction of a small photovoltaic generator[9-11] in a stand-alone wind power station is expected to smooth out the system energy production, significantly decreasing the energy storage requirements, without modifying the first installation cost of the system[12,13]. Additionally, the state subsidy percentage for small photovoltaic (PV) systems is considerably higher (50%-55%) than the small wind power stations corresponding one (30%-40%)[14]. On top of that, the operational life time of a contemporary photovoltaic system is close to thirty years[15].

In this context, the present study investigates the possibility of reducing the battery size of stand-alone wind power installation -mainly installed in medium-low wind potential areas- by incorporating a small photovoltaic generator. Keep in mind that the solar energy distribution is basically periodic,

Kaldellis J.K., Kostas P., Filios A., 2005, *"Minimization of the Energy Storage Requirements of a Stand-Alone Wind Power Installation by Means of Photovoltaic Panels", Wind Energy International Journal, on-line available in http://www3.interscience.wiley.com.*

while wind speed presents a stochastic behaviour. The proposed analysis is accordingly applied to representative remote consumers located at selected areas with enlightening results.

2. The Proposed Configuration

The proposed configuration (figure (1)) is consisting of a micro-wind converter, a small photovoltaic generator and a battery storage device, along with the corresponding electronic equipment. More precisely it involves:

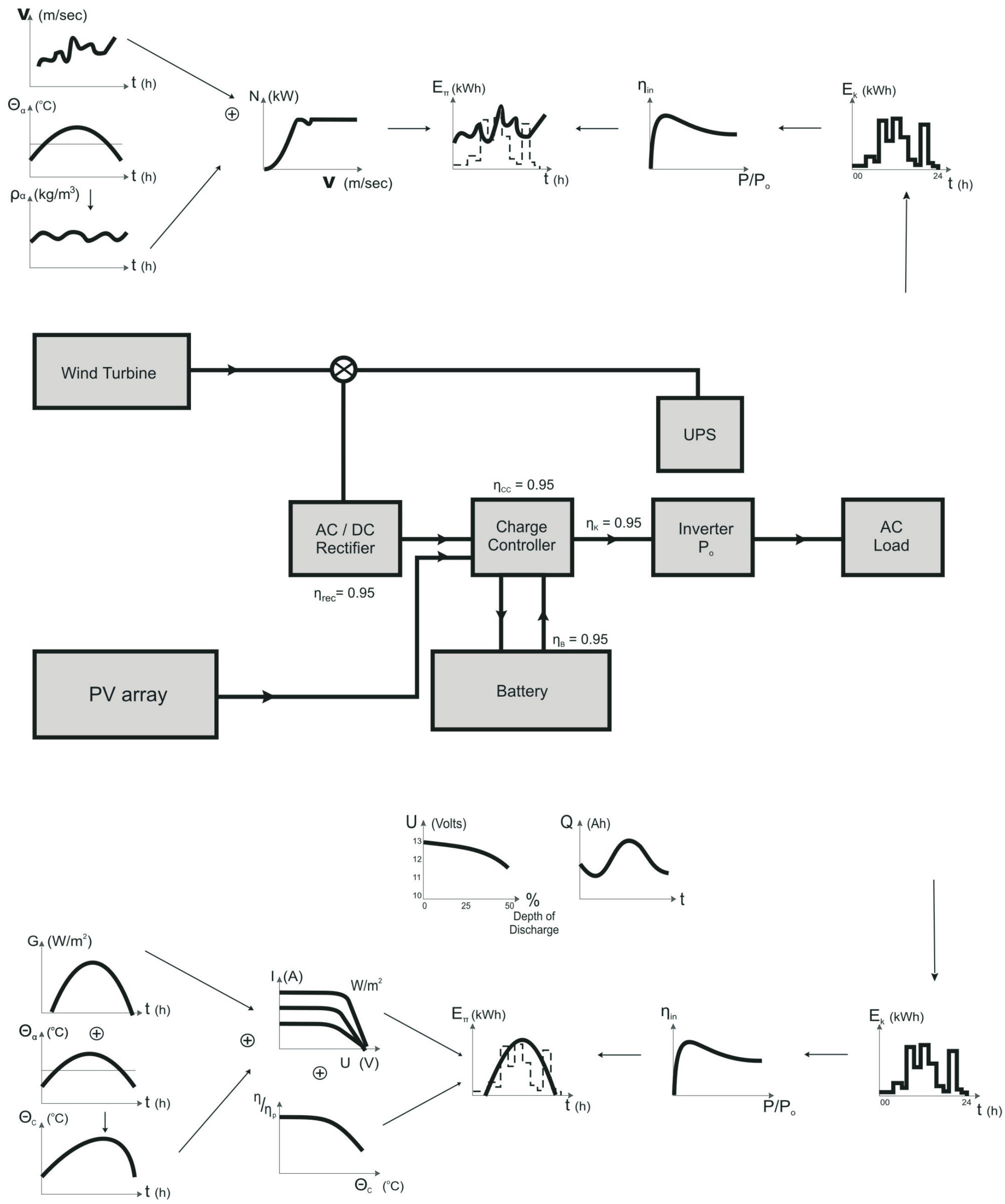

Figure 1: Proposed Wind-Solar Stand-Alone System

a. A micro wind converter of rated power "N_o" and given power curve N_w=N(V) for standard day conditions (i.e. air density taken equal to 1.225kg/m^3).
b. A photovoltaic array of "z" panels ("N_+" maximum/peak power of every panel) properly connected to feed the charge controller to the voltage required.
c. 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}".
d. An AC/DC rectifier of "N_o" kW.
e. A DC/DC charge controller of "N_c" rated power.
f. A UPS (uninterruptible power supply) of "N_p" kW, frequency of 50Hz, autonomy time "δt" and operation voltage 230/400V. The utilization of this device is optional and it is used to protect the installation from any unexpected electricity production fluctuations due to the stochastic behaviour of the wind.
g. A DC/AC inverter of maximum power "N_p" able to meet the consumption peak load demand, frequency of 50Hz and operational voltage 230/400V.

In the present analysis the above described system is used to meet the electrification requirements of a typical remote consumer, see figure (2), located in one of the several small islands of the Aegean Archipelago. The corresponding load profile used is basically a rural household profile (not an average load taken from typical users) selected among several profiles provided by the Hellenic Statistical Agency[1,6], see also[16,17]. More precisely, the numerical load values vary between 30W (refrigerator load) and 3300W. According to the consumption profile approved, the annual peak load "N_p" does not exceed 3.5kW, while the annual energy consumption "E_y" is around 4750kWh.

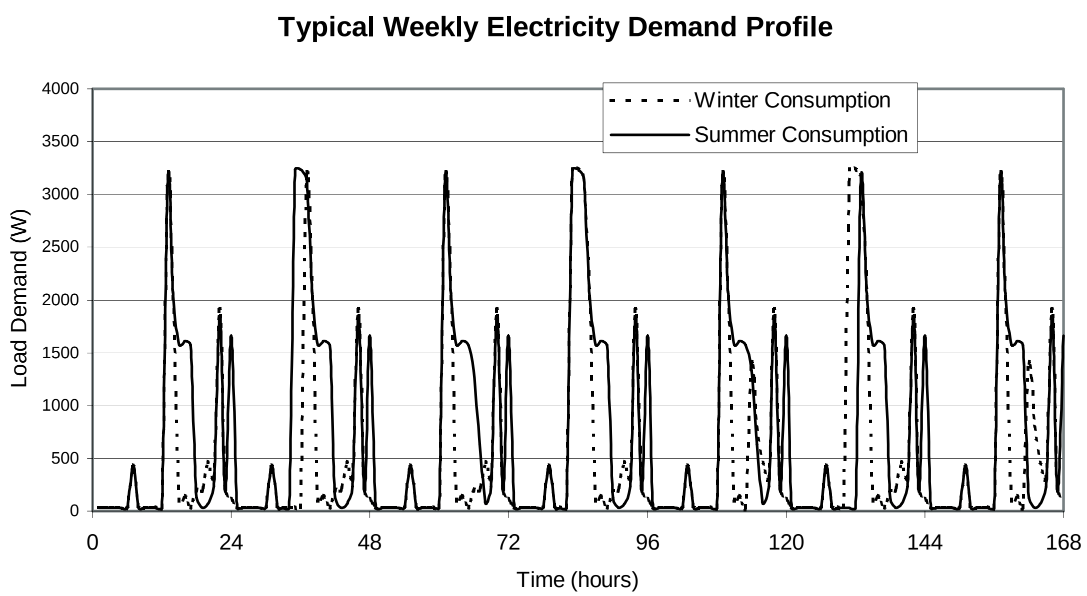

Figure 2: Typical Electricity Demand Profile of the Remote Consumer Analyzed

For the complete energy analysis of the proposed installation, the corresponding wind potential, the ambient temperature and pressure, along with the solar irradiance measurements -usually at horizontal plane- for a given time period (e.g. one year) are also needed. Finally, there are also required the operational characteristics of all the components composing the stand-alone system under investigation, e.g. wind power curve at standard day conditions, operational characteristics (current, voltage (I-U)) of photovoltaic modules selected, inverter efficiency, battery bank characteristic etc.

3. Description of the Operational Modes-Proposed Analytical Model

During the long-lasting operation of the proposed stand-alone system (figure (1)), the following situations may appear:

a. The power demand "N_D" of the consumption is less than the power output "N_w" of the wind turbine, ($N_w>N_D$). In this case the energy surplus ($\Delta N=N_w-N_D$) is stored via the rectifier and the battery charge controller along with the energy production of the photovoltaic generator "N_{PV}". If the battery is full ($Q=Q_{max}$), the residual energy is forwarded to low priority loads.
b. The power demand is greater than the power output of the wind turbine, ($N_w<N_D$) but less than the sum of powers of photovoltaic station and wind converter put together, i.e. ($(N_w+N_{PV})>N_D$). In this case the remaining load demand is covered by the photovoltaic station via the DC/AC inverter. Any energy surplus from the photovoltaic station is stored in the battery via the charge controller. If the battery is full ($Q=Q_{max}$), the residual energy is forwarded again to low priority loads.
c. The power demand is greater than the power output of the two renewable stations, i.e. $(N_w+N_{PV})<N_D$, where $(N_w+N_{PV})\neq 0$. In similar situations, the energy deficit ($\Delta N=N_D-(N_w+N_{PV})$) is covered by the batteries via the DC/DC converter and the DC/AC inverter. During this operational condition, special emphasis is laid on the three-electricity production subsystems management plan.
d. There is no renewable energy production (e.g. low wind speed, machine non available and zero solar irradiance), i.e. $(N_w+N_{PV})=0$. In this case, all the energy demand is covered by the battery-DC/DC controller-DC/AC inverter subsystem, under the condition that $Q>Q_{min.}$ In cases (c) and (d), when the battery capacity is near the bottom limit, an electricity demand management plan should be applied; otherwise the load would be rejected.

According to the above, for the estimation of the appropriate configuration that guarantees the energy autonomy of a remote consumer located in a specific area, under given wind and solar potential conditions, a new algorithm "WT-PV-II" is devised, using the experience obtained from the already presented[1,12] "WINDREMOTE-II" and "FOTOV-III" algorithms. In this context the proposed algorithm uses the following steps:

Step 1: Define the number "z" of PV panels to be used (N_+, $I=I(U,G,\theta)$), taking into consideration the existing solar intensity "G" and the corresponding ambient temperature "θ"
Step 2: Determine the size "N_o" of the wind converter to be used along with the corresponding power curve (i.e. $N_W=N(V)$)
Step 3: Select a battery capacity value "Q_{max}", taking into account the desired hours of the system's energy autonomy
Step 4: At each time step, starting at t=0, complete the following steps:
Step 5: At the current time step "t" estimate the energy produced by the wind turbine
Step 6: At the current time step "t" estimate the energy produced by the photovoltaic station
Step 7: Check if the output of the wind turbine production branch is greater than the energy demand of the system. If this is true, charge the batteries of the installation with the energy surplus, under the condition that the batteries are not full. The photovoltaic generator energy production is also stored at the system battery bank, if possible. In the opposite occasion, the energy surplus is forwarded to low priority loads. Then proceed to the next time step, i.e. Step (10).
Step 8: If the wind turbine cannot fulfil the energy demand, the energy deficit is covered by the photovoltaic generator. In case of energy surplus, the batteries are charged, provided that they are not full. In the opposite case, the energy surplus is forwarded to low priority loads. Then proceed to the next time step, i.e. Step (10).
Step 9: If the energy demand cannot get covered by the renewable energy production systems, the energy deficit is covered by the system batteries, under the assumption that the batteries are not near the maximum permitted depth of discharge. Otherwise, the battery capacity is increased by a given amount "δQ" and go back to Step (4).
Step 10: Proceed to analyze the next time step, Steps (5) to (9), until the complete time period is

examined.

Step 11: Increase the wind turbine size and repeat Steps (3) to (11).

Step 12: Increase the photovoltaic panels number and repeat Steps (2) to (12).

After the analysis is completed, the distribution $Q_{max}=Q_{max}(N_o;z)$ is predicted, taking into account that every set of "Q_{max}", "N_o" and "z" guarantees the energy autonomy of the remote consumer for the entire period analyzed.

4. Application Results

The proposed combined wind-solar solution is first applied at the island of Kea. This is a small island (2300 inhabitants, area 103km^2) close to Athens (figure (3)), with a relatively low wind potential[6], since the annual mean wind speed is slightly above 5.5m/s at 10m height, being marginally appropriate to feed contemporary wind turbines for electricity production. In fact, figure (4) presents the year-long daily mean wind speed distribution, demonstrating the quite long low wind speed periods, especially during June. More specifically, according to previous long term analysis[1], the maximum calm spell period of the area during an-entire 5-year period approaches the 200 hours (approximately 8 days). Thus, the utilization of an extremely huge battery bank size reported in Kaldellis and Tsesmelis[6] is quite rational for such a long calm spell period. During that study, an attempt was made to guarantee the energy autonomy of a typical remote consumer on the basis of a wind only based stand-alone system; see also figure (5) for z=0.

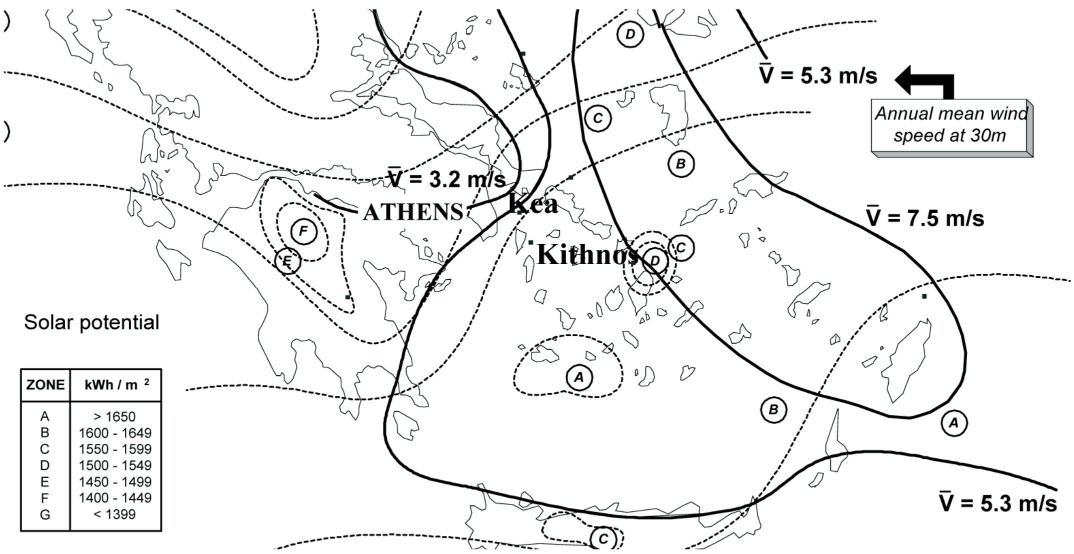

Figure 3: Wind-Solar Potential in Greece

According to the calculation results, one should use a wind turbine of rated power equal to 7kW minimum, in order the required battery (24Volt) capacity not to exceed the 25000Ah. Considering, however, the high solar potential (figure (6)) of the area, which belongs to the "C" solar potential type of figure (3), a significant battery size reduction is encountered by introducing a small number of photovoltaic panels. At the same time, the wind turbine rated power required is also decreased. More precisely, using 20 photovoltaic panels of 51W_p (or 1020W), the required wind turbine rated power is less than 5kW, while the corresponding battery capacity drops to 20000Ah. In addition, a larger number of photovoltaic panels (e.g. z=100 or 5.1kW) can practically establish a viable energy-autonomous solution, by using only 8000Ah of battery capacity and a wind converter of 5kW.

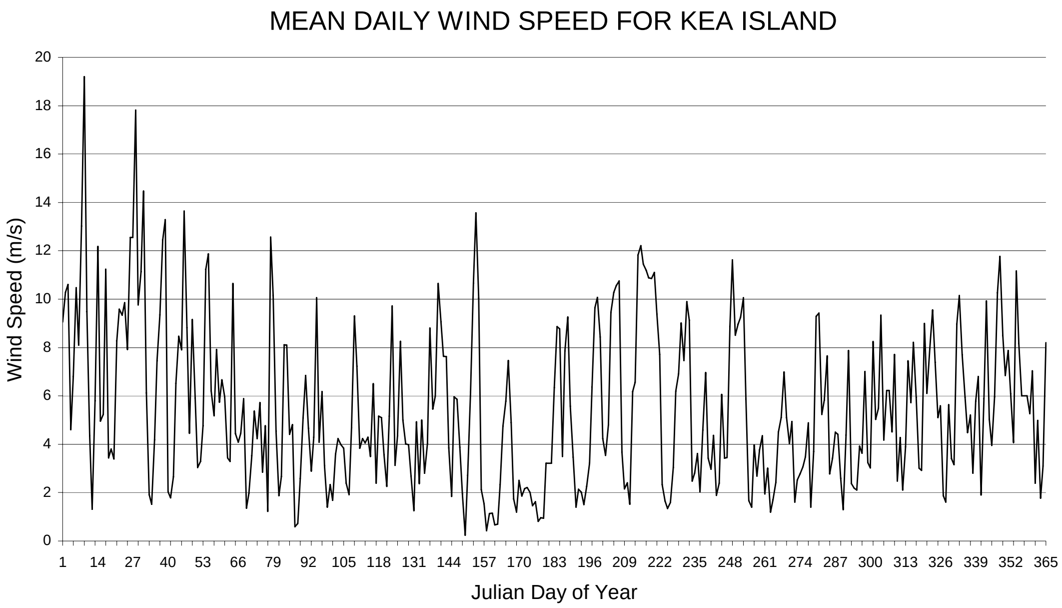

Figure 4: Wind Speed Time Series for Kea Island

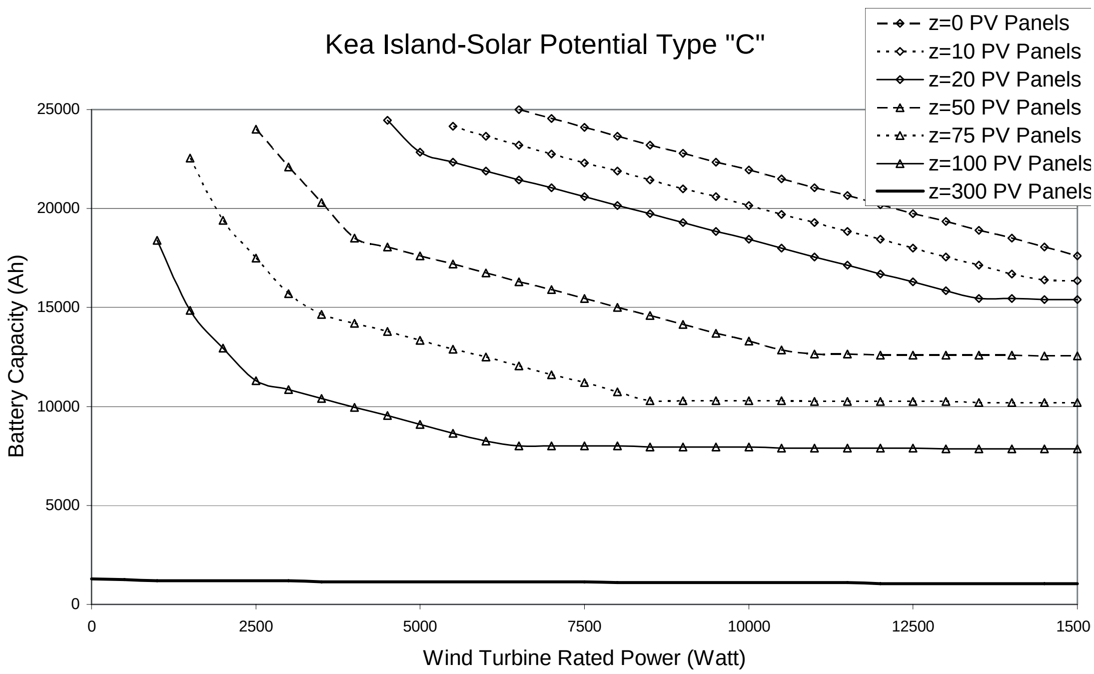

Figure 5: Energy Autonomous Configuration of Wind-Solar Stand-Alone Systems

Accordingly, one may examine the resulting battery size reduction in the hypothetical case that -for the island analyzed- the solar potential is better (case "A") than the one corresponding to case "C" of figure (6). In this case however, due to the higher solar radiation available, the ensuing battery size reduction is much greater, figure (7), as -by using 20 photovoltaic panels- the corresponding battery reduction approaches the 25% in comparison with the zero PV panels (or wind only) solution, while the corresponding wind turbine size decreases down to 3kW. Subsequently, one may accomplish the installation energy autonomy by using only 50 panels -instead of 100 of figure (5)- where the corresponding battery capacity is less than 10000Ah. Finally, by increasing the photovoltaic panels' number, there is not only a battery capacity decrease but also a considerable reduction of the wind converter rated power required, figure (7).

The second region examined is the island of Kithnos, possessing a better wind potential than the Kea island. More specifically, Kithnos is also a small island (1700 inhabitants, area of 94km²) in the Aegean Sea, located approximately 60km southeast of Athens, figure (3). Due to the insufficient infrastructure (e.g. road network) there are many isolated consumers, who have no access to the local electrical grid. The island has a medium-strong wind potential, since in several locations the annual mean wind speed exceeds

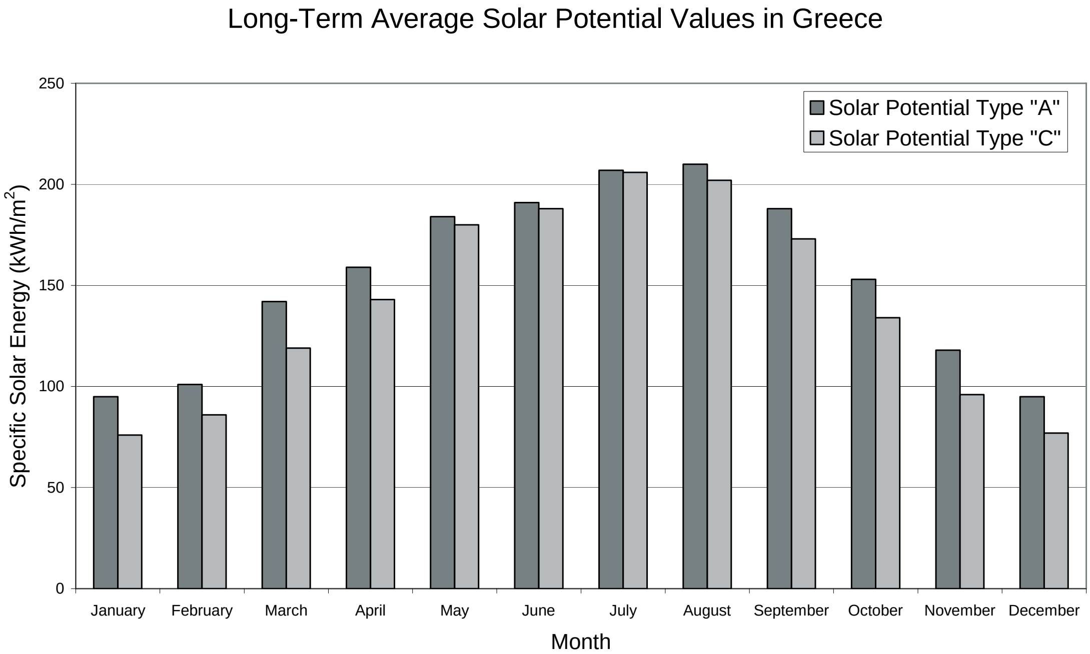

Figure 6: Solar Potential Monthly Profiles for the two Cases ("A" and "C") Investigated

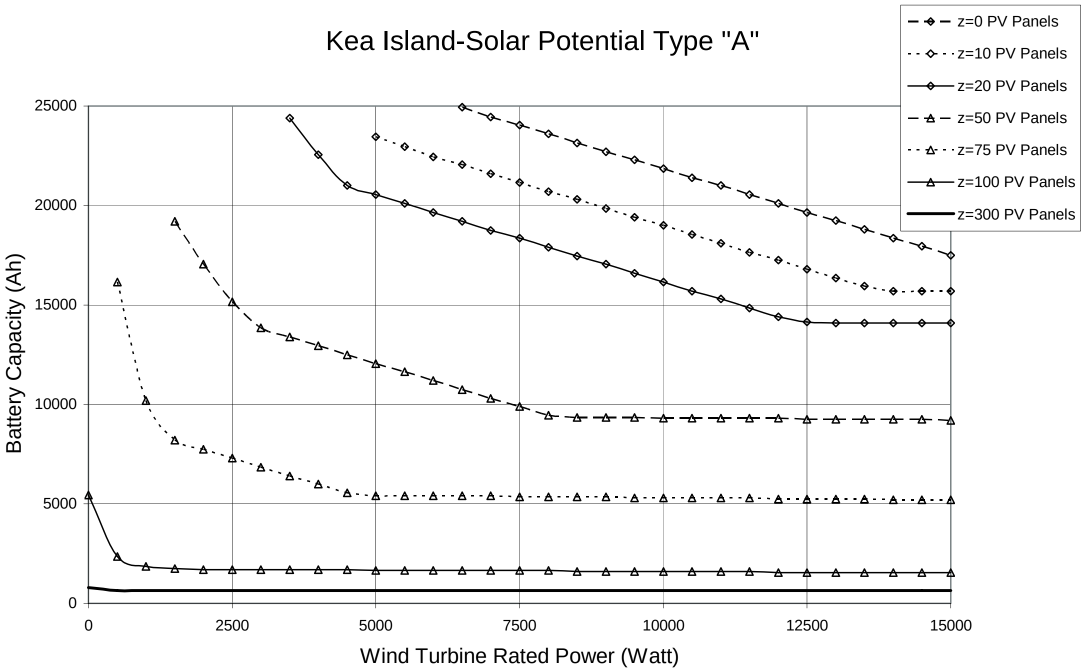

Figure 7: Energy Autonomous Configuration of Wind-Solar Stand-Alone Systems

6.5m/s, at a 10m height. Despite the higher annual mean wind speed of the area, the seasonal profile is quite similar to the one of Kea, hence the corresponding calm spells are almost equally long to the ones of the Kea island, appearing also during summer. Thus, as in the previous case, the required dimensions of a wind power stand-alone system are rather sizeable, according to the results by Kaldellis[1].

Applying the WT-PV-II algorithm and using the solar potential of case "C" of figure (3), one may estimate a significant battery capacity reduction by incorporating 20 to 50 photovoltaic panels of $51W_p$; figure (8). For example, the predicted battery capacity drops from 16800Ah (for the wind only system) to 13100Ah (z=20) and to only 8500Ah (z=50) in case of a solution based on a 7.5kW wind converter. In the extreme case that a 5kW photovoltaic generator is adopted, the corresponding battery capacity drops below 5000Ah for a 5kW micro wind turbine based system.

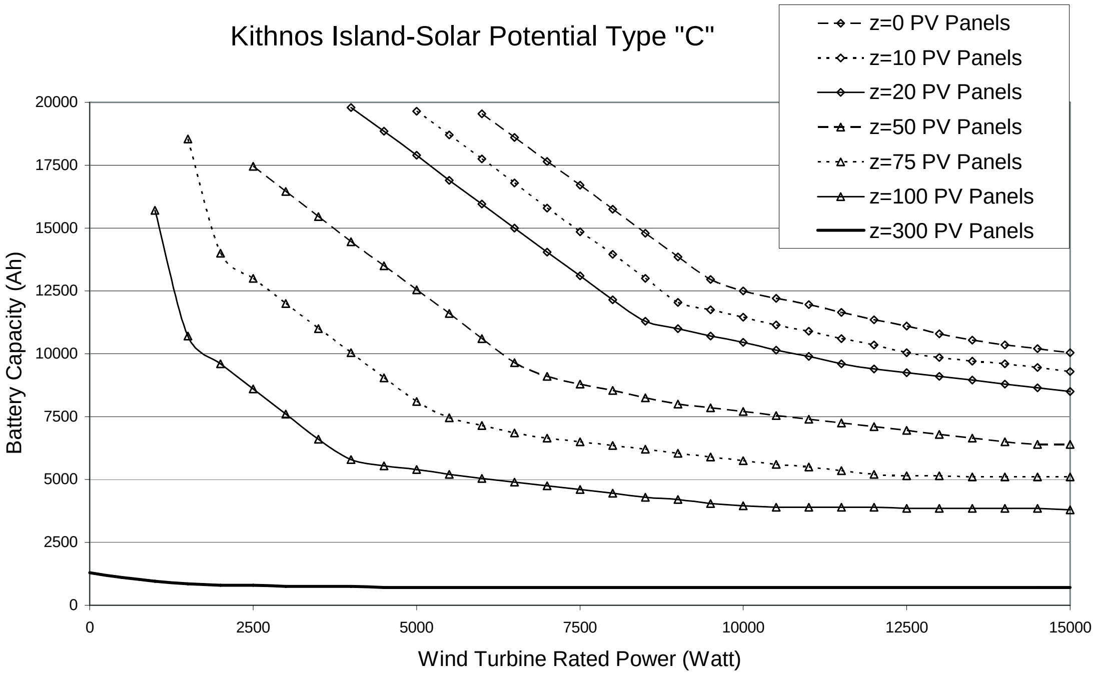

Figure 8: Energy Autonomous Configuration of Wind-Solar Stand-Alone Systems

Finally, in the theoretical case that the solar potential of the area examined corresponds to the case "A" of figure (3), the corresponding battery size decrease is even greater, figure (9). In fact, by including a $1kW_p$ photovoltaic generator (i.e. z=20) in a 7.5kW wind power stand-alone system the installation's energy autonomy is fulfilled by using a battery capacity of only 10000Ah. On top of this, by adding 75 photovoltaic panels on a typical 3kW wind-based stand-alone system the corresponding battery size drops below 3500Ah.

Before completing this section it is important to address the possible economic advantage of the proposed solution in comparison with the utilization of a dispatchable generator. Generally speaking the utilization of a dispatchable generator may solve some of the energy demand problems of remote consumers in short-term time horizon. However, the long-term (life-cycle) cost-benefit analysis does not justify the incorporation of a diesel-electric generator in Greek remote island areas. In as much, the optimization of a wind-solar stand-alone system is being attempted in view of the uncontrollable oil price augmentation and the continuous environment degradation due to the usage of fossil fuels.

More precisely, in order to check the viability of the proposed wind-solar based solution, to meet the electricity demand of a remote consumer with rational cost, a preliminary comparative study is undertaken including also the possibility to use a small autonomous diesel-electrical generator system.

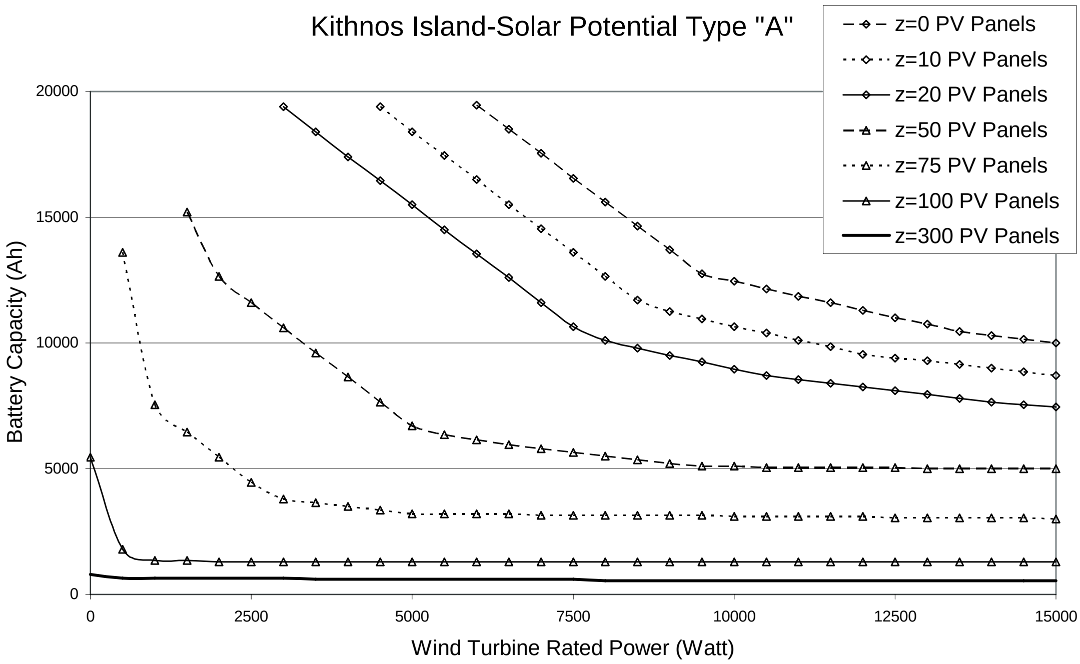

Figure 9: Energy Autonomous Configuration of Wind-Solar Stand-Alone Systems

The most widely applied (up to now) solution for the remote consumers to fulfill their electrification needs is to install a small internal combustion engine in combination with an appropriate electrical generator. Although the efficiency of such a system is quite small (≈20%) the corresponding buy cost is very low (≈240Euro/kW), increasing the short-term economic attractiveness of this solution. On the other hand, the service supplied, based on the life span of a continuously through the year operating system, is taken equal to six (6) years and the corresponding long-term average M&O cost (mainly due to fuel cost) is assumed equal to 7000 Euro per year. Consequently, selecting a 5kW autonomous system the total electricity cost "C_d" of the installation after "n" years of operation is given as:

$$C_d = 1200 + 7000 \cdot n + V_n \tag{1}$$

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

Accordingly, using the proposed configuration based (e.g. Kithnos island, figure (8)) on a wind turbine of rated power 7.5kW and taking into consideration a 3% (m=0.03) annual maintenance and operation cost coefficient[4], the total electricity production cost by applying the wind-solar energy solution can be approximated as:

$$C_{WE} = IC_o + m \cdot IC_o \cdot n + V'_n \tag{2}$$

while "V'_n" term is used to describe the battery replacement cost (depending on the photovoltaic panels selected) every seven years. The initial installation cost "IC_o" of the proposed solution includes the ex-works price of the wind turbine (7.5kW), the battery and the photovoltaic panels purchase cost (Table I) and the corresponding balance of the plant cost, including any additional electronic equipment required. Bear in mind that similar applications, based on the exploitation of renewable energy sources are strongly subsidized by the Greek State, up to 50% for combined wind-solar based systems.

For comparison purposes, the calculation results are summarized in figure (10), for various combinations of photovoltaic modules and battery capacity (Table I). As it is clearly understood by figure (10) the dispatchable diesel generator scenario presents a financial advantage during the first five to eight years of operation of the installation, excluding any excessive oil price augmentation. Accordingly, the proposed stand-alone system is by far the best alternative, especially if the number of photovoltaic modules exceeds the twenty (20).

Table I: Main Parameters of the Kithnos Stand-Alone System Analyzed

Photovoltaic modules number	Battery Capacity (Ah)	Initial Cost (€)	Initial Cost (€), including subsidy	Battery replacement cost
0	16700	58666	29333	39425
20	13100	57898	28949	31518
50	8800	58930	29465	21840
100	4600	66949	33475	12009

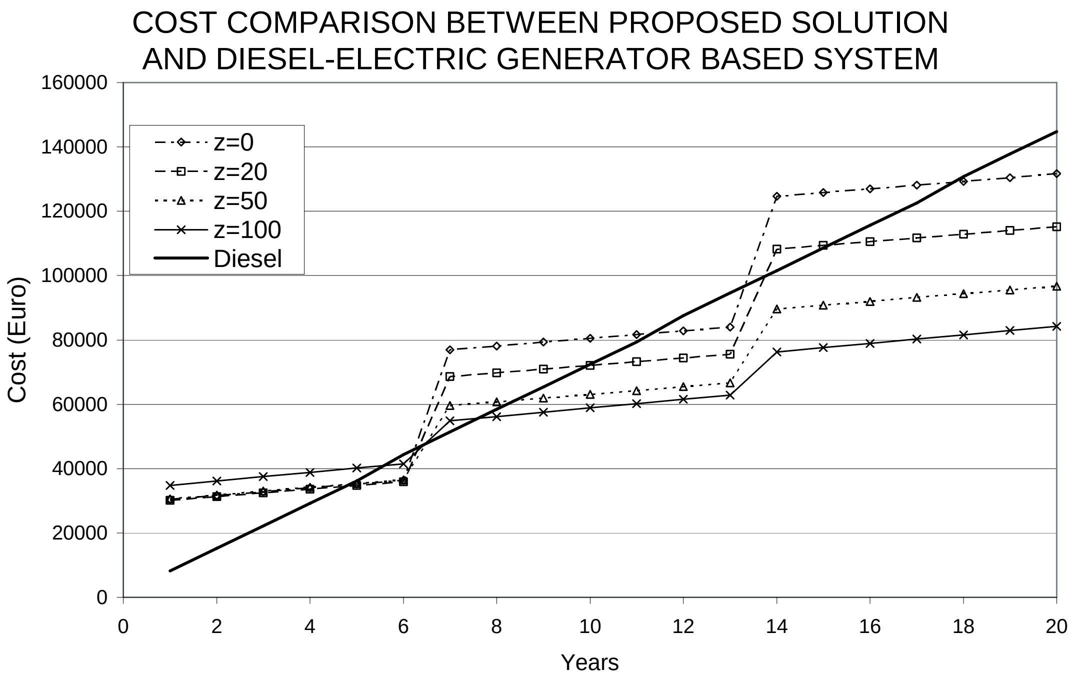

Figure 10: Life-Cycle Cost Analysis: Comparison Between the Proposed Wind-Solar Based and a Typical Dispatchable Diesel Generator Solution

5. Battery Size Reduction

According to the results of figures (5), (7), (8) and (9), a significant battery size reduction is encountered for two representative wind power stand-alone systems located in medium-low wind potential Greek islands, when a small photovoltaic generator is introduced in the original wind power stand-alone system, designed to meet the electrification needs of a typical remote consumer. On the other hand, the incorporation of photovoltaic panels in similar systems may be characterized as a rather expensive improvement, which does not have practical results. Contrarily to this general belief, one may prove that this proposal is in fact financially beneficial, if the money saved by the replaced battery capacity counterbalances or overwhelms the introduced photovoltaic panels' ex-work price, under a constant wind turbine rated power value, see also figure (10). In this case the entire system energy production cost is respectively reduced. One should not disregard the fact that a typical lead-acid battery must be replaced every 4 to 7 years, while the photovoltaic generator has a life span period of more than 20 years[18]. This fact is obvious if one compares the z=0 and the z=100 solutions of figure (10). More precisely, the z=100 solution is definitely less expensive than the z=0 one on life-cycle base analysis, although the z=0 solution (zero photovoltaic panels utilization) presents lower initial cost, see also Table I. This may be attributed to the lower battery replacement cost in case of increased photovoltaic panels' utilization as well as to the remarkable (50%) initial cost subsidy by the Greek State.

In this context, one may consider a greater ratio value of the battery reduction per photovoltaic panel ($51W_p$) (in absolute terms) than the value calculated by equation (3). More specifically, in equation (3) one may estimate the marginally considered "ΔQ/Δz" value according to the following relation:

$$(\Delta Q / \Delta z) = \frac{A}{B} \qquad (3)$$

where "A" is the ex-works price of one ($51W_p$) photovoltaic polycrystalline panel and "B" is the present value of the purchase cost plus the replacement cost (every 4-7 years) corresponding to the battery capacity (24Volt) reduction by one Ah. More specifically, if the slope of the curve of the battery capacity decrease vs. PV panels number (ΔQ/Δz) for each wind turbine size tested is steeper than the value of equation (3), then the battery replacement by PV panels is a less expensive option. On the other hand, if the corresponding slope is less than the one of equation (3), one should use lead-acid batteries instead of additional PV modules.

Using the available current market prices[19,20], the numerical value of equation (3) varies between -250 (battery decrease vs. photovoltaic panel increase) and -100. Thus, when the battery reduction rate per photovoltaic panel introduced exceeds (in absolute terms) a specific value (e.g. $|\Delta Q/\Delta z|=150$), the replacement of lead-acid batteries by photovoltaic panels is financially beneficial. For instance, the expense for installing one additional photovoltaic panel of $51W_p$ is below the purchase and replacement cost of the battery (greater or equal to 150Ah) module -no further required to guarantee the system energy autonomy- in constant (present) values.

In order to get a clear-cut picture of the proposed modification, figures (11) and (12) demonstrate the battery capacity versus photovoltaic panels variation, resulting from figures (5) and (8) for the two island cases analyzed. More specifically, in figures (11) and (12) one may find the (Q_{max}-z) distributions for selected constant wind turbine rated power values (ranging from 5kW to 15kW).

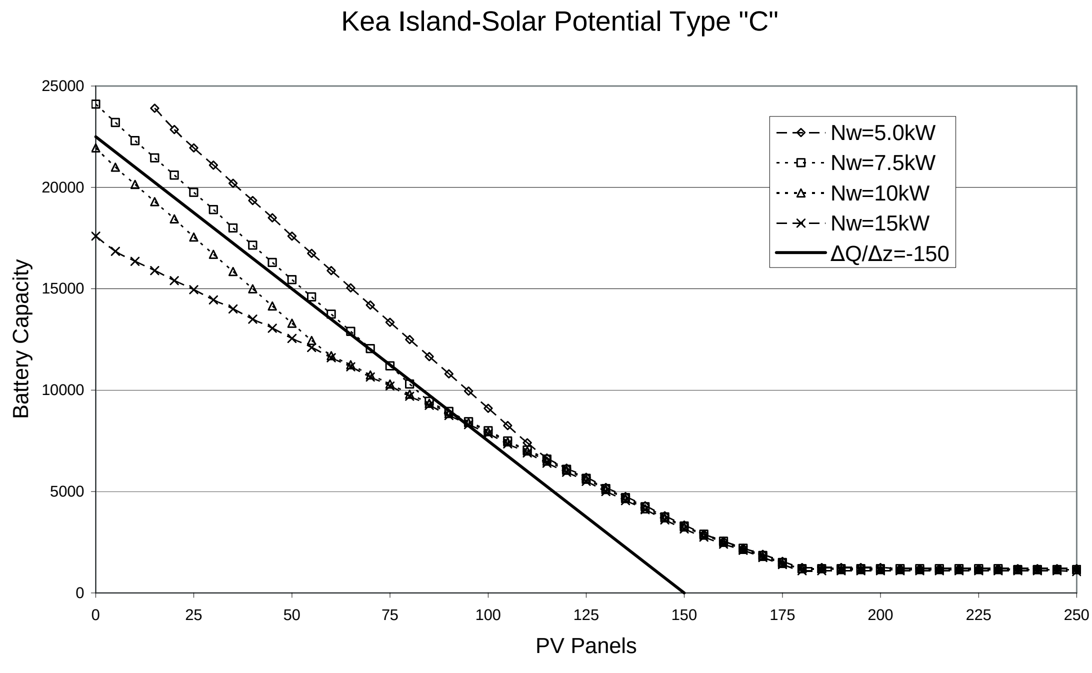

Figure 11: Maximum Battery Size Reduction Due to Photovoltaic Panels Introduction in a Wind-Solar Stand-Alone System of Kea Island (Solar Potential Type "C")

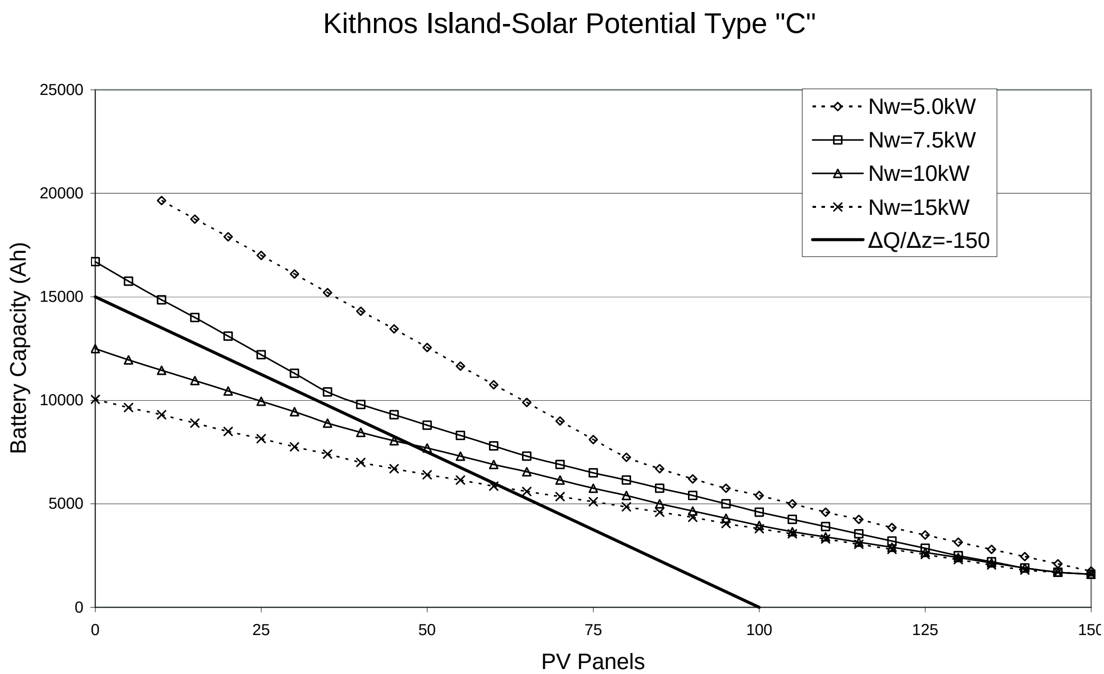

Figure 12: Maximum Battery Size Reduction Due to Photovoltaic Panels Introduction in a Wind-Solar Stand-Alone System of Kithnos Island (Solar Potential Type "C")

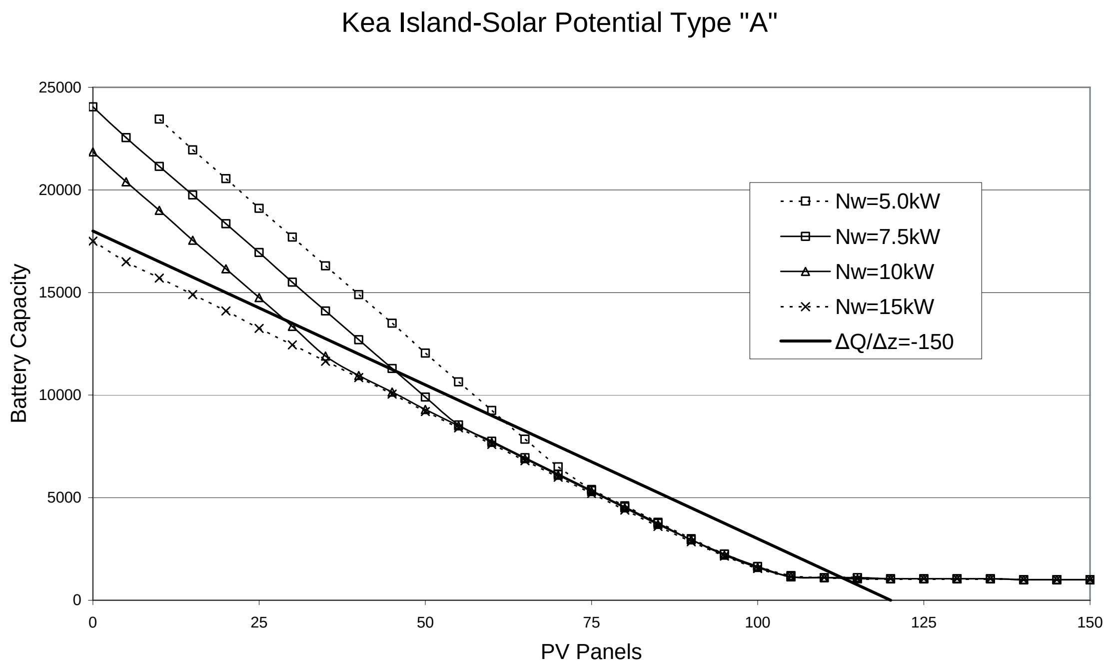

Figure 13: Maximum Battery Size Reduction Due to Photovoltaic Panels Introduction in a Wind-Solar Stand-Alone System of Kea Island (Solar Potential Type "A")

In the same figures the $|\Delta Q/\Delta z|=150$ constant slope lines are also drawn. Bear in mind that the precise "ΔQ/Δz" value depends on the local market prices[19,20] and the technological time evolution [18] expected. The financial attractiveness of the proposed battery substitution by photovoltaic panels is more obvious for stand-alone systems based on relatively small wind turbines (i.e. $z \leq 115$ for N_o=5kW and $z \leq 60$ for N_o=10kW; Kea island, figure (11)). Besides, the lower the available wind potential of the stand-alone system location the bigger the photovoltaic panels number accepted (i.e. z ≤ 85 for Kea island and z ≤ 35 for Kithnos island; N_o=7.5kW, figures (11) and (12)).

In case that the two examined islands possess the "A" solar potential type of figure (3) (the best solar potential type in Greece), more photovoltaic panels can be incorporated to replace battery modules, figures (13) and (14), than the ones of figures (11) and (12) due to the better solar potential available. In this context, the maximum number of photovoltaic panels to be installed is greater, e.g. z ≤ 85 for solar potential type "C" and z ≤ 95 for solar potential type "A", Kea island, N_o=7.5kW, figures (10) and (12) or z ≤ 35 for solar potential type "C" and z ≤ 40 for solar potential type "A", Kithnos island, N_o=7.5kW, figures (12) and (14).

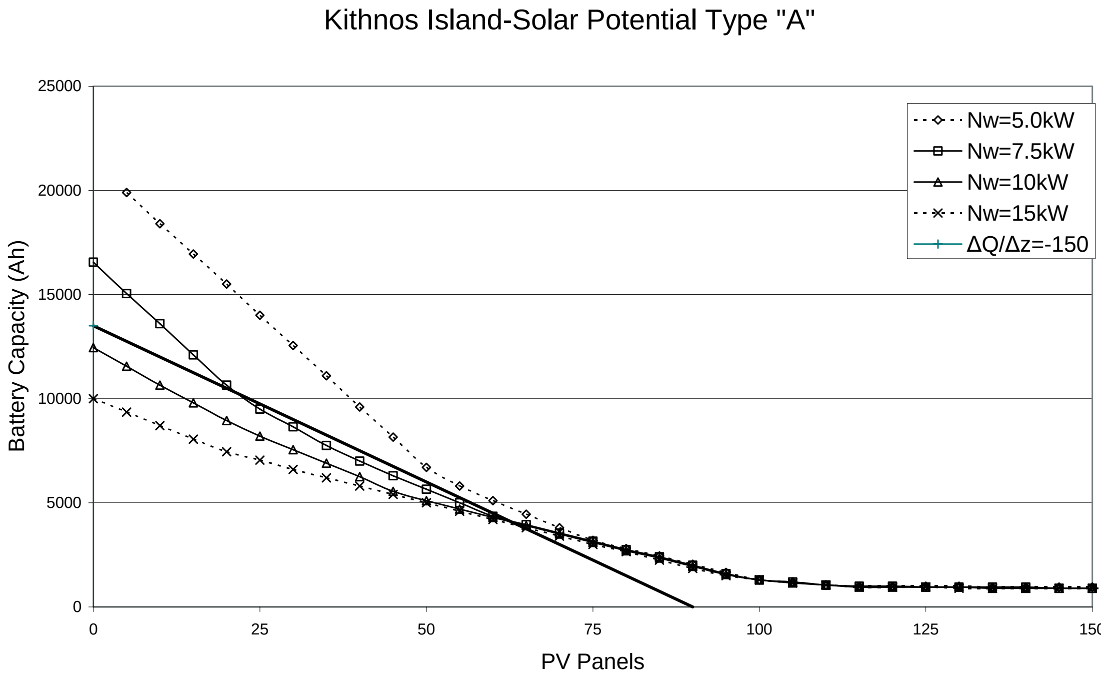

Figure 14: Maximum Battery Size Reduction Due to Photovoltaic Panels Introduction in a Wind-Solar Stand-Alone System of Kithnos Island (Solar Potential Type "A")

Recapitulating, one may state that the introduction of a small number of photovoltaic panels (normally up to 50 of $51W_p$) leads to a significant battery size reduction of a wind driven stand-alone system. This reduction is in proportion to the corresponding solar potential and in reverse proportion to the available wind potential. The exact size of the photovoltaic power penetration in the wind power stand-alone system should be the result of a detailed cost analysis based on the battery and photovoltaic panels market prices, considering the expected forthcoming technological improvements of the sector[15,18].

6. Conclusions

The possibility of remarkably reducing the energy storage requirements of wind based stand-alone systems by adding a rational number of photovoltaic panels is investigated. For this purpose, an integrated energy production installation -based exclusively on renewable energy resources- is proposed. The recommended power station is able to guarantee the energy autonomy of a typical isolated consumer devoid of other energy imports. Accordingly, a new numerical algorithm is developed, able to estimate the appropriate dimensions of a similar renewable based system, taking into account the combined energy production of a small wind converter and a small photovoltaic generator.

Subsequently, the above-described methodology is applied to selected Greek islands, possessing medium-low wind potential and fairly high solar radiation. On the basis of the calculation results, utilizing long-term experimental measurements, the introduction of the photovoltaic panels considerably reduces the complete installation dimensions and decreases the corresponding operational cost, due to the imposed significant battery capacity diminution. This reduction is higher for low wind and high solar potential areas, although its exact value depends on the current and future market prices of all the stand-alone system components involved.

As a general conclusion, one may definitely state that the introduction of a rational number of photovoltaic panels in a wind only stand-alone system remarkably decreases the system energy storage requirements, improves the entire installation reliability, simplifies the corresponding maintenance procedure and strengthens the financial competitiveness of similar renewable energy applications.

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SIZING A HYBRID WIND-DIESEL STAND-ALONE SYSTEM ON THE BASIS OF MINIMUM LONG-TERM ELECTRICITY PRODUCTION COST

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Abstract

Hybrid wind-diesel systems are an interesting solution for the electrification of isolated consumers. The proposed system, including a properly sized battery, leads to significant reduction of the fuel consumption, in comparison with a diesel-only installation, also protecting the diesel generator from excessive wear. On the other hand, a properly designed wind-diesel installation remarkably reduces the required battery capacity, in relation to a wind-only based stand-alone system, especially in medium-low wind potential areas. In this context, a complete sizing model based on a long-term energy production cost analysis is developed, able to predict the optimum configuration of a hybrid wind-diesel stand-alone system on the basis of minimum long-term cost. According to the application results obtained for representative wind potential cases, the proposed hybrid system guarantees one year's long energy autonomy of a typical remote consumer, presenting a significant cost advantage in relation either to a diesel-only or to a wind-based stand-alone system.

Keywords: Hybrid Wind-Diesel System; Stand-Alone; Optimum System Sizing; Energy Cost; Long-term Operational Cost

1. Introduction

Stand-alone wind power systems provide an interesting solution for the electrification of various isolated consumers[1,2]. One important technical problem of similar installations results by the highly fluctuating power output of the wind turbine, which is generally incompatible with the demand of typical domestic or commercial users. To face this problem, an appropriate energy storage device is usually incorporated, which however significantly increases the initial cost of stand-alone installations[3].

On the other hand, diesel-electric generator sets, while being relatively inexpensive to purchase, are generally expensive to operate and maintain, especially at partial load levels[4]. In absence of energy storage, a high start-stop cycling frequency is evident. This will lead to an increased wear of the diesel and, therefore, to an increased demand of maintenance[5].

A hybrid wind-diesel system (with energy storage) reimburses the capital cost of the wind turbine and the operating costs of the diesel-electric generator, while remarkably decreasing the battery bank size[6,7]. In this context, a hybrid wind-diesel system, including a properly sized battery bank, leads to a significant reduction in the start-stop cycling frequency of the diesel, along with fuel consumption shrinkage, compared with the diesel only operation system. Besides, the proposed hybrid system remarkably reduces the required battery capacity in relation with a wind based stand-alone system, especially in relatively low wind potential areas.

Thus far, optimal sizing of stand-alone systems is usually based on simplified cost analysis, mainly concentrated on the initial installation cost. Although this analysis provides a first estimation, a long-term cost investigation is required, including maintenance and operation cost. Thus, in this paper a

Kaldellis J.K., Kondili E., Filios A., 2006, *"Sizing a Hybrid Wind-Diesel Stand-Alone System on the Basis of Minimum Long-Term Electricity Production Cost", Applied Energy Journal, on-line available in www.ScienceDirect.*

complete long-term energy production cost method of a wind-diesel hybrid system is developed. This method considers the fixed and variable costs of maintenance, operation and financing, in addition to initial costs. By using the proposed model, the optimum configuration of a hybrid stand-alone system may be defined based on minimum long-term cost.

2. Proposed Solution

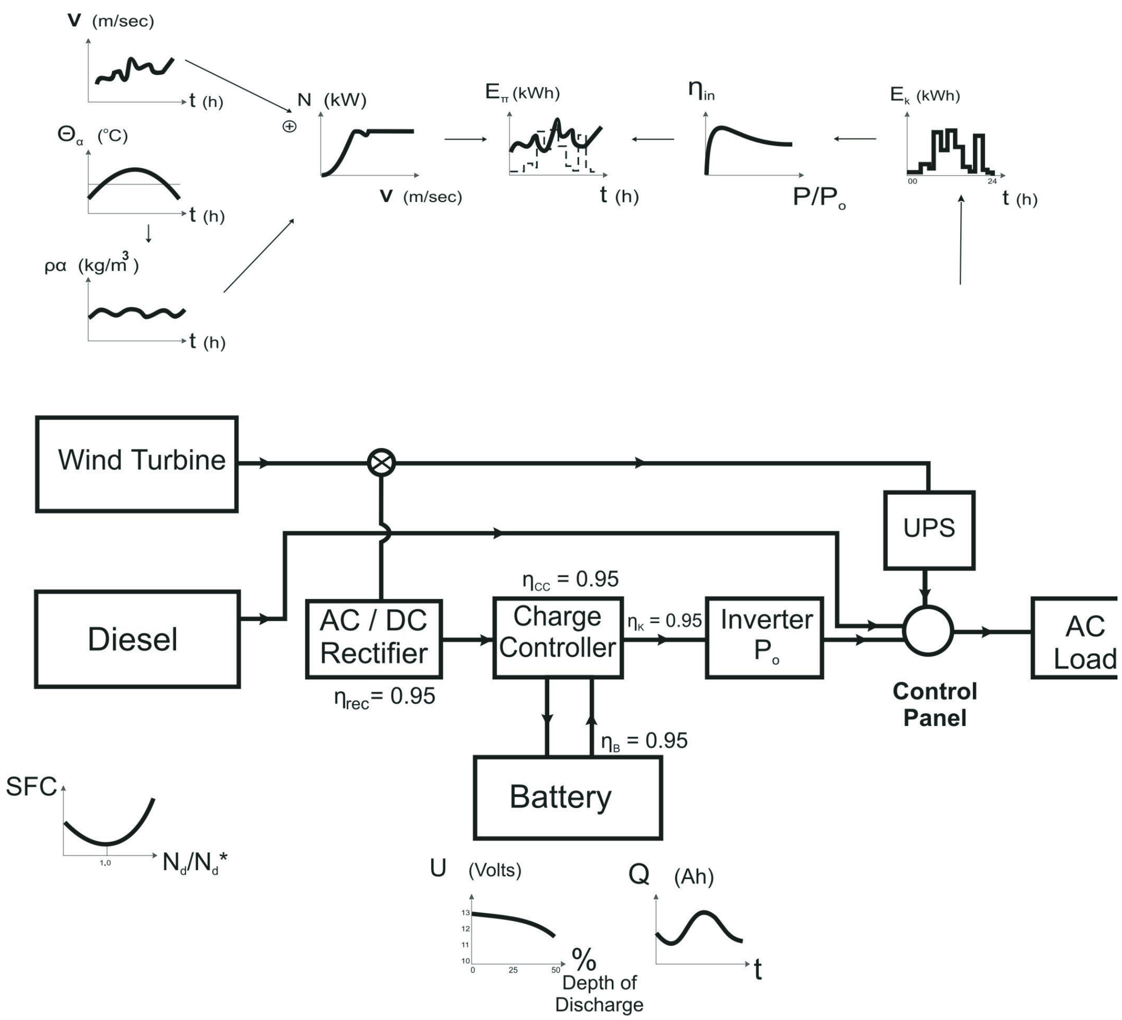


Figure 1: Proposed Autonomous Wind-Diesel Hybrid System

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

a. A micro wind converter of rated power "N_o" and given power curve N=N(V) for standard day conditions[2]
b. A small internal combustion engine of "N^*" kW, able to meet the consumption peak load demand "N_p" (i.e. $N^* \geq N_p$), presenting a typical specific fuel consumption curve versus partial loading of the engine[4]
c. A lead-acid battery storage system for "h_o" hours of autonomy, or equivalent total capacity of "Q_{max}", operation voltage "U_b" and maximum depth of discharge "DOD_L"
d. An AC/DC rectifier of "N_o" kW and U_{AC}/U_{DC} operation voltage values
e. A DC/DC charge controller of "N_o" rated power, charge rate "R_{ch}" and charging voltage "U_{CC}"

f. A UPS (uninterruptible power supply) of "N_p" kW, frequency of 50Hz, autonomy time "$\delta t \approx 2$min" and operation voltage 220/380V. The UPS utilization -between the installation wind turbine and the AC load- is optional and it is proposed here in order to stabilize the wind turbine output as well as to protect the sensitive devices from undesired power fluctuations.

g. A DC/AC inverter of maximum power "N_p" able to meet the consumption peak load demand, frequency of 50Hz and operational voltage 220/380V

This system should be capable of facing the electricity demand of a remote consumer (e.g. a four to six member family), with rational first installation and long-term operational cost. The specific remote consumer investigated[8-10] presents a load profile described in figure (2). This is basically a rural household profile (not an average load taken from typical users) selected among several profiles provided by the Hellenic Statistical Agency[2,6]. More precisely, the numerical load values vary between 30W (refrigerator load) and 3300W. According to the consumption profile approved, the annual peak load "N_p" does not exceed 3.5kW, while the annual energy consumption "E_y" is almost 4750kWh.

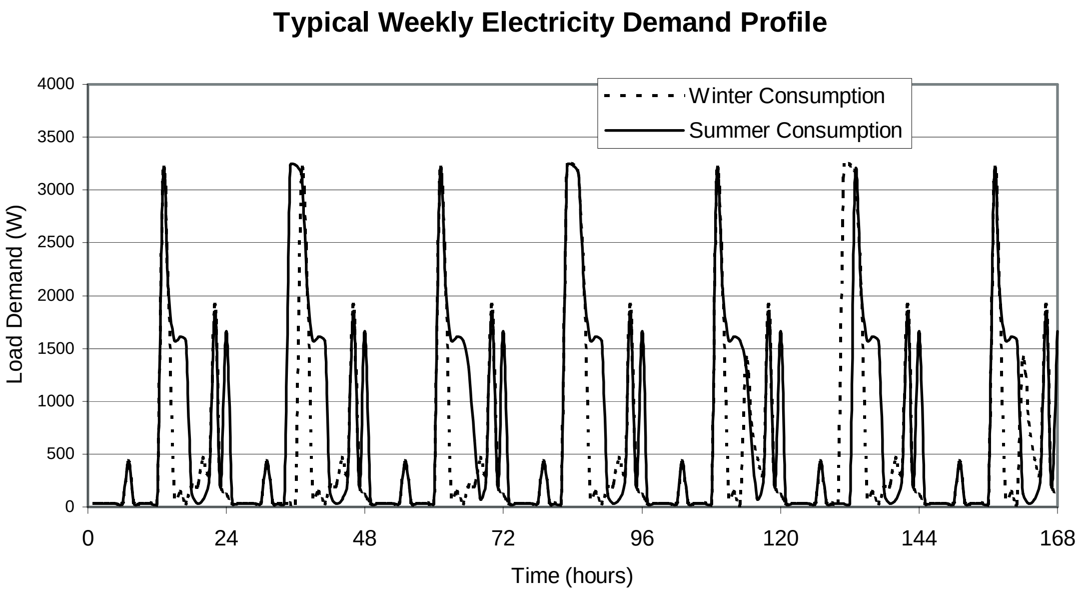


Figure 2: Typical Electricity Demand Profile of the Remote Consumer Analyzed

Thus, the annual electricity consumption on an hourly basis, being also depended on the portion of the year analysed (i.e. winter, summer, other), is the first input of the present analysis, see also figure (2). Additionally, the corresponding wind potential and ambient temperature and pressure are also necessary to integrate the system sizing calculations. Finally, the operational characteristics of all the components (e.g. wind power curve at standard day conditions, diesel generator specific fuel consumption, inverter efficiency, battery bank characteristic etc.) composing the hybrid system under investigation are also required.

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

- ✓ The energy (AC current) is produced by the micro wind converter and it is directly sent to consumption via the UPS
- ✓ The energy (AC current) is produced by the small diesel-electric generator and it is forwarded to consumption
- ✓ The energy output of the wind turbine (not absorbed by the consumption-energy surplus) is transformed to DC current (via AC/DC rectifier) and it is subsequently stored at the batteries via the charge controller

✓ The battery is used to cover the energy deficit via the charge controller and the DC/AC inverter

For estimating the appropriate configuration of the proposed wind-diesel hybrid system, three governing parameters should be defined: the rated power "N_o" of the wind turbine used, the battery maximum necessary capacity "Q_{max}" and the annual fuel consumption "M_f". For the solution of this problem, the already presented[2,11] computational algorithm "WINDREMOTE-II" is hereby expanded to include a small diesel-electric generator. This new numerical code "WIND-DIESEL I" is applied to carry out the necessary parametrical analysis on an hourly energy production-demand basis, targeting to estimate the wind turbine rated power "N_o" and the corresponding battery capacity "Q_{max}" given the annual permitted oil consumption "M_f"; see also figure (3).

More specifically, given the "M_f" value -for each "N_o" and "Q_{max}" pair- the "WIND-DIESEL I" algorithm is executed for all the time-period selected (e.g. for one month, six-months, one year or even for three years) and emphasis is laid on obtaining zero-load rejection operation. Using the proposed algorithm, for every (N_o, Q^*, M_f) combination ensuring the energy autonomy of the remote system, a detailed energy production and demand balance is available along with the corresponding time-depending battery depth of discharge, "DOD" and diesel-oil consumption time evolution. The optimum configuration is subsequently predicted on the basis of the minimum long-term cost configuration.

3. Cost-Benefit Analysis of the Proposed Solution

The present value of the entire investment cost of a stand-alone wind-diesel hybrid system operating for an n-years period is a combination of the initial installation cost and the corresponding maintenance and operation cost[12].

3.1 First Installation Cost

The initial investment cost "IC_o" includes the market (ex-works, i.e. not including the installation cost) price of the installation components (wind turbine, $IC_{WT;}$ diesel generator, IC_d; battery, IC_{bat}; inverter, UPS, rectifier, charge controller; IC_{elec}) and the corresponding balance of the plant cost, expressed as a fraction "f" of the wind turbine purchase cost. Thus one may write:

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

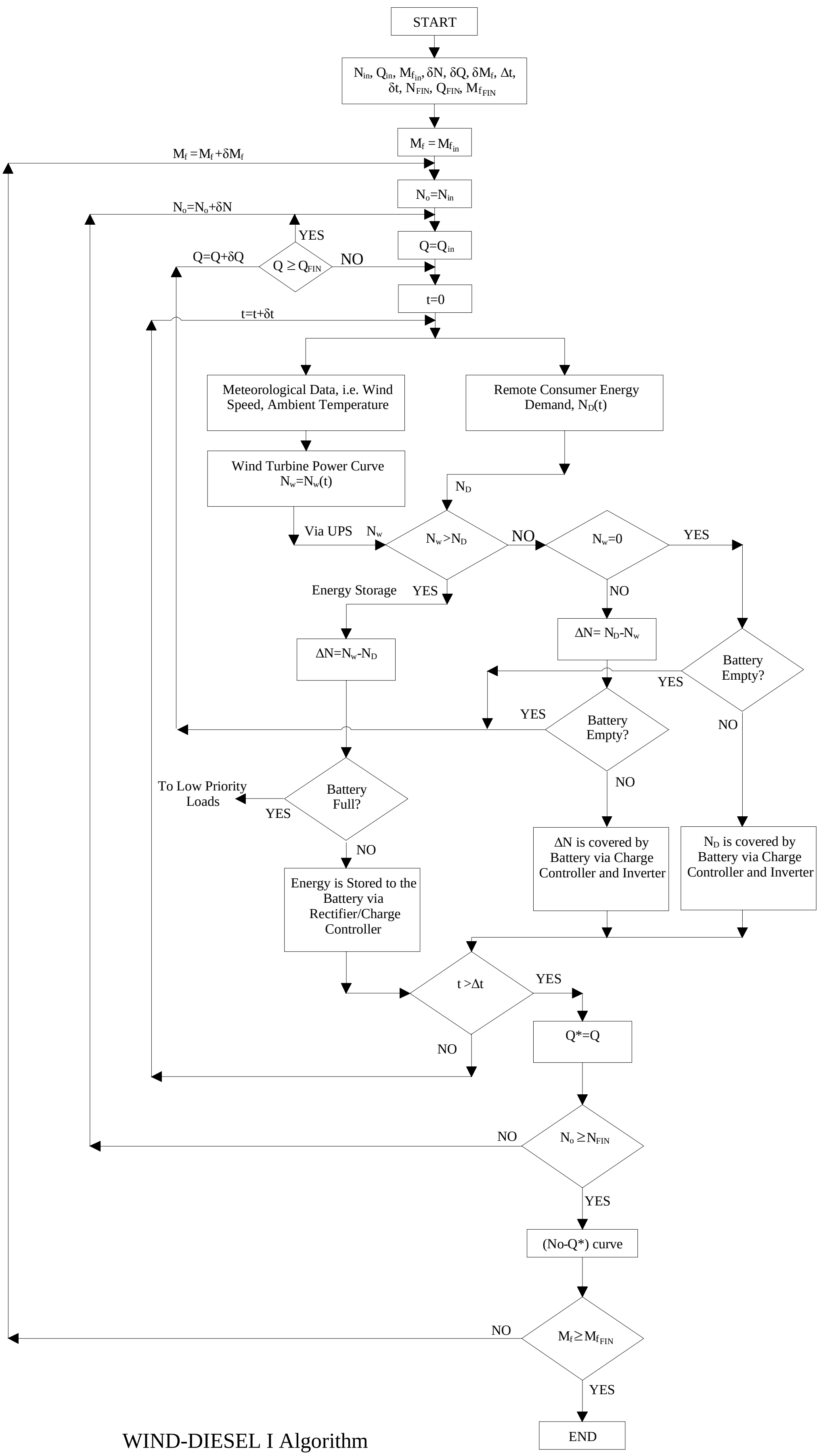
Using the analysis of previous work[13,14] the following expression is assumed valid:

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

where "N_o" is the wind turbine rated power, "N_d" is the diesel-electric generator nominal power, "N_p" is the consumption peak load demand (including an appropriate safety factor, e.g. 1.3) and "Q_{max}" is the battery capacity. Besides "a, b, x and c" are numerical constants used to convey[13] the ex-works price of small wind converters (up to 100kW) in the local market. Their numerical values are equal to $8.7x10^5$Euro/kW, 621, 2.05 and 700Euro/kW respectively. Similarly, parameters "ξ and ω" are instructed[14] to describe the battery bank initial cost, thus ξ=5.04Euro/Ah and ω=0.078, while "φ" represents the diesel-electric generator specific purchase cost (e.g. φ=150-250€/kW). Finally, parameters "λ, τ and B" are respectively equal to 483Euro/kW, 0.083 and 380Euro/kW, used also to assess[14] the electronic devices initial cost.

3.2 Maintenance and Operation Cost

During long-term operation of a hybrid wind-diesel system, the maintenance and operation (M&O) cost can be split[12] into the fixed "FC_n" and the variable "VC_n" maintenance cost. Usually, the annual fixed M&O cost of a stand-alone wind power system is expressed as a fraction "m" of the initial



WIND-DIESEL I Algorithm

Figure 3: WIND-DIESEL-I Algorithm

capital invested. On top of this, an annual increase of the fixed M&O cost is taken into account (M&O cost mean annual inflation rate "g_m"), incorporating the annual changes of labor cost and the corresponding spare parts.

In a wind-diesel hybrid system, one should also consider the diesel generator M&O cost, expressed as a function of the annual diesel oil consumption "M_f". Besides, the corresponding specific price "c_o" includes any lubricants' consumption. In this context one may write:

$$FC_n = m \cdot IC_o \cdot x \cdot (1 + x + x^2 + ... + x^{n-1}) + c_o \cdot M_f \cdot y \cdot (1 + y + y^2 + ... + y^{n-1}) \tag{3}$$

with

$$x = \frac{1 + g_m}{1 + i} \tag{4}$$

and

$$y = \frac{1 + e}{1 + i} \tag{5}$$

where "i" is the local market capital cost, while "e" is the diesel-oil price mean annual escalation rate.

The variable maintenance and operation cost "VC_n" mainly depends[3] on the replacement of "k_o" installed major parts, sustaining a shorter lifetime "n_k" than the complete installation. Using the symbol "r_k" for the replacement cost coefficient of each one of the "k_o" major parts (battery, diesel generator, rotor blades, etc.) the "VC_n" term can be expressed as:

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

Bear in mind that "VC_n" takes into consideration the diesel-electric generator "$r_d.IC_o$" and the battery "$r_b.IC_o$" replacement cost every "n_d" and "n_b" years respectively ($n_d \approx 4$ to 6 and $n_b \approx 5$ to 7 years), while "g_d" and "g_b" describes the diesel-electric generator/battery purchase cost mean annual inflation rate.

It is important to note that the "Ψ" term expresses the replacement cost of specific (major) parts of the installation, given as a fraction of the initial installation cost. For example, at the end of the fifth year, the diesel-electric generator should be replaced taking into consideration its expected purchase cost increase (or decrease) and the corresponding capital cost impact (since the present value model is adopted here). Similarly, the installation batteries should be replaced at the end of the seventh year. Thus one may write:

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

3.3 Long-Term Cost of the Hybrid System

Using the analysis of sub-sections 3.1 and 3.2, one may estimate the long-term cost of a wind-diesel hybrid system in present values as follows:

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

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

Finally, "γ" is the subsidy percentage (e.g. 30%-40%) by the Greek State, according to the current development law (e.g. 3299/04) or the corresponding National Operational Competitiveness Program[12].

4. Optimum Configuration Prediction for Various Typical Cases

4.1 Final Equations Used

According to equations (1) and (2), the initial cost "IC_o" of the proposed hybrid station is a function of the wind turbine rated power "N_o", the battery capacity "Q_{max}" and the corresponding peak load demand "N_p", while there is no contribution of the oil cost. On the other hand, the total operational cost "C_n" takes into account the system M&O cost as well as the annual oil consumption cost, whilst it is also influenced by the local market inflation rate, the capital cost and the oil price annual escalation rate.

Subsequently, considering the replacement cost of the diesel-electric generator and the system batteries every "n_d" and "n_b" years respectively, a significant modification of the optimum solution values (N_o*, Q_{max}*, M_f*) is expected in comparison with the one based on the initial cost minimization only[15].

In the following, the ten-year and the twenty-year total operational cost (in present values) of the hybrid station under consideration is to be used as the dominant choice criterion, expressed as follows:

$$C_{10} = IC_o \cdot \left[(1-\gamma) + m \cdot x \cdot \frac{x^{10} - 1}{x - 1} + \frac{c_o \cdot M_f}{IC_o} \cdot y \cdot \frac{y^{10} - 1}{y - 1} + r_d \cdot x^5 + r_b \cdot x^7 \right] \quad (9)$$

and

$$C_{20} = IC_o \cdot \left[(1-\gamma) + m \cdot x \cdot \frac{x^{20} - 1}{x - 1} + \frac{c_o \cdot M_f}{IC_o} \cdot y \cdot \frac{y^{20} - 1}{y - 1} + r_d \cdot \left(x^5 + x^{10} + x^{15}\right) + r_b \cdot \left(x^7 + x^{14}\right) \right] \quad (10)$$

accepting that $g_d \approx g$ and $g_b \approx g$.

4.2 High Wind Potential Case

The first case analyzed concerns a remote consumer located at a high wind potential area, e.g. the island of Andros. Andros is a medium-sized island (the second biggest one) of the Cyclades complex (population 12000 habitants, area of 384km^2), located in the middle of the Aegean Sea. The local terrain is very intense, including several rocky mountains with relative sharp slopes. The island has one of the best wind potential in Greece (annual mean wind speed, $\overline{V} \approx 10$m/s), since the minimum monthly average wind speed[16] exceeds the 6.5m/s, figure (4). At the same time, the number of zero-wind-production days (daily average wind speed below 4.0m/s) is minimum, see also figure (5), underlining the fact that the maximum calm spell period of the island is 37 hours.

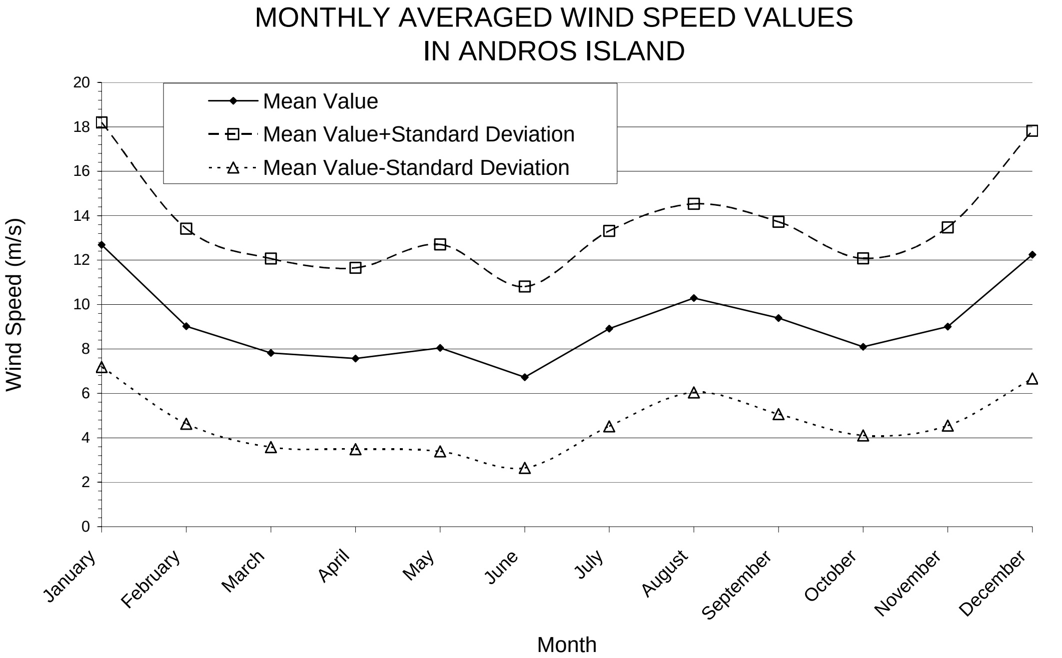


Figure 4: Wind Speed Values at Andros Island

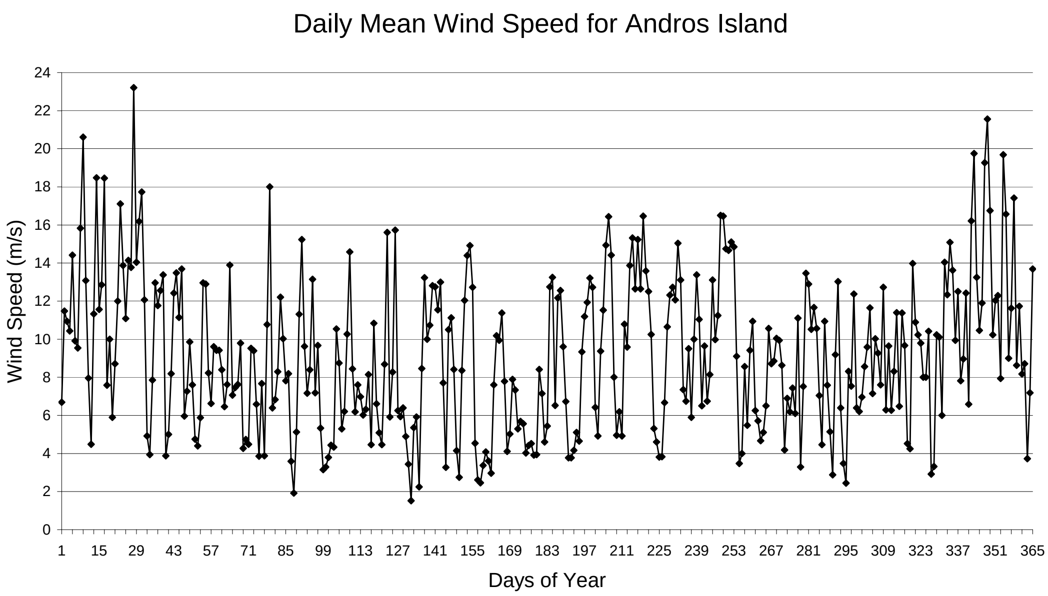


Figure 5: Daily Mean Wind Speed at Andros Island

Applying the proposed solution for the Andros case, one may obtain the (Q_{max}-N_o) distribution that guarantees one year energy autonomy for various typical annual oil quantities (i.e. M_f=0kg/y up to M_f=1000kg/y); see figure (6). Bear in mind that approximately 2000kg of oil are necessary in order the diesel-electric generator to meet the electricity requirements of the specific consumer under investigation without any other additional energy source. Rationally, the dimensions of the hybrid system are remarkably reduced as the contribution of diesel oil is increased. In fact, this reduction is greater when small quantities of diesel oil are used, while for larger oil quantities the battery bank size is slightly decreased for given wind turbine rated power.

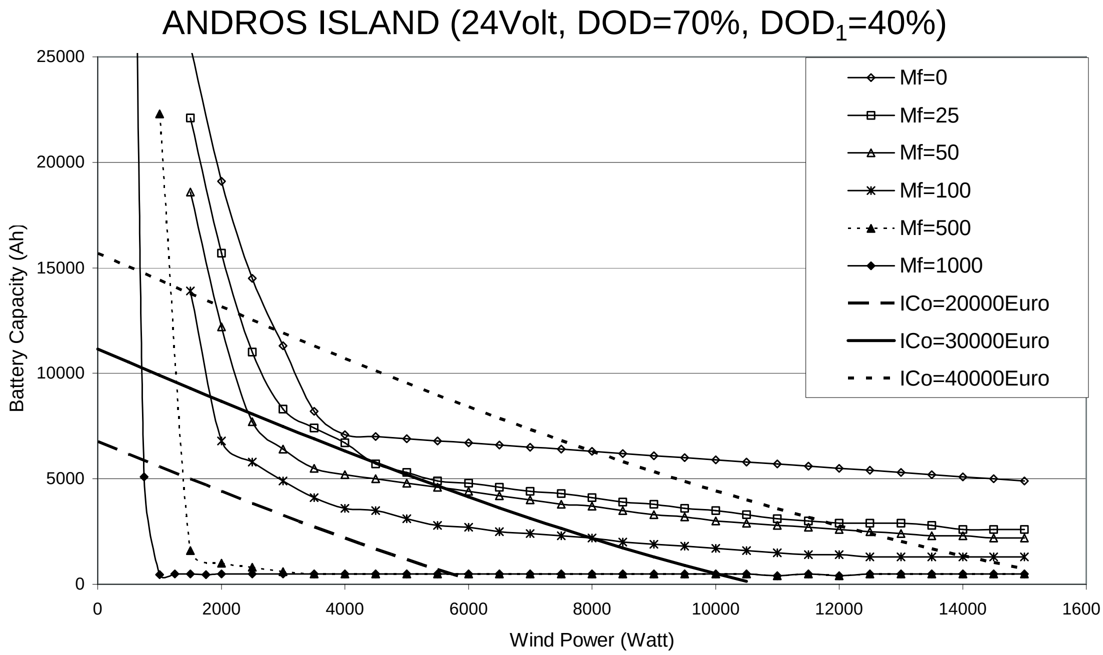


Figure 6: Energy Autonomous Configuration for a Wind-Diesel Hybrid System, Including First Installation Cost, Andros Island

Accordingly, the constant initial cost (IC_o=ct) curves are drawn in the same figure (6), which however does not take into account the annual oil quantity consumed. In this context, one should certainly select the maximum diesel oil consumption solution, since this choice minimizes the initial cost of the hybrid station. In figure (7), however, one has the opportunity to investigate the ten-year cost variation for selected representative cases. More specifically, figure (7) presents:

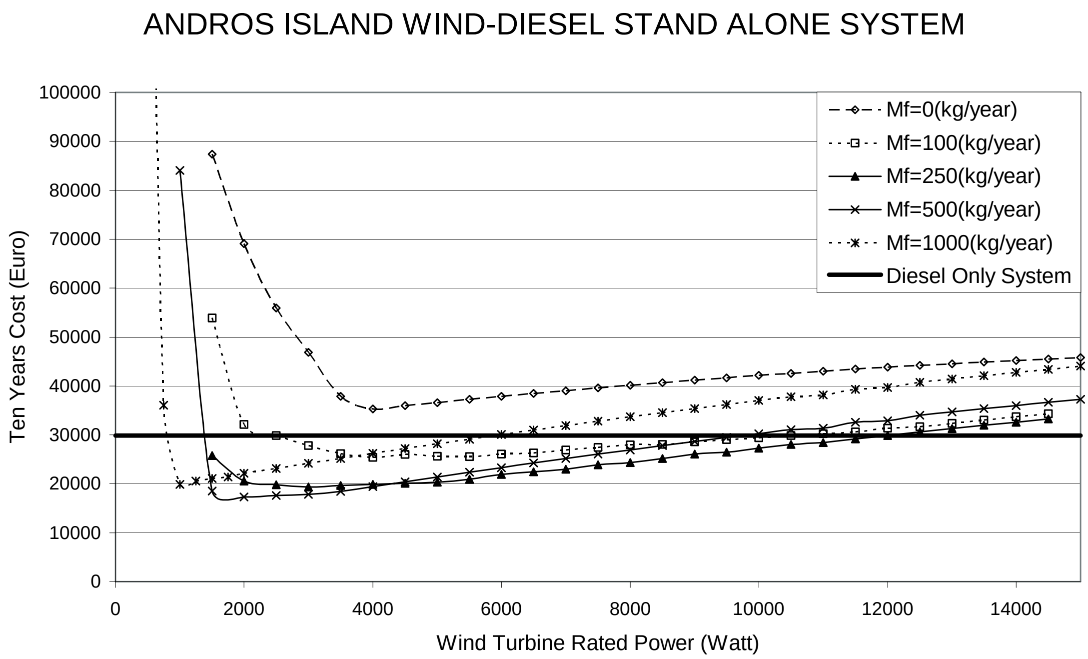


Figure 7: Ten-Year Cost Analysis of a Wind-Diesel Hybrid System, Andros Island

i. The autonomous wind-battery solution (M_f=0kg/y)
ii. The diesel only solution (M_f=M_{fmax}=2000kg/y)
iii. The 5% annual diesel-oil penetration (M_f=100kg/y)
iv. The 12.5% annual diesel-oil penetration (M_f=250kg/y)
v. The 25% annual diesel-oil penetration (M_f=500kg/y)
vi. The 50% annual diesel oil penetration (M_f=1000kg/y)

After a closer inspection of the calculation results and considering the numerical values of Table I regarding parameters of equations (7) and (9), we may state the following comments for the ten-year cost solution:

- The optimum zero-oil solution should be based on a 4kW wind turbine and 7100Ah battery capacity, while the corresponding ten-year cost is fairly higher than 35300€.
- In any case the zero-oil solution is slightly more expensive than the diesel-only solution, i.e. by almost 5000€ (≈15%), on the ten-year basis.
- By increasing the diesel oil contribution the ten-year cost is remarkably reduced, being quite lower than the diesel-only solution.
- For each M_f=ct configuration there is a minimum cost area, which leads to lower battery capacity and wind turbine rated power as the diesel-oil penetration increases.

Table I: Numerical Values of the Parameters of Equations (7) and (9)

Parameter	**Symbol**	**Value**
n_d	Diesel-electric generator service period	5 (years)
n_b	Lead-acid battery replacement period	7 (years)
IC_d	Diesel-electric generator purchase cost (5kW)	750 (€)
g_d	Mean annual increase of diesel-electric generator purchase cost	2%
g_b	Mean annual increase of lead-acid battery purchase cost	2%
m	Installation annual M&O cost coefficient	2%
c_o	Diesel-oil specific cost	1.5 (€/kg)
x	see equation (4)	0.9444
y	see equation (5)	0.9815
i	Mean annual capital cost	8%

Using also figure (8), one may estimate the optimum diesel oil contribution that minimizes the 10-year system cost. Hence, the corresponding optimum configuration for the specific hybrid system under investigation is based on a 2kW wind turbine and a battery bank of 1000Ah, while the annual fuel consumption is 500kg/year and the minimum 10-years cost approximates the 17300€ in present values, being less than 60% of the diesel-only solution (≈29300€).

This situation is quite different in case that a 20-year time horizon is concerned. More precisely, even the autonomous wind power solution is less expensive than the diesel-only system operation, figure (9). Additionally, the 20-year system cost diminishes as the oil penetration increases. This situation is inversed after a minimum cost point is achieved, figure (10). Thus the optimum configuration system is based on a 2.5kW wind turbine, 1700Ah battery capacity, 300kg/y diesel-oil consumption, while the corresponding 20-year cost in present values is 26300€, less than 50% of the one corresponding to the diesel only solution.

Recapitulating, one may state that in this high wind potential area, a wind-diesel hybrid system presents a competitive advantage in comparison with a diesel only or a wind power stand-alone system. The optimum system configuration is based on 2-2.5kW wind turbines and on 1000 to 1700Ah battery capacity. These solutions annually save over 75% of the fuel required by a diesel-only system in order to obtain full energy autonomy of the installation, while the corresponding 10-year or 20-year total operational cost ranges between 60% and 50% of the diesel-only configuration, respectively.

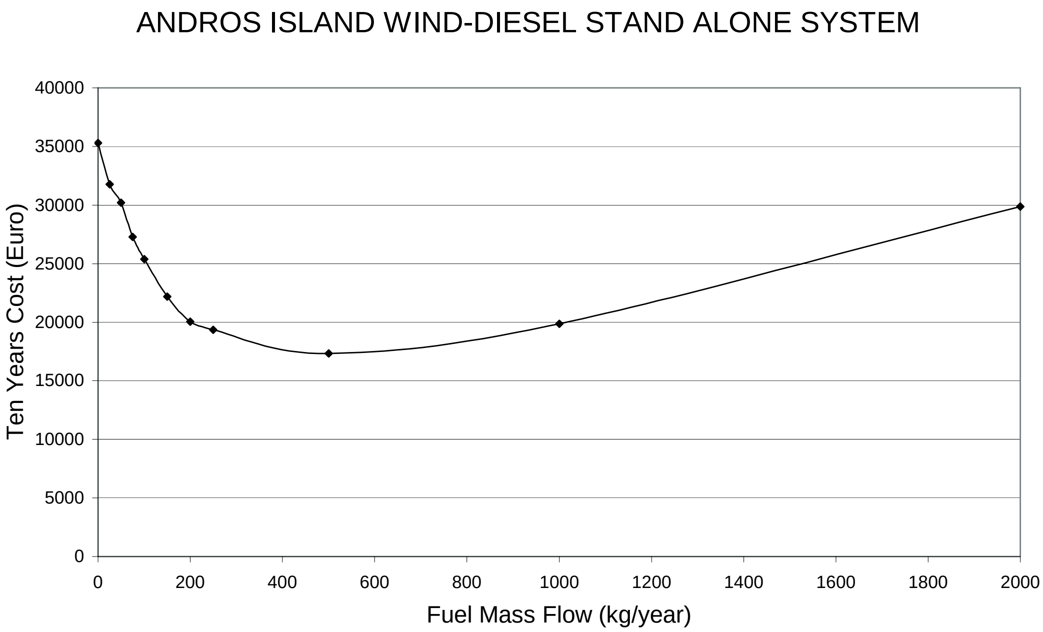


Figure 8: Minimum Ten-Year Cost of a Wind-Diesel Hybrid System, Andros Island

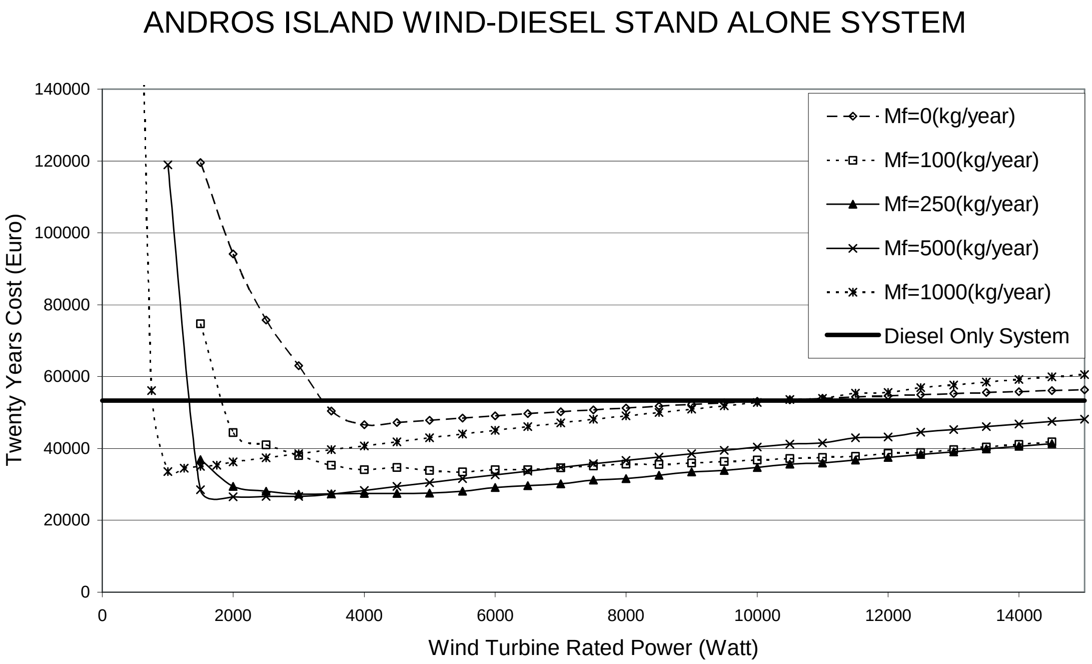


Figure 9: Twenty-Year Cost Analysis of a Wind-Diesel Hybrid System, Andros Island

4.3 Low Wind Potential Case

The second case analyzed concerns a remote consumer located at a relatively low wind potential area, e.g. the island of Kea. Kea is a small island (2300 habitants, area 103km^2) close to Athens. The topography of the island is typically Aegean, i.e. gentle slopes, absence of flat fields, low mountains and sparse vegetation, while the main economic activities of the local society are agriculture, cattle breeding, beekeeping and tourism. The corresponding wind potential[16] although quite lower than the one of Andros, is good enough (annual mean wind speed ≈6.0m/s, figure (11)) to feed contemporary wind turbines, for electricity production. In this case, the number of zero wind production days (daily average wind speed below 4.0m/s) is quite remarkable, see also figure (12), therefore the maximum calm spell period of the island is approximately 170 hours (almost one week).

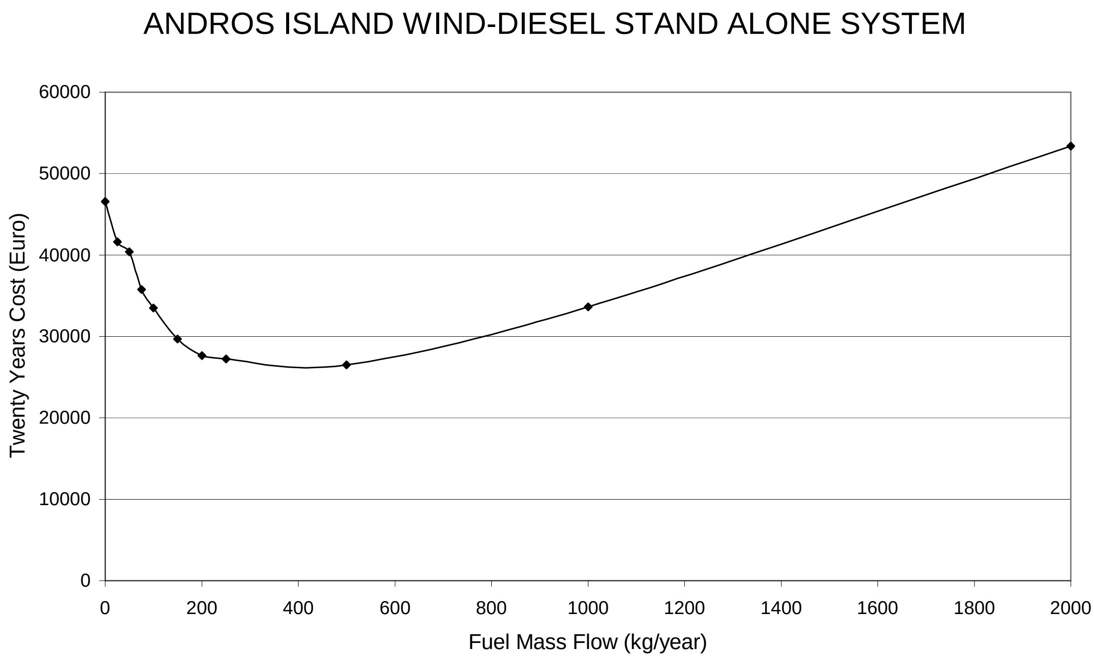


Figure 10: Minimum Twenty-Year Cost of a Wind-Diesel Hybrid System, Andros Island

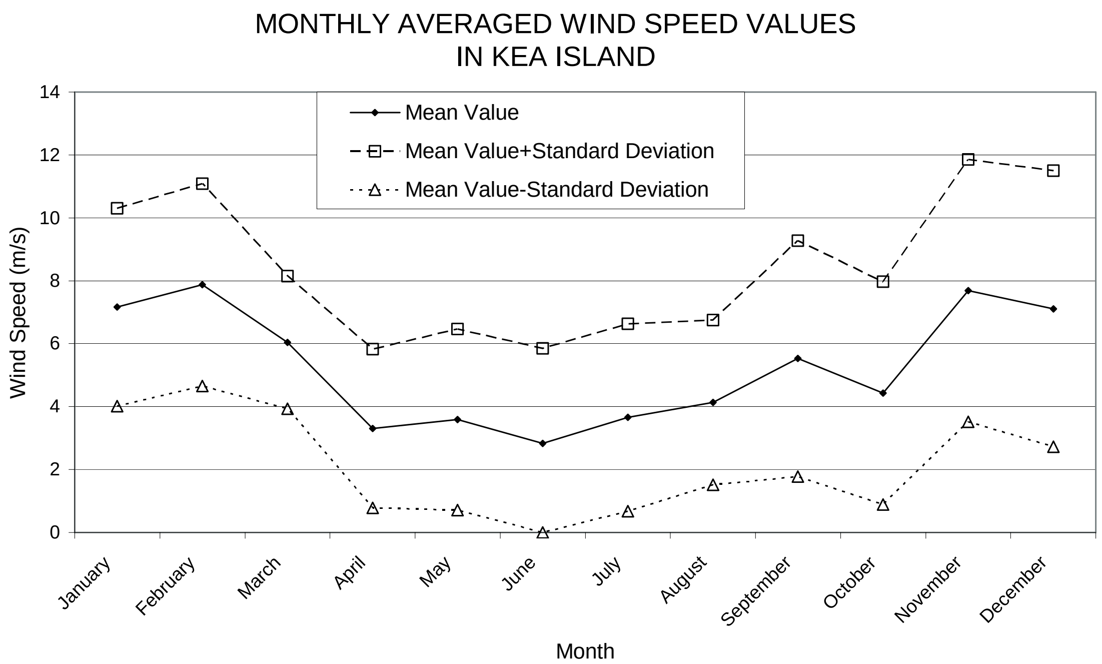


Figure 11: Kea Monthly Mean Wind Speed

Applying the proposed methodology for the Kea case, one may obtain the (Q_{max}-N_o) distribution that guarantees one year energy autonomy for various typical annual diesel-oil quantities (i.e. M_f=0kg/y up to M_f=1500kg/y); see figure (13). As in the Andros case, the dimensions of the hybrid system are remarkably reduced as the contribution of diesel oil is increased. In fact, this reduction is greater when over 100kg of diesel-oil is consumed per year, since for lower diesel oil quantities the system size is not seriously modified. Obviously, for given wind turbine rated power, the battery bank size is not analogically decreased as larger oil quantities are used. In fact after the M_f=1000kg/year value the battery capacity convergences to the same -very low- value of 450Ah.

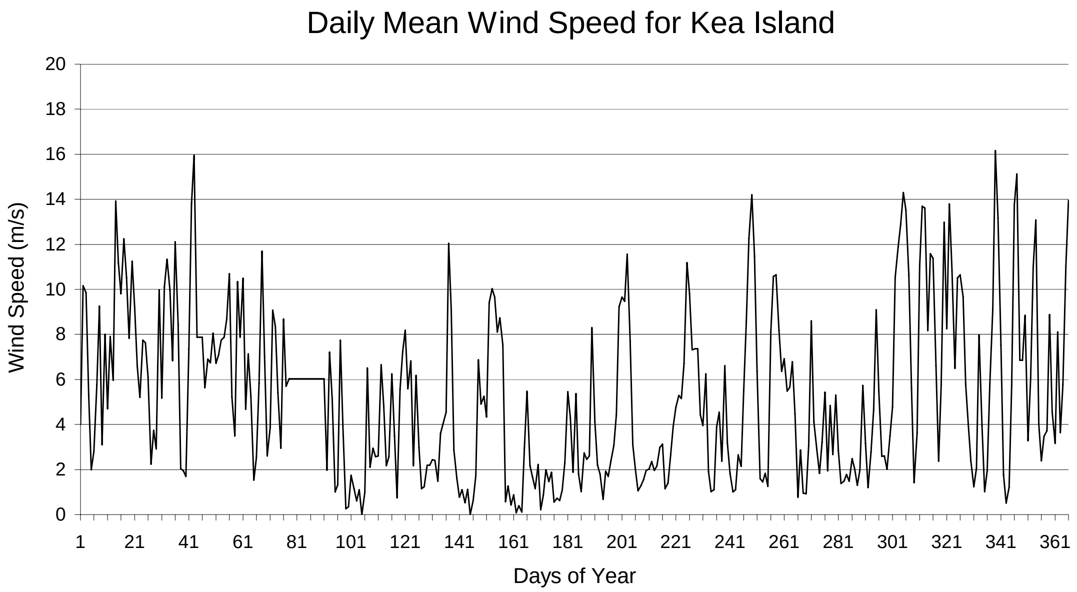


Figure 12: Kea Daily Mean Wind Speed

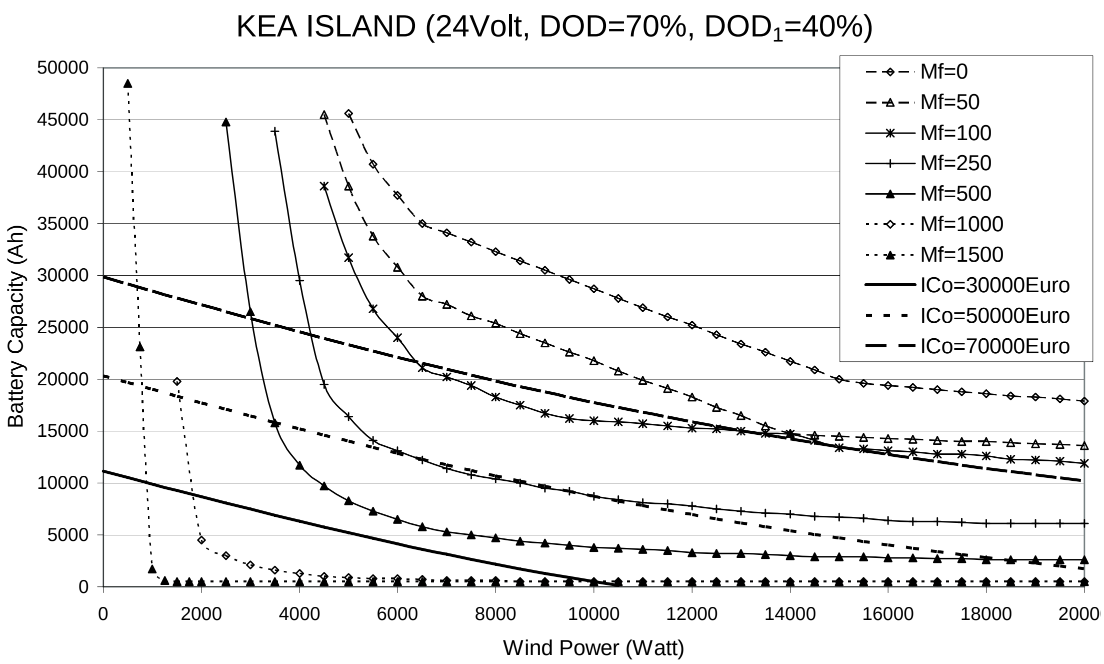


Figure 13: Energy Autonomous Configuration for a Wind-Diesel Hybrid System, Including First Installation Cost, Kea Island

Accordingly, the constant initial cost (IC_o=ct) curves are drawn in the same figure (13), not including the annual diesel-oil consumption. Since the fuel cost is excluded, it is quite rational that the minimum initial cost solution is the one that uses the maximum diesel-oil quantity. On the other hand, by examining the ten-year cost variation in figure (14) for selected annual diesel-oil consumption quantities, one can easily extract the following conclusions:

- There is no optimum zero-oil solution under the precondition that the wind turbine rated power is less than 15kW. For bigger wind turbines (15kW≤N_o≤20kW) a minimum cost solution may be achieved.
- The diesel-only solution is almost the most cost effective choice, excluding the high diesel-oil penetration solutions (i.e. M_f≥1000kg/y).

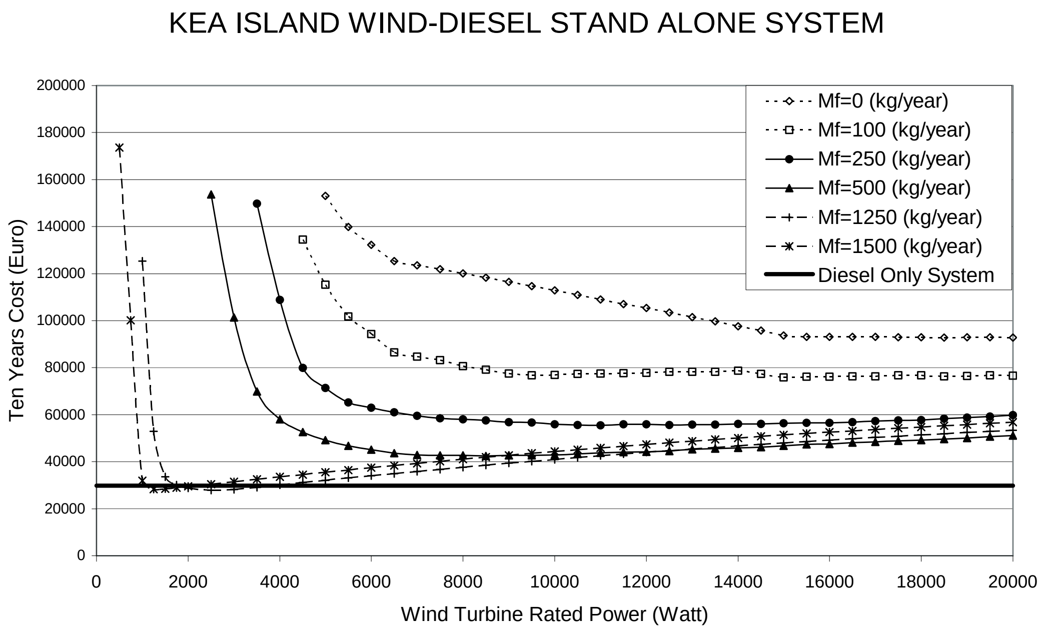


Figure 14: Ten-Year Cost Analysis of a Wind-Diesel Hybrid System, Kea Island

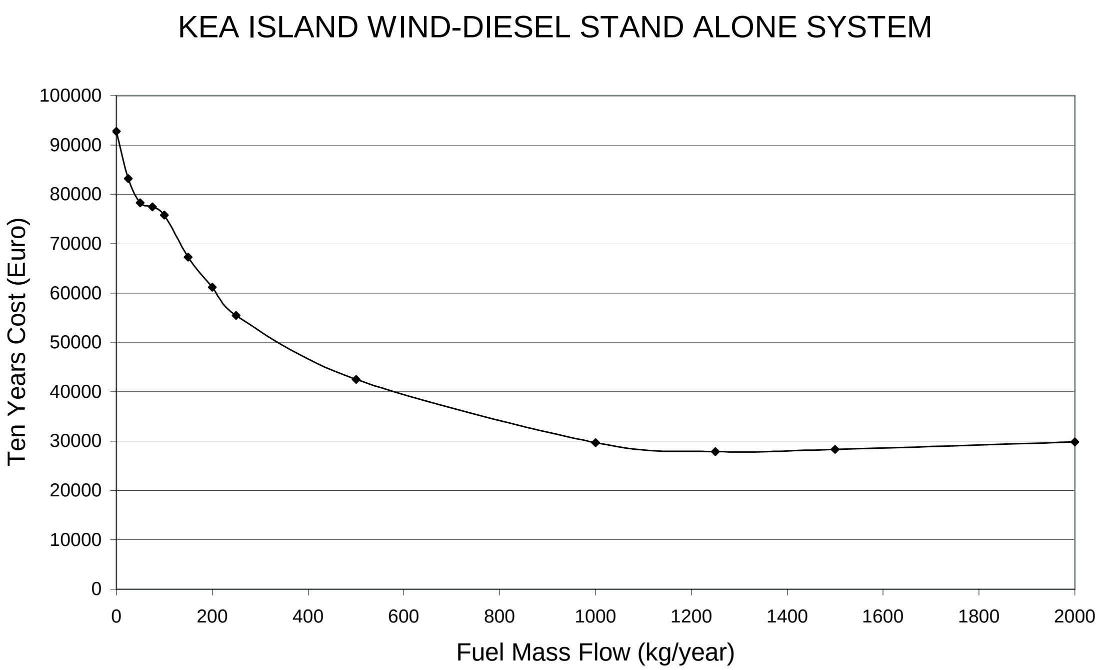


Figure 15: Minimum Ten-Year Cost of a Wind-Diesel Hybrid System, Kea Island

- There is a considerable ten-year cost reduction by increasing the annual diesel-oil penetration.
- For each M_f=ct configuration there is a minimum cost area, which leads to lower battery capacity and wind turbine rated power as the diesel penetration increases.

Using also figure (15), one may estimate the optimum diesel oil contribution that minimizes the 10-years system cost. Hence, the corresponding optimum configuration for the specific hybrid system located in this medium-low wind potential area consists of a 1.5kW wind turbine and a battery bank of 1300Ah, while the annual fuel consumption is 1250kg/year and the minimum 10-year cost approximates 28500€ in present values, being slightly below the diesel only solution (≈29300€).

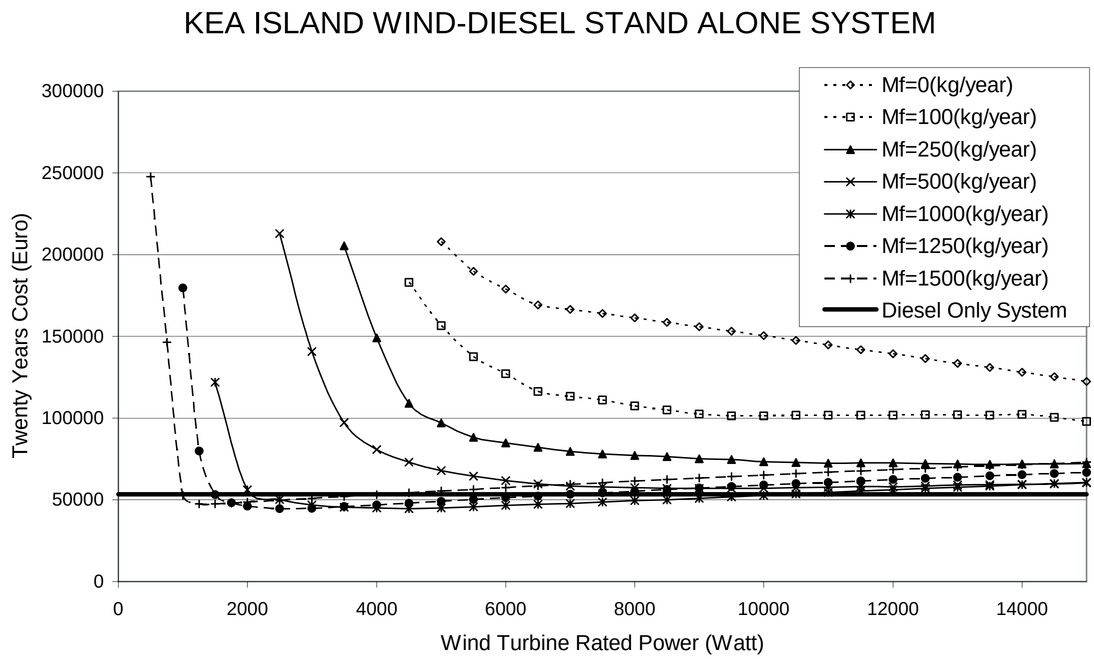


Figure 16: Twenty-Year Cost Analysis of a Wind-Diesel Hybrid System, Kea Island

This situation is somewhat different in case that a 20-year time horizon is concerned. More precisely, in this long-term analysis one may use lower diesel-oil annually in order to obtain the minimum cost operation, figure (16). Thus, initially the 20-years system cost diminishes as the oil penetration increases. This situation is inversed after a minimum cost point is achieved, figure (17). Thus the optimum configuration system is based on a 2.5kW wind turbine, 3500Ah battery capacity, 1000kg/y diesel-oil consumption, while the corresponding 20-year cost in present values is 43000€, almost 20% lower than the diesel-only solution case.

Summarizing, even in this medium-low wind potential area, a wind-diesel hybrid system is less expensive than a diesel only solution (especially for a long-term time horizon basis), while it is definitely more cost effective than a stand-alone wind power one. Of course, one should not disregard the fact that the proposed hybrid system presents additional environmental and increased reliability advantages that may compensate the increased first installation and operational cost.

5. Discussion of the Results

Considering the calculation results regarding two extreme wind potential cases, a wind-diesel stand-alone system presents significant cost advantages in comparison with diesel-only or wind power stand-alone systems. These advantages are more obvious for high wind potential areas and for long-term operation. More specifically the mean annual cost for Andros island is almost the 40% of the corresponding cost of Kea island; see figure (18). Additionally, the minimum 10-year annual cost for

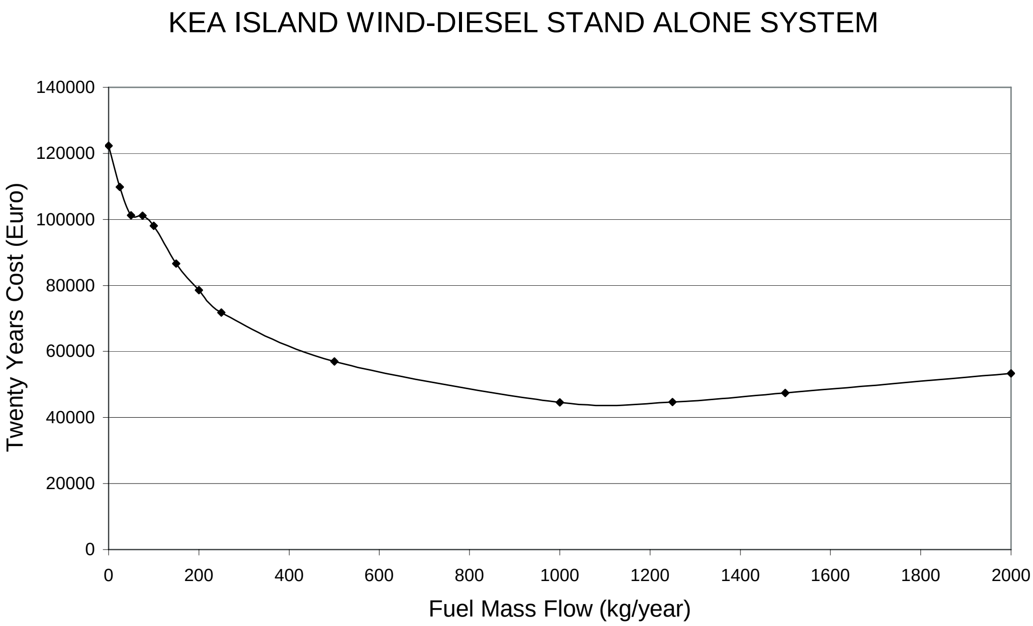


Figure 17: Minimum Twenty-Year Cost of a Wind-Diesel Hybrid System, Kea Island

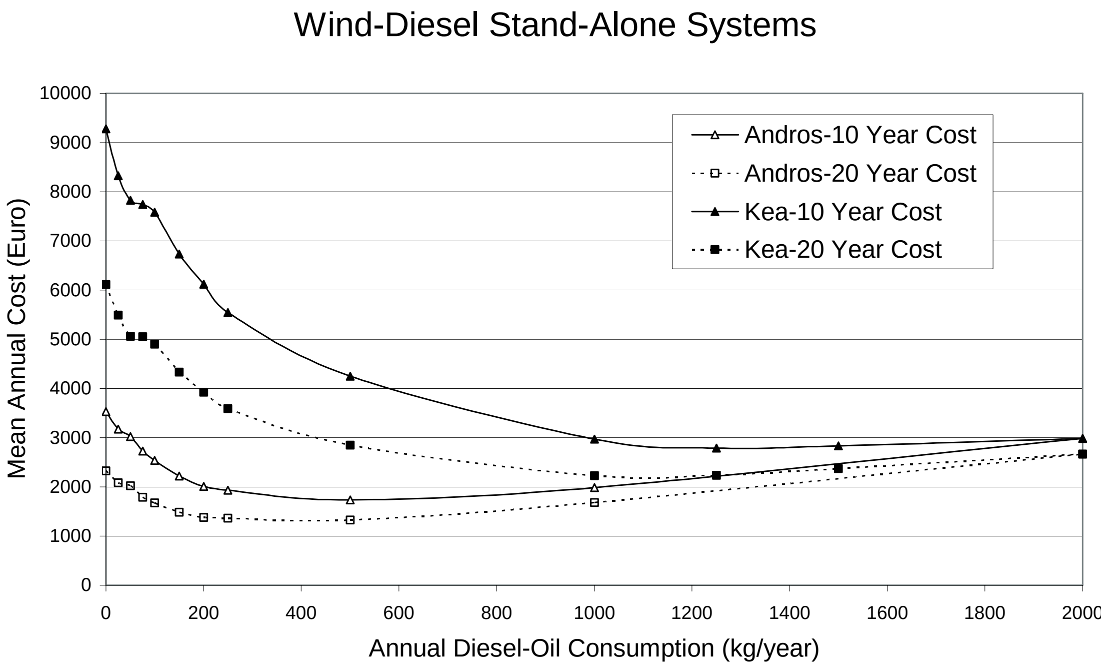


Figure 18: Comparison of Mean Annual Cost of Typical Wind-Diesel Hybrid Configurations on 10-Year and 20-Year Basis

Andros island is 1700€ for M_f≈500kg/year, while the corresponding value for Kea island is 2800€, while the annual diesel-oil consumption is approximately 1250kg/year. The electricity production cost difference is more obvious in case of low diesel-oil penetration, due to the wind potential variation between the two islands examined.

The same behaviour is also valid for the 20-year operation of the wind-diesel installation. It is interesting to note that the optimum system configuration for both islands is realized for lower diesel-oil penetration than the 10-year optimum solution. On top of this, as time passes the mean annual cost becomes lower for both islands, hence the corresponding 20-year mean annual value is 1300€ and 2200€ respectively. Finally, the optimum solution is moving towards lower diesel-oil penetration values, underlining the competitive advantage of power stations based on renewable energy sources, if a life-cycle cost analysis is considered.

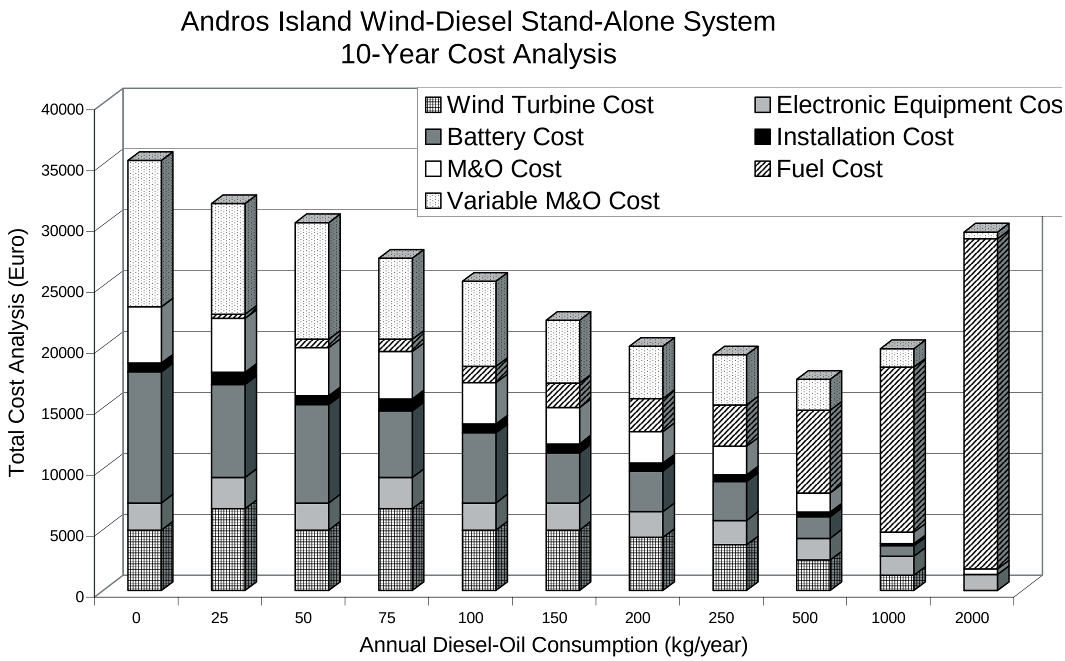


Figure 19: Total 10-Year Cost Analysis of a Typical Wind-Diesel Hybrid System, High Wind Potential Case

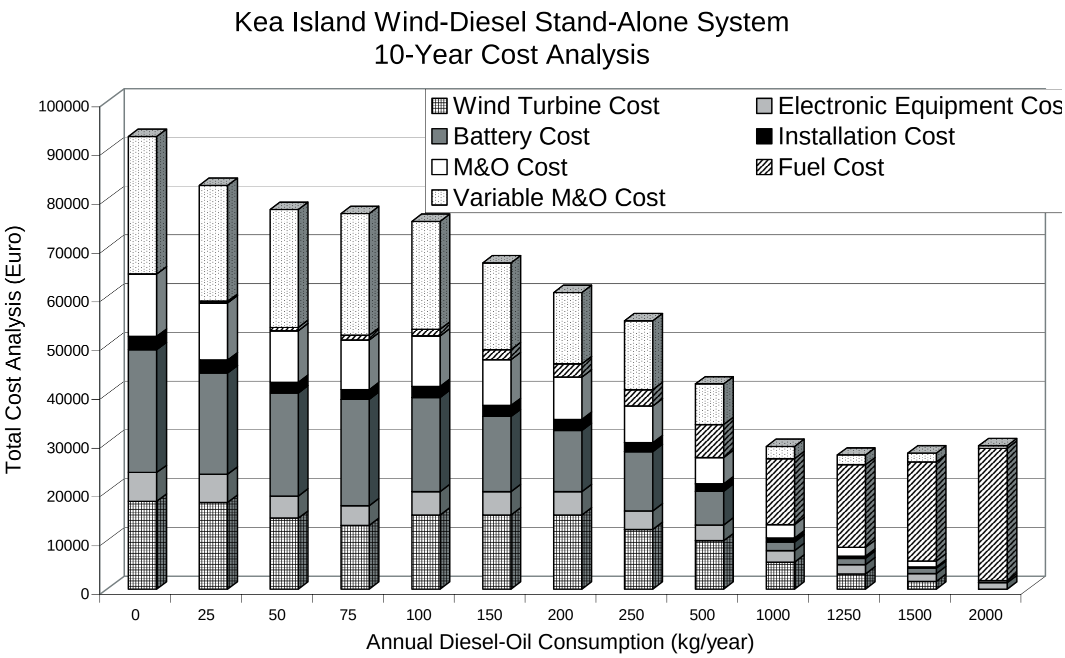


Figure 20: Total 10-Year Cost Analysis of a Typical Wind-Diesel Hybrid System, Medium-Low Wind Potential Case

Interesting conclusions may be derived by analyzing the 10-year minimum cost distribution; see figures (19) and (20). As it originates from these figures, for low diesel-oil penetration the main cost contribution is due to the high battery cost (including the variable M&O cost-battery replacement) and the fixed M&O cost. One cannot also disregard the wind power contribution, which represents approximately 15% of the total system cost. On the other hand, for high diesel-oil penetration, diesel-oil purchase cost represents over 50% of the entire system cost. On top of this, for the optimum system configurations the diesel-oil and the battery bank correspond to 40% and 35% of the total system cost in Andros island, while for the low potential case (i.e. Kea island) the optimum system configuration, diesel-oil represents almost the 2/3 of the system total cost. In both cases, the wind turbine ex-works price does not exceed 15% of the system 10-year total cost.

1. Conclusions

The central target of the present study is to estimate the optimum dimensions of a hybrid wind-diesel stand-alone system based on the minimum long-term electricity production cost. For this purpose, first the proposed energy production configuration is described along with an appropriate algorithm that estimates the combinations of wind turbine rated power, the corresponding battery capacity and the annual oil consumption required in order to guarantee energy autonomy of the entire stand-alone installation.

Accordingly, a total energy production cost calculation model is developed. The application of the developed model gives the opportunity to define the optimum size of the hybrid system under investigation on a 10-year or on a 20-year long minimum electricity production cost basis. Finally, the application of the complete analysis on two selected low and high wind potential regions indicates that the proposed hybrid system is more reliable and cost effective than a diesel-only installation or a wind-only based stand-alone system.

Recapitulating and considering the representative long-term results of the present study, one may state that a hybrid wind-diesel stand-alone system is a motivating techno-economic solution to meet the electricity demand of remote consumers, especially in regions with medium or low wind potential. In this context, an appropriately sized hybrid system should replace diesel-only generators, minimizing also the usage of imported oil and avoiding the environmental impact accompanying the operation of internal combustion engines.

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PART FOUR

ENVIRONMENTAL IMPACT

- Water Use
- Agriculture Production
- Delicate Social Groups
- Indoor Environment

WATER USE PLANNING WITH ENVIRONMENTAL CONSIDERATIONS FOR THE AEGEAN ISLANDS

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Abstract

The problem for the optimal water systems planning is tackled in this work, taking into account environmental considerations and sustainability issues related to the water sources and the water allocation to various users. The mathematical model that is developed integrates in a systematic way the benefits that can be expected from the water use and the costs of the various water supply methods. The model variables include the time varying water quantities supplied by different water sources and the also time varying water quantities being delivered to various users. The model parameters include the capacities of the water supplies, the different demands of the users, and the costs of each water supply method and the benefits of the water allocation to different users. Model constraints express the demands, the limitations in the capacity of the various water sources, as well as technical specifications that must be followed in the water allocation. Criteria for the optimisation of the water planning and their corresponding mathematical expressions are proposed. The optimisation model highlights some interesting aspects of the water systems planning and operation such as the most efficient allocation of existing water supplies, even in cases of limited water availability.

Keywords: Mathematical Modelling and Optimisation; Water Allocation; Water Systems Optimisation; Sustainability of Water Systems

1. Introduction and Background to the Present Work

Water is a constrained resource and in many areas of the planet water shortage is considered to be the most important problem. Actually the lack of fresh and of suitable quality water in an area practically prohibits its plan for development.

More than 25% of the world population lives in dry or semi-arid areas[1], the water supply chain management and optimisation is evolving as one of the most difficult and urgent problems[2]. The problem of the optimal water system design and planning is created mainly in cases where water is supplied from various different sources and needs to be distributed to users with possibly conflicting requirements. The unit cost of water is different for each one of the supply methods, and its value is different for specific allocation. The dimension of time plays a serious role in the problem, since the water's demand and availability, as well as all the other parameters vary significantly with time. Furthermore, the environmental factor should be incorporated in the definition of the problem and thus to avoid any unsustainable water supplies and allocations.

Several methodologies from systems engineering, particularly mathematical modelling, have increasingly been used over the last few decades for the optimal design, planning and operation of water resource systems. Optimisation models have also been applied for the solution of a number of problems related to the optimal planning of supply sources or dealing with the total water resources management system[3-5]. However, limited research work has been carried out for the most difficult and urgent problem of the integrated water supply chain optimisation.

Kondili E., Kaldellis J.K., 2005, *"Water Use Planning with Environmental Considerations for Aegean Islands", presented at the 13th International Symposium of MESAEP, Thessaloniki-Greece.*

The present work approaches the water systems planning problem taking into account the characteristics of both, supplies and demands. Emphasis is in particular given to the environmental implications of water supply and water use. The methodology and the optimisation model proposed are generic and can be applied in any water system exhibiting relevant characteristics. For illustration purposes, special emphasis is given in the implementation of the model in the area of Aegean islands.

2. Overview of the Water Resources Management Problem in Hellenic Aegean Sea

2.1 Water Demand

Water is a constrained resource in many areas of the planet. Aegean Sea is an area with many varying size islands. Most of the Aegean islands suffer from severe lack of good quality fresh water, mainly because of the low precipitation and their specific geomorphology. Water supply shortage in the islands of Cyclades (a group of islands in the Central and Southern Aegean Sea) amounts annually to almost 5 million m^3 of water[1]. On the other hand, these places accept many tourists; especially during the summer period their population may be five times more than the winter population, thus resulting in more serious and acute water shortage problems. Figure (1) shows a typical daily water demand profile for an Aegean Sea island and its variation during the year.

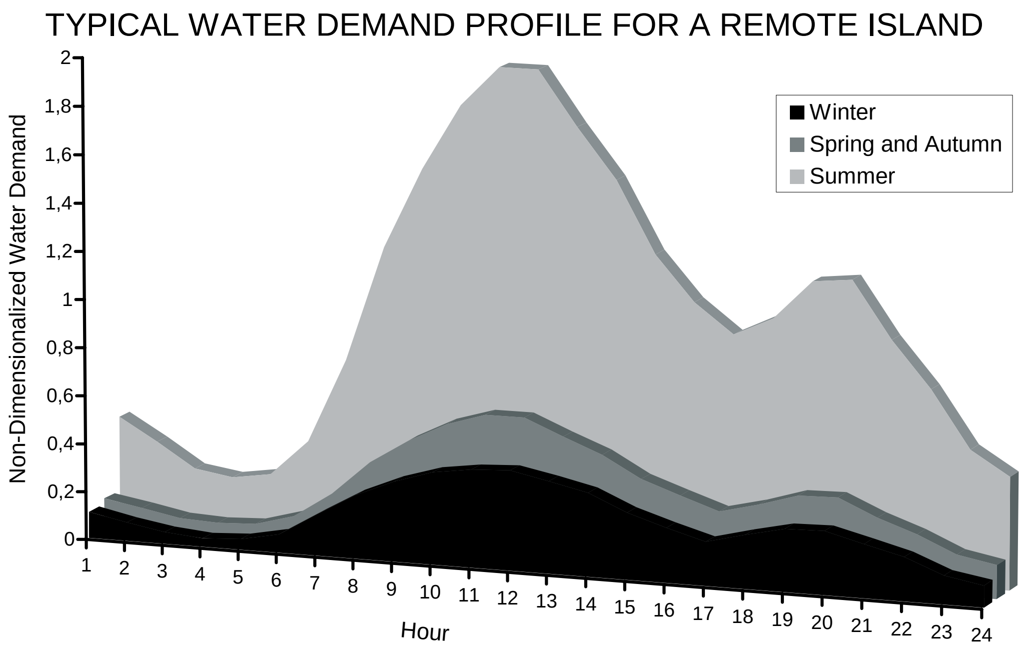

Figure 1: Typical Water Demand Profile for a Remote Island

Classification of the water consumption includes urban users (commercial, permanent and seasonal domestic users), industrial and agricultural users. However, in the area under discussion, water demand originates mainly from the agricultural and the urban users. Industry is not a significant water consumer in the islands.

The use and corresponding shortage of water in the urban and the agricultural sector, the water demand and availability and the water distribution in the two sectors in Cyclades islands are shown in Figures (2), (3) and (4) respectively.

2.2 Water Supply

The most common water supply sources in remote areas with limited water resources are the following:

- Ground reservoirs and dams associated with water treatment plants
- Desalination plants
- Wells and boreholes
- Water transfer with ships
- Water recycle and reuse (not commonly used yet).

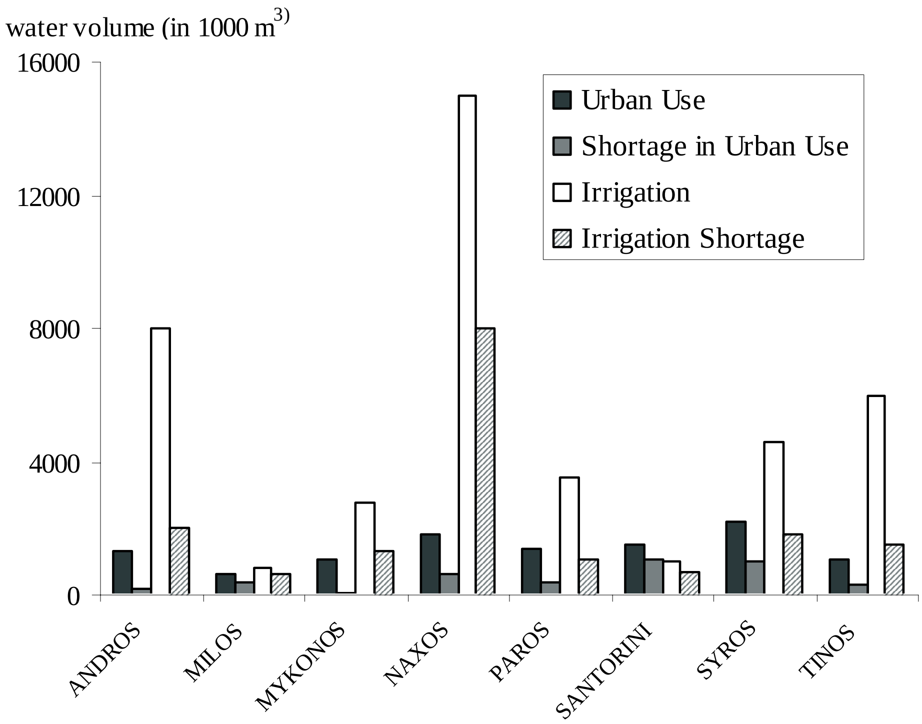

Figure 2: Water Use and Shortage in Urban and Irrigation Sectors

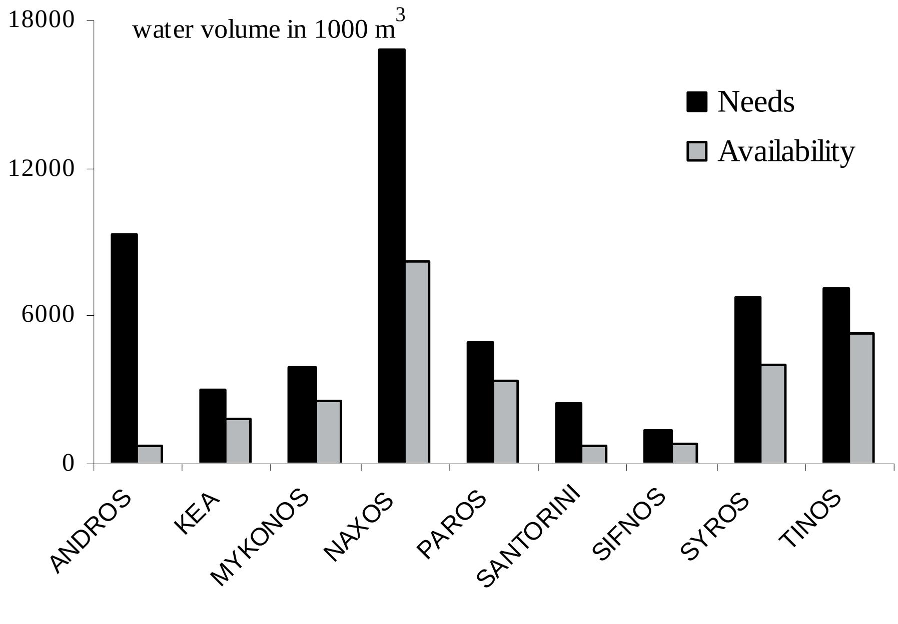

Figure 3: Water Demand and Availability in Aegean Islands

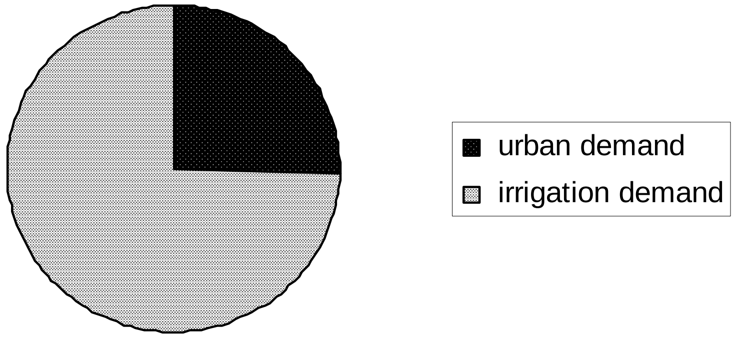

Figure 4: Average Water Demand Distribution in Aegean Islands

For a long time, increasing water demand was covered by transfer through ships in the Hellenic islands. However, there are very significant economic costs associated with this method, as well as the faith that it is completely unsustainable and does not create any infrastructure for the long-term problem solution.

The resulting costs of water are different for each of the above sources. In practice, the cost includes a fixed term, associated to the depreciation of the capital investment and a variable cost term. The desalted water has a significant operating cost, while the water from ground reservoirs and dams has s serious fixed cost term, because of the high capital investment required. Figure (5) shows the different water costs for various sources[6].

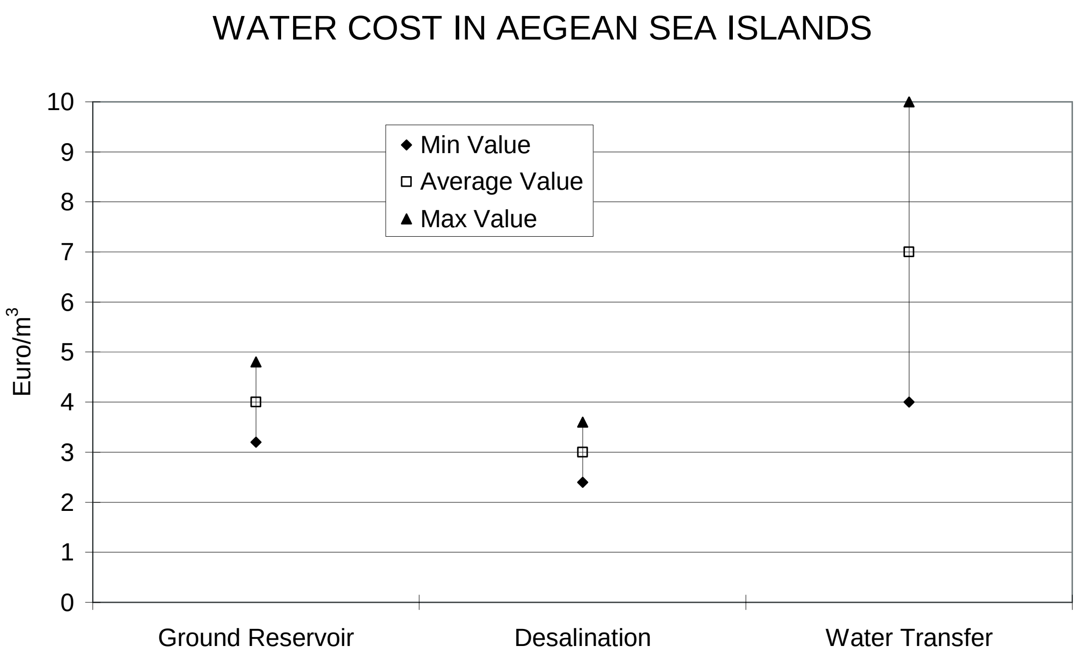

Figure 5: Water Costs from Various Sources (Ground Reservoir: 200,000 m^3)[6]

3. Sustainability Issues in Water Supply and Use

Water is a renewable natural resource. However, its availability depends highly on the season and the geographical region. In areas with shortage, water is overexploited and that affects seriously its quality and its future availability. Therefore, the planning process should take into account sustainability considerations in a consistent way and embed the environmental factor in the operation of the water system. In the present work, sustainability issues play an important role in the optimisation of the water system. Namely, the environmental factor is included in the proposed approach as follows:

- Water shortage is allowed in the system; i.e. there may be cases and certain time periods, when the water demand exceeds water availability. In this case, the resource allocation is done according to a predetermined set of priorities and some needs may be partially covered or not covered at all. Actually, this approach contributes substantially to the most efficient water allocation in contrast to the unsustainable way of continuously seeking new water resources for the satisfaction of the increasing needs.
- Water is supplied through various sources. However, some of them are very expensive and do not create any infrastructure for the future; for example, water transfer with ships. Assigning a high cost to this supply source, the system will avoid it unless the expected benefits from the allocation of the corresponding water quantities use exceeds costs.

4. The Proposed Mathematical Model

4.1 Basic Characteristics and Structure of the Proposed Model

The mathematical model that is proposed in the present work identifies the optimal solution in the operation of the water system, taking into account:

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

The objective of the model is to determine the appropriate input flows from each supply source and the quantities allocated to each user, keeping in mind that the total water availability may be less than the total demand. Therefore, not all the demands will be covered. 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[7]. 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 (6) shows a schematic representation of the system under consideration.

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.

4.2 Water Supply

The usual supply sources taken into account in the present work are:

- Desalination units
- Ground Reservoirs and dams
- Water transfer by ships
- Own water resources (e.g. wells)
- Others

In fact the model can accommodate any type of water supply. The information that is required is its cost, capacity and any existing operational constraints.

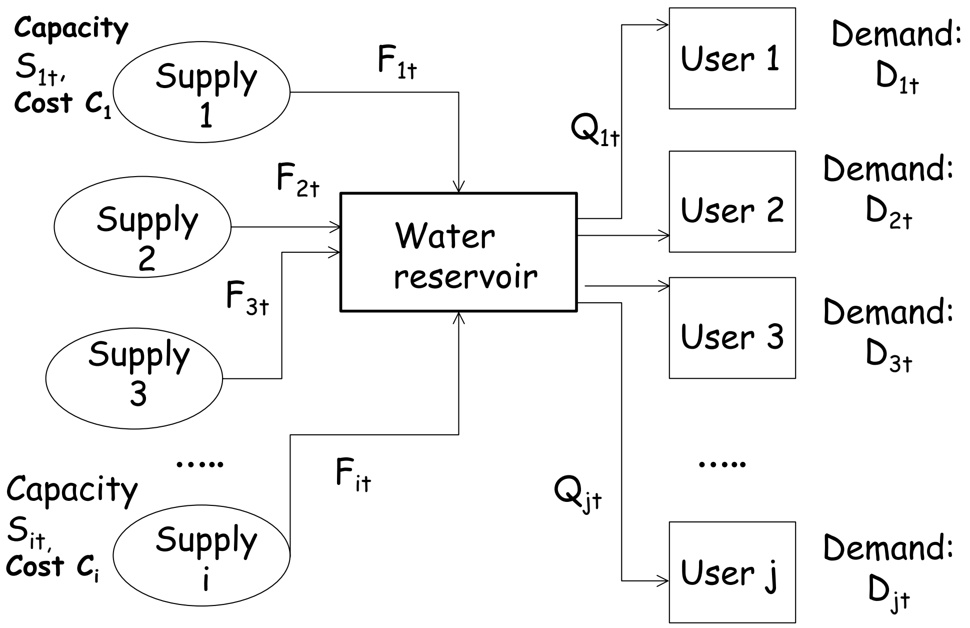

Figure 6: Schematic Representation of the Water System

The supply limits are determined from the capacity of each specific source. For the desalted water, the supply limit is the desalination unit's capacity, for the ground reservoir the supply limit is in practice the capacity of the water treatment plant, since in most cases the water from a reservoir needs to be treated before reaching the consumer. The ship transfers water into the storage tank at specific time periods. The capacity limit in this case is determined by the quantity that has been transferred by the boat.

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[8]; the same is valid for the ground reservoir and the dam. On the contrary, the water transferred by ships has only a rather high variable cost term.

4.3 Water Allocation

The users take water from the storage tank. The upper limits of the quantities being delivered to the various users are the corresponding time-varying demands.

The water users are:

- The agriculture (irrigation)
- The urban use (including permanent and seasonal domestic use and commercial use)
- The industry
- Other secondary uses.

In case the required water quantity exceeds the available one, not all the requirements will be satisfied. This will definitely cause some consequences to the users (e.g. cancellation or limitation of expansion plans, losses etc.). The allocation of water to users will be determined by the optimisation. However, 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 any case, the discrepancy between the allocated quantity and the demand should be penalised. Actually these penalties are expressed as extra 'costs' 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.

One of the most important dimensions of the present work is that environmental considerations should also be taken into account in the water allocation. The simplest way to achieve that is to assign high costs in the most unsustainable water supply methods. However, other more formal methods exist to take into account the environmental costs of each water supply method[9].

5. Mathematical Model Development

5.1 System Parameters and Variables

The variables and the parameters of the system are shown in Tables I and II 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. Actually, the length of the time horizon will also indicate the time interval that will be the basic step for the optimisation model.

Table I: Model Parameters

Parameter	Magnitude
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)
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)
C_{it}	Cost of water from supply source i at time interval t (€/m3)

Table II: 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)

5.2 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 including environmental benefit and costs, i.e.

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

$$\text{Total Benefit} = \sum_t \sum_j B_{jt} * Q_{jt} \tag{1}$$

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

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

$$\text{Total Cost} = \sum_t \sum_i C_i * F_{it} + \sum_t \sum_j p_{jt} * (D_{jt} - Q_{jt}) \tag{2}$$

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:

$$\text{Max} \sum_t \sum_j B_{jt} * Q_{jt} - [\sum_t \sum_i C_i * F_{it} + \sum_t \sum_j p_j * (D_{jt} - Q_{jt})] \quad (3)$$

As shown in the objective function (3), 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, a detailed study for the proper quantification of these Benefit magnitudes is needed. Actually these benefits should be reflected to the water pricing. On the other hand, the Penalties for not satisfying part or all the demand may express the priorities among various competing users.

5.3 Model Constraints

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

The continuity equation in the water storage tank: $V_t = V_{t-1} + \sum_i F_{it} - \sum_j Q_{jt}$ (4)

Upper and lower bounds of the water in the reservoir: $V_{min} <= V_t <= V_{max}$ (5)

Capacity limitations of each supply scheme: $F_{it} <= S_{it}$ (6)

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.

$$Q_{jt}^{min} <= Q_{jt} <= D_{jt} \quad (7)$$

6. Application Results

6.1 Case Study Characteristics

The above Mathematical Programming model is applied in a simple case study to illustrate the type of results that can be expected of this work. A typical island of Aegean Sea is considered. The basic parameters of the problem are shown in Table III.

Table III: Data and Basic Assumptions for the Case Study

Time Horizon	Twelve months, time step: 1 month
Supply Sources	1: Desalination, 2: Ground reservoir, 3: Transfer by ships
Users	A: Urban, B: Irrigation
Demand Profile	Shown in figure (7)
Benefits	Shown in Table IV
V^{MAX}, V^{MIN}	1,000,000 m^3 and 10,000 m^3 respectively
Supply sources capacity	S_1=300,000, S_2=200,000m^3/month, S_3=1,000,000 m^3/year
Supply Costs	C_1= 3 €/m^3, C_2= 4.4 €/m^3, C_3= 7 €/m^3

The effects of the following problem parameters will be indicated in this simple case study.
a) effect of the Benefits for each user
b) environmental considerations taking into account the costs of the unsustainable supply methods

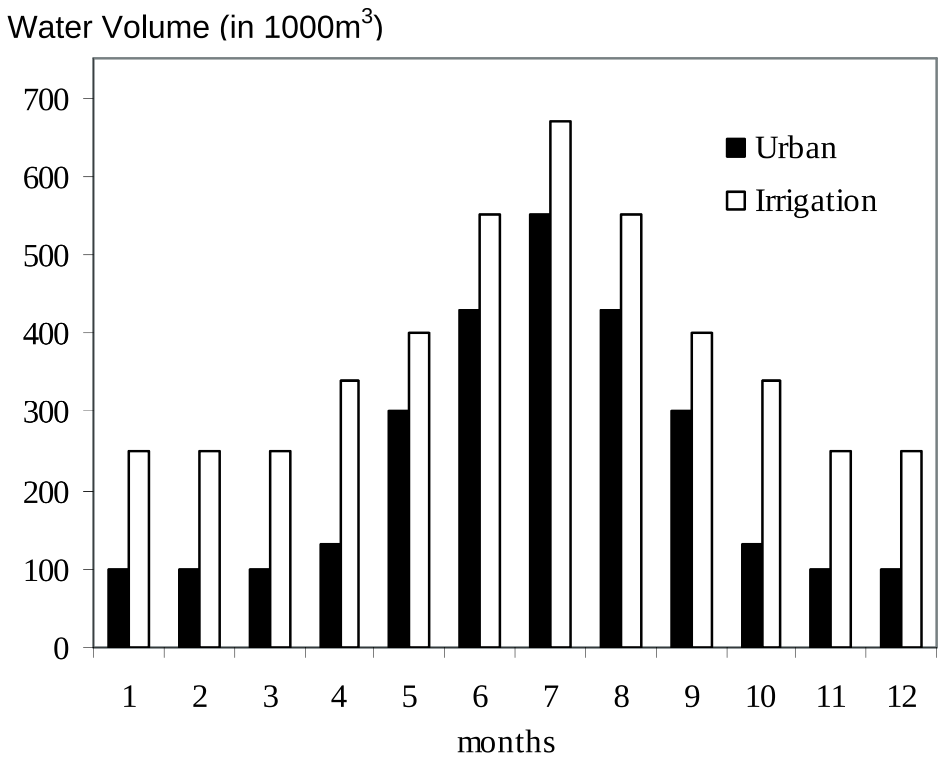

Figure 7: Demand Profile for the Case Study

6.2 Effect of Benefits

In order to isolate the effect of the water allocation benefits in the problem, it is solved taking the penalties for non-covering the demands equal to zero. Therefore, only the allocation benefits and the supply costs affect the problem solution.

The problem is solved for two cases:
Case A1: Initially the Benefits are shown in Table IV, where for user A (urban consumption) they are much higher for the summer months and for user B they are the same throughout the year.

Table IV: Benefits for the Users of the Case Study for Twelve Months (in €/m^3)

Months	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
B_{At}	5	5	5	15	20	25	25	25	10	5	5	5
B_{Bt}	5	5	5	5	5	5	5	5	5	5	5	5

As shown in the results of figure (8), the water is mostly allocated to the user with the highest Benefits. This also affects the water quantities that are stored in the storage tank. As shown in figure (9), the water is stored during the winter months and is allocated to users in the months that the benefits are high.

Case A2: Then the problem is solved with the Benefits being the same for both users throughout the year (Table V).

Table V: Benefits for the Users of the Case Study for Twelve Months (in €/m^3)

Months	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
B_{At}	5	5	5	5	5	5	5	5	5	5	5	5
B_{Bt}	5	5	5	5	5	5	5	5	5	5	5	5

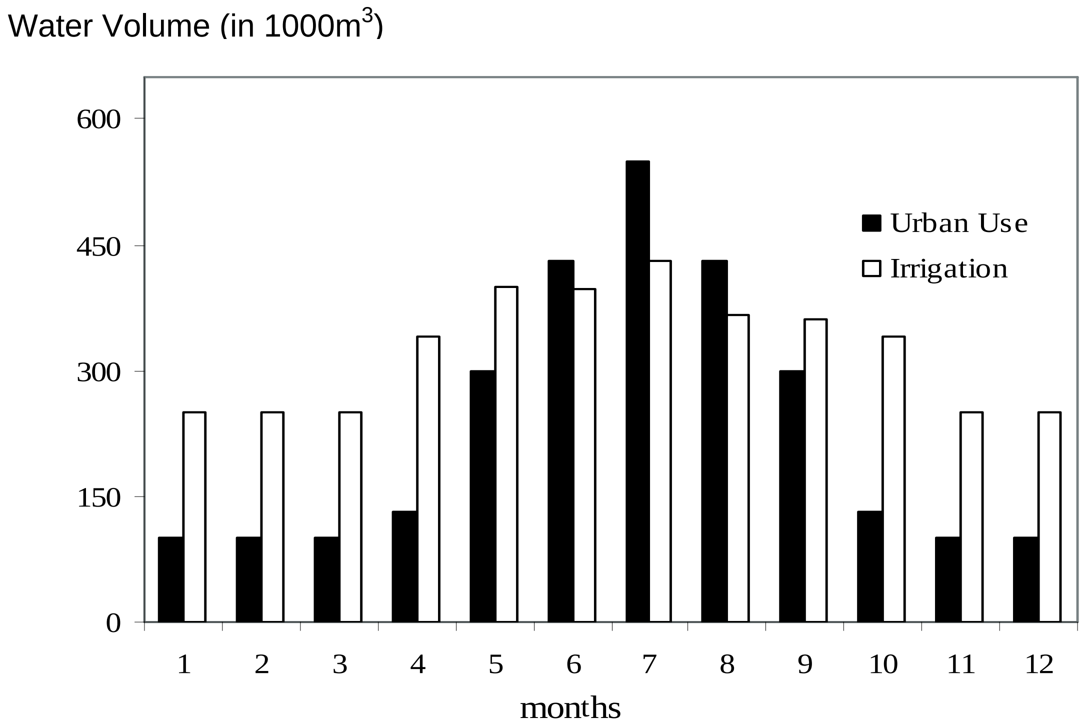

Figure 8: Model Results - Water Distributed to Users for Case A1

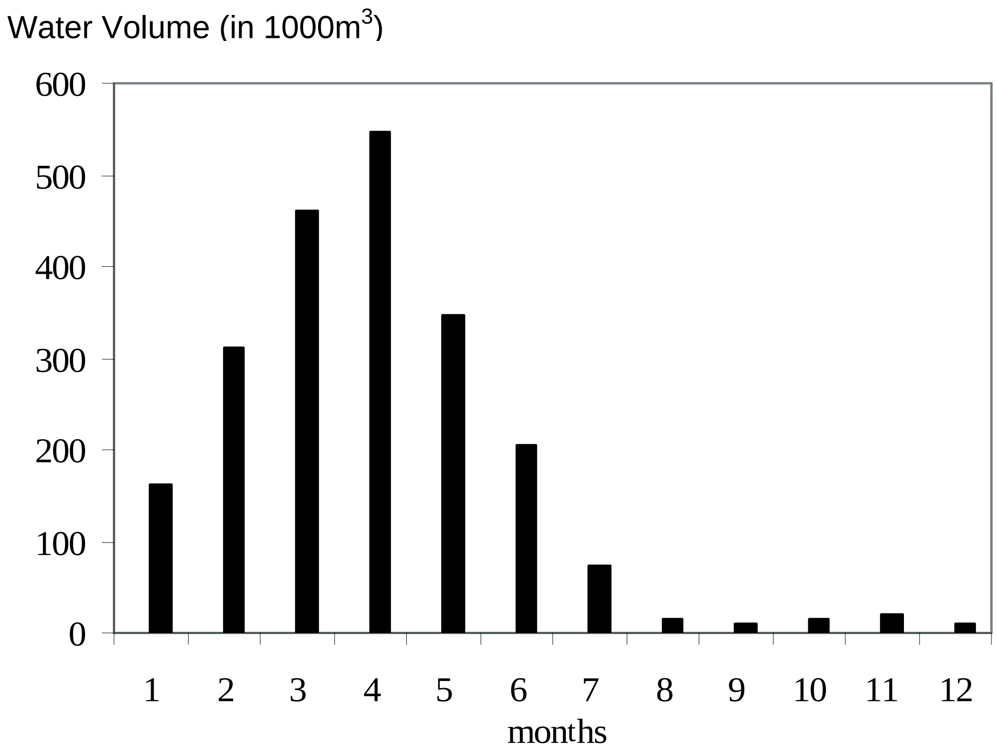

Figure 9: Model Results - Water Volume in the Storage Tank for Case A1

6.2 Effect of the Supply Costs

The problem is solved for the same demand profile as the one shown in figure (7) and for two cases:

In Case B1 the supply costs are:

$C_1 = 3\ €/m^3$, $C_2 = 4.4\ €/m^3$, $C_3 = 7\ €/m^3$ (8)

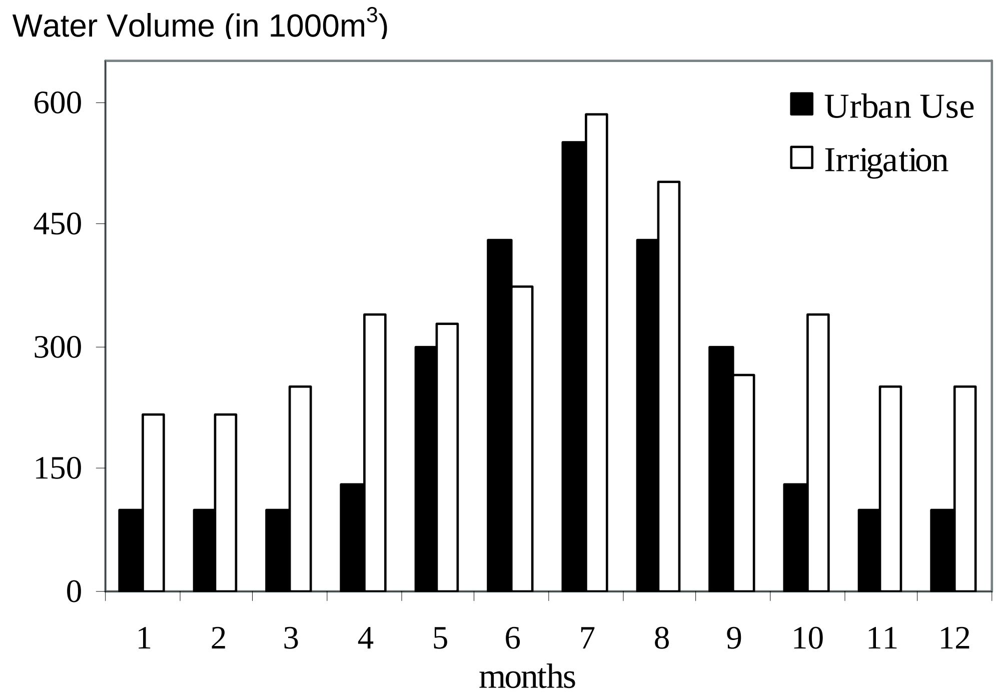

Figure 10: Model Results - Water Distributed to Users for Case A2

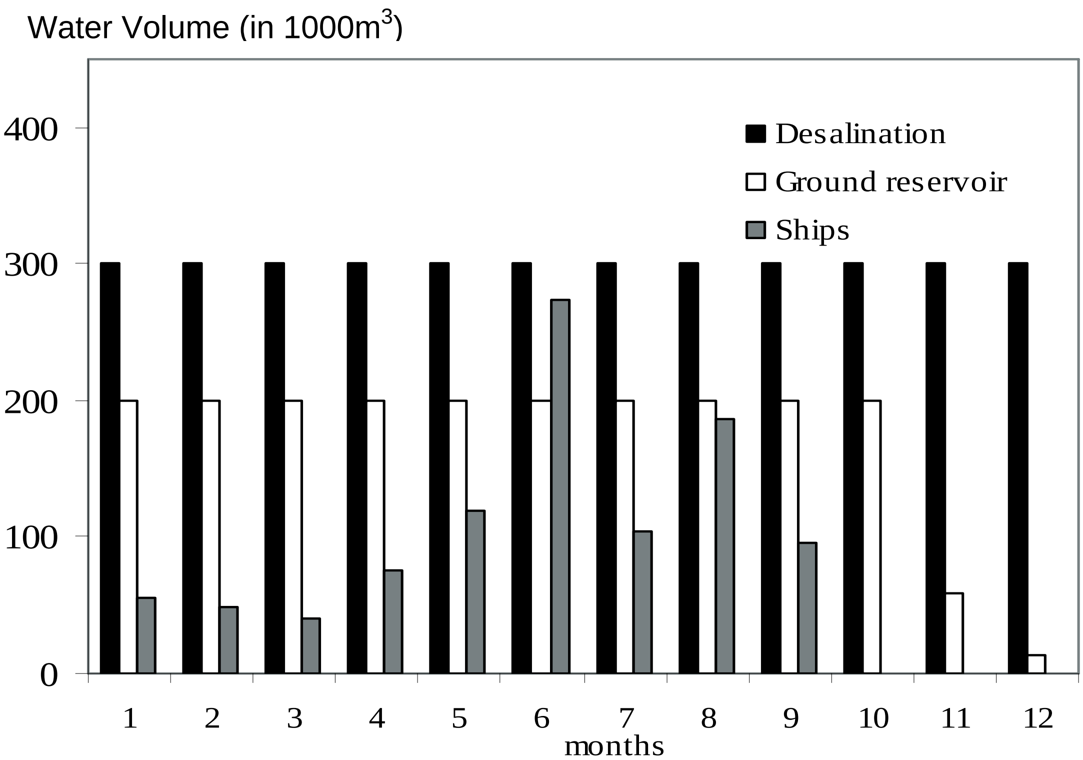

Figure 11: Model Results - Water Supply Quantities for Case B1

In Case B2 the supply costs are:

C_1= 3 €/m^3, C_2= 4.4 €/m^3, C_3= 10 €/m^3 (9)

As shown in the above figure (10), in this case the water allocation price follows the demand profile.

The cost of the water from supply source 3 is more expensive in this case in order to indicate the effect of an unsustainable supply source, as is the water transfer by ships. It is noted that both Cases B1 an B2 are implemented with the Benefits taken as in Case A2 (all the same throughout the year).

The corresponding water supply quantities from the different supply sources are shown in figures (11) and (12) respectively.

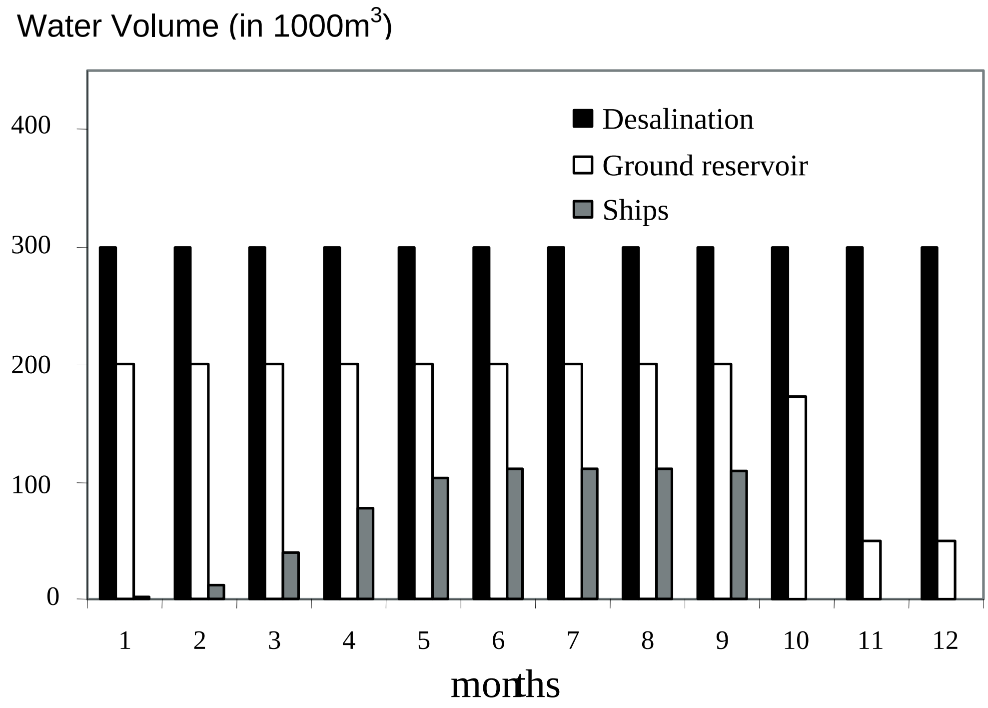

Figure 12: Model Results - Water Supply Quantities for Case B2

As shown in the above figure (12), the optimisation has resulted in much less supply quantities of the expensive (unsustainable) source than the corresponding ones in Case B1. In Case B1 all the availabe quantity of water transferred by ships is finally transferred and delivered to the system (1,000,000 m^3), while in Case B2 the water quantity that has been transferred is 676,000 m^3 .

7. Conclusions and Significance

An optimisation model has been proposed in order to carry out the optimal planning in complex water systems with multiple supply sources and multiple users, taking into account environmental considerations. The implementation of the resulting mathematical programming model evaluates the water flows from each supply source and the flows allocated to each user, in order to optimise an economic / operation efficiency criterion.

The model takes into account the costs of each supply source and the benefits from the water allocation to each user and allows the water availability to be less than the total demand. Thus, the work introduces the idea of optimally allocating the existing resources and eliminates existing inefficiencies rather than continuously seeking ways to expand the existing sources. Thus, environmental considerations are inherently taken into account in the operation of the system.

The systems engineering approach to the 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 various problem issues and to the analysis of the influences of different operating modes. The present study, being part of an ongoing research, provides a basis for further formal modelling. The model will be refined and extended in a number of ways and emphasis will be given in more formal ways to express environmental costs to each supply method. In addition, the behaviour of other supply sources such as the water reuse will be studied, which is another important and efficient method for water conservation.

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EFFECT OF SURFACE OZONE EXPOSURE ON VEGETATION IN THE RURAL AREA OF ALIARTOS, GREECE

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Abstract

The critical level of air pollutants in the atmosphere is the concentration above which adverse effects occur on sensitive receptors, such as plants and ecosystems. Ozone is the most important air pollutant in Europe affecting vegetation and forest ecosystems and its increase in the last decades is significant. The current European critical levels of ozone for the protection of crops, natural and semi-natural vegetation and forest trees are based on exposure-response relationships using the AOT40 exposure index. The results described in this work are derived from an analysis, concerning the six-year period 1996-2001, of hourly surface ozone concentrations measured at the rural station of Aliartos about 90 km NW of Athens. This station is the only EMEP-Project station in Greece and South Balkan Peninsula. The analysis showed a strong seasonal variation. Some differences between the warm and cold period mean diurnal patterns were also noticed. This research reports the information on the relation between AOT40 exposure index levels and reductions in agricultural and horticultural crop production, at the rural area of Aliartos for a six-year period started in 1996.

Keywords: Ambient Air Pollution; Surface Ozone; AOT40 Exposure Index; Aliartos-Greece

1. Introduction

The importance of ozone effects on human health, animal population, plant growth, and its significant role in the energy budget of the troposphere have been reported in the literature[1-3]. Increased tropospheric (background) ozone concentrations are currently a matter of concern since they have more than doubled during the last decades[4-7]. The high background ozone values observed in Mediterranean regions may be attributed to the high levels of solar UV in combination with locally emitted anthropogenic ozone precursors. Since weather conditions (sunshine, high temperatures and low winds) significantly affect ozone formation, high concentrations occur mainly during the summer, in urban, suburban and rural areas. A number of works[8-16] on tropospheric ozone regarding eastern Mediterranean regions, underline the problem.

Ozone is an omnipresent air pollutant that is responsible for foliar injury, reductions in crop yield and seed production, and growth impotence of forest trees[17-25].

Ozone potential to damage vegetation has been known for over 30 years, but it is only over the last fifteen years that its impacts have become of great concern in Europe. Furthermore, because ozone is a pollutant with a regional distribution, has the ability to infect large areas of rural Europe[26]. Until now, the dose-exposure indices[27-32] best related to plant response are of accumulative exposure type. Ozone impact on crops, vegetation and forests can be assessed by introducing an ozone concentration threshold value above which plants seem to be sensitive, the Accumulated Ozone Threshold (AOT) index which seems suitable to relate daylight exposure to plant response, at least for crops like wheat[22]. In this study the relation between AOT40 index levels and reductions in agricultural and horticultural crop production at the rural area of Aliartos are analysed for the six-year period 1996-2001.

Paliatsos A.G., Koronakis P.S., Kaldellis J.K., 2005, *"Effect of Surface Ozone Exposure on Vegetation in the Rural Area of Aliartos, Greece", presented at the 13th International Symposium of MESAEP, Thessaloniki-Greece.*

2. Materials and Methods

In the current work an attempt is made to give a statistical evaluation of surface ozone based on the data recorded at the rural station of Aliartos for a six-year period starting in 1996. The measuring site Aliartos is located about 90 km northwest of Athens and about 30 km to the northwest of Thiva at 38° 23’ northern latitude and 23° 06’ eastern longitude. This station is located at an altitude of 110 m in the Copais plain. A detailed description of the Copais plain is found in various publications[10]. The air pollution monitoring station has been operating since 1996 by the Ministry of the Environment, Physical Planning and Public Works (MEPPPW) monitoring background pollution (Co-operative Programme for Monitoring and Evaluation of Long-Range Transboundary Air Pollutants in Europe - EMEP project). This is the station, from the EMEP network, with the longest record of surface ozone measurements in Greece.

The climate of Aliartos is Mediterranean with wet, mild winters and hot, dry summers. The mean daily temperature is 8°C and 26.3°C for the winter and summer period, respectively. The Mediterranean climate is characterized by rainfall deficiency during the warm period of the year. Therefore, from the annual mean rainfall of 583 mm, most of it occurs in the winter months. The sunshine duration per month varies between 112.8 hours in January and 352.7 hours in July. In the Copais plain, the prevailing winds blow from the NW almost throughout the whole year period.

3. Data Analysis and Discussion

Figure (1) shows the seasonal variation of surface ozone concentrations at the rural station of Aliartos, for the examined 6-year period (1996-2001). The seasonal variation of ozone concentrations is characterized by a maximum during the warm period (May to September) and a minimum during the cold period of the year (October to April).

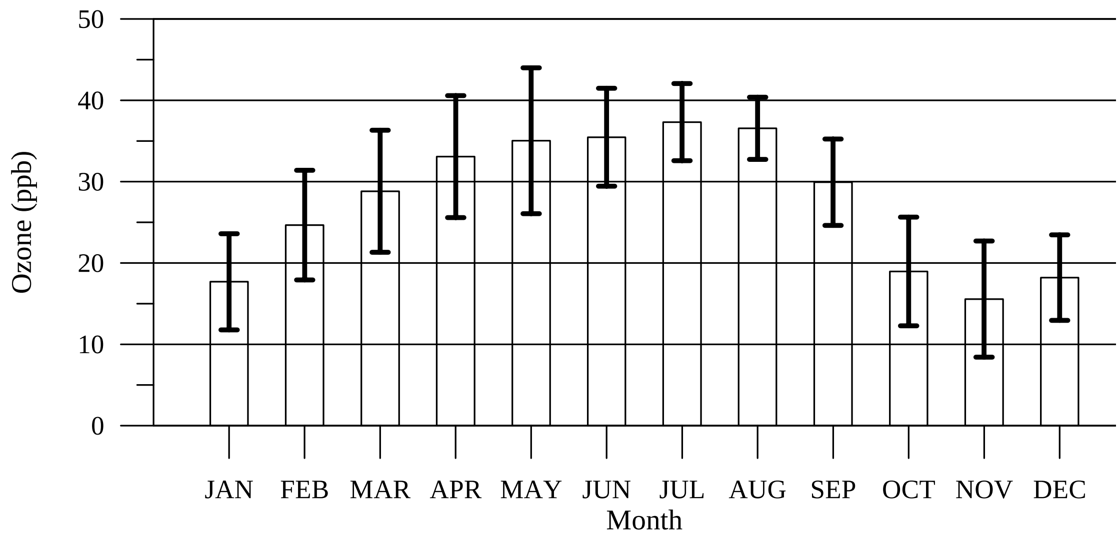

Figure 1: Mean (± SD) Monthly Concentrations of Surface Ozone Concentrations at the Measuring Site of Aliartos, from 1996 through 2001

The minimum value observed in November and the maximum value in July with a ratio 1:2.4. As a consequence, the AOT40 index (ppb hours) expresses the accumulated excess of hourly ozone concentrations above 40 ppb over a given period using only the 1 hour values measured between 08:00 and 20:00, Central European Time each day[33]. The UN Economic Council for Europe (UN-ECE) has recommended a critical load of 3000 ppb hours in the three-month period (May-July) for crops, and 10000 ppb hours in the six-month period (April-September) for forests[34]. In the presence of intense solar insolation, photochemical production of ozone becomes the dominant process during the warm period of the year[35]. Similar patterns of seasonal variation have also been observed in other rural sites in Europe[8, 10, 15, 35-37].

The strong dependence upon the total solar UV irradiance reaching the earth of the photochemical surface ozone production is more clearly seen in the mean diurnal variation of surface ozone concentrations. Figure (2) presents the plot of surface ozone concentrations ($[O_3]$) against sunshine duration (SSD), both expressed as mean monthly values over the examined period, as well as the best line of fit given by the Eq. (1):

$$[O_3] = 5.7589 + 0.0394 * SSD \quad (1)$$

where $R^2 = 0.795$ (or 79.5%), SSD and $[O_3]$ are expressed in hours and ppb, respectively, and the multiplier has dimensions of ppb $hours^{-1}$. The SSD values used in Eq. (1) come from the Hellenic Meteorological Service.

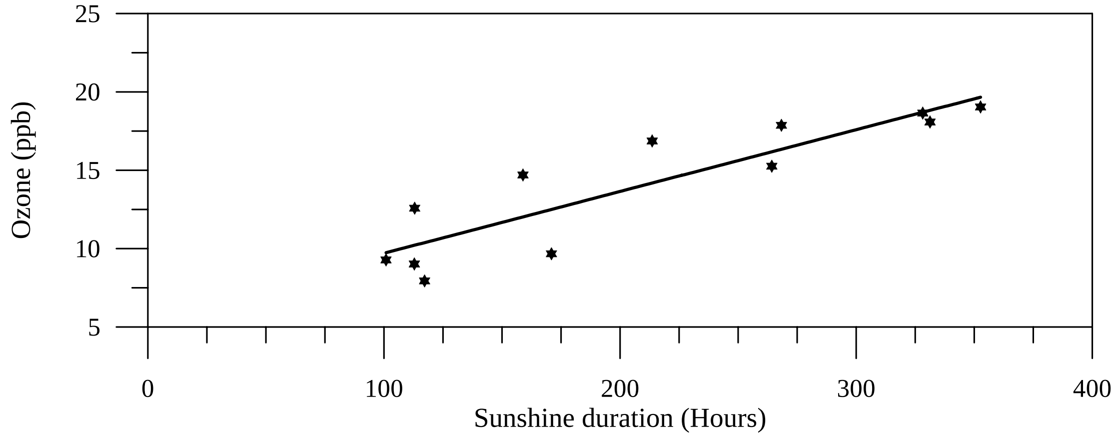

Figure 2: Scatter Diagram of Mean Monthly Values of $[O_3]$ Against SSD at the Measuring Site of Aliartos (1996-2001). The Solid Line is the Best-Fit Curve Expressed by the Equation $[O_3] = 5.7589 + 0.0394 * SSD$

The ozone concentrations in the troposphere follow a characteristic diurnal course with high concentrations in the early afternoon hours (when radiation and temperature favour ozone formation) and low concentrations during the late night hours until early in the morning (when only ozone distraction takes place). Using data for the period 1996-2001, the mean diurnal variation of surface ozone concentrations, separately during January, April, July and October, at the measuring site of Aliartos, is shown in figure (3). These months were chosen throughout this paper to contrast the surface ozone concentrations patterns from the climatic point of view.

As it appears from figure (3) the diurnal variation of surface ozone concentrations has a single peak structure. This peak is observed between 13:00 - 16:00 LST in January, 11:00 - 19:00 in April, 10:00 - 20:00 in July, and 12:00 - 17:00 in October. The amplitude of the diurnal variation ranges from 16 to 44.3 ppb, for January and July respectively. The high amplitude of surface ozone diurnal variation, in July, is probably due to the high photochemical ozone production caused by the high solar insolation during the daytime period. It should be mentioned at this point that the diurnal variation pattern of surface ozone is consistent with the known built-up of ozone in the morning hours, which is caused partly by mixing down of the ozone-rich air from above and later on by photochemical production[38]. During the evening and night hours surface ozone is substantially decreased by chemical destruction and dry deposition[8, 39-40]. This result emphasizes the strong dependence upon the total UV-solar irradiance reaching the earth of the photochemical surface ozone production. Similar patterns of seasonal variation have also been observed in other rural sites in Europe[8, 15, 41].

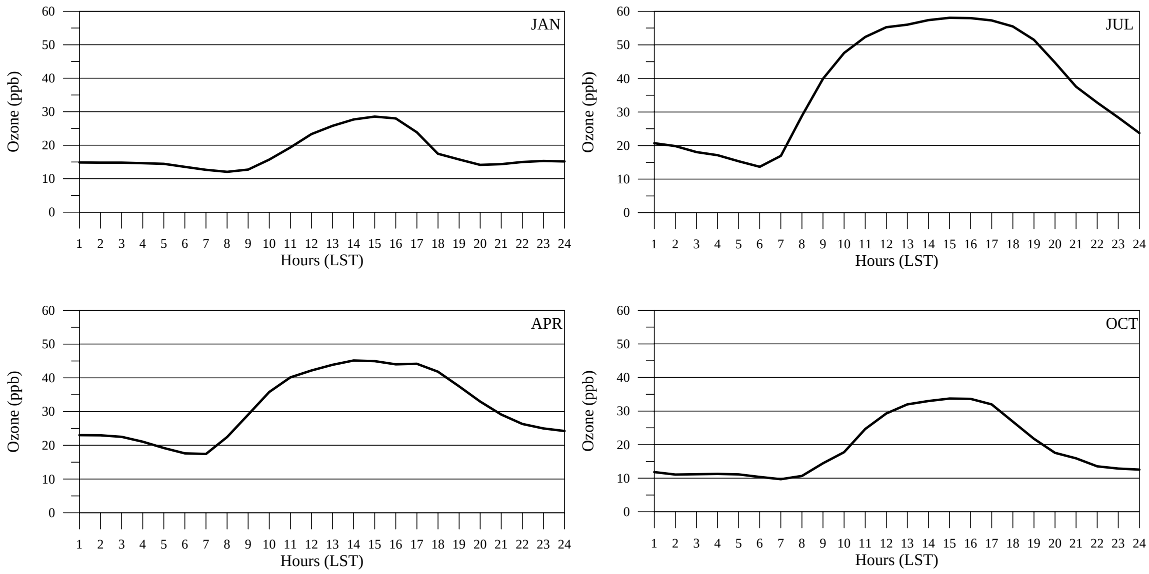

Figure 3: Mean Diurnal Variation of Surface Ozone Concentrations, for the Period 1996-2001, at the Measuring Site of Aliartos for January (JAN), April (APR), July (JUL) And October (OCT)

The diurnal ozone concentration pattern in rural areas is typically different from that in urban areas. While the maximum concentration is often lower than in the urban and near-urban areas, the peak area is broader. That is, rather than a relatively brief, high spike in concentrations, concentrations in rural areas are elevated over much of the date (and even night), but elevated to lower maxima than in urban areas. This diurnal pattern observed in rural areas is due to the fact that, precursor pollutants and ozone itself continue being replenished by air masses moving in, such that the temporal pattern of emission in cities gets blurred be long distance transport, more over pollutants that react with ozone (e.g. NO) are in lower concentrations in rural areas, such that ozone can persist longer in rural areas than in cities. The result is that, in rural areas, daily average ozone concentrations can actually be higher than in urban or semi-urban areas.

As for the analysis of violations, it is evident that the extremely hot and sunny weather (where high temperatures show up early in the spring and last through the autumn) provided conductive ozone conditions resulting in extensive episodes of high ozone concentrations.

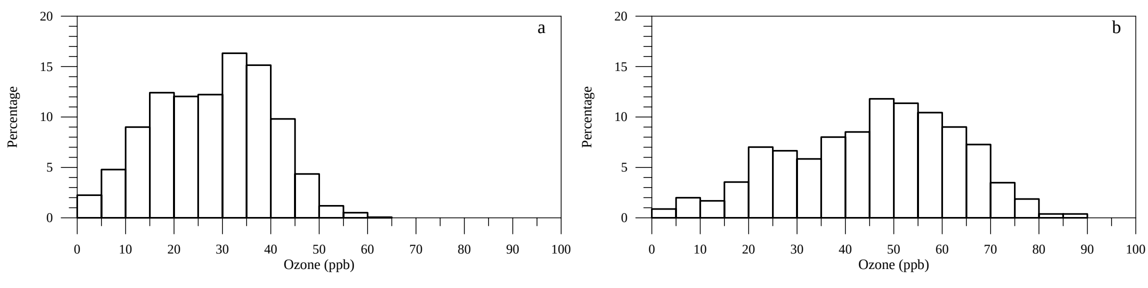

Figure 4: Histograms Showing the Surface Ozone Concentration Occurrences of, (A) Daily Averages, and (B) Daily 1-Hour Maximum Values at the Aliartos Site, for the Period 1996-2001

The ambient air pollution 24-hour limit value for damages to vegetation, set by the European Union, which is also a WHO guideline, is 33 ppb[42-43]. At the measuring site of Aliartos, the daily averages of surface ozone concentration ranged between 2 and 62 ppb for 1996 to 2001 (figure (4a)). The daily averages exceeded the 24-hour limit by 185, 102, 136, 132, 34 and 23 days for 1996 to 2001, respectively. During the warm period (April - September), the daily averages exceeded the 24-hour limit by 152, 83, 123, 103, 31 and 23 for 1996 to 2001, respectively. This means that the levels of surface ozone concentration in the rural area of Aliartos remain, for the most part of the examined period, above the EU limit values[16].

The data analysis carried out shows that the daily 1-hour maximum values of surface ozone concentration were ranged between 3 and 89.8 ppb for 1996 to 2001 (figure (4b)). The 1-hour limit of 100 ppb for the protection of vegetation was not exceeded during the whole experimental period. The highest 1-hour ozone concentration, 89.8 ppb found, was for April 1998. Moreover the conducted analysis showed that the AOT40 index (ppb∗hours) from May to July ranged between 3100 and 16307 ppb∗hours for 1996 to 2001, while for April to September ranged between 6151 and 27721 ppb∗hours for the same period, indicating that the ozone levels were highly phytotoxic. A previous study[32] analysed the surface ozone levels in the greater region of Messogia – Attica also found very high AOT40s values.

In order to provide quantitative relations between the production rate of cotton and the exposure index AOT40, scatter diagrams were constructed (figure (5)). Figure (5) presents the plot of cotton production rate (CPR) against AOT40, both expressed as annual values over the examined period, as well as the best line of fit given by the Eq. (2) during May-July and (3) during April-September:

$$CPR = 340.410 - 0.0041 * AOT40, \quad r^2 = 0.655 \qquad (2)$$
$$CPR = 337.602 - 0.0023 * AOT40, \quad r^2 = 0.732 \qquad (3)$$

Where, CPR and AOT40 are expressed in kg per 1000 m^2 and ppb∗hour, respectively, and the multipliers have dimensions of (kg per 1000 m^2)∗(ppb∗hours)$^{-1}$. From these results it appears that, for May-July, by using the linear model, only 65.5% of the variance (r^2 = 0.655) of annual values of cotton production rate can be explained by the variations of AOT40 values. On the contrary, for April-September, using the linear model, 73.2% of the variance (r^2 = 0.732) of annual values of cotton production rate can be associated with the variations of AOT40 values.

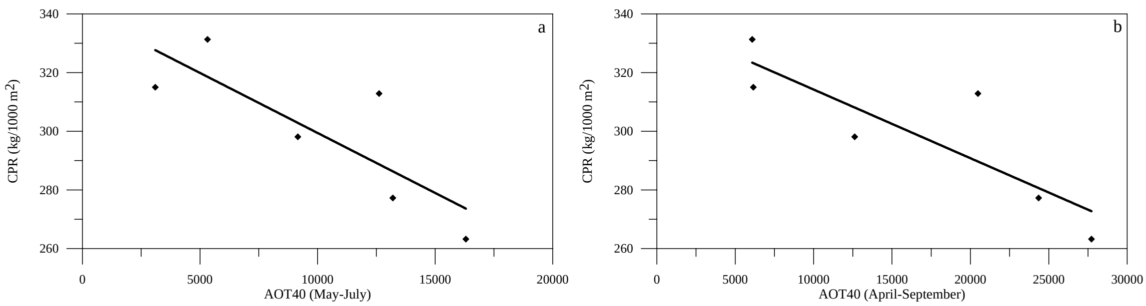

Figure 5: Production Rate of Cotton (kg per 1000 m^2) Vs AOT40 (ppb∗Hour), During May-July (A), and April-September (B), at Aliartos for 1996 to 2001

In Table I, the results from an analysis of visible surface ozone effect upon agricultural crops are presented by means of a linear model, in order to provide quantitative correlations between the production rate (PR) of agricultural crops and the exposure index AOT40.

Table I: Relation between the Annual Values of Agricultural Crop Species Production Rate and the AOT40 Index Values for 3-Month (May-July) per Growing Season by Using Linear Fitting Models PR = a+bAOT40, where r^2 is the Variance

Agricultural crop	**r^2**	**a**	**b**
Wheat	0.090	298.008	0.00049
Clover	0.688	1475.65	-0.01672
Watermelon	0.046	3873.61	0.00817

The dependence of wheat and watermelon production rates on the AOT40 index 3-month period (May-July) is not so strong where only 9% and 4.6% respectively of their production rate depends on respective AOT40 values. However, surface ozone effects on the yield of wheat plants grown under Mediterranean climatic conditions (without irrigation) are undoubtedly lower than expected[22]. Interestingly, the analysis of wheat and clover production rate data and precipitation values during their growing period (February-April) lead to stronger dependences where 21.1% of wheat and 49.9% of clover production rate can be associated to the precipitation values during their growing period.

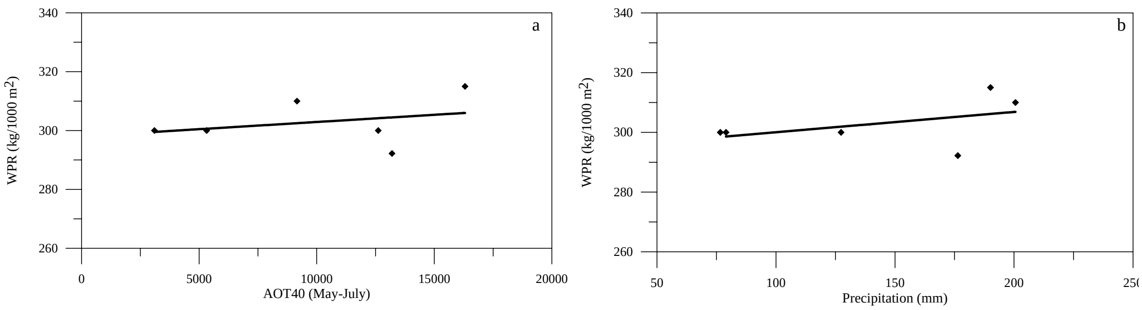

Figure 6: Production Rate of Wheat (kg per 1000 m^2) vs AOT40 (ppb*hour), During May-July (a), and Production Rate of Wheat (kg per 1000 m^2) vs Pecipitation (mm) During the 3-month Period February-April (b), at Aliartos for 1996 to 2001

From Table I it appears that, for May-July, using the linear model, only 4.6% ($r^2 = 0.046$) of variance of watermelon production rate could be attributed to the variation of the respective 3-month period AOT40 values. It is noteworthy to point out that ozone-induced losses on horticultural crops can be greater than expected, as surface ozone effects might be more apparent in early harvests when crop value is the greatest[44].

According to information presented in the scientific literature[2, 14, 25, 44] there is plenty of evidence that ambient surface ozone concentration in the Mediterranean region induce yield losses in the range 17-39% in crops such as wheat, beans, watermelon and tomato.

4. Conclusions

The hourly surface ozone concentrations measured at the rural station of Aliartos, continuously monitored for the 1996-2001 parcels, were examined in order to study both the seasonal and the diurnal variation. From this analysis the following conclusions can be drawn:

(i) The seasonal variation of surface ozone concentrations presents a minimum during the cold period of the year and a maximum during the warm period.

(ii) The mean diurnal variation of surface ozone concentrations at this rural measuring site has a single peak structure. This peak is observed between 13:00 - 16:00 LST in January, 11:00 - 19:00 in April, 10:00 - 20:00 in July, and 12:00 - 18:00 in October. The amplitude of the diurnal variation ranges from 13 to 30 ppb, for January and July respectively.

(iii) The morning peak during January is very small because of the weak UV-irradiance and the resulting photochemical production during the cold period of the year. On the contrary, the morning ozone peak for July is probably due to the local high photochemical ozone production during the daytime period in combination with the influence of air masses rich in ozone that arrive at Aliartos transported from various distances.

(iv) The analysis shows that ambient ozone concentration levels remain high in this Mediterranean rural measuring site and the ozone threshold (33 ppb as a 24-hour average) of European Union directive for damages to vegetation, is exceeded systematically for at least 6 months of the year (April - September), during the examined period.

(v) There is plenty of evidence that the AOT40 index values adversely affect crops such as horticultural crops that are normally irrigated. Under irrigated conditions, the variations of AOT40 index values can be linked with the variance of production rates at percentages such as 65.5% of cotton, 27.9% of tomato, and 4.6% of watermelon. However, AOT40 index effects on the yield of wheat and clover plants grown in the studied area, under Mediterranean conditions (without irrigation) are lower than those due to higher precipitation during the growing period (February-April).

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THE EFFECT OF WEATHER TYPES ON THE FREQUENCY OF CHILDHOOD ASTHMA ADMISSIONS IN ATHENS, GREECE

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Abstract

The aim of this study was to investigate the influence of weather conditions on the number of admissions for childhood asthma in Athens, Greece. Daily counts of childhood asthma admissions (2764) of the three main Children's Hospitals in Athens, from hospital registries during a 3-year period (2001-2003), were obtained. The meteorological data reviewed consists of daily values of 20 parameters recorded at the National Observatory of Athens during the study period: maximum temperature (T_{max}); minimum temperature (T_{min}); mean temperature (T_{mean}); diurnal temperature range ($T_{range} = T_{max} - T_{min}$); day-to-day change in maximum temperature (ΔT_{max}); day-to-day change in minimum temperature (ΔT_{min}); day-to-day change in mean temperature (ΔT_{mean}); day-to-day change in diurnal temperature range (ΔT_{range}); mean relative humidity (RH); day-to-day change in mean relative humidity (ΔRH); mean water vapor pressure (e); day-to-day change in mean water vapor pressure (Δe); mean atmospheric pressure at sea level (P); day-to-day change in mean atmospheric pressure (ΔP); mean irradiance (I); day-to-day change in mean irradiance (ΔI); mean sunshine (S); day-to-day change in mean sunshine (ΔS); mean wind speed (v) and day-to-day change in mean wind speed (Δv).

The performed statistical methods were: (i) Pearson's χ^2 test, using contingency tables and (ii) Factor and Cluster analysis. The application of this 2-part analysis revealed the relationship between the extracted weather types and the frequency of childhood asthma admissions in Athens. The results showed that weather conditions with low temperature, low water vapor pressure and cold anticyclonic presence were significantly correlated with an increase in the number of asthma admissions among children in Athens. The impact of these specific weather conditions on asthma exacerbation should be interpreted either by the asthmogenic effect of humid weather per se or the association with respiratory viral infection, mold's and mites' allergy.

Keywords: Childhood Asthma; Weather Types; Athens

1. Introduction

Childhood asthma is a common health problem associated with high morbidity burden. The worldwide increase in the incidence of asthma suggests that environmental factors may influence the seasonal variations in pediatric asthma. The weather conditions have been reported by several studies as risk factors in childhood asthma admissions (CAA).

Nastos P.T., Paliatsos A.G., Priftis K.N., Kaldellis J.K., Panagiotopoulou-Gartagani P., Tapratzi-Potamianou P., Zachariadi-Xypolita A., Kotsonis K., Kassiou K., Saxoni-Papageorgiou P., 2005, *"The Effect of Weather Types on the Frequency of Childhood Asthma Admissions in Athens, Greece", presented at the 13th International Symposium of MESAEP, Thessaloniki-Greece.*

Acute asthma and acute laryngitis, are correlated with the afternoon gradients of air temperature, heat content (the thermal energy of the ambient air), and modified heat content factor (the energy required to heat the air water vapor to the ambient temperature), but not correlated with the absolute values of air temperature and water content[1]. Low air temperature is associated with increased CAA[2-5]. Also, the asthma epidemic was significantly associated with a drop in air temperature six hours previously and a high grass pollen concentration nine hours previously. Non-epidemic asthma was significantly associated with lightning strikes, increase in humidity or sulphur dioxide concentration, a drop in temperature or high rainfall the previous day, and a decrease in maximum air pressure or changes in grass pollen counts over the previous two days[6]. Altitude and the annual variation of temperature and relative humidity outdoors were negatively associated with asthma symptoms[7], as well as admission to emergency room for asthma count was negatively correlated with ambient temperature and strong wind existence on previous days. It was also positively correlated with ambient relative humidity[8]. Hashimoto et al.[9] suggest that childhood asthma increases when climate conditions show a rapid decrease from higher barometric pressure, from higher air temperature and from higher humidity, as well as lower wind speed while the presence of mist and fog causes the exacerbation of asthma in children[10]. The occurrence of fog or liquid precipitation was associated with an increased number of asthma visits, while snow was associated with a reduced number ($P<0.05$)[11-12], as well as CAA found to be associated with high atmospheric pressure[13]. Furthermore, a study by Goldstein[14], showed that almost every asthma epidemic in both New Orleans and New York City, was preceded by the passage of a cold front (by one to three days) followed by a high pressure system.

Very large sferic densities are associated with moderate rises in hospital admissions for acute asthma. However, typical thunderstorm days are not associated with spectacular asthma epidemics of the scale previously reported in the literature. Thunderstorm-associated excesses are amplified after a run of high pollen counts[15]. In most patients symptoms began at the time of sudden climatic changes associated with a thunderstorm[16].

In this study, we try to find out the manner in which weather and childhood asthma are related. The first step is to determine the appropriate weather types in Athens and the second to examine the influence of these weather types to the incidence and severity of childhood asthma.

2. Data and Analysis

The medical data were obtained from the hospital registries of the three main Children's Hospitals of Athens for the 2001-2003 period. All children admitted with the diagnosis of "asthma", "asthmatic bronchitis" or "wheezy bronchitis", aged 0-14 years, living in the metropolitan area of Athens were included. There were 2764 asthma admissions in total during the entire study period.The males' admissions are almost 2fold the females' and there is an exponential decrease of the admissions as children grow up. Children's admissions at the age of one-year old come up to 556 (male) and 300 (female), while at the older age of fourteen, they count 16 (male) and 7 (female), as it is depicted in figure (1). Also, this pattern was found by Crighton et al.[17] studying asthma hospitalizations in Ontario, Canada. They suggest that young males (0-4 years) were hospitalized at two or three times the rate of females of the same age and rates were much lower in the older age groups.

The meteorological variables analysed, included daily values of 20 parameters recorded at the National Observatory of Athens during the period 2001-2003 and they are the following: maximum temperature (T_{max}); minimum temperature (T_{min}); mean temperature (T_{mean}); diurnal temperature range ($T_{range} = T_{max} - T_{min}$); day-to-day change in maximum temperature (ΔT_{max}); day-to-day change in minimum temperature (ΔT_{min}); day-to-day change in mean temperature (ΔT_{mean}); day-to-day change in diurnal temperature range (ΔT_{range}); mean relative humidity (RH); day-to-day change in mean relative humidity (ΔRH); mean water vapor pressure (e); day-to-day change in mean water vapor pressure (Δe); mean atmospheric pressure at sea level (P); day-to-day change in mean atmospheric pressure (ΔP); mean irradiance (I); day-to-day change in mean irradiance (ΔI); mean sunshine (S); day-to-day change in mean sunshine (ΔS); mean wind speed (v) and day-to-day change in mean wind speed (Δv).

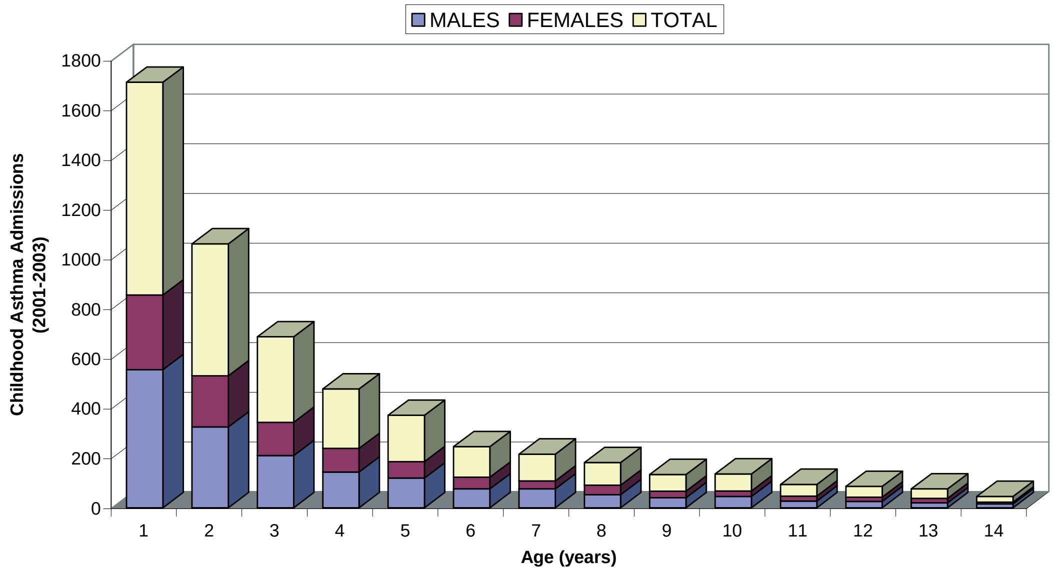

Figure 1: The Number of Childhood Asthma Admissions per Age for the Males, the Females and the Total

The relationship between CAA and the aforementioned meteorological parameters was calculated by the application of: a) Pearson χ^2 test, the most widely used method of independence control of groups in lines and columns in a table of frequencies and b) Factor Analysis (FA) and Cluster Analysis (CA). In the first step of the detailed statistical analysis, the values of each meteorological parameter were grouped in five quintiles, so that the first quintile contain the lowest 20% and the fifth quintile the highest 20% of the values. In the process, the number of days with 0, 1, 2, 3, 4 and 5 or more events of CAA in the Hospitals was calculated for each quintile and then a contingency table was constructed for every parameter. The Pearson χ^2 test was applied in each one of the 20 contingency tables, checking the null hypothesis that the quintiles of each meteorological parameter are not related (hence they are independent) to the number of CAA. The use of contingency tables instead of Pearson correlation considered more accurate, because the medical data present large divergence from a Gaussian (regular) distribution. In the second step of the performed analysis, the application of FA and CA to meteorological parameters resulted in seven weather types, which were examined for impacts to CAA. Table I presents the contingency tables for the mean air temperature and the mean water vapor pressure. It is clear that many days with 1 event of CAA appear within the fifth quintile of the mean air temperature and water vapor pressure (shaded values in the Table I). These findings are statistically significant (T_{mean}: χ^2= 247.15, df =20, p<0.001 and e: χ^2: 151.781, df=20, p<0.001).

The main applications of FA are to reduce the number of variables and to detect structure in the relationships between variables that is to classify variables. Therefore FA is applied as a data reduction or structure detection method. The data should have a bivariate normal distribution for each pair of variables, and observations should be independent. Therefore each of the *p* initial variables $X_1, X_2, \ldots, X_p$ can be expressed as a linear function of *m* $(m<p)$ uncorrelated factors: $X_i = a_{i1}F_1 + a_{i2}F_2 + \ldots + a_{im}F_m$ where $F_1, F_2, \ldots, F_m$ are the factors and $a_{i1}, a_{i2}, \ldots, a_{im}$ are the factor loadings which express the correlation between the factors and the initial variables. The values of each factor are called factor scores and they are presented in standardized form, having zero mean and unit variance[18, 19]. The number *m* of the retained factors has to be decided, by using various rules (eigenvalue ≥ 1, scree plot) and considering the physical interpretation of the results. Another important point of the analysis is the rotation of the axes, which maximizes some factor loadings and minimizes some others and in that

way a better separation among the initial variables is succeeded. Varimax rotation is generally accepted as the most accurate orthogonal rotation, which maximizes the sum of the variances of the square factor loadings, keeping the factors uncorrelated[20].

Table I: Number of Days With 0, 1, 2, 3, 4 and 5 or More Childhood Asthma Admissions in Relation to the Mean Air Temperature (T_{mean}) and Mean Water Vapor Pressure (e) Over 3-years Period (2001-2003)

Childhood Asthma Admissions/day						
T_{mean} (^oC)	**0**	**1**	**2**	**3**	**4**	**≥5**
1	22	38	43	32	41	43
2	15	43	44	40	26	53
3	24	29	39	44	26	55
4	47	53	41	39	10	33
5	94	75	28	14	1	3
Childhood Asthma Admissions/day						
e (mm Hg)	**0**	**1**	**2**	**3**	**4**	**≥5**
1	24	40	43	36	39	40
2	17	37	44	42	24	52
3	28	47	36	47	24	42
4	49	54	41	25	13	36
5	84	60	31	19	4	17

Cluster Analysis is a way of grouping cases of data based on the similarity of responses to several variables. In our analysis we applied the average linkage cluster analysis based on the calculation of the Euclidean distances of already standardized data[21]. It seems the most appropriate for our case as it has been proven that it gives the most realistic results in climatological studies[22].

The Euclidean distance between two values *i* and *j* is defined as:

$$D(i,j) = [\Sigma_\kappa(M(\iota,\kappa) - M(j,k))^2]^{1/2} \quad (1)$$

where M is the original matrix, $k = 1,\ldots, N$ are the different variables characteristics for the values to be classified and D the similarity matrix.

3. Results and Discussion

The medical dataset included 1736 male and 1028 female children within the age 1-14 years old. The mean monthly distribution of CAA (figure (2)) showed that increased admissions appear during the cold period of the year (October to March) with a peak in March. Afterwards, the CAA are decreased rapidly towards the minimum appeared in August. This pattern is similar to the seasonality of asthma admissions in Malta[4] and in Ankara, Turkey[8].

In order to reveal the relationship between CAA and each one of the examined meteorological parameters the χ^2 test was applied in each one of the 20 contingency tables, checking the null hypothesis that the quintiles of each meteorological parameter are not related (hence they are independent) to the number of CAA. The interpretation of the results suggests that many days with minimum CAA (1 event) coincide with the high (fifth percentile) values of T_{mean}, T_{max}, T_{min}, T_{range}, e, I, S and v. This relationship is statistically significant ($p<0.01$) and is in agreement with other researchers' findings[3, 9, 23]. Furthermore, on the days with maximum CAA (>5 events), the mean atmospheric pressure was higher (fifth percentile) and the relative humidity was lower (first percentile) than on days with minimum admissions and this is statistically significant ($p<0.01$). A relevant study by Ehara et al.[24], revealed the same relationship in Hakodate, Japan.

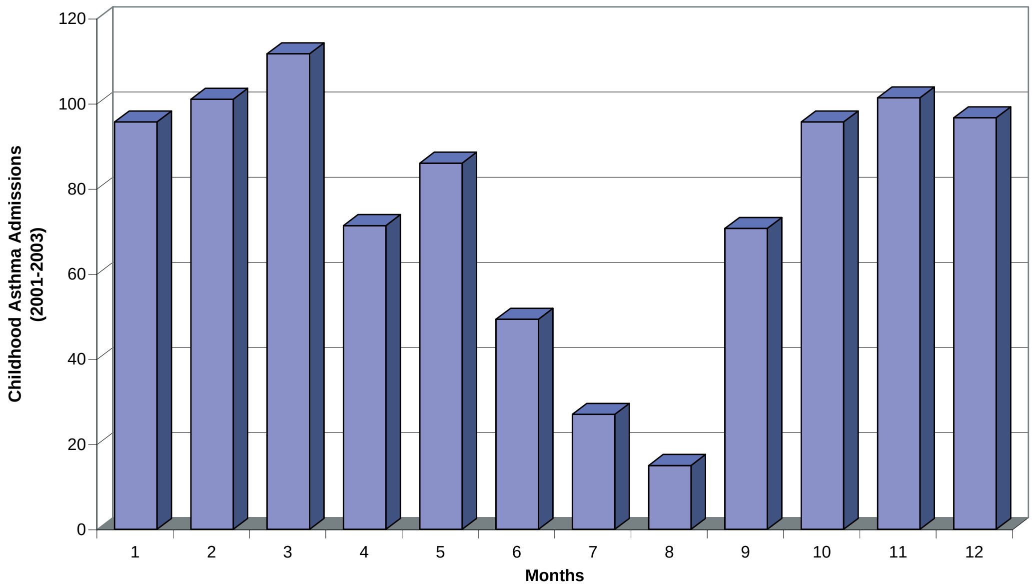

Figure 2: Mean Monthly Distribution of Childhood Asthma Admissions During the Years 2001-2003

Regarding the effects of the day to day changes in the examined meteorological parameters to CAA, no statistically significant relationship was found, with an exception of day-to-day changes in T_{min}, which influence CAA in such a way that high changes (Fifth percentile) in T_{min} are related to minimum CAA (1 event) and this is statistically significant ($p<0.01$).

In the process, FA was applied to the 20 meteorological parameters and resulted in 5 factors, which explained 80% of the the variability of the weather in Athens. Subsequently, CA was applied to the 1095 factor scores cases (days) in order to group them into classes of days with a characteristic type of weather and this procedure led to 7 clusters (Table II and III). These steps of analysis have been considered necessary by many researchers[25, 26, 27].

In order to reveal which weather type influences more the CAA, the χ^2 test was applied to a contingency table constructed by the number of days with 0, 1, 2, 3, 4 and 5 or more events of CAA in the Hospitals for each weather type (Table IV).

Weather types 1 and 2, occurred mainly during the warm period of the year, seem to be associated with low CAA. On the other hand, weather types 3-7, prevailed mainly during the cold period of the year, are responsible for worsening CAA. More specifically, the weather type 2, which is identified by high air temperature, high absolute humidity, high total solar radiation and sunshine, minimizes CAA, while the weather types 5 and 6, characterized by cold anticyclonic conditions after the passage of a cold front, are the drivers for the onset of high CAA. These findings are statistically significant ($p<0.01$), using the χ^2 test ($\chi^2=159.53$, df=30). Furthermore, Goldstein[14] studying the weather patterns and asthma epidemics in New York City and New Orleans, USA, concluded that a cold front (by one to three days) followed by a high pressure system was associated with asthma epidemics.

A more descriptive analysis is appeared in figure (3) where the relative frequency (%) of the CAA per 10-Days Interval as a function of the 7 weather types (clusters) along with the variation of the total number of admissions per 10-Days Interval (blue line) and the polynomial fitting (black line) are depicted in figure (3). The bars appeared in each interval represent the percentages of CAA associated with the particular weather types. It is well depicted that the weather type 2 (red colour) is associated with low CAA and weather types 5-6 (light green and orange) are mainly related with high CAA.

Table II: Mean Values of the Meteorological Parameters for Each Weather Type (Cluster)

Meteorological Variables	**Weather Types**						
	1	**2**	**3**	**4**	**5**	**6**	**7**
T_{max} (^oC)	23.37	32.46	17.77	21.15	17.07	18.91	18.37
ΔT_{max} (^oC)	-2.23	.33	-2.42	2.83	1.28	-1.60	.62
T_{min} (^oC)	16.14	22.17	11.34	12.53	9.11	12.73	12.45
ΔT_{min} (^oC)	-.47	.15	-2.59	-.23	-.25	.59	2.18
T_{mean} (^oC)	19.21	26.65	14.28	16.31	12.43	15.30	15.02
ΔT_{mean} (^oC)	-1.32	.22	-2.29	1.22	.38	-.35	1.38
T_{range} (^oC)	7.23	10.28	6.42	8.62	7.96	6.18	5.92
ΔT_{range} (^oC)	-1.75	.18	.17	3.06	1.53	-2.19	-1.56
RH (%)	50.06	50.08	73.95	67.86	65.10	69.70	72.52
ΔRH (%)	-8.34	.55	3.19	-6.30	-.27	6.86	1.37
e (mm Hg)	8.27	12.66	9.24	9.48	7.15	9.13	9.43
Δe (mm Hg)	-2.11	.29	-.77	-.29	.14	.79	.93
P (hPa)	1004.85	1001.19	997.36	999.77	1008.63	1006.75	1001.42
ΔP (hPa)	2.72	-.18	-1.57	-2.00	1.75	.17	-3.57
I (W m^{-2})	213.13	276.80	94.23	174.72	148.98	107.95	101.76
ΔI (W m^{-2})	16.11	.21	-19.27	79.21	19.30	-66.67	-19.39
S (hrs)	8.48	11.62	2.92	7.63	7.51	3.51	3.52
ΔS (hrs)	.52	.08	-1.08	5.29	1.80	-4.68	-1.90
v (m sec^{-1})	5.53	3.04	3.91	3.03	2.59	2.83	4.14
Δv (m sec^{-1})	1.79	-.19	.33	.01	-1.14	-.41	1.34

Table III: Weather Properties of the Seven Types (Clusters) Extracted for Athens

Weather Type	**Weather properties**	**Incident**
1	Low relative humidity, decrease of relative and absolute humidity, high wind speed, increase of barometric pressure and wind speed, decrease of daily air temperature range	Mostly during warm period of the year
2	High air temperature, high absolute humidity, high total solar radiation and sunshine	
3	Low pressure, low total radiation and sunshine, decrease of air temperature, increase of relative humidity	
4	Increase of daily air temperature range, increase of total solar radiation and sunshine	
5	High pressure, low air temperature, low absolute humidity and wind speed, decrease of wind speed	Mostly during the cold period of the year
6	Increase of relative humidity, decrease of total solar radiation and sunshine	
7	Increase of air temperature and absolute humidity, low daily air temperature range, decrease of pressure	

Table IV: Number of Days With 0, 1, 2, 3, 4 and 5 or More Childhood Asthma Admissions Related to the Weather Types Over 3-years Period (2001-2003)

Childhood Asthma Admissions/day						
Weather Types	**0**	**1**	**2**	**3**	**4**	**≥5**
1	14	25	28	19	12	17
2	118	109	53	47	13	34
3	14	15	12	8	12	22
4	7	11	14	20	9	15
5	23	34	36	42	33	44
6	9	26	22	20	18	33
7	10	18	29	12	7	21

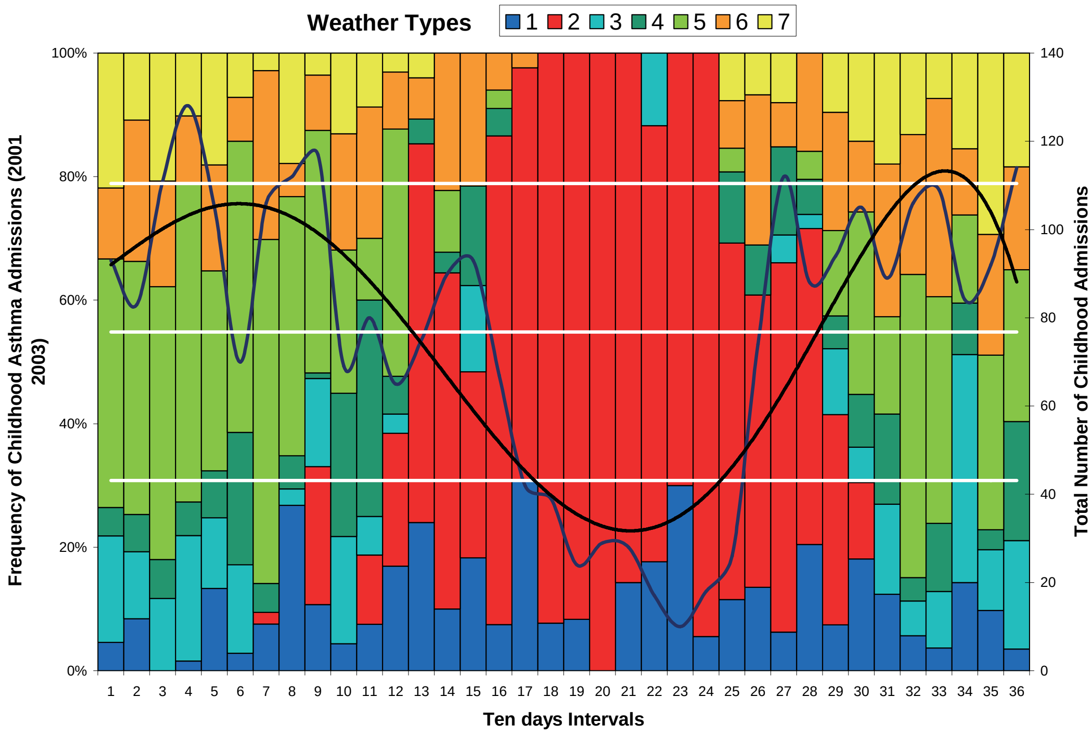

Figure 3: Relative Frequency (%) of the Childhood Asthma Admissions per Ten-Days Intervals as a Function of the Weather Types (Clusters) Along With the Variation of the Total Number of Admissions per Ten-Days Interval (Blue Line) and the Polynomial Fitting (Black Line). Three Reference Lines (White Lines) Concerning the Mean, the Mean+SD and the Mean-SD are Also Depicted.

4. Conclusions

The childhood asthma admissions in the Hospitals of Athens appear a seasonality with peak in March and minimum in August. The male children are more vulnerable to asthma than the female ones and the admissions are decreased rapidly as the time goes by and they are minimized at the age of fourteen.

The multivariate analysis applied to the meteorological and medical datasets revealed that there is a statistically significant negative relationship among daily mean, maximum and minimum air temperature, diurnal air temperature range, absolute humidity, mean irradiance, mean sunshine, wind speed and CAA. On the other hand, high atmospheric pressure and low relative humidity are the meteorological factors for increased CAA. Besides, it was found that the day-to-day changes of the examined meteorological parameters do not affect CAA, except T_{min} changes which influence negatively CAA.

In addition, the weather types (extracted by Factor and Cluster analysis) that are associated with high incidence of CAA appear during the cold period of the year. More specifically, the cold anticyclonic conditions are the most accountable for worsening CAA. On the contrary, weather types characterized by high air temperature, high absolute humidity, high total solar radiation and sunshine, are related to low CAA.

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DEVELOPING EFFICIENT TOOLS TO EVALUATE INDOOR ENVIRONMENT ISSUES: ON-SITE MEASUREMENTS AND NUMERICAL SIMULATION OF INDOOR AIR FLOW IN A TEST ROOM

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Abstract

Advance and efficient building design can be achieved by gathering information about air quality and the behavior of the airflow in the rooms of the building. An accurate understanding of indoor air distribution is crucial to the design of heating, ventilating, and air-conditioning installations that provide thermal comfort and indoor air quality. In this context, a full-scale test room was built with the purpose to conduct experiments under various test conditions to evaluate specific building issues, including different insulation materials and techniques, different heating/cooling/ventilation technologies, etc. The test room is located at the Technological Educational Institution of Halkida in the rural area of Psachna. The dimensions of the test room are 4m x 6m x 4m and its roof is covered with roman tiles and a radiant barrier reflective insulation system. The room is accessed from two doors located in the opposite walls and it is ventilated through these openings. The design and construction of the test room has been completed and the measurement plan has been organized to proceed with the measurements of the indoor air quality quantities in the test room. A three-dimensional steady state numerical model has been developed to describe indoor airflow in the room. Runs have already been conducted to study important issues including grid independence and application of the adequate turbulence model. Comparison of modeling predictions with preliminary experimental measurements shows that there is a sufficient agreement.

Keywords: Indoor Air Quality; CFD Model; Experiments

1. Introduction

Nowadays, indoor air quality and thermal comfort have become a crucial topic of concern. Indoor air quality affects human health and productivity in a significant way while proportions of respiratory illnesses and lung cancers may be caused by avoidable indoor pollution. Indoor air pollution may consist of compounds from different sources including environmental pollutants (tobacco smoke, radon), inorganic (CO_2, CO, etc.), organic (volatile organic compounds, VOCs), and biological agents (fungi, mites, etc.)[1]. Airflow within a room affects the emission rate at which contaminants emit into the air from sources within the room.

The options currently available to determine indoor airflow and quality are measurement and mathematical modeling[2-5]. A measurement plan should account for measurement of air velocity, temperature, humidity and pollutant concentrations. Simulation can determine and predict airflow and concentrations for all possible combinations of building and weather conditions. There are two main types of mathematical models: microscopic scale models (Computational Fluid Dynamics, CFD) that calculate the values of all relevant parameters at discrete points in the flow field with a high degree of resolution[5]; and macroscopic models (including multi-zone and zonal models) which assume that large zones of the building contain well mixed air and calculate flows between these zones[2-4]. Over

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the past decade there has been a substantial body of work completed using both methods to examine various aspects of indoor air flows, air quality and contaminant transport.

In the context of the above, the objectives and steps of this on-going research work are:

a. to explore and summarise the options for measurement of indoor air quality parameters with respect to accuracy, sensitivity and applicability
b. to review the current capabilities in the numerical simulation of indoor air flow
c. to develop efficient simulation tools for the evaluation of indoor air quality in a test room developed for the research purposes
d. to perform systematic measurements in the test room according to the existing standards that can be used for comparison with simulations, and as a final stage
e. to perform a cost-effective analysis to show the linksbetween improvements in the indoor environment and the potential financial benefits.

An extended literature review has already been carried out to explore existing measurement methodologies and techniques to assess indoor air flow and quality as well as to review the situation in the related modeling area. The design and construction of the test room has been completed and the measurement plan has been organized to proceed with the measurements of the indoor air quality quantities in the test room. Preliminary measurements have been obtained for air velocity and temperature. A three-dimensional steady state numerical model has been developed to describe indoor airflow in the room. Various cases have been considered accounting for isothermal and non-isothermal conditions. Runs have been conducted to study important issues including grid independence and application of the adequate turbulence model. Comparison with preliminary experimental results shows that the model predicts with sufficient accuracy the air flow in the test room

2. Experimental Part

2.1 Description of the Test Room

Aiming to the validation of the computational simulation and for the conduction of systematic experimental measurement plan the test room of figure (1) has been designed and constructed at the premises of the Technological Educational Institution of Halkida located in the agricultural area of Psachna.

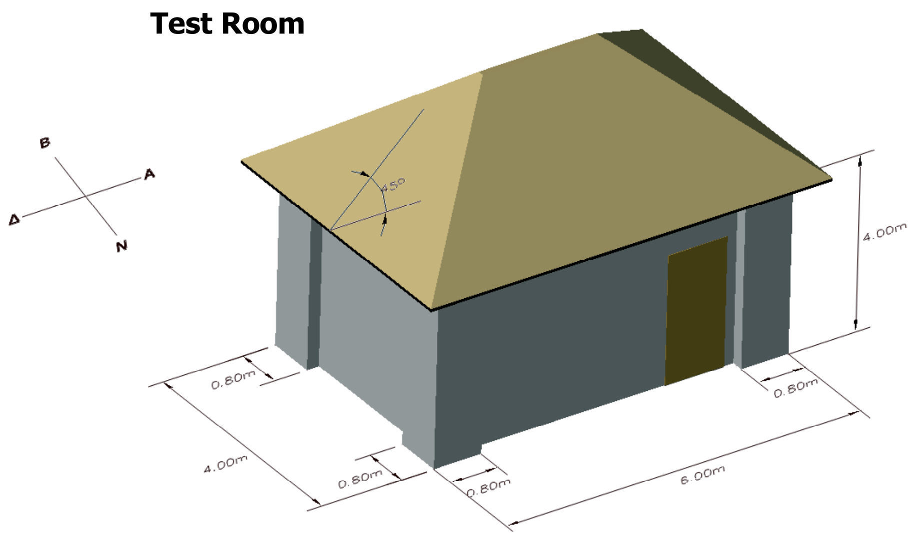

Figure 1: Outside View of the Test Room

The dimensions of the test room are 4m x 6m x 4m and its roof is covered with roman tiles and a radiant barrier reflective insulation system. The side walls are a two series brick construction with a bubble material laminated between layers of aluminum foil placed in the 20mm gap of the brick layers. The side wall total thickness is 210mm including a 20 mm thickness of the wall sheathing in each side. The selection of the above mentioned insulation materials used in residential construction in attics, walls, ceilings, and radiant floor heating applications is due to the requirement for an excellent thermal resistance regarding the shell of the test room. Two doors are located in the north and south-facing walls and the room is ventilated through these openings. A small partition with the height of 1m is located at the north wall.

2.2 Experimental Plan

The experimental plan focuses on the measurement of air velocity, temperature and at a later stage pollutants concentration that describe the flow field characteristics and the contaminant level in the test room considered. Detailed measurements of indoor air flow are difficult to accomplish because similar to numerical simulations behavior at the boundaries of rooms (e.g. walls, internal partitions) can have a large effect on the fluid motion. The selection of the sampling method for use in conducting indoor air studies depend on the research objectives, the contaminants of concern and the required sampling duration which should be representative of occupants' exposure time. In the current phase of the implementation of the experimental plan certain air quality measurements that are indicative of common indoor air quality concerns, such as temperature and indoor air flow have been obtained. The air velocity and temperature were measured at several strategic locations in the test room, e.g. close to the inlet, close to the outlet, at the middle of the room and at other locations in the test room as recommended by the ASHRAE standard[6]. Air velocity has been measured with the KIMO VT 200 hot wire anemometer. Hot wire anemometry has been widely used to measure air velocities in buildings. The advantages are that it provides high resolution in time and space, and is able to measure velocity, and turbulence intensity in time and space. The accuracy of the measurements is estimated at ±3% of reading ±0.03m/s.

3. Model Development

3.1 Introduction

An extended literature review of indoor airflow models has been carried out to investigate their advantages and limitations. There are two main methods for simulating indoor airflow and pollutant levels, macro models and micro models. Macro models include multi-zone models and zonal models. In multi-zone models[4] uniform conditions inside a room (zone) are assumed and the airflow is modeled through links or flow paths between zones. The network of links is described by a set of equations that are solved simultaneously to provide a converged solution. In zonal models[3,5] the room interior is divided into a small number of zones or cells and the mass and heat balance equations are applied to them. The solution of the set of coupled equations provides the air flow and temperature distribution in the room. Micro models refer to Computational Fluid Dynamics (CFD) that was deployed for the simulation of indoor airflow after the development of the first code by Nielsen[7]. In this type of models the equations are discretised in order to solve the flow field numerically. Multi-zone models are considered easier, and cheaper to use than CFD models, however, as they assume the air inside a room is uniformly mixed, they cannot be used to predict local air velocities or concentrations variations inside rooms. In this context, in the present work the CFD approach has been adopted.

3.2 The Physical Problem and its Mathematical Formulation

3.2.1 The Governing Equations

For the case of isothermal conditions the simulation of the indoor airflow in the test room of figure (1) the equations that describe the conservation of mass and momentum in three dimensions are solved. In the non-isothermal case the energy equation is also solved. The steady state conservation equations for the dependent variable φ (for continuity equation $\varphi=1$, for momentum equations $\varphi=u,v,w$, for energy equation $\varphi=T$) may be written in the general form[8] of:

$$\mathrm{div}\left(\rho\vec{u}\phi\right) = \mathrm{div}\left(\Gamma_\phi \mathrm{grad}\phi\right) + S_\phi \quad (1)$$

where ρ, is the mixture density, $\vec{u}$, is the velocity vector, Γ_ϕ, is the effective exchange coefficient and S_ϕ, is source rate per unit volume. These governing flow equations are highly non linear and to obtain their solution it is necessary to use numerical techniques.

Airflow in the test room is normally three-dimensional, recirculating and turbulent. Because the turbulent fluctuations affect the transport of momentum and energy they must be included in the formulation and solution of the eq. (1). Turbulence transport models account for the influence of turbulence on the time-mean motion. The job of the turbulence model is to calculate the distribution of the eddy viscosity (μ_t) throughout the flow domain. For the numerical simulation of the turbulent flow inside the test room four turbulence models have been tested: the standard k-ε model, the RNG k-ε model, the realizable k-ε model and the Spalart-Almaras model provided by Fluent®. The standard two-equation k-ε turbulence model involves the solution of two additional partial differential equations for the turbulent kinetic energy (k) and its dissipation rate (ε)[9-10]. The values of the constants C_μ, C_1, C_2, σ_κ and σ_ε applied are 0.09, 1.44, 1.92, 1.0 and 1.3 respectively[9-10]. The RNG k-ε model is essentially a variation of the standard k-ε model, with the used constants estimated rather through a statistical mechanics approach than from experimental data. The values of the constants C_μ, C_1 and C_2 applied are 0.0845, 1.42 and 1.68, respectively[11]. For the realizable model the term "realizable" means that the model satisfies certain mathematical constraints on the Reynolds stresses, consistent with the physics of turbulent flows. The realizable k-ε model contains a new formulation for the turbulent viscosity. Also, a new transport equation for the dissipation rate, ε, has been derived from an exact equation for the transport of the mean-square vorticity fluctuation[12].

Traditionally there are two approaches for modeling of the near-wall region. In the first approach, the viscosity-affected inner region is not resolved. Instead a wall function is used to bridge the viscosity-affected region with the fully turbulent region. In the second approach, the turbulence model is modified to enable the viscosity-affected region to be resolved with a mesh all the way to the wall (enhanced wall treatment). In Fluent® there are three different models to choose between for calculating the flow behavior near the wall: i) standard wall function, ii) non-equilibrium wall function and iii) the enhanced wall treatment. Models i) and iii) were tested.

In the isothermal case fluid properties are held constant with values corresponding to a room temperature of about 305.5K. The air density is 1.16kg/m^3 and the viscosity 1.79e-5 kg/(m.s). In the non-isothermal case effects of buoyancy were modeled based on the Boussinesq-approximation. This model treats density as a constant value in all solved equations, except for the buoyancy term in the momentum equation. The model is valid as the temperature differences in the domain are not large.

3.2.2 Grid Development

The applied coordinate system and the respective grid used in the simulations is shown in figures (2a), (2b). A quite large number of grid sizes have been tested and it has been concluded that a grid independent solution is possible when the computational domain is discretised with approximately 86925 tetrahedral grid cells (figures (2a), (2b) and (3)).

The type of grid used is ideally suited for the discretisation of complicated geometrical domains and allows an exact description of the test room geometry. As the flow field is a complex one, therefore there is no advantage in using a hexahedral (structured) mesh since the flow is not aligned with the mesh. Furthermore, the grid can be refined without adding unnecessary cells in the other parts of the domain as happens in the structured grid approach (hexahedral cells).

3.2.3 Boundary Conditions

The equations are solved with boundary conditions at the air inlet and outlet, and on the internal surfaces and any obstructions in the test room.

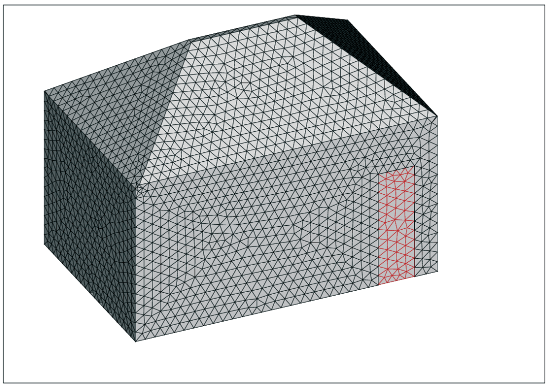

Figure 2a: View of the Grid Employed

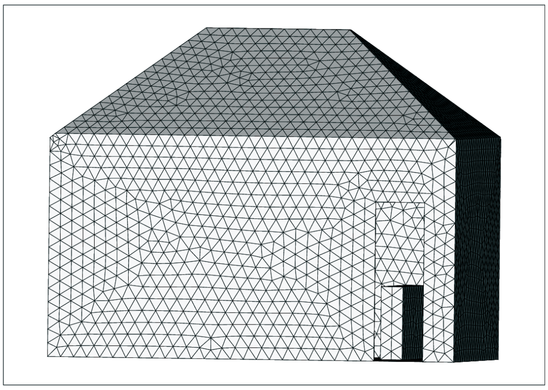

Figure 2b: View of the Internal Wall in the Grid Employed

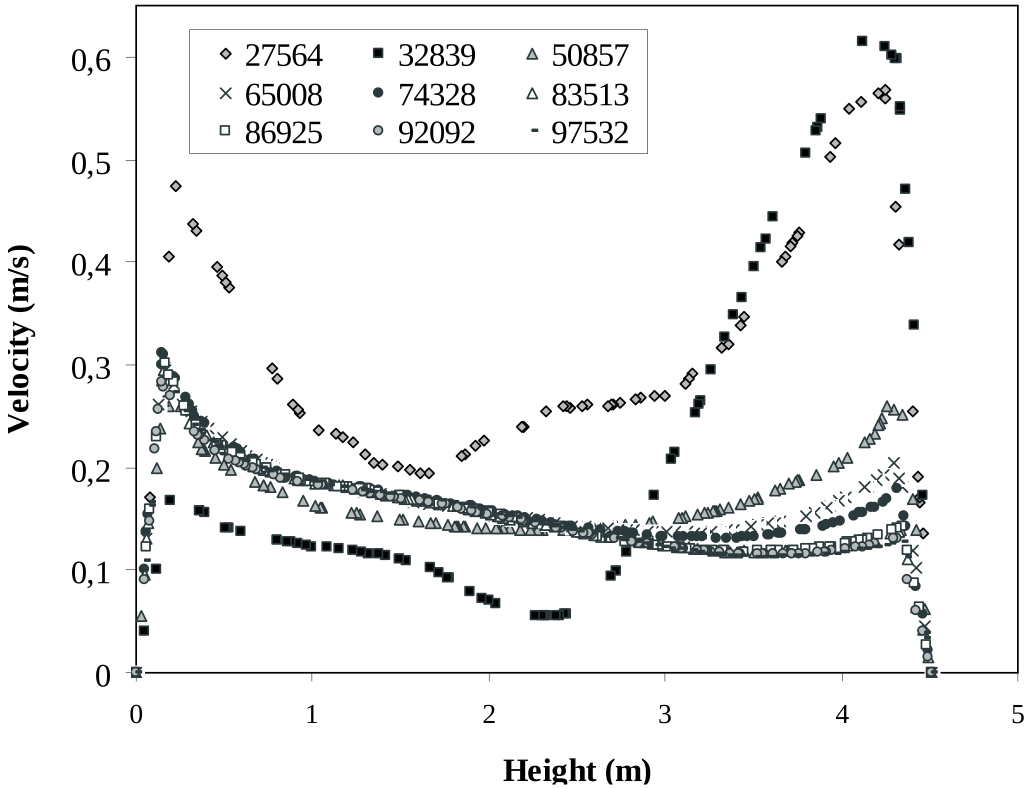

Figure 3: Velocity Profile at the Middle of the Room (X=2.97, Y=2.03) for Different Grid Sizes. Inlet Airflow Rate=2.18kg/s. Isothermal Conditions.

Inlet-Outlet: Various inlet airflow rates assuming uniform inlet velocity profile have been applied (0.5-2.5kg/s) with inlet temperature T_{in}=305.5K. However, various factors, including a temperature difference between the room and supply air, may create velocity profiles at the inlet which are far from uniform. In the cases studied the two doors located in the opposite walls of the test room are considered open, thus air enters the room through the one door and leaves through the other. In all cases the inlet air direction was taken to be normal to the inlet. Values for the turbulent kinetic energy, k_{in} (m^2/s^2), and dissipation rate, ε_{in} (m^2/s^3) at the inlet were found from literature[5]. At the outlet, zero reference pressure has been specified. The kinetic energy of turbulence (k) and its dissipation rate (ε) at the outlet are not required due to the upwind computational scheme used.

Walls: As the walls are impermeable, the normal velocities are zero at the boundaries. Two options were checked: 1) The boundary conditions at the walls for velocity components and k-ε are specified using the logarithmic wall functions[10]. The standard wall function has been found to work reasonably well. 2) Enhanced wall treatment which is a near-wall modeling method[13] that combines a two-layer model with enhanced wall functions.

In the non-isothermal case a fixed temperature condition is applied at all the internal walls equal to T_w=302K.

3.2.4 Computational Details

The solution of the set of the equations together with the boundary and internal conditions has been made with the segregated steady-state solver[12] embodied in Fluent® commercial software. Because the governing equations are non-linear (and coupled), several iterations of the solution loop must be performed before a converged solution is obtained. In addition, the presence of internal wall in the flow may introduce an additional stability problem during the calculation. For pressure-velocity coupling Fluent® provides three methods in the segregated solver: SIMPLE, SIMPLEC, and PISO. SIMPLE has been used in all cases studied.

Because of the non-linearity of the problem the solution process is controlled via relaxation factors that control the change of the variables as calculated at each iteration. The convergence is checked by several criteria (e.g. the conservation equations should be balanced; the residuals of the discretised conservation equations must steadily decrease).

4. Results and Discussion

In this section typical results of the research work presented above are shown and discussed. In figures (4) and (5) the computed velocity profile assuming isothermal conditions is shown at the middle of the room and close to the west side using the three different turbulence models.

As it is shown there are important differences between the predicted results. The RNG k-ε and Spalart-Almaras models predict higher velocities in the roof area. The standard k-ε model with standard wall functions and with enhanced wall treatment, and the realizable k-ε model give almost the same results. The applicability of the turbulence model that will be used for the simulation of indoor airflow in the test room will be decided after comparison with systematic experimental measurements that have already been scheduled for the next steps of the work. First results show that the standard k-ε model with standard wall functions predicts sufficiently the air flow in the test room. In figure (6) the computed velocity profile at the middle of the room (x=2.97, y=2.03) for various airflow rates is shown for isothermal conditions. In all cases studied, the velocity is higher closer to the floor level decreasing with height increase and slightly increasing in the roof area.

For the validation of the numerical predictions a number of measurements have been conducted. These measured values were used for setting the boundary conditions in the numerical predictions, in order to achieve comparable conditions to the experiments. As it is shown in Table I both models predict velocity magnitude with sufficient accuracy and the non-isothermal model seems to give slightly better predictions. This is due to the fact that the temperature difference inside the room is quite small thus its influence is small in the calculation of the flow field. In Table II typical values of temperature at various points inside the test room are presented. The model predicts with sufficient accuracy temperature especially over the height of 1m.

Next steps of this work focus on further improvement of the model and additional validation of numerical predictions on indoor air flow. Also, as measuring and predicting the air velocity and temperature alone is not sufficient to assess the quality of air in the indoor environment it is planned to study and other parameters including pollutant concentrations and humidity.

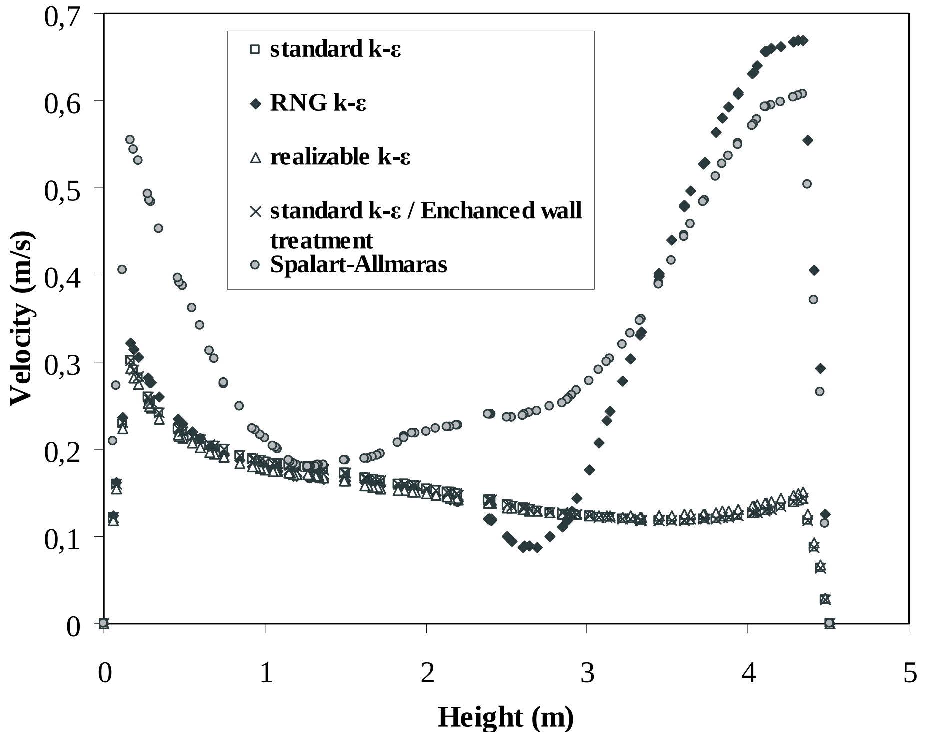

Figure 4: Velocity Profile at the Middle of the Room (x=2.97, y=2.03) Using Various Turbulence Models. Inlet Airflow Rate=2.18kg/s. Isothermal Conditions.

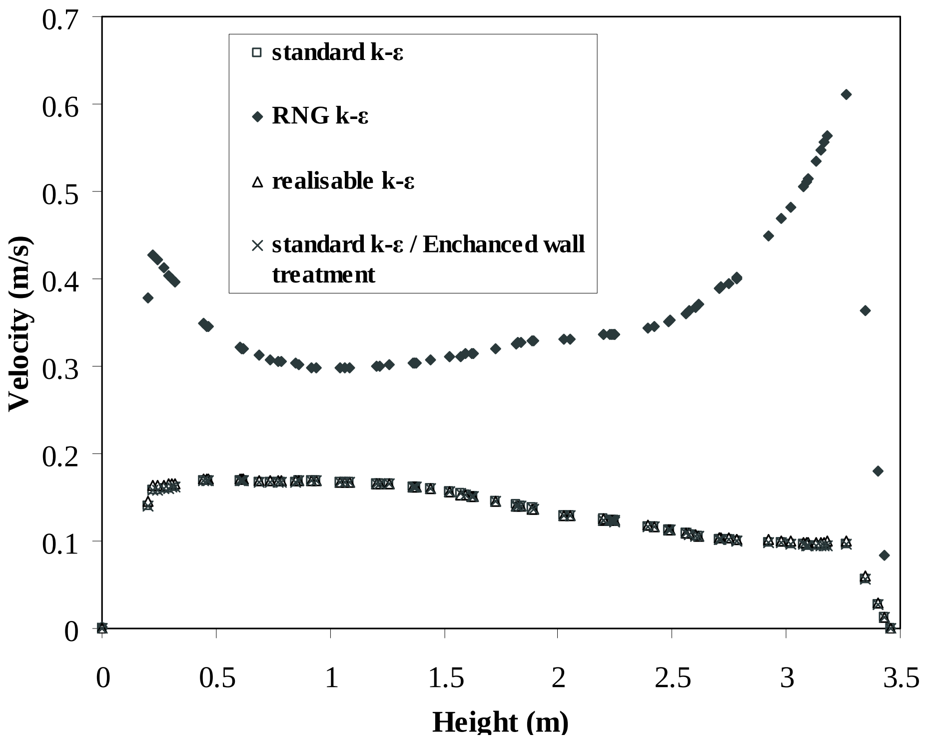

Figure 5: Velocity Profile Close to the West Side (x=0.7, y=2.03) Using Various Turbulence Models. Inlet Airflow Rate=2.18kg/s. Isothermal Conditions.

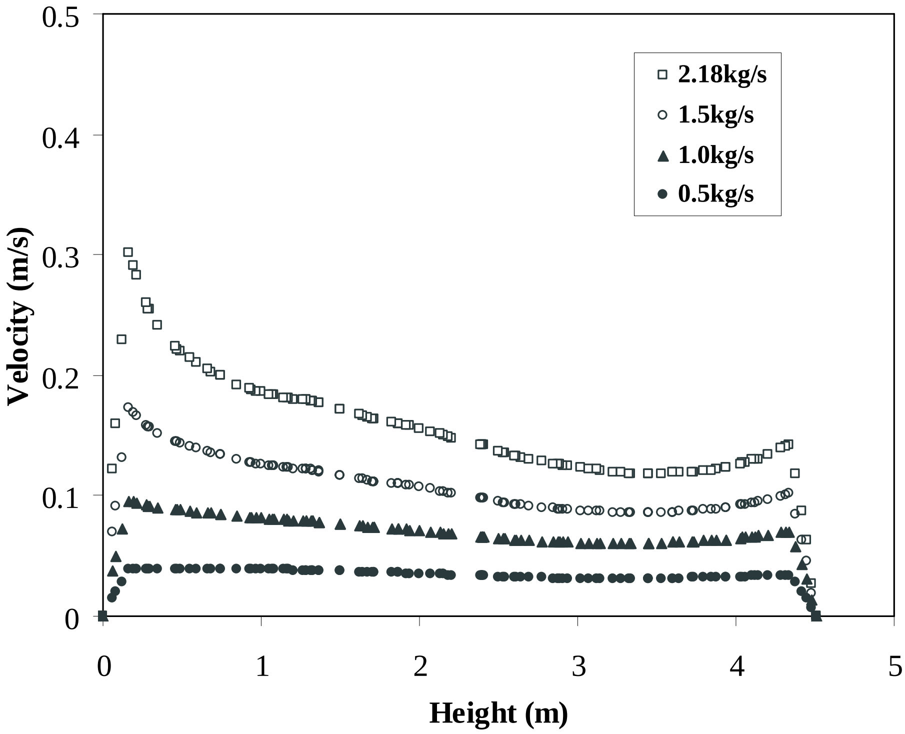

Figure 6: Velocity Profile at the Middle of the Room (x=2.97, y=2.03) Using Various Inlet Feed Rates. Isothermal Conditions

Table I: Model Validation. Typical Values of Velocity Magnitude at Various Points Inside the Test Room. Inlet Airflow Rate=2.18kg/s. T_{in}=305.5K
1: Middle of the test room
2: Close to the west side (x=0.7,y=2.03)

	Distance from the floor (m)	Isothermal Model (m/s)	Non-Isothermal Model (m/s)	Measurement (m/s)
1	0.20	0.28	0.28	0.30
1	2.60	0.13	0.10	0.12
1	3.00	0.12	0.21	0.22
2	0.50	0.16	0.29	0.24
2	1.00	0.16	0.27	0.17
2	2.00	0.12	0.28	0.14

Table II: Model Validation. Typical Values of Temperature at Various Points Inside the Test Room. Inlet Airflow Rate=2.18kg/s. T_{in}=305.5K
1: Middle of the test room
2: Close to the east side (x=5.3,y=2.03)

	Distance from the floor (m)	Non-Isothermal Model (K)	Measurement (K)
1	1.00	304.84	303.9
1	1.60	304.89	304.8
1	2.00	304.92	304.5
2	0.50	304.80	304.5
2	1.00	304.87	305.5
2	1.50	304.92	305.5

5. Conclusions

A full-scale test room was built with the purpose to conduct experiments under various test conditions to evaluate specific building issues. The measurement plan has been organized to proceed with the measurements of the indoor air quality quantities in the test room. Preliminary measurements have been obtained for air velocity and temperature. A three-dimensional steady state numerical model has been developed to describe indoor airflow in the room. Various cases have been considered accounting for isothermal and non-isothermal conditions. Comparison with preliminary experimental results shows that the model predicts with sufficient accuracy the air flow in the test room.

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PART FIVE

AIR POLLUTION

- Electricity Sector
- Power Stations Planning
- Islands Electrical Networks

DETAILED EXAMINATION OF GREEK ELECTRICITY SECTOR NITROGEN OXIDES EMISSIONS FOR THE PERIOD 1995-2002

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Abstract

The importance of energy in economic development has been globally recognised. A considerable electricity consumption increase has taken place in Greece subsequent to the country's incorporation in the European Union. Unfortunately, the electricity generation up to now is mainly based on fossil fuels. As a direct result of this policy, electricity generation is one of the main contributors to the Greek air-pollutant emissions. The present work is focused on investigating in detail the corresponding nitrogen oxides emissions for the period 1995-2002. One of the most negative observations resulting from the presented analysis is the undesirable NO_x emissions factors increase, mainly during the last three years of the analysed period. On top of this, the annual NO_x emissions continue increasing, as a result of the noteworthy electricity consumption amplification registered the concerned period. Therefore, local data were compared with similar information from the literature regarding other territories and then used accordingly to evaluate the Greek compliance with the existing E.U. decisions (e.g. Directive 2001/80/EC). Finally, considering that more than 90% of the national electricity production is based on carbon containing fuels, further emissions of nocuous nitrogen oxides increase is expected for the next decade, unless the appropriate abatement technologies will be promptly applied.

Keywords: Electricity Generation; Thermal Power Station; Nitrogen Oxides; Emissions Factor; Air Pollution

1. Introduction

The importance of energy in economic development has been globally recognised, since historical data confirm a strong relationship between the energy consumption and economic expansion. In Greece, subsequent to the country's incorporation in the European Union, a considerable energy consumption increase has taken place in view of the local economy amplification and standard of living improvement [1,2]. Considering that electricity is one of the most user-friendly energy resources in modern societies, the corresponding national production "E" (practically coincides with consumption) presented[3] an almost parabolic variation (i.e. $E=28.182y^2-110,869.251y+109,057,119.953$, $R^2 \approx 99\%$, *y=1980 to 2002 and E in MWh*) during the period 1980-2002, see figure (1). Thus far, unfortunately, the electricity generation is mainly based on fossil fuels, i.e. low quality locally extracted lignite and imported heavy-oil[4]. In this context, the contribution of renewable energy sources (mainly wind) and large hydropower units rated less than 10% during the entire period examined[5,6].

As a direct result of this fact, electricity generation is one of the main contributors to air-pollutants emissions in the country[7]. More specifically, according to several official reports[8,9,10], Greek electricity production sector 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. As a country member of the E.U., Greece has accepted specific obligations concerning the reduction of the greenhouse gas emissions[11] and concerning the protection of population from the dangerous toxic effects of various harmful gases[12] and particles release, like nitrogen oxides, sulphur dioxide etc. It is, therefore, very important

Kaldellis J.K., Vlachos G.Th., Paliatsos A.G., Kondili E., 2005, *"Detailed Examination of Greek Electricity Sector Nitrogen Oxides Emissions for the Last Decade", Journal of Environmental Science and Policy, Vol.8/5, pp.502-514.*

for national purposes to evaluate the time series concentrations of all these flue gases emitted by the power stations of the corresponding national electricity generation sector.

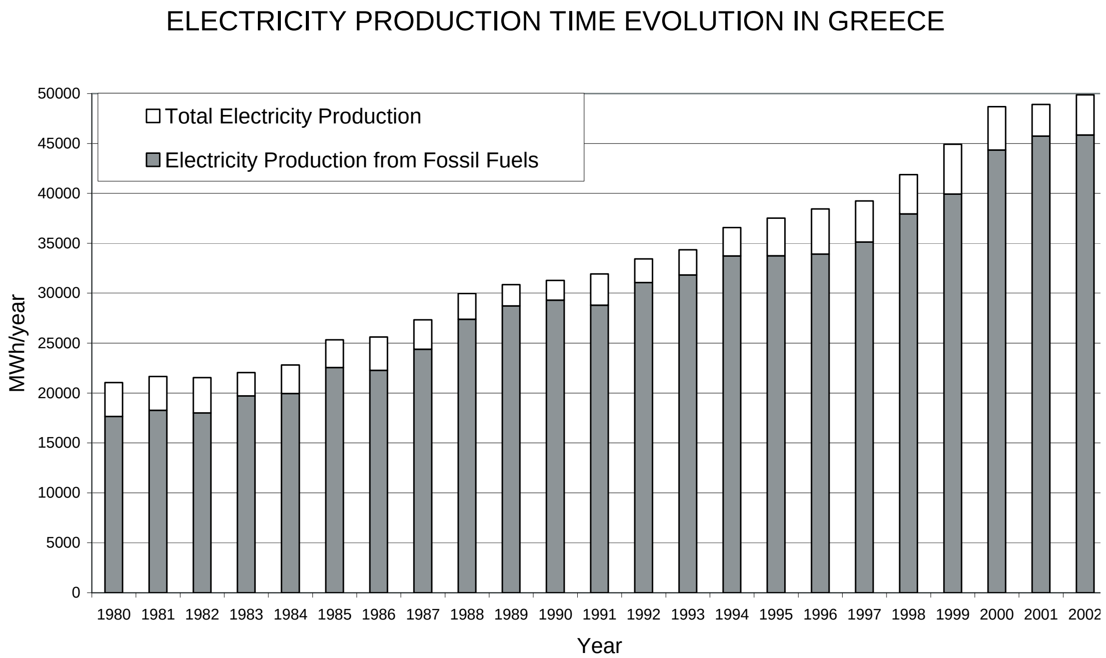

Figure 1: Electricity Production from Fossil Fuels in Comparison with Total Electricity Generation in Greece (1980-2002)

It is worth mentioning that -since eighties- the European Community has come to a decision on NO_x emissions by power installations in the framework of Directive 88/609/EC on the limitation of certain pollutants emissions from Large Combustion Installations. In addition to the above-mentioned air pollutants, several other flue gases -like carbon monoxide, volatile organic compounds and particulate matters (PM)- are equally characterized as dangerous air pollutants. However, the contribution of electricity production sector to carbon monoxide and volatile organic compounds is limited[13], while only recently a systematic recording of particulate matters production by local Thermal Power Stations (TPS) has commenced[14].

As already mentioned, electricity generation impact on the national sulphur oxides production is dominant, while its contribution on the nitrogen oxides production is moderate. Despite this fact, however, the "NO_x" emissions present a more rapid escalation than the "SO_2" ones (figure (2)), following the growth of energy requirements. More precisely, nitrogen oxides production is increasing with development of economy, while the usage of sulphur-rich fuels is typically decreasing with transfer to high tech economy. Hence some authors[15] suggest the investigation of the ratio of "NO_x" to "SO_2" emissions as an index characterizing the pollution and economy structure, figure (2). The "N/S" ratio could be considered as an indicator of economy development. For all these reasons, the work presented here is focused on investigating in detail the corresponding nitrogen oxides emissions for the last decade[16,17]. Collected local data is first compared with relative information regarding several other territories found globally in the literature and then used accordingly to evaluate the country’s compliance with the existing E.U. decisions (e.g. Directives 2001/80/EC and 2001/81/EC), also considering a simple forecast of the expected air pollutants production for the near future.

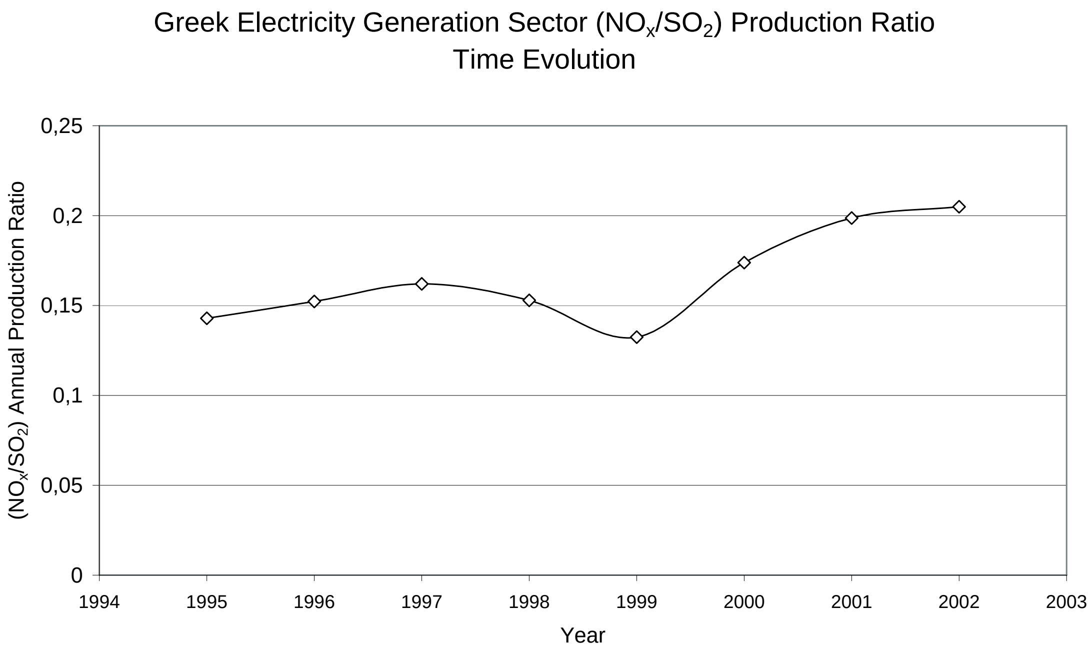

Figure 2: (NO_x / SO_2) Emission Ratio from Greek Electricity Generation System

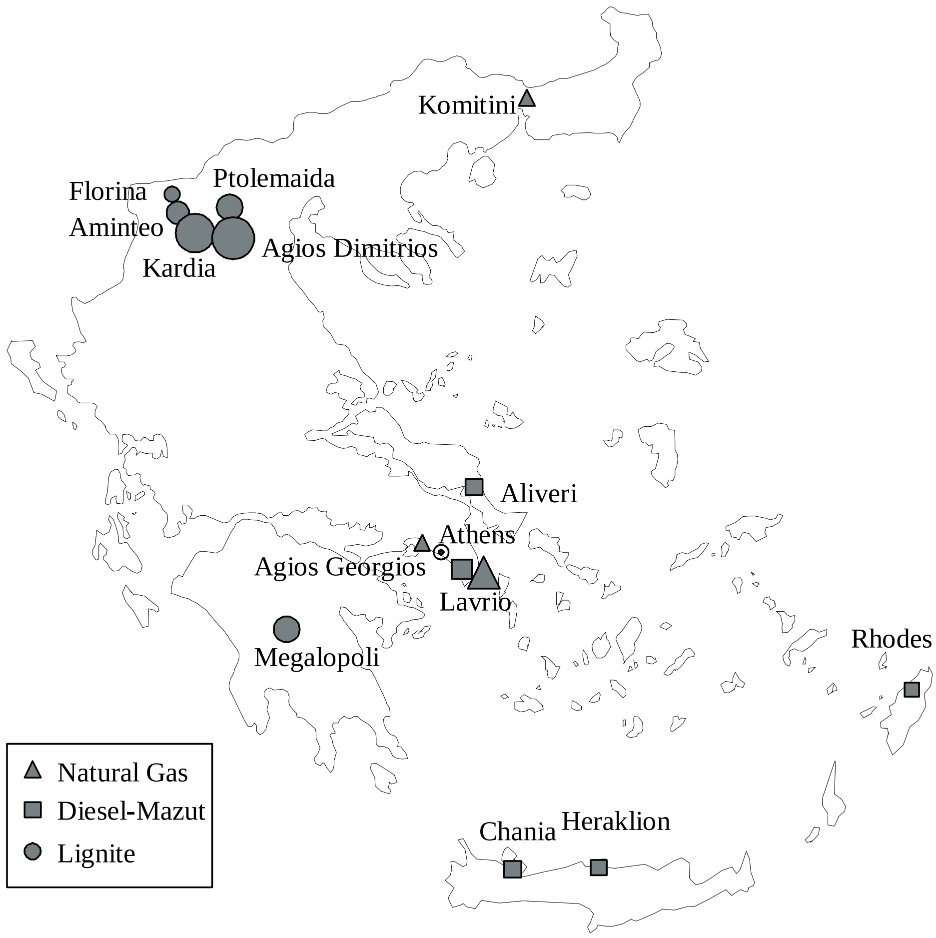

Figure 3: Greek Major Thermal Power Stations, 2002

2. Greek National Electricity Generation System

The Greek Electricity Generation System (EGS) is normally divided in two branches. The first one includes the interconnected mainland electricity production network based on eleven large-scale power stations (total capacity of 7200MW), using local lignite, imported heavy fuel oil and natural gas, figure (3). Fifteen large hydropower stations in conjunction with several other small hydropower units belong to this main branch. It has been built throughout the mainland[6] with a total capacity of 3100MW. Finally, during the last five years, several wind parks have been erected -mainly in Southern Euboea and Thrace- with total capacity approaching the 280MW[5].

The second branch includes 35 medium-small Autonomous -diesel and heavy fuel oil fired- Power Stations (APS) spread out all over the Aegean Archipelago[17]. Belonging to this group are also considered the medium sized -heavy fuel oil fired- power stations of Crete and Rhodes islands (540MW+210MW). On top of this, wind parks of rated power higher than 100MW are operating throughout the Aegean Sea, partially exploiting the excellent wind potential of the area[18].

In the study presented here, only attention was paid to the thermal electricity production plants (Table I), as they are among the major air pollutants sources[19] of the country. More specifically, major Greek thermal power stations are cited in Table I, where -for every TPS- one may find the rated power along with the number of units, the fuel used, the location and the operation start up time. The national electricity production center is located in West Macedonia[2], see figure (3), where the four biggest TPS (Agios Dimitrios, Kardia, Aminteo and Ptolemaida) are operated with the local lignite deposit reserves. In Southern Greece, a lignite-fired station operates in Megalopolis (Peloponesse), while in central Greece one may find a heavy-oil-fired station in Aliveri of Euboea and two natural gas-fired TPS in the Attica major region -where Athens is located, see figure (3). A new gas-fired (combined cycle) station operates in Komotini (Thrace), while a lignite-fired one in Florina (NW Macedonia) has recently joined the national EGS[16].

Furthermore, a total power capacity of 400MW of mazut-fired (heavy fuel oil) medium and small size power stations and another 750MW of small diesel fired internal combustion engines should be considered. These power stations are located in the numerous Greek islands of Aegean Archipelago, including Crete and Rhodes islands[17,18].

To understand what is the contribution of each fuel-type used in the Greek electricity production sector, figure (4) displaying the time-series of national electricity generation during the last decade is presented. The figure considers the TPS examined and the type of fuel used. After a thorough investigation of figure (4), the main conclusions drawn were the following:

- There is a significant electricity production (and consumption) increase during the last decade, going from 36,000GWh in 1994 to almost 52,000GWh in 2003.
- Two thirds (2/3) of the national electricity generation was realized in Western Macedonia, on the basis of local lignite, where the TPS of Agios Dimitrios, Kardia, Aminteo and Ptolemaida are located.
- The contribution of renewable energy sources to the national electricity production -including the large hydro power stations of the mainland- is limited and slightly decreasing during the period examined, with respect to the total amount of energy sources.
- A noticeable natural gas contribution is encountered during the last five years of the examined period.
- The contribution of imported heavy fuel-oil in the local EGS is remarkable (≈15%), despite the penetration of natural gas into mainland network. This could be explained by the exponential electricity consumption increase of Greek islands.
- The contribution of Southern Greece lignite to the local electricity production is practically constant during the entire period analysed, i.e. approximately 5000GWh per year.

Table I: Basic Characteristics of Greek Major Thermal Power Stations

Power Station	Power Unit	Start Up	Rated Power MW	Fuel Used	Location
Liptol	I	1959	10	Lignite	W. Macedonia
	II	1965	33		
Ptolemaida	I	1959	125	Lignite	W. Macedonia
	II	1962	125		
	III	1965	300		
	IV	1973	300		
Kardia	I	1975	300	Lignite	W. Macedonia
	II	1975	300		
	III	1980	300		
	IV	1981	300		
Agios Dimitrios	I	1984	300	Lignite	W. Macedonia
	II	1984	300		
	III	1985	310		
	IV	1986	310		
	V	1997	366.5		
Aminteo	I	1987	300	Lignite	NW. Macedonia
	II	1987	300		
Megalopolis-A	I	1970	125	Lignite	Peloponessos
	II	1970	125		
	III	1975	300		
Megalopolis-B	IV	1991	300	Lignite	Peloponessos
Aliveri	I	1953	40	Mazut	Euboea
	II	1953	40		
	III	1968	150		
	IV	1969	150		
Lavrio	I	1972	150	Mazut	Attica
	II	1973	300		
	IV	1996	174	Diesel/ Natural Gas	
	New	2002*	570		
Agios Georgios	VIII	1997	160	Natural Gas	Athens
	IX	1998	200		
Florina	I	2002*	330	Lignite	NW. Macedonia
Komotini	I	2002*	492	Natural Gas	Thrace
Linoperamata	Various	1965	253	Mazut-Diesel	Crete
Chania	Various	1969	330	Diesel	Crete
Rhodes	Various	1967	208	Diesel	Rhodes
APS (Autonomous Power Stations)	Various	1967	547	Diesel-Mazut	Aegean Archipelago

(*) The station has been operating, during 2002, under initial testing rates

One should also bear in mind that during the observed period there were no solid fuel imports for electricity production, while only a small portion from the almost 100,000,000 barrels of crude oil imported annually was used for electricity generation. On the other hand, more than one billion cubic meters of natural gas per year (representing almost 1/3 of the current national imports) were consumed by the existing TPS covering approximately 15% of the national electricity demand. Finally, only a small portion (≈ 3.5%) of the national annual electricity demand is covered by electricity imported from neighbouring countries.

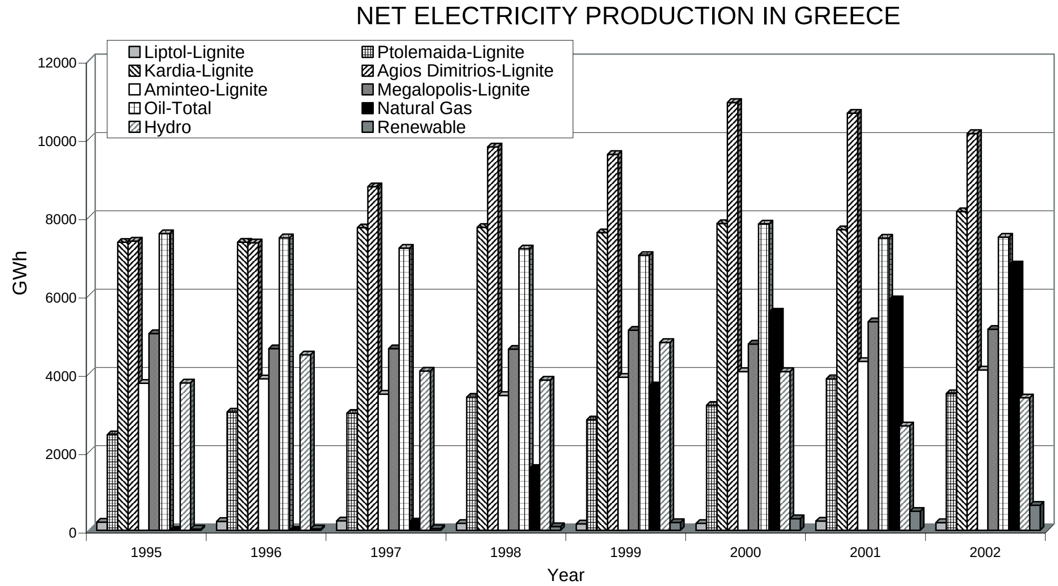

Figure 4: Time-Series of National Electricity Generation and Fuel Sources for the Period 1995-2002

3. Time Evolution of Electricity-Related Nitrogen Oxides Annual Emissions

The burning of fossil fuels releases several flue gases, like nitrogen oxides, sulphur dioxide, carbon dioxide, etc. The study presented here -concentrated on the electricity generation sector- is focused on investigating the time-series of nitrogen oxides "NO_x" production from local power stations. More precisely NO_x is a collective term used normally to describe two types of oxides, namely nitric oxide (NO) and nitrogen dioxide (NO_2). In some cases small amounts of (N_2O) are produced, while this specific flue gas is said to participate in global warming, being over 310-times more effective (nocuous) than CO_2. Both oxides NO_x (NO, NO_2) result from the reaction between nitrogen and oxygen in very high temperatures like inside car combustion chambers, power stations, industries and central heating systems. Note that this chemical reaction gives a 95% NO and only a 5% NO_2. It is also interesting to note that the NO is a colourless, flammable and odourless gas, which is not a real pollutant by itself. However, it is easily transformed to NO_2 -one of the most dangerous gases[20]. The NO_2 has a brown-red colour and a very characteristic annoying smell. NO_2 plays a major role in the atmospheric reactions that produce ozone and smog, while in the atmosphere NO_2 is mixing with water vapour producing nitric acid. Hence, NO_2 is one of the prime gases appearing in photochemical smog and contributing in ground level ozone formation, being also assumed responsible for the acid rain[21,22].

According to official data[16,17], Greek EGS is found responsible for an annual production of more than 70ktn of nitrogen dioxide during the years 1995 to 2002, marginally violating the E.U. emissions ceilings concerning the limitation of "NO_x" production from large combustion installations (2001/80/EC). In addition, one cannot disregard the remarkable time variation of NO_x annual production presenting a minimum in 1999 due to the remarkable natural gas penetration replacing heavy fuel-oil of high sulphur content. figure (5) shows that after 1999 the NO_x production increased gradually, despite the introduction of natural gas in the local market. Note that, as shown in figure (2), the NO_x increase rate is steeper than the SO_2 one.

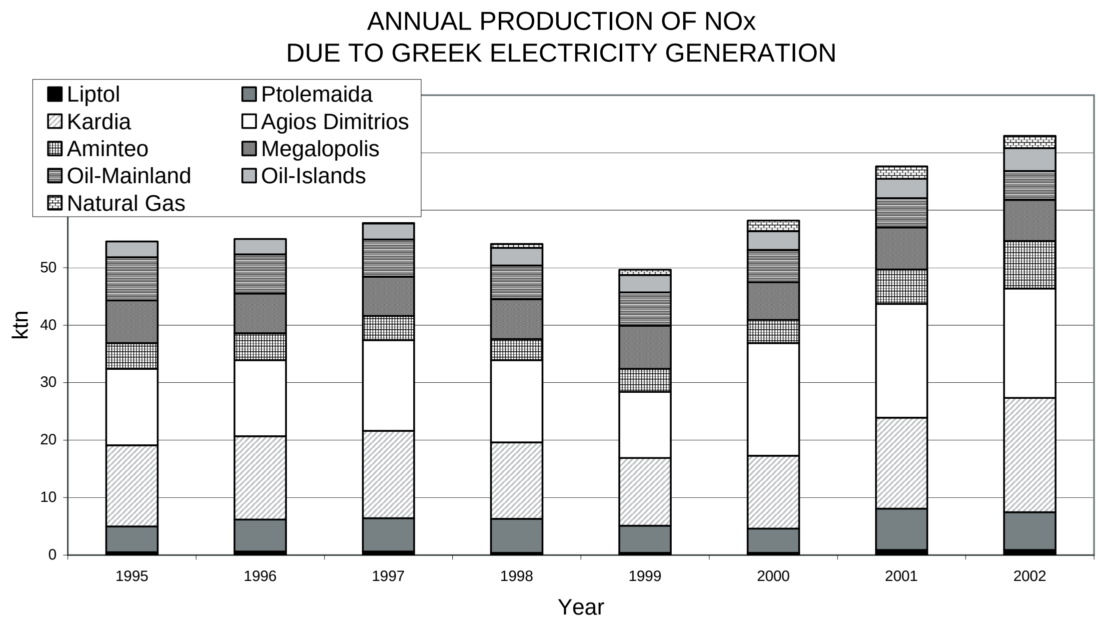

Figure 5: Annual Emissions of Nitrogen Oxides (NO_x), Attributed to Greek Power Stations for Electricity Generation.

Examining the available information more carefully, one should stress the fact that the Northern Greece lignite fired TPS produced more than 80% of the sector's annual production, although the contribution of natural gas cannot be neglected. One should also keep in mind that the Southern Greece lignite fired TPS produced only a small part of sector NO_x emissions (9-10%), while the contribution of oil-fired TPS approached the 15%. Finally, it should be pointed out that the two biggest national TPS (i.e. Agios Dimitrios 1600MW and Kardia 1200MW) are together responsible for almost 50% of the NO_x annual release. Nevertheless, during the last three years of the studied period, a considerable NO_x production increase has been observed from the operation of these two TPS.

4. Electricity Generation NO_x Emissions Factors

Using information taken from sections 2 and 3 of this work, it is possible to investigate the specific air pollution factors of every Greek thermal power station as a function of time, concerning the NO_x emissions for the studied period. In order to get a distinct picture of the electricity related NO_x air pollution burden on every consumer, an attempt is made to express the NO_x production in relation to 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 TPS and line transmission losses (1%-5%) from the TPS to the main consumption centers. Thus, the coefficients given are expressed in gr (or kg) of NO_x released per kWh consumed. For this purpose one may use measurements concerning the annual flue gas emissions of every thermal power unit of Greek EGS along with the corresponding net electricity generation, modified in order to estimate energy line transmission losses.

Thus, the NO_x emissions factor "e_j" of the "j" TPS can be defined as:

$$e_j = \frac{(m_{NO_2})_j}{E_j} \qquad (1)$$

where "$(m_{NO2})_j$" is the annual mass production of equivalent "NO_2" and "E_j" is the annual energy yield of the "j-th" TPS, including line transmission losses.

Calculation results shown on figure (6), concerning the Agios Dimitrios 1600MW TPS (consisting of 5 units), indicate a considerable time variation of the corresponding emissions factors on an annual basis. However, a continuous increase can be observed after 1999, excluding the second unit of the TPS, where a new DENOX system is recently (2002) installed. More precisely, the NO_x reduced emissions factors range between 1.0gr/kWh to almost 2.0gr/kWh during the last decade. It is also interesting to mention that all five units -including the latest one built in 1997- show an almost identical tendency (until 2001), mainly due to the similar characteristics of the lignite consumed. This remarkable NO_x emissions value becomes even more important due to the fact that Agios Dimitrios is the biggest Greek power station, presenting an annual utilization factor in the order of 70%.

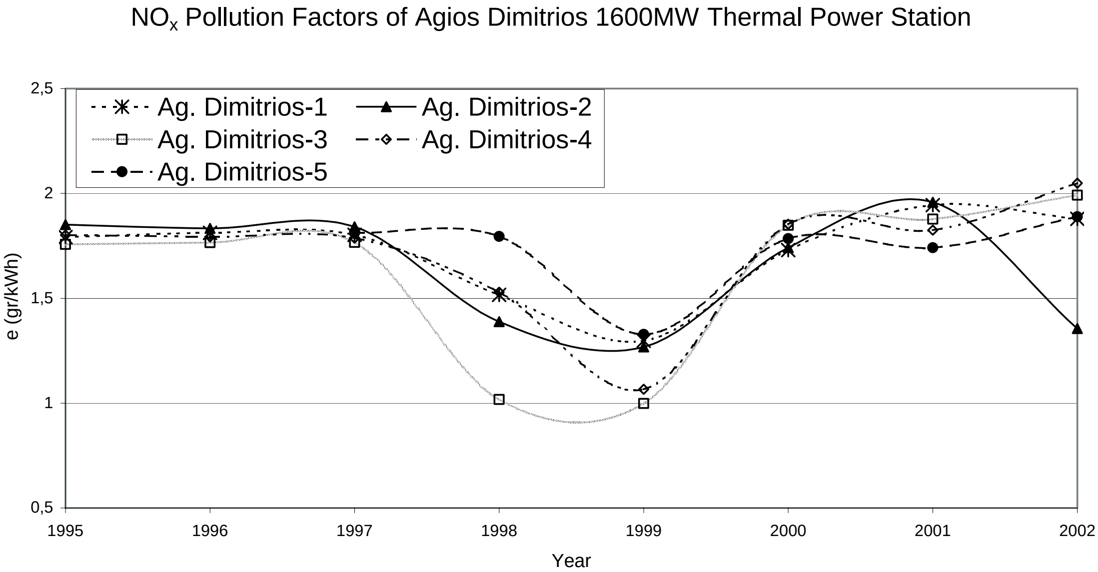

Figure 6: Time Series of NO_x Emission Factors for the Agios Dimitrios Power Station (1600MW)

Subsequently, from the data presented in figure (7), one may examine the NO_x time-series emissions factors of Kardia 1200MW TPS units. As previously, a substantial expansion of emissions factors has been observed after 1999 -mainly due to low quality of fuels used- pushing the corresponding values above 2.5g/kWh by 2003. Note that all four Kardia units cover base load (utilization factor over 70%), while their thermal efficiency is almost constant (≈ 33%) during the period examined.

Similarly, the four units of Ptolemaida 620MW TPS were investigated, see figure (8). Using the calculation results obtained from official measurements[16], one may observe a remarkable time variation of NO_x emissions factor for all four-power units. On top of this, remarkable discrepancies appear even between the units of the power station self. As a result of this, all the Ptolemaida units' emissions factors approach the 2.0gr/kWh during the last three years presented. At this point, one should consider the difference in size and age between these stations, see also Table I. In addition -according to information provided by PPC- these units were periodically renovated during 1999-2001, including maintenance of the existing abatement technologies, in an attempt to keep Ptolemaida TPS in accordance with the Large Combustion Plant Directive (2001/80/EC) emissions limits for existing plants.

Next, the last three lignite-fired TPS of Northern Greece are analysed, including the two Aminteo units (2x300MW) and the Liptol (10MW+33MW) power station. Liptol is the oldest TPS of all lignite fired Greek TPS, operating since the fifties. After 2000, the Liptol corresponding NO_x emissions factor time series present a dramatically increasing tendency, although during the previous years its emission factor values remained almost constant, see figure (9). Similarly, the Aminteo TPS emissions factor, being by far the lowest in Northern Greece (1.1gr/kWh up to the year 2000), also presents a remarkable amplification after 2000. Thus, following this tendency, by the year 2003 the NO_x emissions factor value would exceed the 2.2gr/kWh -a negative evolution on the environmental impact- attributable to the local electricity generation sector.

Subsequently, the NO_x emissions factor time series distributions for the Southern Greece's lignite-fired TPS are given in figure (10). Using the information provided, the three Megalopolis-A units (550MW) present slightly decreasing NO_x emissions factor values, approaching the 1.2gr/kWh.

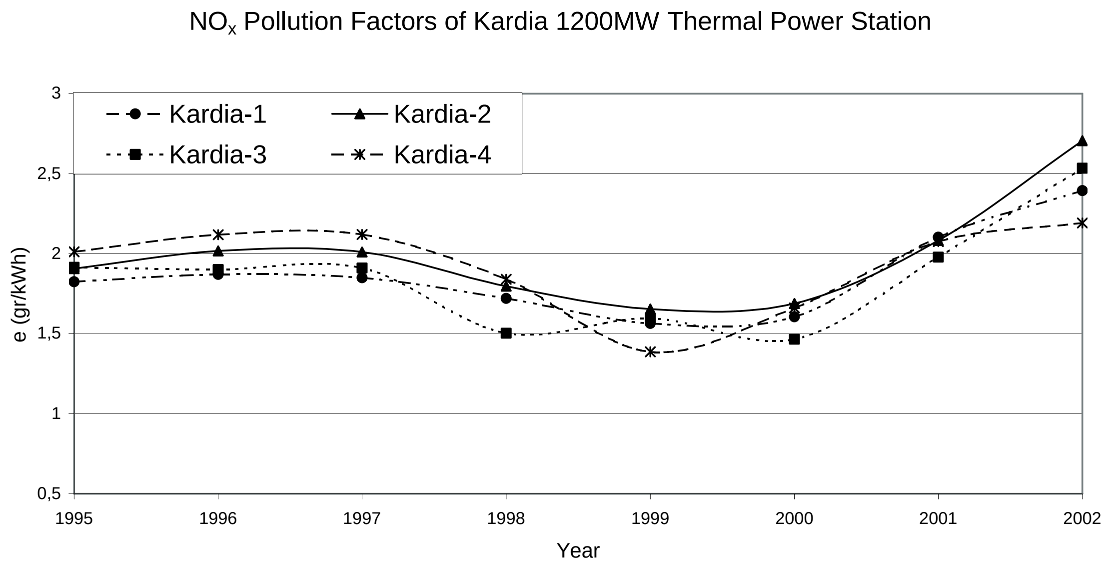

Figure 7: Time Series of NO_x Emission Factors for the Kardia Power Station (1200MW)

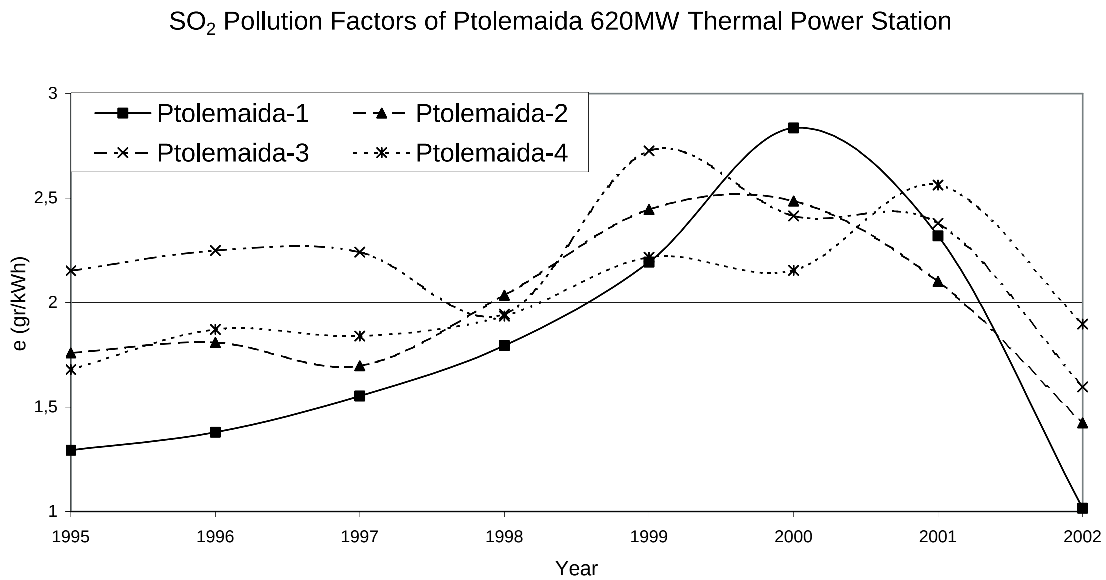

Figure 8: Time Series of NO_x Emission Factors for the Ptolemaida Power Station (620MW)

Exception to the tendency is shown by the Megalopolis-B (300MW) power station, with a gradually increasing emission factor values, approaching the level of 2.0gr/kWh by 2003. Finally, in figure (11) one may find the NO_x emissions factor time series for the oil fired (located in the mainland and the islands) and the natural gas fired TPS. More specifically, the oil-fired TPS shows an almost constant emission factor as a function of the time. Similarly, the natural gas fired TPS emission factor curve shows a relatively constant distribution, slightly oscillating around 0.4gr/kWh.

Summarizing, in figure (12) one may find the time series of the NO_x emissions factors of all Greek major TPS (see also Table I). As explained before, the NO_x emission factors of the Greek TPS show

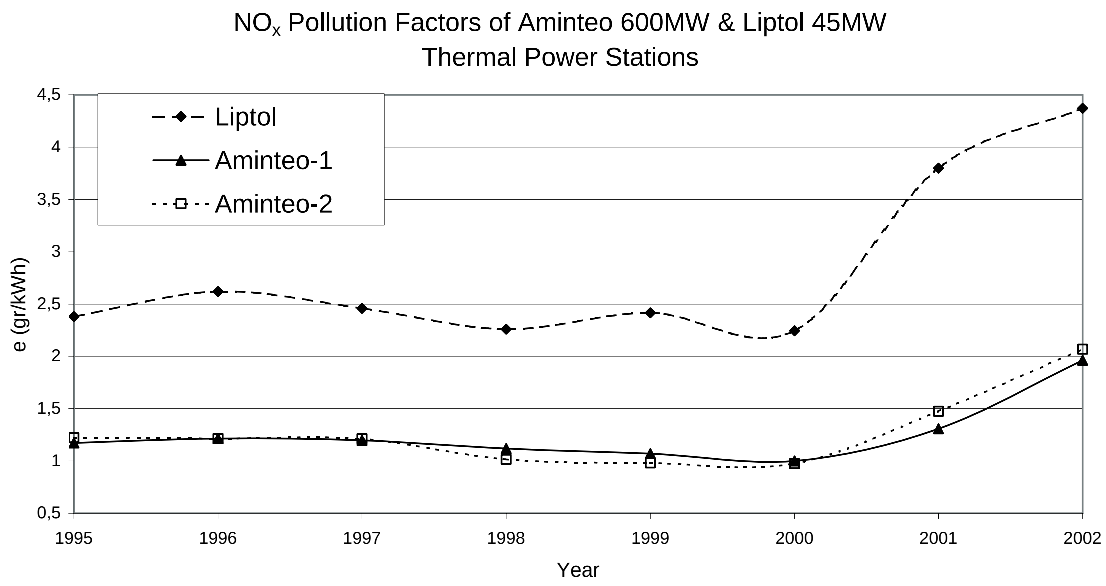

Figure 9: Time Series of NO_x Emission Factors for the Aminteo (600MW) and Liptol (45MW) Power Stations

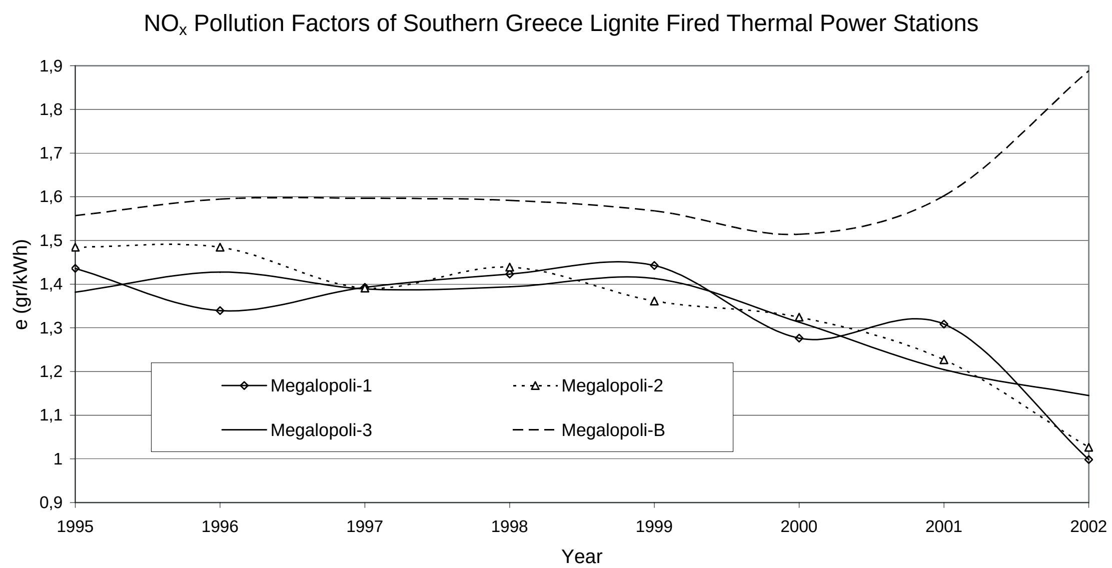

Figure 10: Time Series of NO_x Emissions Factors for the Southern Greece's Lignite-Fired Power Stations

slightly variable distributions, with exception of Liptol small old-fashioned TPS, see figure (9). More specifically, the following remarks are made:

- The total TPS (weighted) emissions factor presents a fair time oscillation, thus after a remarkable decrease during the years 1998 and 1999, it rises again from the year 2000 exceeding the 1995 value, i.e. 1.6gr/kWh.
- The above-mentioned increase may be explained by the corresponding increase of the Northern Greece TPS emission factors, which represent the main (65%) national electricity generation.
- On the other hand Southern Greece emissions factors remain almost constant for the entire period investigated. It is interesting to note that the new Megalopoli TPS produces higher NO_x quantities than the old units per kWh produced, since they use different lignite deposits. In fact, Megalopolis-A emission factors show a decreasing trend after 1999.

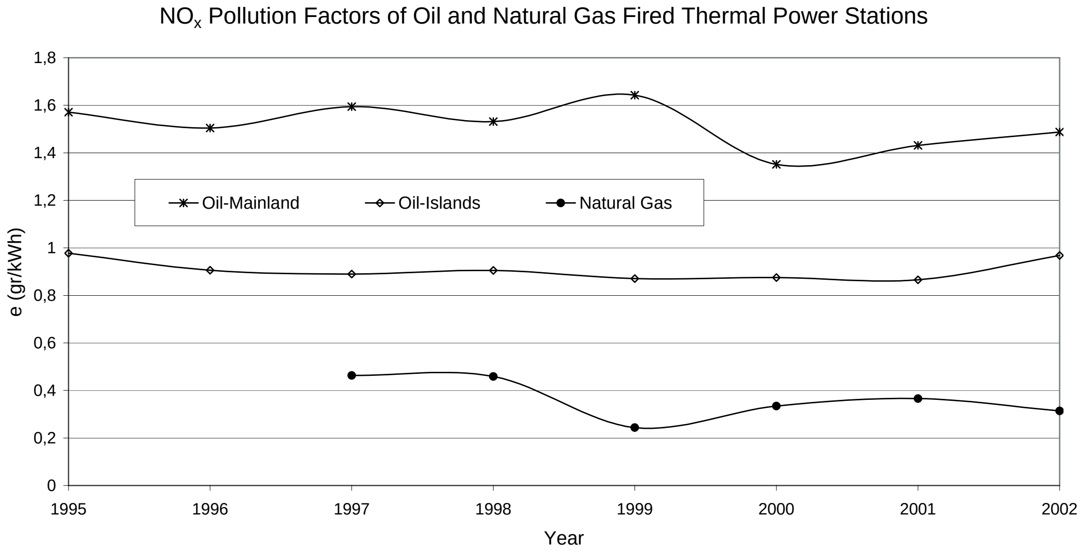

Figure 11: Time Series of NO_x Emissions Factors for Oil-Fired (Mainland and Islands) and Natural Gas Fired Power Stations

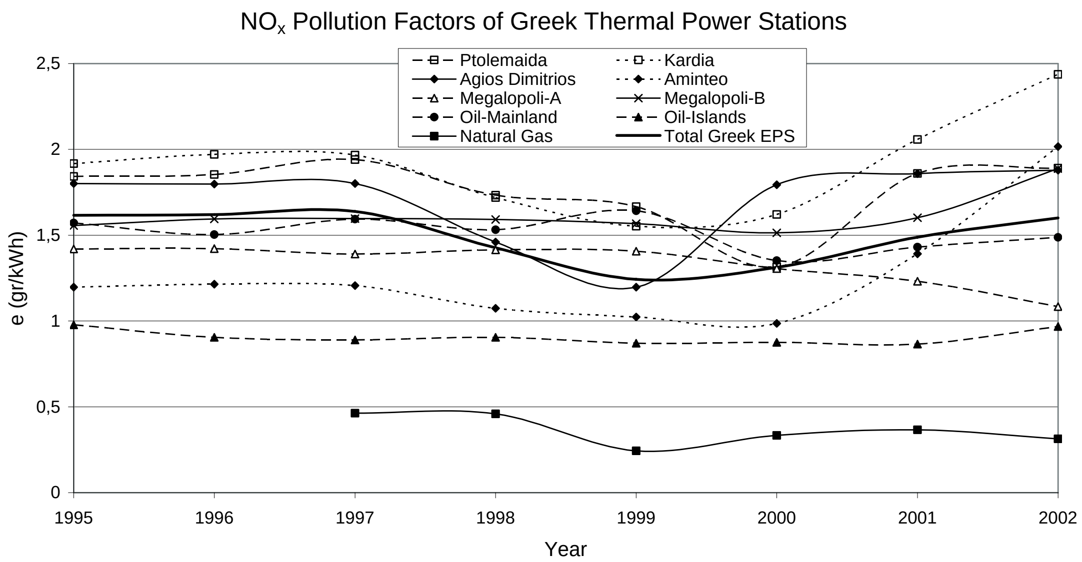

Figure 12: Time Series of Nitrogen Oxides Emission Factors for All Greek Major Electricity Generation Power Stations

- Accordingly, the oil-fired TPS show constant NO_x emission factor distributions during the analysed period, with TPS mean values lower than the national mean value.
- Finally, the contribution of imported natural gas on the nitrogen oxides production, although less than other fuels, is not negligible, presenting values equal to one third of the national mean value. Note that an OFA (Over-Fire Air) DENOX system operates in Agios Georgios TPS reducing by almost 25% the corresponding NO_x emissions.

Recapitulating, during the observed period, from where reliable official data of the electricity generation sector exist (values of 2003 are not yet officially announced), the national electricity generation sector is found responsible for the emissions of almost 1.5gr NO_x for every kWh consumed in Greece. Unfortunately, during the last three analysed years, a 15% increase was found for the corresponding national mean emission factor, a fact that definitely impedes E.U. efforts to develop a coherent acidification strategy.

5. Discussion of the Results

According to the data presented, the specific NO_x emissions factor of most TPS of Greece present values between 1.0 and 2.0gr/kWh, excluding the small old-fashioned Liptol TPS and the recently functioning natural gas fired TPS, see figure (13). More specifically, one may observe for the studied period a mean value of the NO_x emissions factor of every major lignite fired Greek TPS, together with the corresponding standard deviation. With the exception of the Liptol TPS, the relatively limited differences encountered may be attributed to the fuel characteristics (e.g. lower heating calorific value) and the variable technology applied in each thermal unit. At this point, one should also take into consideration the absence of specific DENOX measures, although recently a similar procedure -to the one installed in unit 2- is planned for all Agios Dimitrios TPS units.

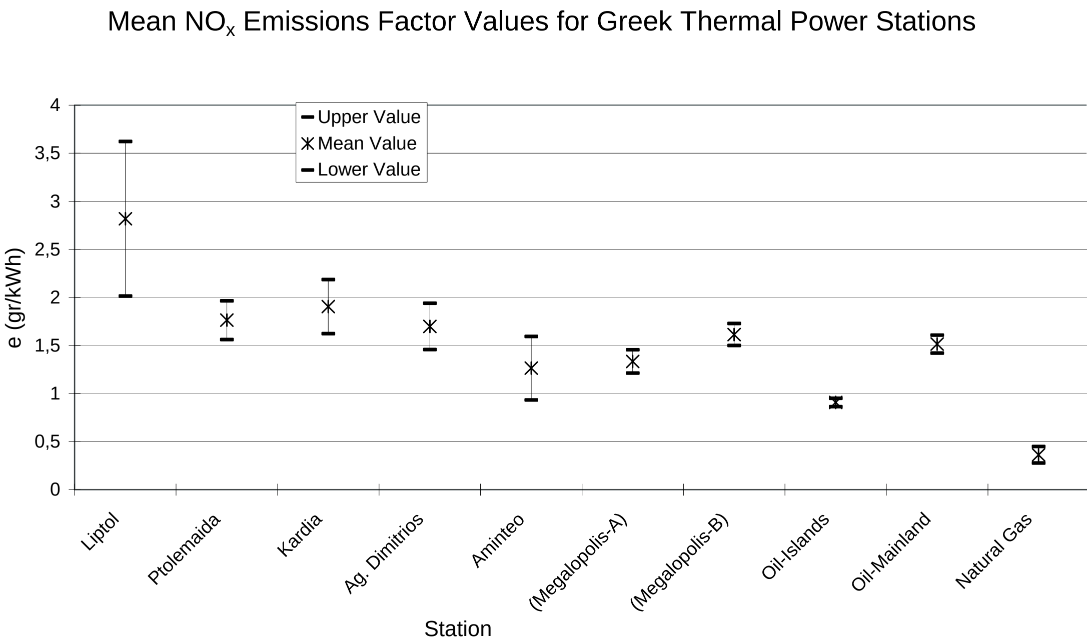

Figure 13: Mean Spread of No_x Emission Factors for the Greek Thermal Power Stations Considered (1995-2002)

In this context one should bear in mind that NO_x emissions could be normally controlled either during or after combustion[23]. Examples of this are post-combustion techniques, such as selective catalytic reduction, which use NH_3 or other nitrogen sources in the presence of a catalyst to transform NO_x into nitrogen and water. This technique can be used at moderate temperatures (150°C-450°C) and it is characterized as a relatively expensive abatement strategy.

On the other hand, combustion methods, such as reburning, prevent NO_x creation. According to this method, in the reburning zone (downstream of the main combustion zone) additional fuel is introduced without combustion air, leading to an oxygen-deficient environment. Due to this lack of oxygen, NO_x -produced in the main combustion zone- react with the additional hydrocarbon radicals to produce atmosphere nitrogen. Over-fired air completes the combustion process in the burnout zone.

Due to the complex reaction mechanism of NO_x formation, there is no explicit relation found that describes the specific NO_x emissions factor value. The majority of NO_x emissions from coal and oil-fired stations is formed from fuel nitrogen. Depending on combustion temperatures, a small portion of atmospheric nitrogen is finally transformed to thermal-NO_x, representing the 15%-30% of the total NO_x production as a maximum. This is not the case for natural gas-fired TPS, since only thermal NO is formed, as natural gas contains no organically bound nitrogen. Note that the formation of thermal NO increases exponentially with combustion temperatures above 1300°C. The formation mechanism of nitrous oxide (N_2O) has not yet been clarified. It has been found, that lower combustion temperatures, particularly below 1000°C, cause higher N_2O emissions. At higher temperatures the N_2O formed is reduced to N_2.

For a first estimation of NO_x emissions expressed as NO_2 one may use[24] the following general equation (not valid for natural gas fired TPS[25]), i.e.

$$^{(NO_x)}e_j(t) = (1-\eta_{pr\,j}) \cdot \frac{1000000}{\eta_{e_j} \cdot (1-\zeta) \cdot H_u} \cdot (1-\eta_{\mathbf{sec}_j} \cdot \beta_j) \cdot \frac{46}{30} \cdot (1+\xi) \cdot (0.285 + \phi \cdot \gamma_N) \quad (gr/kWh) \tag{2}$$

Where:
"$(\eta_{pr})_j$" is the reduction efficiency of primary measures,
"$(\eta_e)_j$" is the TPS thermal efficiency,
"ζ" is the corresponding electricity transmission losses decimal factor,
"H_u" is the lower specific calorific value of fuel,
"$(\eta_{sec})_j$" is the efficiency of the process,
"β_j" is the availability of the existing anti-pollution measures for the j-th TPS,
"ξ" is the thermal-NO fraction of fuel NO,
"Φ" depends[24] on the fuel used characteristics (i.e. fuel contain of volatiles, fixed carbon in fuel and specific flue gas volume) and
"$(\gamma_N)_j$" is the fuel nitrogen content.

Typical values for "Φ" range between 2.5 and 25. For the application of equation (2), the fuel characteristics and the lower specific calorific value provided by PPC for each TPS and for the entire time-period analysed were adopted[16,17]. More specifically, the lower specific calorific value of Southern Greece's lignite varies between 16300KJ/kg and 19700KJ/kg, while the corresponding values of Northern Greece are 21000KJ/kg and 26000KJ/kg, respectively. The thermal efficiency of major Greek TPSs varies between 31% and 36% and the electricity transmission losses decimal factor equals to 0.03, on the average. Finally, the numerical values of efficiency and availability of the existing abatement technologies are taken from the international literature[10,24] according to the type of each TPS.

Results coming from equation (2) are fairly in agreement when compared to the corresponding official data, Table II. As the exact nitrogen content of the fuel used is not known, its maximum and minimum values are used; hence the corresponding minimum and maximum values of NO_2 emissions factors are derived. Considering the absence of effective abatement technologies, most discrepancies can be explained either by questioning the real nitrogen content of the fuel used or by investigating the lower specific calorific value of the locally mined lignite.

Table II: NO_x Emissions Factors for Greek Thermal Power Stations (1995-2002) in gr/kWh

Thermal Power Station	**Min-no measures(*)**	**Max-no measures**	**Mean Value(+)**	**2002 Values(+)**
Liptol	1.85	7.35	2.82	4.37
Ptolemaida	1.62	6.45	1.76	1.89
Kardia	1.54	6.15	1.91	2.44
Agios Dimitrios	1.60	6.39	1.70	1.88
Aminteo	1.75	6.95	1.26	2.02
Megalopolis-A	1.94	6.70	1.33	1.08
Megalopolis-B	2.03	7.05	1.61	1.89
Oil-Mainland	1.67	3.91	1.51	1.49
Natural Gas	-	-	0.31	0.36

(*) According equation (2) and the chemical characteristics of the fuel used
(+) According to assessed experimental data[16]

The specific emissions factor values obtained from the previous analysis of the local TPS data were compared with corresponding values presented by the authors in a previous study[26] and by E.U. report in 1999[27], Table III. At this point one should note the date difference between the data compared. More precisely, one can observe the wide range of the values given for representative E.U. countries, concerning the NO_x emissions factor values from the electricity generation sector. In this context, UK and Danish electricity generation industries produced during 1994-1998 higher NO_x emissions per kWh consumed than the Greek power sector in 1995. On the other hand, the Dutch electricity generation surcharge is minimal, taking into account the limited utilization of coal in the country's electricity generation plants.

Table III: Specific Emissions (kg/MWh) from Fossil-Fuelled TPS (1994-1998)

Air Pollutant	**Netherlands[27]**	**UK[27]**	**Denmark[27]**	**Greece[26]**
NO_x	0.89	2.5-5.3	2.6	2.3

Similar results are presented for the Turkish electricity production sector[28], where a detailed analysis of the air pollutants emissions for the various TPS is presented. In addition, the same order of the nitrogen oxides emissions magnitude is mentioned[29,30] for Malaysian, Thai and South Korean power sectors. Similar data is also validated for U.K. electricity production sector[31], during a study analyzing the lifetime pollution of various technologies of electricity generation. Finally, the results obtained here are also validated by the data provided[32] during a detailed analysis of regional effects of NO_x emissions concerning inter-state NO_x control in the United States.

Recapitulating, one may clearly state that electricity generation plants (usually called large combustion plants) play a decisive role in the E.U. efforts to combat acidification, eutrophication and ground-level ozone. In this context, a NO_x protocol was signed in Sofia in 1988 and came into force in 1991. This protocol has been signed by 25 countries and ratified by 29 countries. According to this protocol the parties agreed to freeze their NO_x emissions at 1987 levels before the end of 1994. As expected, in 1988 the EU adopted the Directive on the limitation of certain pollutions from large combustion installations to control SO_2 and NO_x emissions. This included new plant emissions standards for SO_2 and NO_x. The directive also sets ceilings for the reduction of total national emissions of SO_2 and NO_x from existing plants. The emissions ceilings for 1993 and 1998 for Greece were 70ktn per year. Each country is responsible for the choice of methods used to achieve these targets. The Directive 2001/80/EC amends the existing Directive (88/609/EEC) in an attempt to tighten the Community's restrains against air pollution from new combustion plants. Notably, the Directive of 2001 establishes new requirements for plants licensed before 1st July 1987. In case that these plants prefer to be exempted from compliance with emissions limit values, their operator should declare by 30 June 2004 not to operate the plant for more than 20000 hours starting from 1st January 2008 and ending not later than 31st December 2015.

According to the data concerning the national electricity production sector, one may definitely state that during the observed period there has been considerable demand amplification. Moreover, most experts forecast[2,9,33] a continuous electricity demand increase ranging between 3.0% and 4.0%, up to 2010. If this significant electricity demand increase is to be covered by Northern Greece lignite and imported natural gas, the expected flue gases emissions factors values should keep up with the 2000-2003 values, since the corresponding fuel-mix probably remained almost constant. In addition, one should consider that no remarkable additional natural gas imports are possible without improving the existing infrastructure capacity. Hence the authors expect that a major portion of electricity demand increase (2.0%-2.5%) will be covered by further exploitation of domestic lignite deposits. On the other hand, diesel-oil and mazut (heavy-oil) shall continue to be the sole fuel solution for the electricity power plants of all Greek islands, Crete and Rhodes included.

Hence, excluding the rather hypothetical case that a considerable renewable energy penetration is realized both in the mainland and the islands electrical production systems[5,34,35], the expected annual NO_x production of Greek electricity generation sector should exceed the 80ktn by 2010. For the time being, the annual NO_x per cap release from the Greek electricity generation sector is almost 6.5kg, a value that is higher than the corresponding E.U. mean one (5.4kg/cap).

6. Synopsis and Conclusions

The nitrogen oxides emissions of the electricity generation sector analysed for the period 1995 to 2002 were estimated using detailed official data concerning the major local thermal power stations. According to the results obtained, a slight increase of the national emissions factor of NO_x has been found -mainly during the last three years analysed- despite the natural gas penetration in the local electricity generation sector. On top of this, the annual NO_x emissions production is still increasing, due to the remarkable (50%) electricity consumption amplification registered during the past ten years.

More specifically, the annual NO_x production by the Greek EGS exceeded the 70ktn during the last two years analysed, marginally violating the emissions ceilings of both 88/609 and 2001/80 E.U. Directives. One of the most negative evolutions resulting from the proposed analysis is an undesirable increase of NO_x emission factors for the Northern Greece operating power stations during the last four years, which practically neutralizes any positive impact of the natural gas utilization in the local electricity generation sector. Finally, given that over 90% of the national electricity production is based on carbon containing fuels, a continuous effort on diminishing the release of nitrogen oxides should be made, so that local electricity generation sector may accomplish the Large Combustion Plants Directive (2001/80/EC).

After a detailed evaluation of the Greek electricity sector NO_x concerning air pollution data of the period 1995 to 2002, the conclusions drawn are rather discouraging. For the entire period analysed, there has been a significant increase of NO_x emissions resulting from the continuous energy consumption amplification and the emphatically insistence of the Greek State to cover any further electricity demand using low quality lignite, imported heavy oil and natural gas. If this situation is not drastically altered during the next few years, the Greek national electricity production sector will significantly overload the local environment and the Greek citizens' health, strongly questioning the E.U. effort to control the increased flue gases release in order to protect our planet from several negative aftereffects.

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MINIMUM SO_2 ELECTRICITY SECTOR PRODUCTION USING THE MOST ENVIRONMENTAL FRIENDLY POWER STATIONS IN GREECE

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Abstract

Electricity is characterized as the most end-user friendly form of energy. However, the electricity generation -based so far on fossil fuels- is found guilty of significant air pollution, including the annual emission of more than 350ktnons of sulphur dioxide, representing 80% of the national releases. In this context, the existing large combustion power plants are classified according to their SO_2 emission factor. In the present study we calculate the SO_2 emissions, resulting by using, in priority, the most environmental friendly power stations, to face the electricity load requirements of the Greek mainland. In the methodology adopted one disregards, during the selection procedure among the available Greek power plants, any operational, grid-stability, system-efficiency and cost-effectiveness criteria. Using this purely theoretical methodology, one has the ability to estimate the minimum expected SO_2 annual emission from the existing power plants, used to fulfil the corresponding national electricity demand. The discrepancy encountered is due to the established classification of the existing power plants, which practically neglects the impact of the sulphur dioxide emissions.

Keywords: Electricity Generation; Sulphur Dioxide; Fossil Fuels; Air Pollution

1. Introduction

The crucial role of energy in everyday life quality is well recognized in contemporary human societies[1]. Electricity, being the most end-user friendly form of energy, is dominating the domestic sector holding, also, a major share in the industrial one, while its penetration into the transportation sector is increasing. However, the electricity generation in Greece is found guilty of significant air pollution as well as of local and remote water and soil degradation[2].

The considerably high environmental quality as well as the need for its intensive maintenance is key factors for the long–term welfare that European citizens request[3]. The forthcoming economic growth of the developed and, most of all, the developing countries, will extend the environmental pressures and will threat the planet's capacity to support the raw materials supply and absorption of pollution.

The Greek electricity sector, based on the usage of fossil fuels, is found responsible for the production of numerous air pollutants some of which are considered as very dangerous for the public health. Sulphur dioxide with annual emissions of more than 350ktnons contribute to local environmental degradation[4] as well to long distance, even transboundary, effects of high acidity to manmade and natural ecosystems. On the top of this, the protection of citizens from dangerous toxic effects of the various harmful gases and particles released is appeared to decrease in our country[5].

2. National Electricity Production System

Electricity generation in Greece was based - from its foundation in the early 60's - on lignite and heavy-oil fired stations to meet base and peak load demand respectively. Only recently a remarkable

Kaldellis J.K., Spyropoulos G.C., Chalvatzis K.J., Paliatsos A.G., 2005, "Minimum SO2 Electricity Sector Production Using the Most Environmental Friendly Power Stations in Greece", presented at the 13th International Symposium of MESAEP, Thessaloniki-Greece.

natural gas penetration in the Greek energy market tends to change the fuel mix of the electricity sector. On the other hand, although the hydroelectric power stations amount a rather high installed capacity, they contribute relatively low, basically due to water reserves deficit and applied electrical load management plan[6]. Finally, despite the high wind potential of the country, the contribution of the wind parks to the Greek electricity production is still limited[7].

Using official data[8,9] from Greek Regulatory Authority of Energy (RAE) and Greek Public Power Corporation (PPC), the local electricity generation system (at the begging of 2005) is divided in two branches. The first part contains the mainland electricity production network based on thermal power stations (TPS) with rated capacity of 7619 MW and over 3000MW of large and small hydropower installations. The second part includes medium-small autonomous thermal power stations (APS) in the island network[10].

In this context, the Greek thermal power stations can also be categorized according to the fuel used, as follows:

a. 4438 MW using N. Greece lignite
b. 850 MW using S. Greek lignite
c. 1581 MW using Natural Gas
d. 750 MW using heavy-oil (mazut) in mainland

The major contribution of the lignite-fired power stations to the electricity generation in Greece together with the high sulphur content of the locally extracted fuel, especially in South Greece, result to the electricity sector being the main responsible for the SO_2 emissions. In the current study only official data[11] will be utilized for the year 2001 for which the lignite-fired stations nominal power has been 4088 MW for North Greece and 850 MW for South Greece ones.

The present work is concentrated on the energy production sector; hence emphasis is laid on the sulphur dioxide emissions, as already mentioned. The SO_2 and SO_3 are produced when the sulphur of the solid and liquid fossil fuels is burned with bright flame and strong smell. During combustion, sulphur trioxide SO_3 is normally transformed to SO_2, thus SO_2 represents more than 99.5% of sulphur oxides in the flue gas. The SO_2 -being one of the most common air pollutants of the urban areas- is one of the ingredients of the smog appearing in many cities. The SO_2 is colourless but with a very characteristic smell. In combination with humidity it is finally transformed to sulphuric acid, which is one of the strongest acids being primary responsible of the acid rain.

Using well established data[12], energy sector is found responsible for more than 95% of the total SO_2 emissions, while the rest SO_2 derives from industrial processes, like sulphuric acid production, cement and aluminium industries. The majority of SO_2 is produced by the thermal power plants of PPC[13], operating mainly using low quality lignite and heavy oil. According to official data the sulphur content in N. Greece lignite varies between 0.35 and 0.75%, while the corresponding values for S. Greece range from 1.3% to 1.7%. These values are slightly higher than those of the previous decade, mainly due to the quality deterioration of the available lignite fields. Similarly, the sulphur content of heavy oil (mazut) used by the oil-fired power stations is between 2.8% and 3.6%. Bear in mind that during the last twenty years the local lignite consumption is threefold increased. On the other hand, noteworthy efforts were taken place to reduce the SO_2 emissions by electricity generation activities via the operation of desulphurisation units, especially in South Greece.

3. SO_2 Emission Factors of Greek Thermal Power Stations

An exclusive analysis[14] concerning the SO_2 effects resulting from the electricity generation sector had been carried out, utilizing official data[15]. According to the calculation of the SO_2 emission factors for each power station we can classify them, bearing in mind their environmental impact per electricity generated. For the year 2001 the results are presented in Table I. The classification has taken place by sorting the power stations starting from the one with the lowest emission factor to the one with the highest. The analysis has been carried out separately for each unit of the power stations and the presented differences are a result of the age and the operational characteristics of each one of them.

It is imperative in this point to observe the significantly high differences in the emission factors of South and North Greece. Taking into consideration the results of Table I, along with additional data concerning the rest energy consumption sectors, one may observe the corresponding factors. As expected, the highest SO_2 values characterize the South Greece units of Megalopolis, achieving values equal to 49 kg/MWh, lacking integrated anti-pollution measures except the Megalopolis-B IV unit, which features a desulphurisation unit in operation since year 2000.

The environmental criteria used for pointing out the power stations are referring only to their SO_2 emission factors, exactly because the electricity generation sector is the major responsible for these emissions. It is crucial, therefore, to mention that different criteria e.g. for a variety of air pollutants, would result in a different classification, taking under consideration the weighted environmental impact of each air pollutant, along with the contribution of the electricity generation sector to the national releases of the pollutants in question.

The data used in the current study are extracted from the time evolution curve of the electrical power demand, for the year 2001. The energy and power demand are given on an hour by hour basis and concern only the lignite-fired power stations. The peak demand is a phenomenon noticed to be occurring at the noon and late evening hours.

Table I: SO_2 Emissions Factors for Greek Thermal Power Stations (2001)

Power Station	**Power Unit**	**Rated Power (MW)**	**Emission Factor (kg/MWh)**
Ptolemaida	II	125	2.1
Agios Dimitrios	V	366,5	2.1
Kardia	I	300	2.2
Kardia	II	300	2.2
Agios Dimitrios	III	310	2.2
Agios Dimitrios	IV	310	2.2
Kardia	III	300	2.3
Agios Dimitrios	I	300	2.3
Agios Dimitrios	II	300	2.3
Ptolemaida	I	125	2.3
Kardia	IV	300	2.4
Ptolemaida	III	300	2.4
Ptolemaida	IV	300	2.6
Liptol	I&II	43	4.2
Aminteo	I	300	5.5
Aminteo	II	300	5.8
Megalopolis-B	IV	300	17.2
Megalopolis-A	III	300	48.0
Megalopolis-A	I	125	48.9
Megalopolis-A	II	125	49.0

Moreover the lignite-fired power stations in Greece are introduced in the operational plan as base load units and subsequently the peak load demand is met using the hydropower and heavy oil fired stations. Therefore the power demand curve presents a narrow ranging.

In the procedure adapted one disregards, during the selection process among the available Greek power plants any operational, grid-stability, system efficiency and cost-effectiveness criteria. Hence the calculation methodology takes under consideration only the electricity generation capacity during the year. Studying the maintenance schedule, the ideal annual operational plan for each station can be drawn. In any case the contribution to the grid for one power station is limited to the 90% of its maximum nominal capacity. Therefore "shut down" and "break down" incidents are almost completely excluded.

Additionally an important parameter to be considered is the lowest operational level of an electricity generation unit. Technically, for a lignite-fired power station, it cannot be lower than 60% of its nominal capacity. This is due to the steam turbine cycle characteristics. The methodology developed for the present study seeks to meet the hourly power demand, making use of the most environmental friendly power stations. As a result of the knowledge and characteristics for each station it occurs that eight of them are used for all year round on a defined capacity. Only Agios Dimitrios I is used on 65% of its normal installed capacity while all the rest power stations are used on the maximum available capacity. The power demand, when exceeding the capacity of the aforementioned eight stations is covered by the next power stations as listed in Table I.

More precisely, the energy production by every power unit separately is presented in figure (1). In the dark color one may notice the real net production for the year 2001 as it is known from the official data, while in light color is shown the estimated net production if the proposed model would be in function.

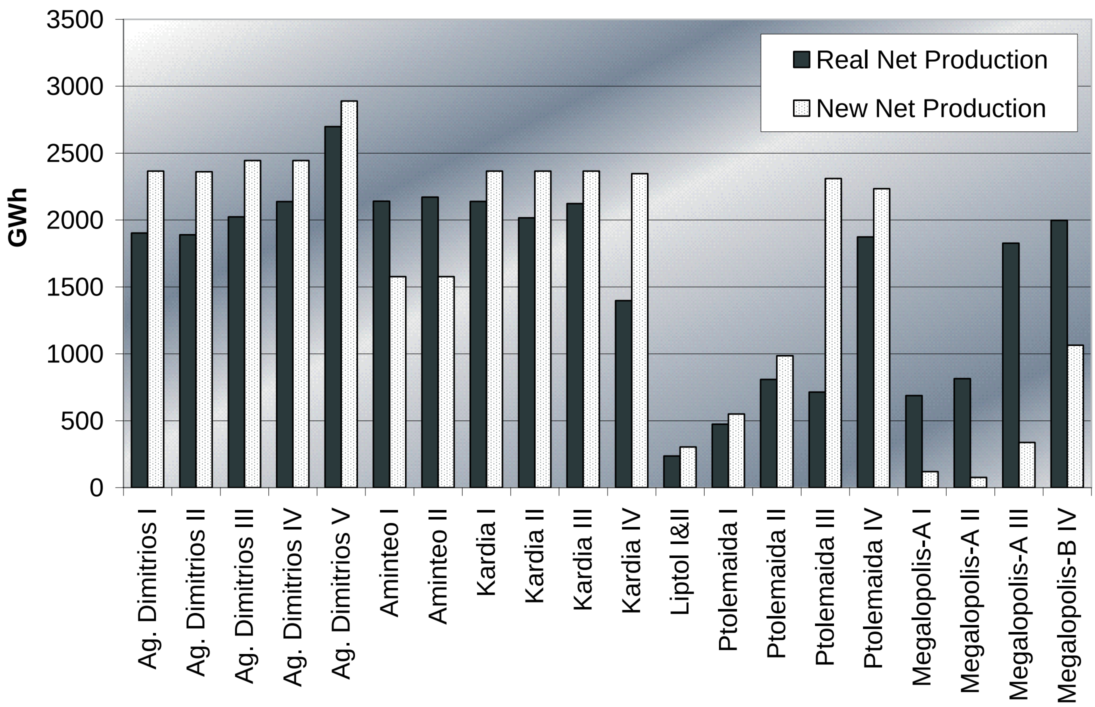

Figure 1: Real and Proposed Environmental Friendly Net Electricity Production for the Year 2001

The base load power stations are utilized in a higher extend, which is on average 1.16%. However for the Kardia IV unit it reaches 1.68% mainly due to the low utilization that it had in the examined year. The Aminteo and Megalopolis power stations –being the most polluting ones– are minimizing their contribution to the electricity grid. Especially the Megalopolis power station having in the year 2001 an actual energy production of 5300 GWh, in the proposed model supports the network with only 1600 GWh.

4. Calculating the SO_2 Annual Production for the Year 2001

Making use of the proposed model to cover the actual energy demand of the grid, the network supervisor should know the diurnal operational time of each power station, the power contributed to the network as well as the SO_2 emissions for each unit of the power stations. In figures (2) and (3) one may notice the SO_2 production for two cases, the real one and also the estimated through the presented model. More precisely, beginning with figure (2), each unit of the North Greece power stations is presented. According to the methodology in use, all the power units are utilized in a higher than their usual extend and therefore their SO_2 releases are increased by 0.16 to 2.33 kton. Only Aminteo I and II are an exception as they are found to be the most polluting units of this group. Therefore their contribution to the electricity grid is reduced with proportional results to the SO_2 emissions decreased by 3 kton.

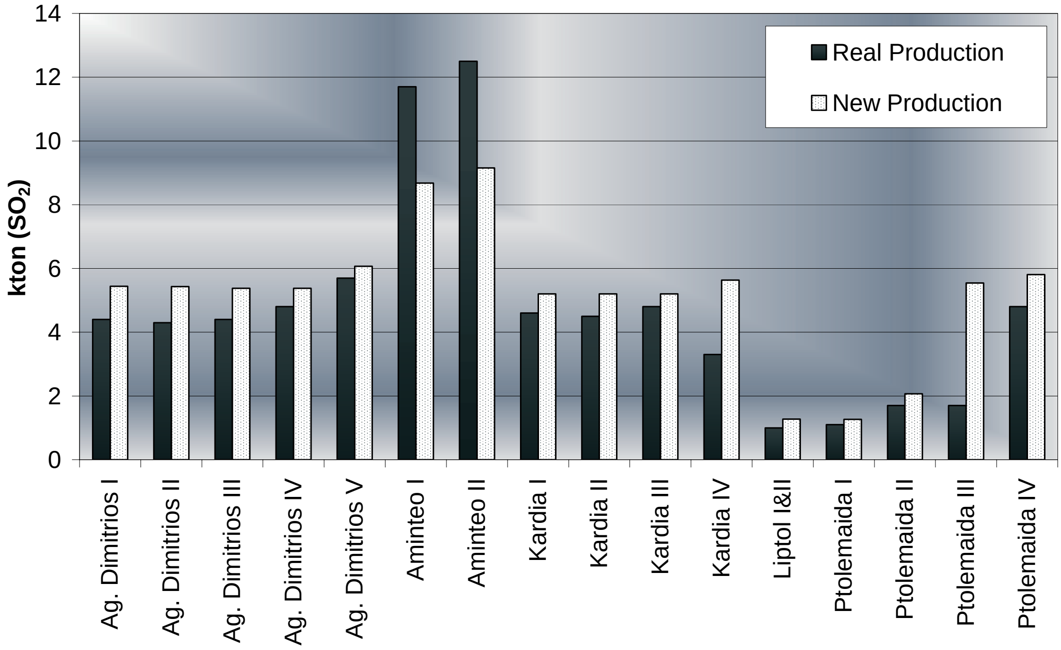

Figure 2: Total SO_2 Releases by the North Greece Power Units

The situation is significantly different regarding the power units of South Greece. It is of utmost importance to mention here that it is mostly these power stations which contribute to the sulphur dioxide releases from the electricity sector in Greece, mainly due to the high sulphur content of the locally mined lignite.

According to the operational plan of the proposed model, the heavy polluting units of South Greece should have a very limited contribution to the electricity grid and in this way their SO_2 releases would proportionally be reduced. More precisely, Megalopolis III SO_2 emissions are decreased by 75 kton, while the total amount of sulphur dioxide not emitted to the environment by the whole station reaches 140 kton.

Although the North Greece power stations are emitting more sulphur dioxide, this increment is only a small fraction of the SO_2 emissions that are prevented of being released by the South Greece power units. Therefore, the overall environmental benefit is considered to be crucial.

In figure (4) one may observe the diurnal electricity generation of Megalopolis power station. Being the most polluting power station of the Greek electricity network this station faces major changes in its operational plan and therefore a more extensive study may be valuable. While the total contribution of Megalopolis power plant for the year 2001 is suggested to be eliminated at 1600 GWh, the rate of its actual production to its nominal capacity falls to 22%. The model is using this station only to cover peak loads as and if they occur.

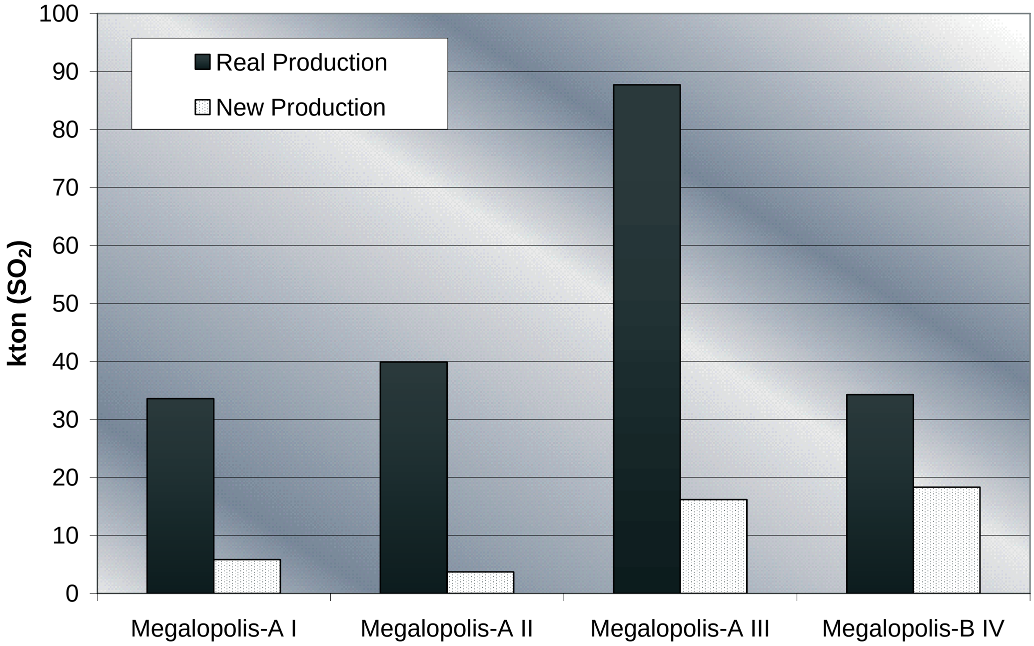

Figure 3: Total SO_2 Releases by the South Greece Power Units

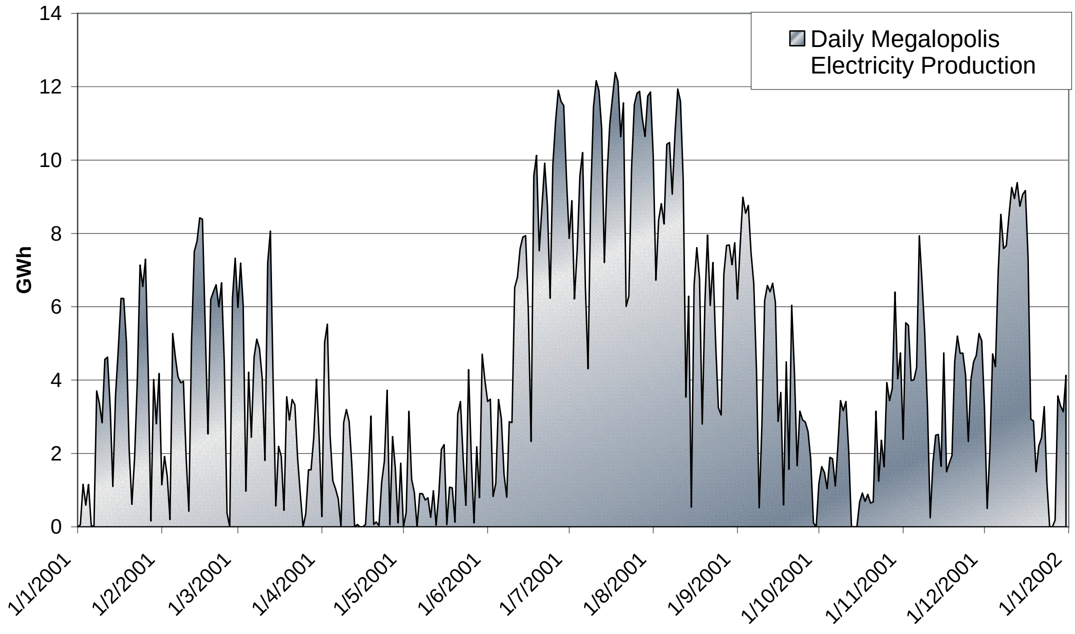

Figure 4: Daily Electricity Production of Megalopolis Power Station

On the top of this, rises the significant insecurity in forecasting the power demand in Greece. While the energy demand forecast is in general successfully projected, the peak loads curve show a correlation to natural parameters like the temperature. In several cases forecasting the peak demand curve in Greece is depended on temperature projection models and this correlation is getting stronger every year, mostly due to the increasing number of air conditioning installations[16].

According to UCTE[17] the reserved capacity demanded to cover random accidents and operational disorders can be secured by hydropower stations. At the same time the aforementioned institute in a study entitled "Load Management", suggests bilateral contracts of the network supervisor and the industries in order to spread out the peak power demand in a diurnal basis. The industrial sector could be attracted in such a step through subsidies and price discounting policies. In this way the peak demand can be met directly without any impacts in the domestic sector.

At the same time the Greek electricity network has one more problem regarding the big distance between the energy generation center and the energy consumption center. While the former is in North Greece the latter is concentrated to Attica prefecture. This raises the need for high frequency electricity transfer cables, which make the system even more complicated and vulnerable to instability especially during the summer months.

5. Discussion of the Results

In figure (5) there is a clear view on the total SO_2 released in particular for South and North Greece. Comparing the actual emissions and those predicted by the presented model one may notice that it is the South Greece power station of Megalopolis which is requested to reduce its activity. While, in reality, each one of the available power stations is necessary to meet the continues demand increase, the suggested actions should be to install desulphurization equipment for the units of Megalopolis I,II,III.

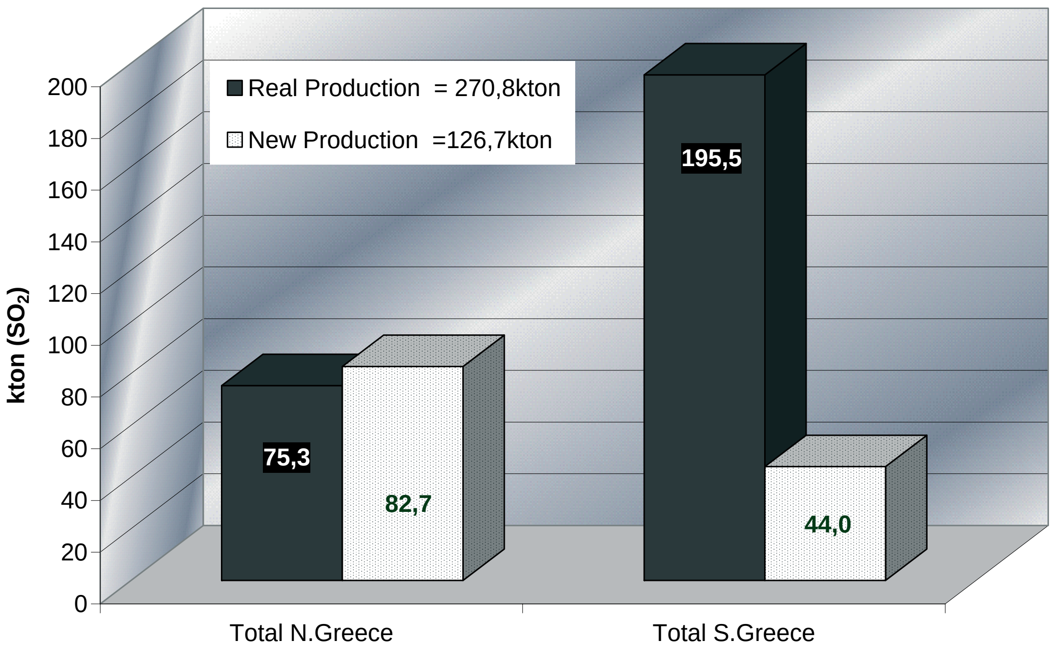

Figure 5: Total SO_2 Emissions for the Year 2001

The investigation among the lignite-fired stations focuses on defining those with the environmentally friendlier operation, and their utilization in a way to support the energy and power demands. Although several barriers are preventing this approach from being realistic, it is obvious that its realization would be a major improvement in the environmental performance of the country. As already mentioned grid stability, system efficiency and cost effectiveness abnormalities would occur in such a case.

6. Conclusion

In the present study the Greek power stations are sorted by their SO_2 emission factor. The operational plan of the electricity grid is totally reconsidered regarding only environmental criteria. As a result the outcome is not a solution characterized for its technical and economical viability. However, the proposed methodology not only presents a benchmark in order to evaluate the environmental behavior of the electricity power sector but also offers the opportunity to quantify one of the major components of the environmental degradation imposed by the current electricity production procedure in Greece.

Finally, since more than 90% of the national electricity production is based on carbon containing fuels, a systematic sulfur dioxide release diminution effort should be made in order for the local electricity generation sector to comply with the current and future legislation. The National Emission Ceilings Directive 2001/81/EC have vast impacts to the electricity sector especially for those countries, like Greece, which are heavily depended on fossil fuels. While the current paper is showing the long distance that the energy generation in Greece has to cover, in order to become environmentally friendly, further examination should be expected especially in satisfying the increasing demand with economically sound solutions.

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SULPHUR DIOXIDE EMISSIONS DUE TO ELECTRICITY GENERATION IN THE AEGEAN ISLANDS: REAL THREAT OR OVERESTIMATED DANGER?

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Abstract

The dominant role of energy, both as a comfort factor and a significant source of pollution, is well recognized by contemporary human societies. According to previous studies, Greek electricity production is mainly based on local lignite and imported crude oil or natural gas. In this context, not only the mainland electricity network but also the islands' autonomous networks impose an important environmental impact on local societies. On the other hand, Greek islands are considered to be a vital tourist attraction, significantly contributing to local and national economy. Therefore, investigating the serious degradation that electricity generation may have on the local environment is undoubtedly necessary. The present paper uses data concerning energy production of the island power stations, focusing on the sulphur dioxide emissions. The assessment takes place utilizing an integrated calculation model along with specified emission factors. The non-existent emission control measures, together with the quality of the fuels, are also examined with reference to the liquid fuels sulphur content Directive 1999/32/EC. Finally, a variety of actions are proposed so as to improve the performance in terms of energy efficiency and renewable energy sources utilization.

Keywords: Aegean islands; Sulphur Oxides; Emission Factors; Fuel Quality; Energy; Air Pollutants Production; Fossil Fuels; Electricity Consumption.

1. Introduction

The crucial role of energy in human activities is undoubtedly recognized in every day life[1]. Electricity, being the most end-user friendly form of energy, is dominating the domestic sector and also holds a major share of the industrial sector, while its penetration into the transportation sector is increasing. However, the electricity generation is found guilty of significant air pollution as well as of local and remote water and soil degradation[2].

The considerably high environmental quality as well as the need for its intensive maintenance are key factors for the long–term welfare that European citizens request[3]. The forthcoming economic growth of the developed and most of all, the developing countries will extend the environmental pressures and threat the planets capacity to support the raw materials supply and absorption of pollution.

The islands, being the case study of the present paper are defined by their visible coastal boundaries which provide them isolation and independence. Usually they are categorized accordingly to their surface and population size, considering as small those which are smaller than 10000km^2 and have population less than 50000 inhabitants. Concerning the small isolated islands these depend upon their geographical boundaries as well as their socioeconomic characteristics[4].

2. Brief Description of the Aegean Islands Autonomous Power Stations

The imported energy sources in the Greek islands consist of liquid fuels like gasoline diesel and heavy oil[5,6], out of which the latter two are used for electricity generation. The contribution of alternative energy sources mainly wind and solar is only limited.

According to official data[7], the island electricity network consists of 36 thermal power stations, 2 hydroelectric, 18 wind parks and 5 photovoltaic power stations. The diesel and heavy oil fired power station are presented more precisely in Table I utilizing data from the Regulatory Authority for Energy[8]. The mean installed capacity reaches 33MW if the middle sized power stations of Crete and Rhodes are included in the calculation, while excluding them reduces it to 12.5MW.

Table I: Diesel and Heavy Oil Stations (Year 2001)

Power Stations	Installed Capacity (kW)	Power Stations	Installed Capacity (kW)	Power Stations	Installed Capacity (kW)
Linoperamata	192800	Othonoi	270	Syros	20000
Chania	328400	Patmos	4380	Samos	46080
Soroni	206000	Samothrace	2200	Chios	38780
Agathonisi	240	Serifos	2000	Andros	9400
Ag. Efstratios	360	Sifnos	4300	Thira	22200
Amorgos	2650	Skyros	4500	Ios	3740
Anafi	355	Lesvos	49500	Kalymnos Kos	69600
Antikythira	140	Lemnos	8900		
Astypalea	1600	Megisti	390	Karpathos Kasos	9000
Donousa	210	Mykonos	21200		
Airekusa	270	Kythnos	2300	Milos	7600
Ikaria	6900	Symi	4350	Paros	43250

During the last twenty years the utilization of wind energy for electricity generation has become a mature and economically feasible technology[9]. The excellent wind potential of the Aegean sea has contributed towards this situation, therefore wind energy is a sustainable, environmentally friendly option for the electricity generation in the Greek islands[10]. The remarkably low contribution of wind energy – not exceeding 36.5MW[11] - to the total installed capacity is a result of the weak network connections among the islands and to the mainland grid.

The electricity generation installations of the islands are overburdened due to the acute energy demand increase, questioning their adequacy during the summertime peak season[12]. Over the time period from 1996 - 2004 the mean annual growth in energy demand reached 5.8%, while the overall increase was 64%. This increase in energy as well as in water consumption is due to the life quality improvement along with the tourism industry, which is the major economic source of the Aegean islands[13].

Meeting the increased energy demand by utilizing fossil-fuel fired stations is not considered to be a sustainable option mainly due to the air and water pollution realized[14] as well as for supply security which is questioned especially in heavy weather conditions[15].

3. Oil Consumption in the Island Power Stations

While the autonomous power stations of the Greek islands are oil fired, significant differences are found in the technology and type of fuel used. Thus in Crete and Rhodes islands there are electricity generators powered by gas-turbines, while the small scale stations operate utilizing Internal Combustion Engines. The fuel for the former is heavy oil while the vast majority of the ICEs are diesel fired.

The total fuel consumption of the Aegean islands' power stations in the 1996-2002 time period is presented in figure (1). One may notice the acute growth of the fuels used during this period, reaching

49% growth for the diesel and 47% growth for the heavy oil. It is noteworthy that the consumed fuel quantities are rising and new installations are introduced in the system the fuel mix does not present particular differentiations.

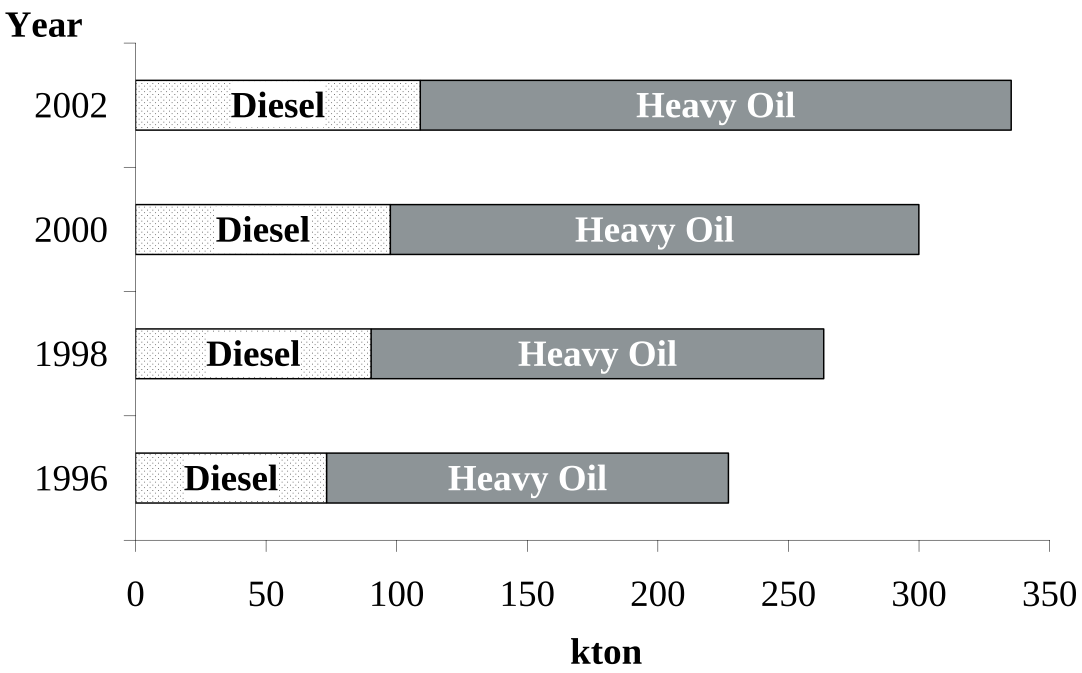

Figure 1: Oil Consumption in Greek Electricity Sector

4. Sulphur Dioxide Emissions in the Larger Islands

The present study is concentrated on the oil fired power stations, hence emphasis is laid on the sulphur dioxide emissions as already mentioned. The environmental impact of the specific air pollutant is connected to local and transboundary air pollution[16], as well as for water and soil acidification.

An integrated numerical model[17], able to estimate the air pollutants quantities resulting from the various energy resources is utilized. According to the fuel characteristics and the activity reported the time evolution of the sulphur dioxide emissions in the large Greek islands is presented in figure (2). The projections shown have occurred through an extensive analysis of the PPC annual program of autonomous power stations[18], considering the forthcoming energy demand along with the new installations that will be introduced.

One may observe in figure (2) that the most heavily polluting power stations are those from the Kalymnos – Kos islands network projecting to emit 5kton of SO_2 by year 2008, while Lesvos, being the second larger island of the Aegean sea comes next with almost 4.5kton. Ikaria is the least polluting from the islands examined as its sulphur dioxide production will not exceed the 0.5kton by year 2008.

While the emissions are rising in all the islands presented, it is important to analyse the rate of increase which significantly differs among them. In this context it is clear that tourism industry development is the leading cause of the rise in energy consumption and air pollutants emissions. Islands Mykonos and Milos present the higher annual increasing rate reaching 25% and 23% respectively. At the same time the sulphur dioxide emissions are rising in the lower rate in Lemnos and Syros islands slightly exceeding 4% and 5% accordingly.

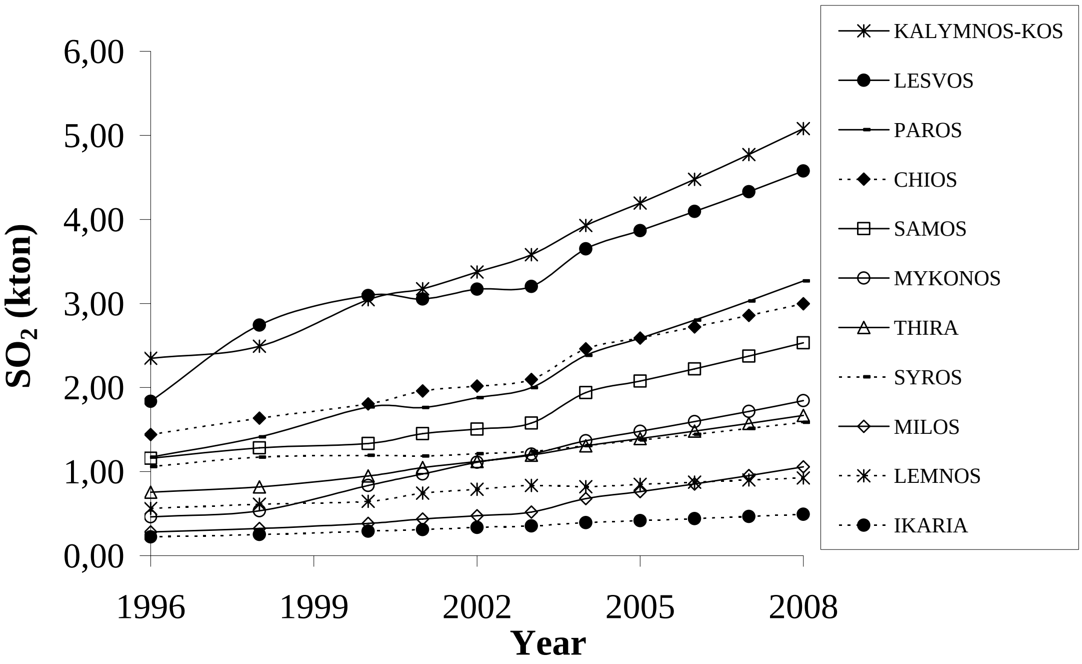

Figure 2: Sulphur Dioxide Production in Greek Electricity Sector

5. Discussion of the Results

As already shown above, the emissions are rising in a threatening trend. Examining the total SO_2 production (see figure (3)) particularly for years 2002 and 2008 one may realize a higher than 50% increment. In the same period of time the diesel oil fired power stations are gaining 8 percentage units over the heavy oil fired stations. The overwhelming tourist development of a large number of small islands, which are equipped only with diesel oil fired power stations, is considered to be responsible for this.

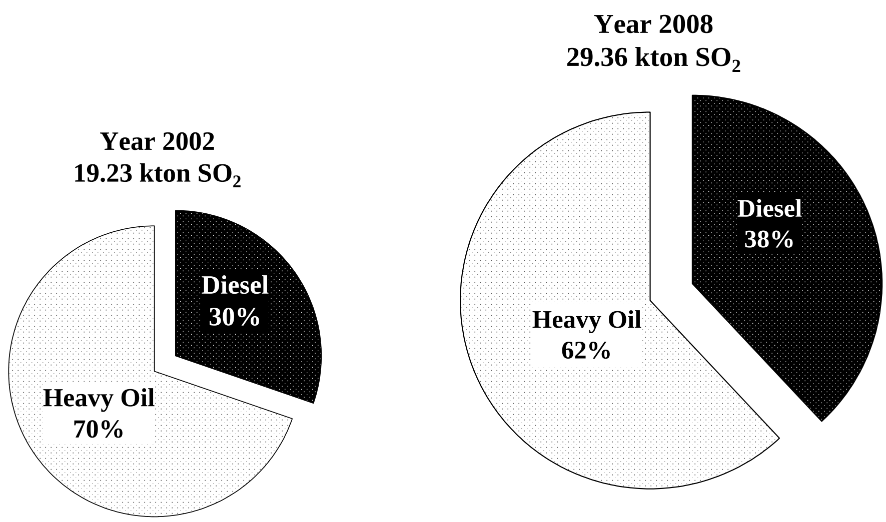

Figure 3: Sulphur Dioxide Production for Years 2002 and 2008

While the energy policy applied in the islands is the fundamental reason for the current situation, the fuels used are also considered as part of the problem. Acid rain is the major method by which SO_2 is transferred from the emitting sources to the environment. Sulphur dioxide emissions are found responsible for numerous environmental hazards like degradation of aquatic and forestal ecosystems together with corrosion of marble and metal constructions. Human health can be very heavily affected if air with high concentration of sulphur dioxide enters in the lungs or touches the skin or the eyes[19].

The forestal ecosystems are damaged in several ways by acid deposition, mostly on the tree's leaves and bole while aquatic ecosystems are degraded and become unable to support fauna and flora in them. The Aegean islands are rich in areas of high ecological value where a variety of rare inhabitants find permanent or temporal refugee[20]. The UN-ECE Convention on Long-Range Transboundary Air Pollution[21] calls for respect in the critical load of acidity that every specific natural ecosystem is able to absorb. The conservation of those biotopes not only is bound to Greece's compliance to the Birds 79/409/ECC and Habitats 92/43/EEC Directives but it is also fundamental for the growth of ecotourism as a key factor for the sustainable development of the islands.

Apart from the natural ecosystems, human health and activities are affected in a severe way. While tourism is the major income source for most of the islands, small scale agricultural and animal husbandry activities also take place. Farming and forage land is degraded via acid rain or dry deposition threatening the agricultural industry. Coastal fisheries and fish farms are also affected, facing serious livestock reductions. The above reasons make the local populations react against any existing and new energy generation plans of conventional technology, expressing the NIMBY syndrome. Public reactions in the island of Lesvos where the power station is inside the city of Mitilene and the oil storage tanks are in the ecologically sensitive gulf of Geras, the island of Kos where the liquid waste treatment plant of the power station already faces leakage problems[22] and island of Syros where the power station is close to a school campus and have already caused lung infection problems to the students[23] are only some examples of the current situation.

6. Conclusion

In order to eliminate the environmental impact of the thermal power stations the authors believe that strict auditing and control measures should be adopted. As the power stations are the major sulphur dioxide emitters of the islands, special attention should be paid to them. Focusing on the implementation of the 1999/32/EC Directive, relating to a reduction in the sulphur content of certain liquid fuels would be an initial step in this direction. Among others the Directive calls for serious reductions in the sulphur dioxide content of heavy oil used in the relatively small (<50MW) combustion plants excluded from the 88/609/EEC Directive. Bear in mind that the heavy oil used in the thermal power stations of the Greek Aegean islands contains approximately 3% w/w of sulphur, while the above mentioned Directive calls for 1% in all the installations. The sulphur content of the fuel is almost proportional to the sulphur dioxide emissions in the flue gazes and therefore one should expect a crucial decrease in the SO_2 resulting from the implementation of the 1999/32/EC Directive, which would undoubtedly be an important relief for the natural and man-made environment of the Aegean sea islands.

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