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STAMOULIS
PUBLICATIONS

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

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

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2. Lab of Renewable Energy Sources **(Lab of RES)**	***5th ″***
3. Applications of Renewable Energy Sources **(RES II)**	***6th ″***
4. Energy 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. Environmental Measurements Technology **(EMT)**	***5th ″***
9. Waste Management Systems **(WMS)**	***7th ″***

Research Areas

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

Published Results:

- **Kaldellis J.K., Vlachos G., 2005**, "Optimum Sizing of an Autonomous Wind-Diesel Hybrid System for Various Representative Wind-Potential Cases", *Applied Energy Journal*, on-line available (05/03/05) in www.ScienceDirect.
- **Kaldellis J.K., Kavadias K.A., Filios A.**, **Garofallakis S., 2004**, "Income Loss due to Wind Energy Rejected by the Crete Island Electrical Network: The Present Situation", *Journal of Applied Energy*, Vol.79/2, pp.127-144.
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- **Kaldellis J.K., Kavadias K., Christinakis E., 2001**, "Evaluation of the Wind-Hydro Energy Solution for Remote Islands", *Journal of Energy Conversion and Management*, Vol.42/9, pp.1105-1120.

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

Published Results:

- **Kaldellis J.K., Kavadias K.A., 2004**, "Evaluation of Greek Wind Parks Visual Impact: "The Public Attitude" *Fresenius Environmental Bulletin*, Vol. 13/5, pp.413-423.
- **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:

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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.
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5. "Flow Field Prediction for High Speed Turbomachines"

Published Results:

- **Kavadias K.A., Kaldellis J.K., 2003**, "An Integrated Aerodynamic Simulation Method of Wind Turbine Rotors", *Applied Research Review* Journal of the TEI of Piraeus, Vol.8/1, pp.221-242.
- **Kaldellis J.K., 1998**, "Static Pressure Gradients inside the Shock-Shear Flow Interaction Region", *Technika Chronika, Scientific Journal of the Technical Chamber of Greece-IV*, Vol.18/2, pp.19-33.
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6. "Techno-economic Evaluation of Renewable Energy Applications"

Published Results:

- **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.
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- **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.
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8. "Evaluation of Energy Storage Systems"

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

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11."Autocats Standardization and Recycling"

Published Results:

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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.
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Published Results:

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- **Sigalas J.S., Kavadias K.A., Kaldellis J.K., 2000,** "An Autonomous Anaerobic Wastewater Treatment Plant Based on R.E.S. Theoretical and Experimental Approach", International Conference, Protection and Restoration of the Environment V, pp.735-743, Thassos Island, Greece.
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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., 2001**, "The Nimby Syndrome in the Wind Energy Application Sector", International Conference on "Ecological Protection of the Planet Earth I", Vol. II, pp.719-727, Xanthi, Greece.
- **Marouli Chr., Kaldellis J.K., 2001**, "Risk in the Greek Electricity Production Sector", 7th International Conference on Environmental Science and Technology, Conference Proceedings, Vol. C, pp.305-314, University of Aegean, Global-NEST, Syros, Greece.

Research Projects under Development *(1/2)*

Participation in Research Programs (2002-2004)

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

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

3. "***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

4. "***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

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

6. "***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

7. "***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

8. "***Optimisation of Water Systems in Islands with Limited Water Resources***", Research Program "Archimedes-II" supported by the Greek Ministry of Education

9. Hellenic/French Collaboration Research Program "Platon" entitled "***Advanced Techniques of Automation in Wastewater Treatment Plants***". (Accomplished)

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

10. "***Development of an Experimental Hybrid Plant based on a Wind Turbine - P/V Station Collaboration***", supported by T.E.I. of Piraeus (Accomplished)

11. "***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)

12. Program "***RENES-Unet***", for the Diffusion of Renewable/Soft Energy Applications in Greece and European Union

13. "***Techno-economic Study of Small Hydro Power Stations***", supported by the private company EMPEDOS SA

14. "***Water Pumping Storage Systems for Crete Island***", in collaboration with the Technical University of Crete and the Enercon Hellas SA

15. "***Desalination System Based on Gas-Turbines Exhausted Gases***" supported by PPC and Crete Municipalities Union

16. "***NATURA-2000***", supported by the Greek Ministry of Environment, Physical Planning and Public Works

17. "***Natural Gas Cogeneration Opportunities in Urban Areas***", in collaboration with the Municipality of Nikaia

18. "***Energy Saving in TEI Buildings***", supported by TEI of Piraeus

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PART ONE

RENEWABLE ENERGY SYSTEMS

- Wind Energy
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EVALUATION OF GREEK WIND PARKS VISUAL IMPACT "THE PUBLIC ATTITUDE"

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Abstract

During the last three years, the installed wind power in Greece has significantly risen from 40MW to almost 300MW. This important wind power ascension was based on contemporary wind turbines of remarkable size, concentrated in few relatively restricted geographical areas. In certain areas, however, this outstanding wind power penetration provokes serious local population reactions, which in several cases lead even to the complete wind power projects cancellation, by claiming important environmental impacts. In this context, "visual intrusion" is found to be one of the major factors determining opposition to wind energy. In order to examine this problem an extensive study is carried out concerning the visual impact of the existing wind parks in Greece. For this purpose, a public opinion survey is carried out all over in Greece, concerning the local habitants' attitude towards a wind park, as far as the "visual intrusion" of existing wind turbines is concerned. The results collected are analyzed in view of the machines general acceptability. According to the data analyzed -sample of 417 respondents in three representative Greek territories-, an important part of local people, including wind energy supporters, claims remarkable visual annoyance of existing wind turbines. Thus, if the target is to accelerate wind power penetration in the local energy market, more attention should be paid on the visual incorporation of new installations in the local landscape.

Keywords: Wind Energy; Visual Impact; Public Attitude; Opinion Survey

1. Introduction

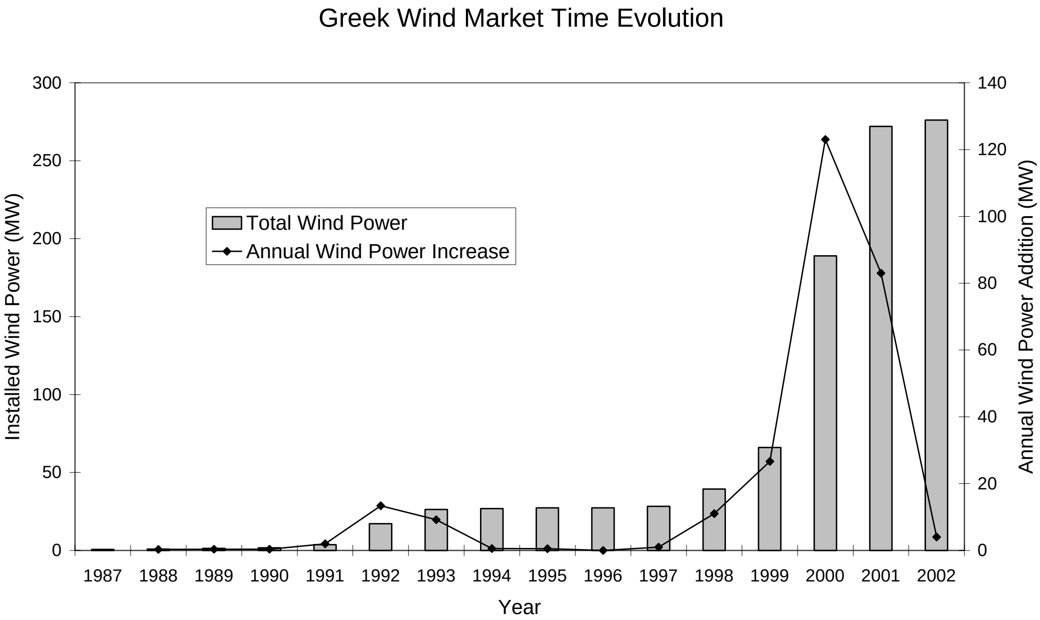

Figure 1: Time evolution of Greek wind power

***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.*

The sudden and significant wind power amplification (from 40MW to 272MW) in Greece during the years 2000 and 2001[1][2] was followed by a new stagnation period of installations (figure (1)), hence only 5MW were added during entire 2002. The main factors limiting the once promising wind energy penetration include absence of appropriate locations possessing suitable electrical network infrastructure[3] and serious local population reactions[4] in some advantageous areas like Euboea and South Peloponessos, which in several cases lead even to the complete wind power projects cancellation, by claiming important environmental impacts[5].

In view of this negative reaction, many researchers believe[6][7] that "visual intrusion" is one of the major factors determining opposition to wind energy, although opposition on aesthetic grounds is characterized as subjective and is often dismissed by public officials. In this context, taking seriously into account the above-mentioned remarks, an extensive study is conducted concerning the visual impact of wind parks in Greece.

More specifically the complete project is divided in two parts. In the first part -presented here- a public opinion survey is carried out all over in Greece, concerning the local habitants' attitude towards a wind park, as far as the "visual intrusion" of existing wind turbines is concerned. The results collected are analyzed in view of the machines general acceptability degree by the local communities. Accordingly, a parallel work is under preparation in order to quantify the visual impact of specific wind parks[8][9][10], where the local public opinion is investigated.

2. Position of the Problem

Public concern about electricity generation technologies has been greatly increased during the last thirty years. Environmental groups and local authorities have often been in the centre of opposition to new energy projects based on fossil fuels or nuclear power. Wind energy, at its early stages of development, appeared not to face such difficulties, since public opinion surveys from several industrial countries[11][12][13] validated the positive public attitude towards wind power applications.

On the other hand, as wind power stations have gradually amplified their size and number, the corresponding planning procedures have at times had to deal with intense contradiction and debate[4]. On top of that, one should also take seriously into consideration the increasing percentage of NIMBY stance[4][14][15]. Thus, although the public opinion is definitely in support of wind power, a remarkable part of the society is opposed to wind turbines in its own living environs (e.g., distance less than 5km from local people residence).

In this context, one should take also into consideration that small water and windmills have been in operation, during the last 800 years, all over in Europe. Recently, wind turbines revived the matter of landscape aesthetics. They have been subjected to hard criticism because of their technical-industrial character and appearance, being also located in highly visible places in order to exploit the available wind potential.

According to our opinion, the reaction to the sight of a wind farm is highly subjective. This attitude often has much more to do with feeling and knowledge than visual perception alone. Therefore, the existence of a wind park in a specific region may be judged either as a positive or as a negative addition to the landscape.

Numerous studies[11][12][13][16] in several active wind power markets demonstrate that people who live near wind turbines tend to be more favorable towards them than city dwellers. A possible explanation to this diversification could be that people living in cities have a more romantic view of the countryside than people from rural areas, which have a more practical relation with nature.

In addition to subjective allegations versus existing wind parks, periodic reflections (glinting) or interruption (shadow flicker) of sunlight from the rotor blades can be objectively recorded and quantified[5][17]. In most cases these localized effects may be easily predicted and avoided[18] by careful turbine-siting and appropriate surface finish of the blades.

In the present essay extensive results, concerning an integrated study about the visual impact assessment of wind farms, properly adapted for Greece, are analyzed. Hence, in order to investigate the public attitude towards wind energy applications, a widespread public opinion survey is carried out in several Greek regions concerning the visual impact of existing wind parks. According to the data gathered, a variety of reactions were encountered, including several cases with local people negative reactions to wind parks. An attempt to analyse and rationalize all these reactions is also made.

3. Preparation of the Survey

In view of the negative reactions against new wind power installations encountered, concerning specific Greek communities, the Soft Energy Applications and Environmental Protection Laboratory of TEI Piraeus has undertaken (since 2000) an extensive study about the public acceptance of wind parks all over in Greece. In this context, the scientific team involved has first scheduled and subsequently conducted[4][8][16][19] a public survey in several representative Greek territories, presenting wind energy development interest. During the planning phase, emphasis is laid on the following topics:

- ✓ The existence and the intensity of wind energy exploitation activities
- ✓ The degree of public knowledge about wind energy applications
- ✓ The public awareness about the environmental and macro-economic impacts of wind energy. Personal annoyance is also recorded

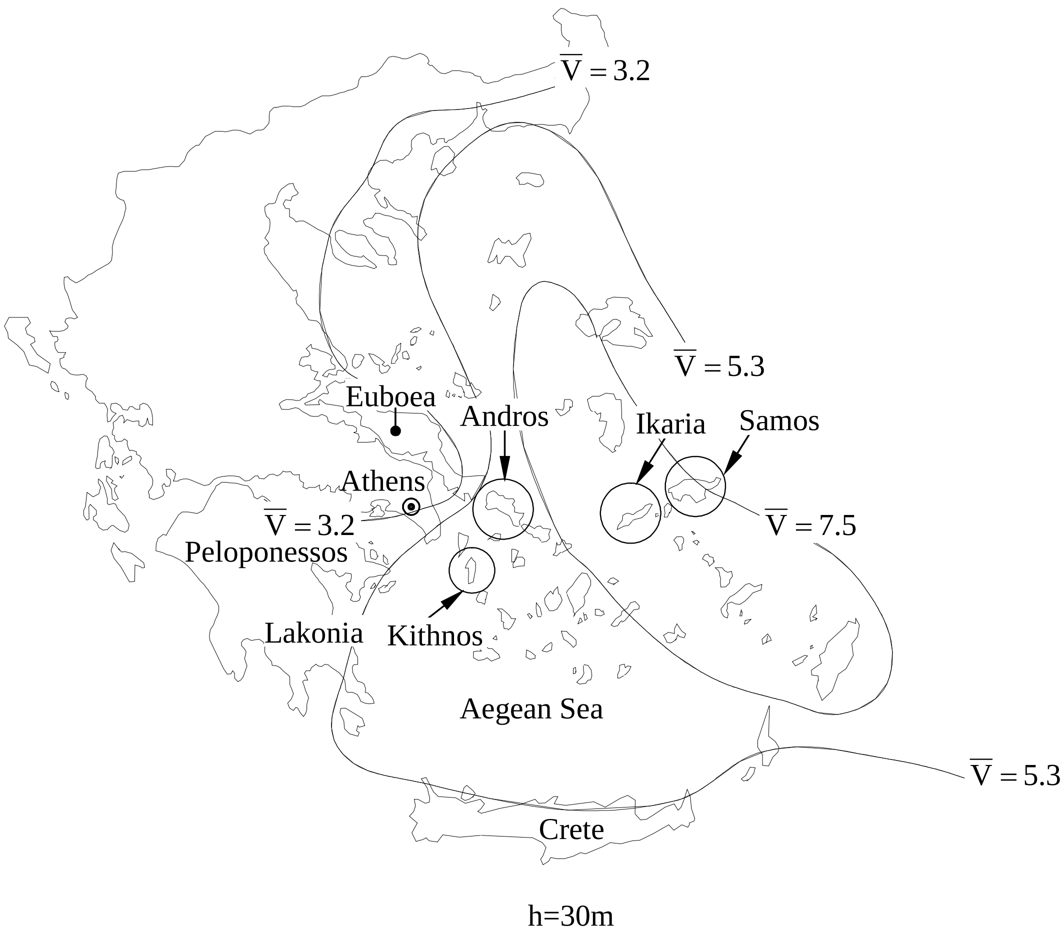

Figure 2: Selected Greek regions for the public survey realization

✓ The public attitude towards wind energy applications, in view of the NIMBY syndrome

Accordingly, for increased reliability and due to the country idiosyncrasy during the present survey the appropriate questionnaires were completed within the interviewer's sight, while the respondents filled in their name and phone, for confirmation purposes. The public response was encouraging, since almost one out of two persons answered the questions eagerly.

The last point to be arranged was the number of interviews needed to draw safe conclusions[20]. Due to the geographical diversity of the study (figure (2)) and the manpower needed, a sample number in the range of 100 to 150 questionnaires was assumed acceptable for each region examined, while 50 interviews were set as the lower limit.

For the preparation of the questionnaire a large number of scientists have collaborated, including statistics experts, sociologists and market survey experts. The relative questions to the subject investigated are summarized in Table I, along with the possible answers. As it is obvious from Table I the first two questions asked guarantee that the people interviewed are familiar to the subject examined. According to the entire sample analyzed (417 questionnaires) 94% of the people interviewed are familiar with the basic wind energy principles (question 1), while only 2% was not sure about the contribution of wind parks in the electrification effort (question 2). Recapitulating, one may clearly state that the samples used have the necessary size to be statistically sound and credible, while the vast majority (≈95%) of the people questioned have quite a good idea about wind energy basic principles and wind power applications.

Table I: Demonstration of the questionnaire used in the present public opinion survey.

Question 1	**What do you know about wind energy?**	
Possible Answers	A	It is obtained from the waves of the sea
	B	It is used in the solar heaters
	C	It is obtained from the wind
	D	It is obtained from nuclear plants
	E	I do not know
Question 2	**The wind converters or wind turbines are usually used:**	
Possible Answers	A	in producing electric energy
	b	in marking regions
	c	for aesthetic reasons
	d	for televising purposes
	e	for other reasons
Question 3	**Do you actually agree with the installation of Wind Turbines in your territory?**	
Possible Answers	a	YES, I do
	b	NO, I don’t
	c	I would agree if only I had proof of their usefulness
	d	I am not interested in this matter
	e	I have no formed opinion
Question 4	**The wind converters or wind turbines of your territory:**	
Possible Answers	a	are visually annoying
	b	have no visual impact on me
	c	are not aesthetically right
	d	I have no opinion on their aesthetic impact
	e	make the area attractive

4. Registration of Visual Impact and Public Attitude Versus Wind Parks

After the arrangement of the necessary preconditions the above-described public survey is realized in three stages. The first stage is executed in two separate phases (during the 1st and 2nd semester of 2001) and it was focused on the S. Euboea area (figure (2)). The sample of 128 interviews -taken during the period examined- is a representative size to extract statistically safe conclusions. Bear in mind that up to the end of 2002, in S. Euboea had been operating wind parks of rated power approaching the 150MW, representing the entirety of Greek mainland wind power installations, see for example figures (3) and (4).

Figure 3: General view of Marmari-Euboea wind park (17x300kW)

Figure 4: General view of Polipotamos-Euboea 12MW wind park.

According to the results of our survey (Table I, question 3), the public opinion is definitely divided (figure (5)). More precisely 4 out of 10 (40%) of the respondents clearly disagree with the existence of

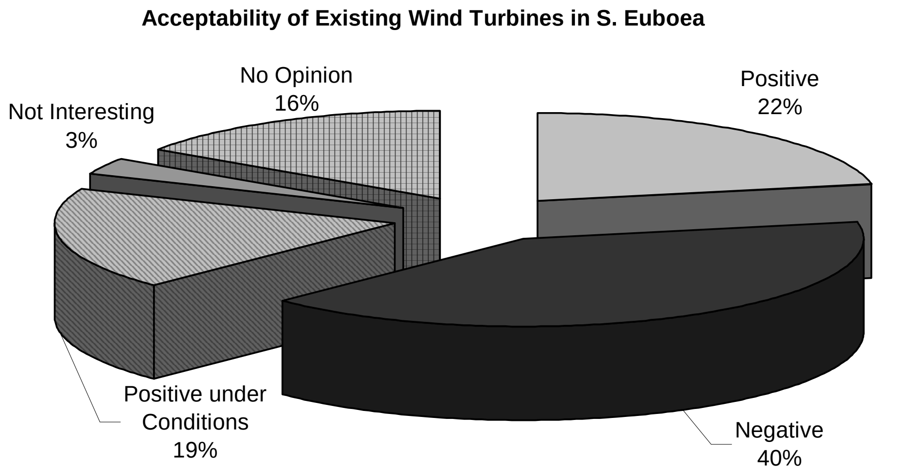

Figure 5: Acceptability of wind energy applications in S. Euboea (2001)

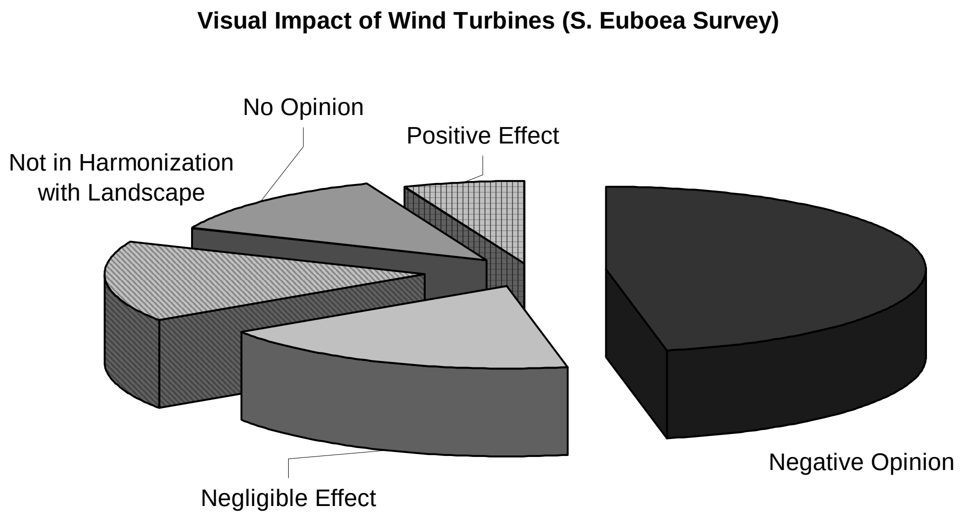

Figure 6: Visual impact of wind turbines in S. Euboea

the wind parks in their region, 22% definitely accept the wind turbines, while 19% tolerate them under the precondition of their proved usefulness.

Another interesting outcome of this two-phase public survey (Table I, question 4) is the negative -by almost 46%- visual impact of wind turbines on the examined region habitants, while another 16% believes that the existing machines are not in harmonization with the landscape. On the other hand, only 6% admit the sight of these machines whereas 19% do not mention any visual intrusion (figure (6)).

Analyzing now the attitude of the respondents, expressing negative opinion towards existing wind turbines, almost their entirety (i.e. 93%) declares visual impact of existing machines. What seems

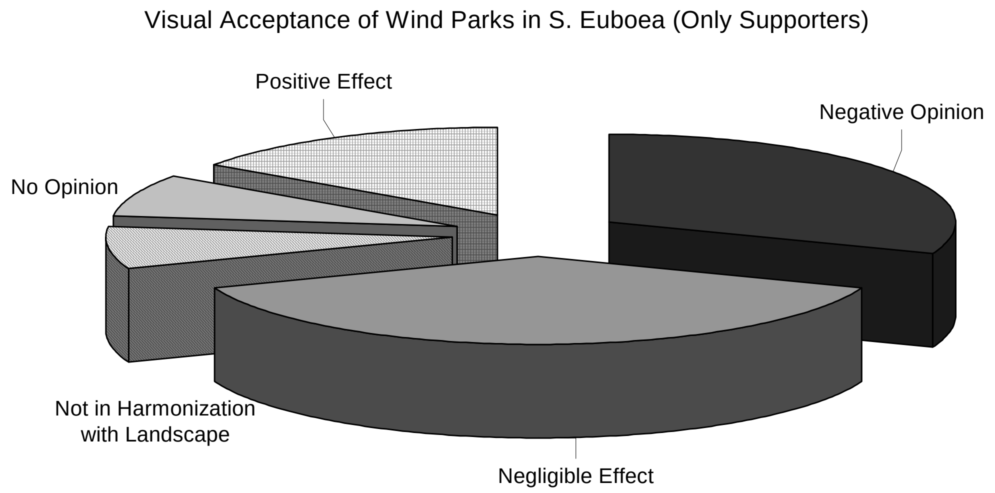

Figure 7: Wind turbines' visual impact in S. Euboea, supporters sample only

Figure 8: Marathocambos wind parks: a) PPC 9x100kW; b) private (250+750)kW

more perturbing is that almost 40% of the habitants being supportive to the wind energy applications in their region state strong (32%) or mild (8%) negative visual impact of wind turbines (figure (7)).

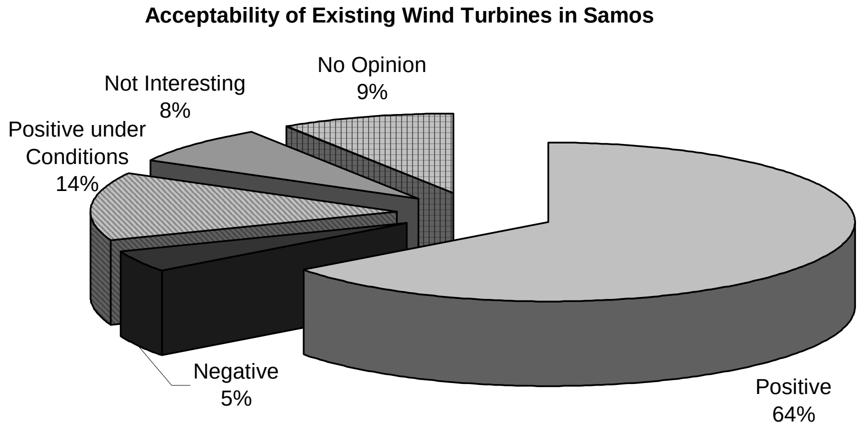

Figure 9: Acceptability of wind turbines in Samos Island

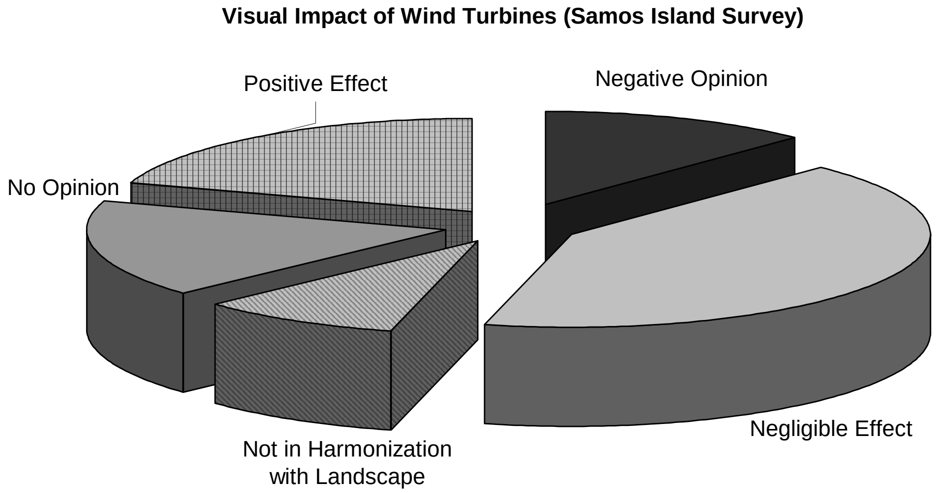

Figure 10: Visual impact of wind turbines in Samos Island

One sound explanation for this unexpected result may be the assumption that this specific subgroup is willing to forgive the visual intrusion of the turbines in the landscape for the presumably higher goals of their operation. However, if turbines are faulty, the public may perceive a wind farm to be unjustified -a waste of visual resources[21].

Accordingly, the second stage was concentrated in Samos Island (figure (2)), where almost two hundred (196) local people have been interviewed during 2001 in two separate attempts. Samos is a medium-sized island in East Aegean Sea, possessing excellent wind potential. In this island, since 1991, there exist two wind parks belonging to Greek Public Power Corporation (PPC), at Marathokambos (9x100kW) and Pithagorion (9x225kW) regions, see for example figure (8). Next to the wind park of PPC at Marathokambos there also exist a small private wind farm of 1MW.

The general picture of the local habitants' attitude towards wind turbines is completely different from the one of S. Euboea. More specifically, the 64% of respondents expressed favourable opinions about the development of wind power stations, while another 14% supported wind farms under the precondition of proper operation (figure (9)). Only the 5% of local people do not accept the operation of wind converters in their region.

Even in this positively reacting society, 12% of the sample mentions negative visual impact of wind turbines, while another 9% declares that these machines are not in harmonization with the landscape (figure (10)). On the contrary, the vast majority of the local people do not point out any visual intrusion, while 2 out of 10 are of the opinion that wind turbines looked decorative.

Finally, the third stage of the public survey was realized in three different close islands of central Aegean Archipelago (figure (2)), i.e. Ikaria, Andros and Kithnos. In all these areas possessing excellent wind potential there is a strong interest for new wind power applications, possibly in collaboration with energy storage systems[22] (wind-hydro) or desalination plants[23]. Additionally, small wind parks belonging to Greek Public Power Corporation, operate in these three regions since 1991, i.e. 8x55kW in Ikaria, 7x225kW in Andros and 4x33kW+500kW in Kithnos, see for example figure (11), with remarkable efficiency[21].

In these three selected cases the total sample was almost one hundred (93 respondents), while the period examined was between June 2001 and June 2002. According to the data collected, an attitude similar to the case of Samos is also shaped for the rest Aegean Archipelago islands. More precisely, the Aegean Sea inhabitants are also in favour of existing wind parks (62% positive and 19% positive under conditions); since they are quite familiar with the long-term operation of wind turbines in their region (figure (12)). Only 6% of the respondents are negatively expressed towards existing wind plants.

On the other hand, there is a remarkable percentage of people disliking the appearance of wind turbines (16%), while a similar percentage supports that these machines are not in harmonization with landscape (figure (13)). A considerable part of respondents (i.e. 29%) does not mention any visual impact from the existing wind parks, while another 26% finds the operating machines decorative. In an attempt to explain the remarkable negative opinion concerning the wind turbines visual impact, one should take into account the present status of these wind turbines, which operate for more than 10 years, without very careful maintenance, e.g. figure (14).

Figure 11: General view of Andros wind park (7x225kW)

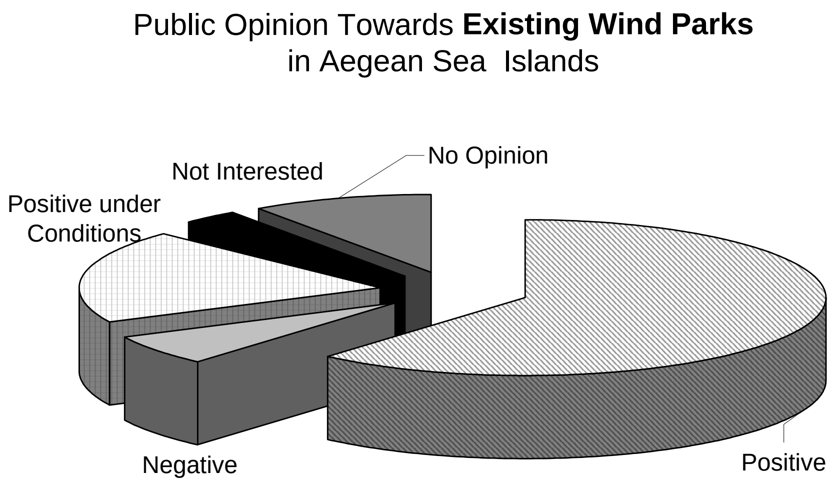

Figure 12: Acceptability of wind turbines in small Aegean Sea islands

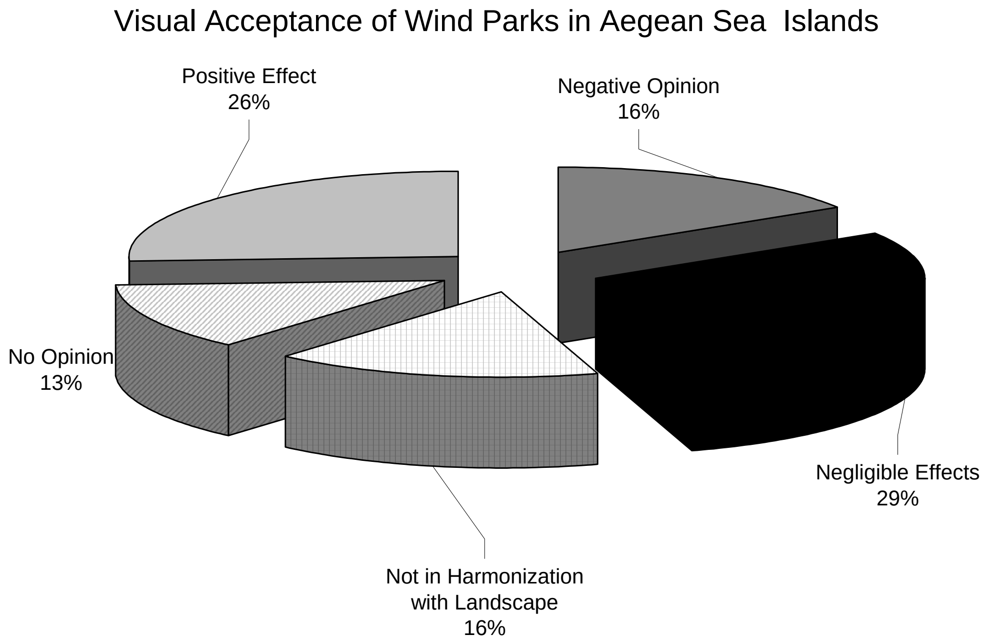

Figure 13: Visual impact of wind turbines in small Aegean Sea islands

Recapitulating, according to the assessed results of three recent public opinion surveys, realized in three successive phases (1st and 2nd semester of 2001 and 1st semester of 2002, total sample 417 respondents), concerning the visual impact of wind turbines along with the social attitude towards existing wind parks, the following conclusions may be drawn:

a. There is a considerable diversification of the public attitude in S. Euboea and in Samos Island. More specifically, the vast majority of the respondents in Samos are in favour of the existing wind parks, while the public opinion in S. Euboea is equally divided in favour and against the existing

Figure 14: Old wind turbine in Kithnos

machines. An attitude similar to the case of Samos is also shaped for the rest Aegean Archipelago islands, although the visual impact attitude is quite different.

b. A remarkable part of the respondents declare significant visual impact of existing wind turbines in the landscape, especially in S. Euboea region, where the wind power concentration is much more intense.

c. Almost all individuals that do not agree with the existing wind turbines in their region dislike their appearance. On top of that, a remarkable part of wind parks supporters claim visual impact of the wind converters.

d. An important share of people interviewed, clearly state that they should support wind energy applications under the precondition of efficiency function. This result means that if turbines do not operate or are perceived to be broken quite often, the public is far less likely to tolerate their intrusion on the landscape.

5. Conclusions

An extensive public opinion survey is carried out all over in Greece, in order to investigate the public attitude towards wind parks, while special emphasis is laid on the visual impact of existing wind turbines. According to the information analyzed, an important part of local people (including several wind energy supporters) claim significant visual impact of existing wind turbines.

In most cases the one fourth to one half of people interviewed mention visual annoyance due to the operation of wind parks in their neighbourhood. This attitude is supported by the insufficient maintenance of existing wind turbines as well as by the diffused unjustified opinion -expressed by PPC authorities- of the already operating wind farms financial incompetence.

In conclusion, visual impact is found to be one of the most important parameters affecting the public attitude towards wind power applications. Hence, if the target is to accelerate wind power penetration in the local energy market, in order to support the sustained development, more attention should be paid on the new installations visual incorporation in the local landscape.

In the authors' opinion, the visual intrusion of existing or new wind parks should be properly analyzed and amended. In the opposite case, any additional wind energy applications may confront serious contradictions, derived from groundless allegations of important visual annoyance.

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INVESTIGATING THE REAL SITUATION OF GREEK DOMESTIC SOLAR WATER HEATING MARKET

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Abstract

Solar thermal applications have been acknowledged among the leading alternative solutions endeavouring to face the uncontrollable oil price variations, the gradual depletion of fossil fuel reserves and the chain environmental consequences caused by its excessive usage. Almost thirty years after the initial emergence of the commercial domestic solar water heating system (DSWHS) in the European market, the corresponding technology is qualified as quite mature. On top of this, the European Commission expects that 100,000,000m^2 of solar collectors are to be installed in Europe by the year 2010 to facilitate durable and environment-friendly heat. In this context, the Greek DSWHSs market is highly developed worldwide, having a great experience in this major energy market segment. The present study is devoted to an extensive evaluation of the local DSWHSs market, including a discerning analysis of its time-variation, taking seriously into account the corresponding annual replacement rate. Accordingly, the crucial techno-economic reasons, limiting the DSWHSs penetration in the local heat production market, are summarized and elaborated. Subsequently, the national policy measures -aiming to support the DSWHSs in the course of time- are cited, in comparison with those applied in other European countries. Next the financial attractiveness of a DSWHS for Greek citizens is examined in the local socio-economic environment. The present work is integrated by reciting the prospects and mustering certain proposals that, if applied, could stimulate the local market. As a general comment, the outlook for penetration of new DSWHSs in the local market is rather grim, as the current techno-economic situation of solar heat cannot compete with oil and natural gas heat production, unless the remarkable social and environmental benefits of solar energy are seriously considered. Hence, the Greek State lacks stimulus to further DSWHSs installations, being strongly in support of the imported natural gas. As a result, the future of domestic solar thermal market and the survival possibilities of the local manufacturers are at stake.

Keywords: Solar Thermal Market; Hot Water Production; Payback Period; Service Life; Utilization Factor; Market Prospects; Market Penetration Barriers

1. Introduction

Solar thermal applications have been acknowledged among the leading alternative solutions endeavouring to face the uncontrollable oil price variations, the gradual depletion of fossil fuel reserves and the chain environmental consequences caused by its excessive usage[1][2]. The first solar thermal systems for water heating were commercially introduced after the first oil crises, in mid-70s, when the majority of the present-day companies were initially founded. The unstable international oil market and the resulting high-energy cost afterwards encouraged some pioneer manufactures to establish their activity and expand on producing small domestic solar water heating systems (DSWHSs). Almost thirty years after the initial emergence of the commercial DSWHS in the European market, the corresponding technology is qualified as quite mature, since more than 15,000,000m^2 have been installed in the EU member states. On top of this, the European Commission -according to the White Paper[3] on Renewable Energies- expects that 100,000,000m^2 of solar collectors are to be installed in Europe by the year 2010 to facilitate durable and environment-friendly heat.

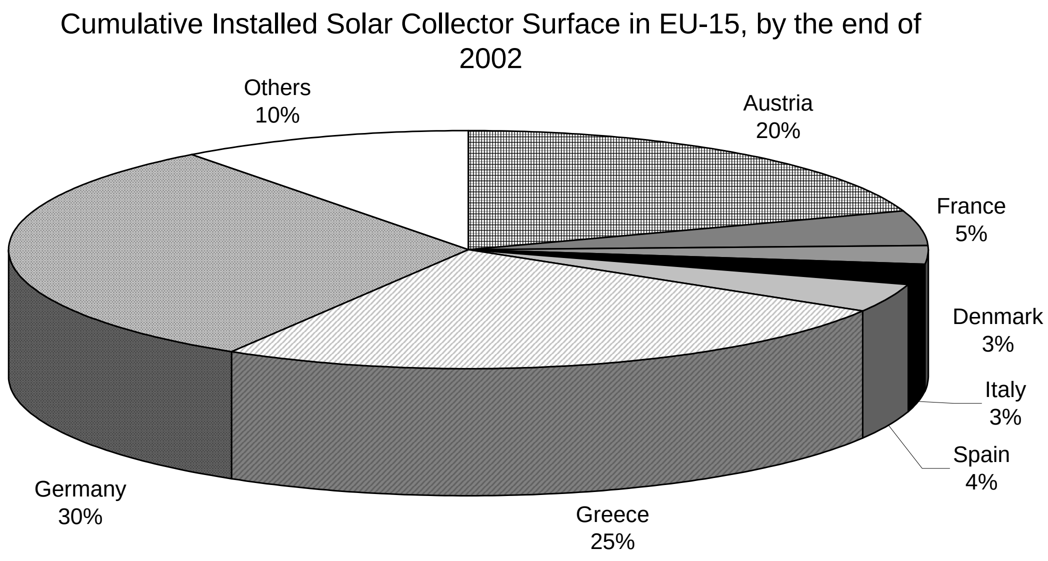

Figure 1: Market shares of the cumulative installed solar thermal collector surface for each individual EU-15 country member, by the end of 2002

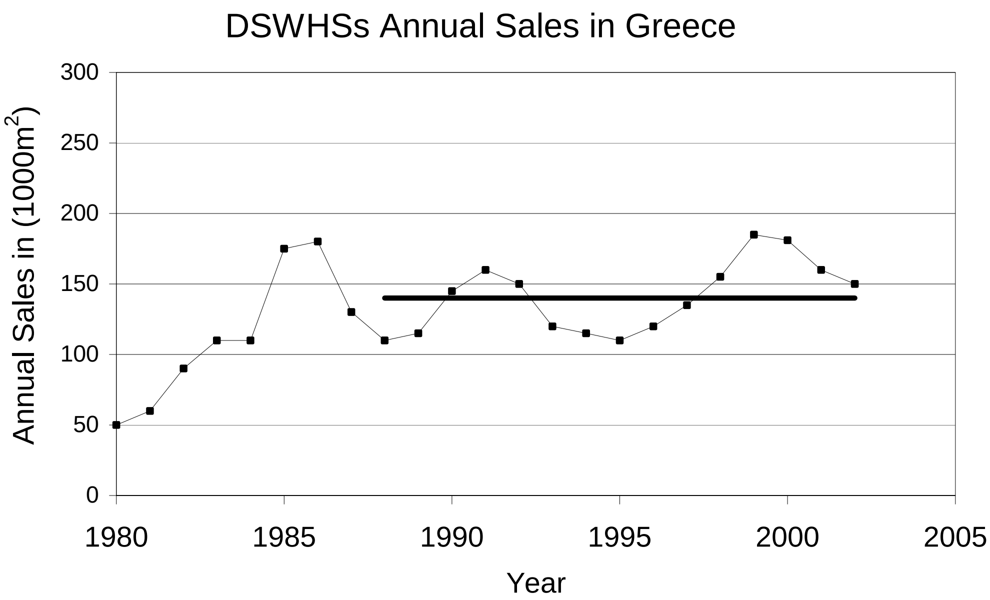

Figure 2: Time Evolution of DSWHSs Annual Sales in Greece

In this context, the Greek DSWHSs market is highly developed worldwide, having a great experience in this major thermal market segment[4][5]. More specifically, Greece has been playing a dominant role in the European solar thermal market, since it represents almost the 25% of the cumulated installed solar thermal collector surface in the EU-15 countries[6] by the end of 2002, figure (1). Recent publications[7][8] support that the local market sets an example of a "success story" with several perspectives of further development. On the other hand, according to recent research by the authors[9][10], the Greek market has actually been growing at a slow pace during the last decade and it appears to have reached saturation point; see figure (2). This is a question that has given rise to much controversy. On one side, a continuously declining initial investment cost evolution in constant terms

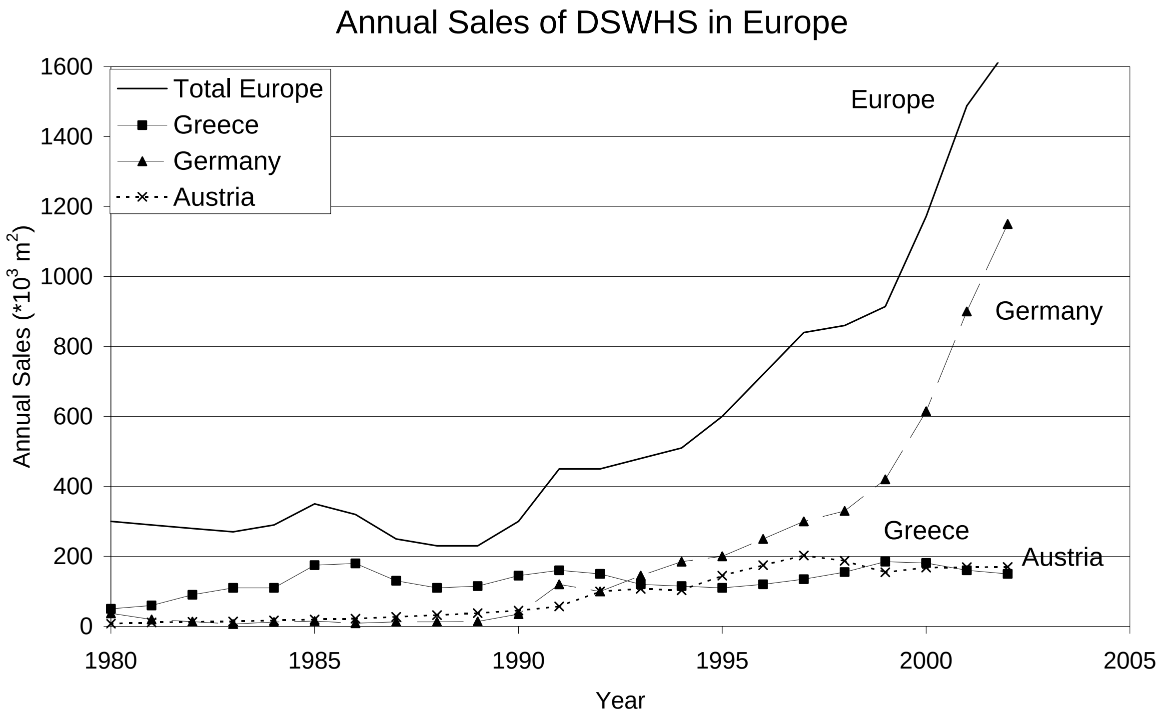

Figure 3: Comparison of DSWHS European Market in the Course of Time

along with an improved production quality is reported. On the other side, a sales and interest rate decrease is testified concerning the domestic solar water heating systems (DSWHS), being in contradiction[11][12] with the thriving dynamic solar market of Germany and Austria; figure (3).

In view of this inconsistency, the present study is devoted to an extensive evaluation of the local DSWHSs market, situated in the entire European Union solar market frame. For this purpose, a discerning analysis of the time-variation of the local market is initially presented, taking seriously into account the DSWHSs annual replacement rate. Accordingly, the crucial techno-economic reasons, limiting the considerable DSWHSs penetration in the local heat production market, are summarized and elaborated. Subsequently, the national policy measures -aiming to support the DSWHSs in the course of time- are cited, in comparison with those applied in other European countries. Next the financial attractiveness of a DSWHS for Greek citizens is examined in the local socio-economic environment. The present work is integrated by reciting the prospects and mustering certain proposals that, if applied, could stimulate the local market.

2. Historical Evolution of Greek Solar Market (1974-2003)

Greek solar thermal market was established in 1975, after the oil crisis of 1973, when the Turkish invasion in Cyprus forced some Cypriots manufacturers to transfer their activities -concerning the DSWHSs sector- in the Greek mainland. During the first decade, the DSWHSs penetration in the local market was progressively rising; motivated by the oil price increase, advertising campaigns and, especially, tax exemptions adopted by the Greek State in support of solar energy applications. As a result, more than 100,000m^2 of glazed solar collectors were sold through 1983-1984; see figure (2). Due to their immature technology, however, those most primitive systems disappointingly presented major malfunctions during their operation[9][13][14].

In the next two years, the local market expanded greatly, approaching the 200,000m^2 per annum, figure (2). A successful state-supported advertising campaign along with the introduction of the value added tax in local economy is the main reasoning behind the DSWHSs sales redoubling. Low interest

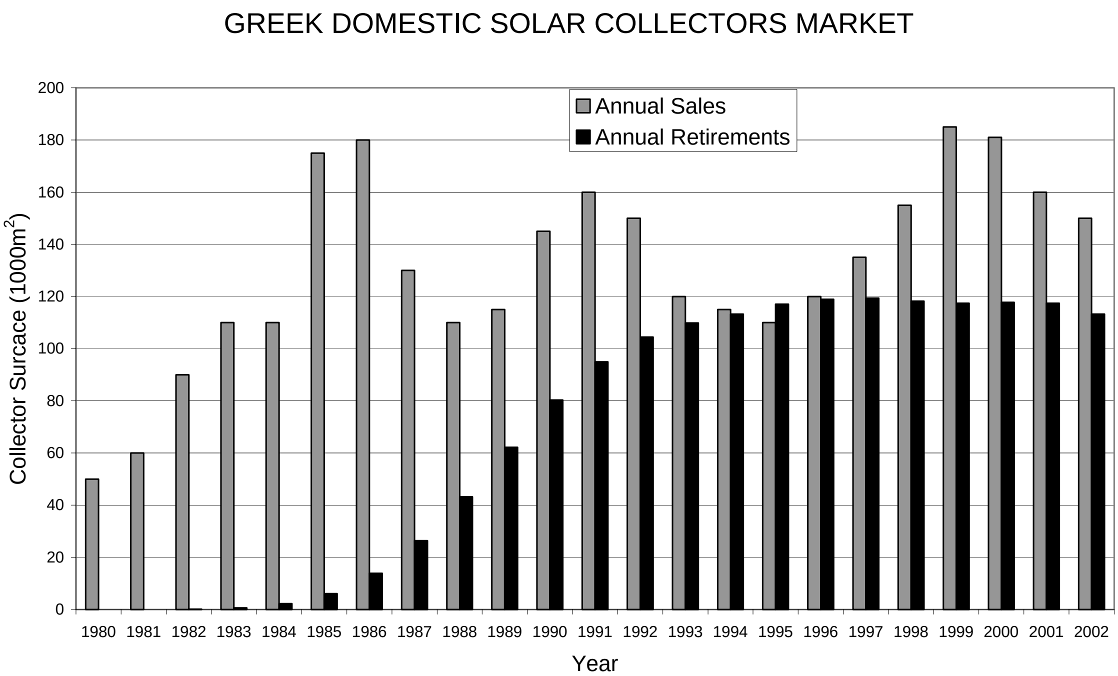

Figure 4: Comparison between new installed and retired DSWHSs in Greece

(soft) loans were also available during this high inflation period, facilitating the purchase of such systems. Since 1987 the local market has oscillated (figures (2) and (3)) around a gradually decreasing mean value, presenting temporary ups (1991, 1999) and downs (1988, 1995, 2002). The long-term (1988-2002) average value of new installed systems is approximately 140,000m^2 per annum. Bear in mind that this value does not represent the annual increase of operating solar collectors in Greece, as a remarkable number of DSWHSs regularly comes out of service as a result of ageing.

In fact, figure (4) compares the annual DSWHSs collector surface installed all over Greece -according to the data provided by ESIF[4][6]- with the corresponding DSWHSs in operation -based on calculation results carried out by the authors. More specifically, the proposed analysis is based on the following assumptions, validated either by several market surveys or experience:

- The European market experts claim that Greek-made systems are technically simplified, presenting a long-term average service life of about 10 years[15].
- The average service period of DSWHSs time distribution adopted in the present study varies from 7.5 years (±2 years standard deviation) for the early (1980-85) systems up to 12.5 years (±3 years standard deviation) for the contemporary ones[16].
- A lognormal Gaussian distribution is adopted to describe the possibility of survival of the local market DSWHSs.
- Extended local market survey -carried out during mid-90s- found out that more than 1/3 of the solar collector users have faced technical problems with their installation[13], part of which were finally abandoned. During the last decade, however, the quality of the products offered is substantially improving[17], especially after the endorsement of standardization procedure[18] by the leading Greek manufacturers.
- Only 2/3 of the owners of a DSWHS that attests an average service life finally replace their old systems with new ones, taking advantage of the existing installation.

The results of the proposed analysis are quite impressive indicating that during the 1993-97 period the actual in service DSWHSs are almost constant; see also figure (5). In fact, during 1995, it appears that more DSWHSs are removed than sold in Greece; figure (4). After 1998 a slight increase of operating

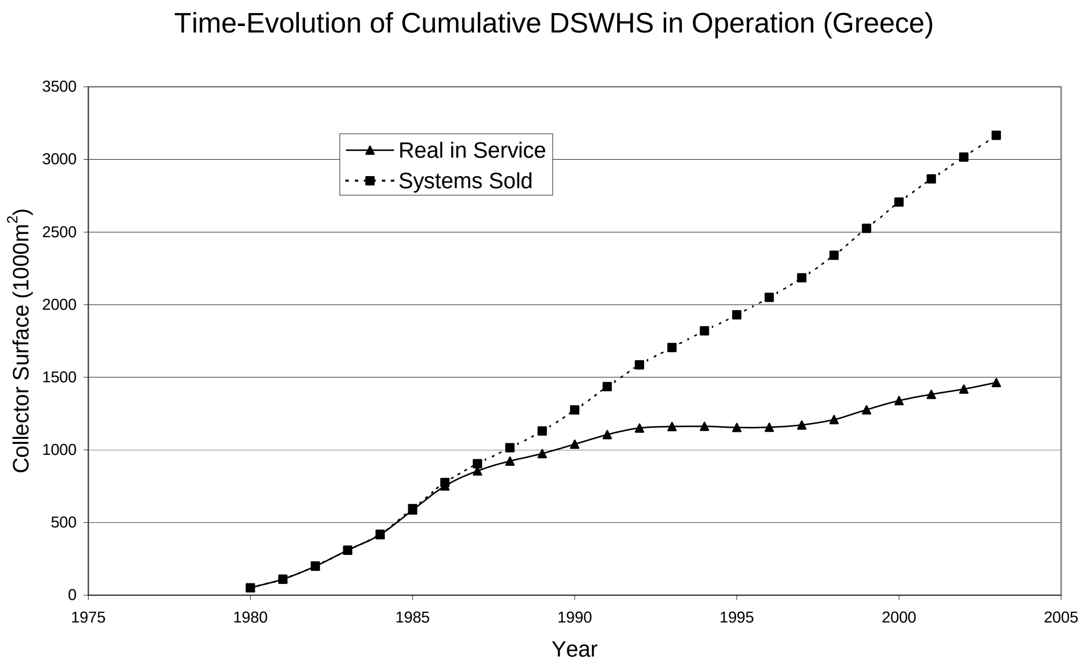

Figure 5: Comparison between total DSWHS sold and being in operation in Greece

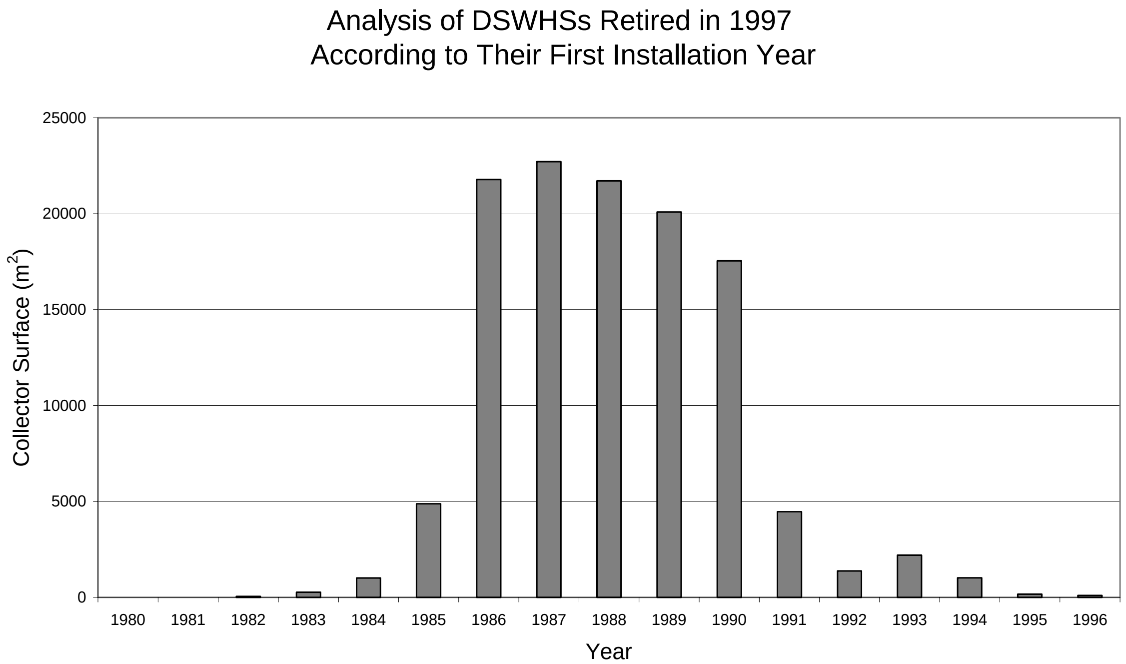

Figure 6: Time-distribution of retired DSWHSs during 1997, on the basis of their first installation year

systems is encountered, though decelerating during the current decade under the pressure of natural gas penetration in the urban tertiary sector[19].

More precisely, in figure (6) one may for example analyse the number of the out of service DSWHSs during 1997 as a function of their first installation year. According to the developed model, a remarkable number of DSWHSs installed during the 1986-1990 (more than 20,000m^2 per year) are removed, after operation of eleven to seven years. It is also interesting to mention that after 1997 the number of the first generation (1980-1985) operating DSWHSs is practically zero (i.e. less than 2000m^2).

As a result, the actual DSWHSs operating in Greece -saving imported oil and preventing emission of several hazardous flue gases- are beneath the 50% of the numbers introduced either by ESIF[6] or local authorities[16]. More to the point, this time lag of the national policy deviates the country from the European targets for the greenhouse gases emissions restriction[20].

3. DSWHSs Major Penetration Barriers in the Local Market

The intermitted nature of renewable energy resources, the important disharmony between energy demand and energy production and the short-term supply fluctuations are the major factors that have so far limited the renewable energy applications, including the solar thermal ones. Despite this crucial problem, during the last thirty years solar energy has proved reliable and economical in cases of hot water production[8][12]. In this context, many researchers claim[4][5][6] that the European DSWHSs market has remarkably expanded during the recent decade, figure (3). After a closer inspection of the available official information, however, one may easily conclude that over 60% of the systems installed in Europe during the last three years were sold in Germany (see figure (3)), while most other countries currently have considerably lower growth rates or are even stagnating. Unfortunately, this is the case for local market, which -after an impressive solar collector diffusion in the 1980-1994 period- is on the ebb, despite the constantly improving quality and efficiency of the products offered[17].

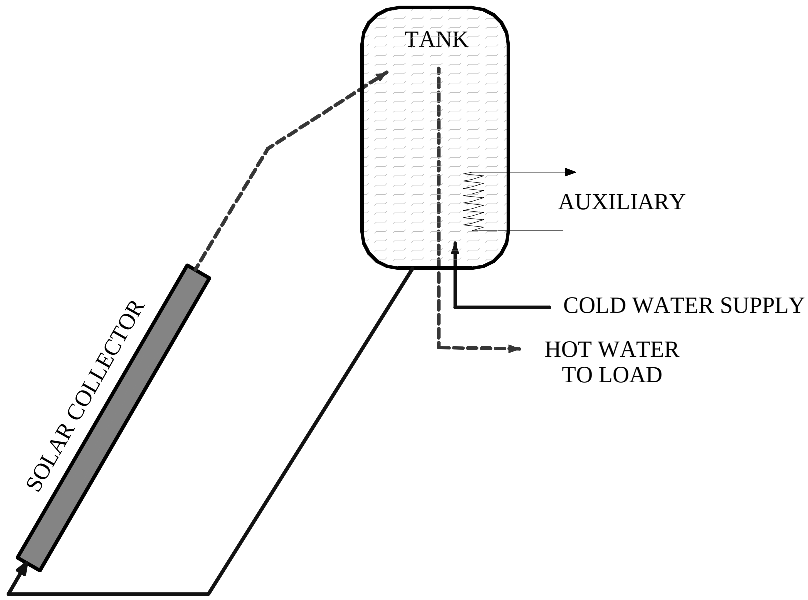

Figure 7: Typical Greek DSWHS Configuration

To get a definite picture of the existing DSWHSs, one should mention that more than 95% of the installed systems -see for example figure (7)- are based on natural circulation. The average size of the natural circulation systems sold, has 2.5 m^2 of collector area and a 150l storage tank. The storage tank, horizontal or vertical, is usually positioned above the collectors, while the volume of the storage tank ranges between 120 and 220l, respectively. All systems use an electrical resistance as a backup-heating source. Only a small minority has an additional heat exchanger connected to a space heating system (usually an oil-fired central heating system). The annual energy output of these systems ranges from 350 to 800kWh per m^2, although this value greatly depends on the daily and seasonal hot water consumption profile of the user.

Using the available information in the published literature[7][8][13][14], along with extended market survey efforts since 1996[9][12][17], one may classify the following barriers concerning the decelerated DSWHSs penetration in the local market.

3.1 Limits of Available Installation Locations

Most DSWHSs are positioned on the roof of buildings, since the architectural type of the Mediterranean buildings, i.e. lack of tilted roofs, does not facilitate the integration of solar collectors. The urbanization degree of the major Greek cities considerably limits the available area for solar collectors installation. Besides several (≈30%) Greek households (especially in urban centers) are not under ownership and, therefore, it is not possible for them to install a DSWHS even if they wish to. Finally, financial constraints have impeded the construction rate of new buildings, while most decision makers in the building sector (architects, house technology planners) are completely unfamiliar with the solar thermal technology.

3.2 First Installation Difficulties

As most DSWHSs of "thermosyphon" type seem "too simple and easy", their installation is often entrusted to unauthorized personnel (untrained plumbers), in anticipation of minimum installation cost. As a result, a remarkable number of DSWHSs either face directions other than true south, or they are significantly shaded by neighbouring buildings, since emphasis is mainly laid on the tilt angle, which does not really affect the annual production[21][22]. In several cases, loose pipe connections, wrong pipe routing, poor insulation and insulation protection or even wrong equipment size may be detected. Installations in rural areas turn out to be even more difficult.

3.3 Technical Problems

It is widely accepted that contemporary DSWHSs are of excellent quality, offering increased longevity and remarkable reliability. On the other hand, early systems have habitually presented technical deficiencies, not being sufficiently integrated into building services systems. As an outcome of that faulty technology, DSWHSs had a rather bad reputation, which -although gradually eliminating- is still a suspending factor complicating the introduction of DSWHSs in some households.

To be more accurate, published works mention[13] that more than one-third of the solar collector users in Greece have faced technical problems with their installation. Boiler and pipe damages and leaking have been the most frequent breakdowns, while collector surface damages and thermostat malfunctions/failures are also reported. Other researchers remark that although the technology of solar water heaters has nowadays matured, problems like mismatching of materials with deterioration due to galvanic action along with selection of materials unsuitable for outdoor use or long UV exposure have frequently been faced in the near past[14]. In addition, material problems are regularly associated either with manufacturing process like poor undercoating of steel parts or insufficient application of quality control systems[18].

The appropriate maintenance and operation of the installation plays an equally important role on the unproblematic operation of a DSWHS. People usually disregard the M&O necessity of similar systems, recalling them only in case of malfunction. As a rule, Mediterranean culture adopts the theory that every problem can easily be faced by the local plumbers, although all eminent companies provide maintenance and technical support to local users via authorized personnel.

In an attempt to improve DSWHSs acceptability by consumers, advanced quality assurance standards are applied by several local manufactures, although Greek law does not enforce the compliance of solar thermal products to specific standards. In this direction, as soon as the major manufacturers established the Greek Solar Industry Association (GSIA) in 1978, testing and certification of thermal solar systems became a prerequisite for being a member of the Association. Consequently, the vast majority of companies operating in this sector use certain quality standards. In the country, there is only one laboratory -belonging to a governmental research centre- accredited for collector testing according to EN 45001. Recently (in 2001) the Hellenic Standardization Organization (ELOT) has re-evaluated the above standards. Finally, one should bear in mind that the imported equipment is not subjected to any mandatory testing in order to receive a marketing license.

3.4 Financial Reasons

All researchers agree[8][10][23][24][25] that acquisition cost is among the major barriers discouraging a DSWHS purchase, as they are more expensive than electrical ones, while their long payback period often exceeds the service life of the equipment.

In Greece, purchasing a DSWHS is practically as simple as purchasing an electric water heater. The customer can easily buy such a system through a distributor, an installer or even directly from the manufacturer. A common practice in Greece is selling solar systems directly to users via exhibitions. Hence the development of solar collector applications in Greece has been following a market-based mechanism.

After an extensive local market survey between 1995 and 2003 by the authors[9][12][17], a small price increase of solar collectors has been encountered -beneath 13% in current values- being equivalent to a system price decrease by 9% in constant terms. Actually, the buy-cost of a typical system for a single-family house (collector area 2 to 3.5m^2 and storage capacity of 120 to 200lt) has been significantly reduced (≈15% in Euro terms) during the last decade. An additional side effect of the sector's continuous technological progress has been the significant quality improvement realized during the last decade, leading to an increased system technical reliability (lower M&O cost) and hence to a better system economic efficiency.

Another significant reason minimizing the competitive advantages of DSWHSs has been the reduced electricity tariffs. More specifically, electricity retail prices have remained almost constant for the last decade, due to Governmental interventions that kept the tariffs of electricity low, in an attempt to limit the local inflation rate. At this point it is important to mention that the electricity production had been a state monopoly up to 2001. Similar policy has also been applied in the central heating diesel-oil market by imposing lower taxation.

As a result of this State policy, being in support of fossil fuels, it is quite rational that even the most elementary technologies, like solar water heating, are still immature to compete with conventional energy in market terms. As several authors verify, it is clearly unfair to compare the renewable energy applications with the well-established fossil fuel ones in pure monetary terms[1][23], in view of the social and environmental benefits resulting from the replacement of fossil fuel energy production by sustainable and clean energy resources. In this context, most European societies subsidize the renewable applications to partially introduce external energy cost in the energy decision prospects[3][26].

Summarizing, the ambitious EU goal -set for 2010- promptly necessitates improved political framework conditions for solar thermal energy. At this point, the funding policy for the solar market development plays a dominant role. All EU countries implement various methods to fund solar technology[4][5]. Subsidies for purchasing solar systems and tax benefits are standard in all countries. In Greece, until recently (2002) the 75% of the system purchase and installation cost was deducted from the individuals' taxable income, leading to a direct first installation cost subsidization ranging from 10% up to 30%. Unfortunately, all these financial incentives were gradually withdrawn, encountering complete lack of solar systems support in the near future. This evolution is a real problem, taking into account the important cost of real estate in the country and the average incomes.

3.5 Public Attitude Towards RES Applications

Greek society has a quite different attitude from other central and northern European countries. Hence, the shortage of energy resources, the environmental destruction and the threatening climate catastrophe, although important are not thoroughly influencing Greek citizens[27] in their water heating selection procedure.

On the other hand, due to the national strong individualism, a large number of house owners are positive in installing a DSWHS in an attempt to obtain a high degree of independence. In any case, however, the available family income is a serious factor.

The insufficient public information level[28] on the emergent worldwide energy reserves shortage and the sharp environmental deterioration problems may also be a good explanation for the socio-cultural stance of the local society. Combination of the above reasoning, along with lack of serious and long-term energy-saving incentives from the Greek State and remarkable aesthetic allegation from certain homeowners, present an unambiguous picture of the local citizens attitude towards DSWHSs. Finally, public unawareness in solar thermal applications may also be attributed to the limited number of real-scale large installations in Greece[7][8]. In order to overcome this problem further demonstration projects are required.

3.6 Insufficient Market Strategies

Among the major barriers for extensive DSWHSs penetration in the local market is the lack of rational marketing planning and activities. Furthermore, the integration of solar into conventional heating technology, the sales and marketing networks procedure for solar providers and the creation of robust distribution network for all solar thermal equipment is relevant in all European countries. The best moment to sell and install solar water heaters is when replacing conventional ones. Regarding the relatively high first installation cost, consumers are prepared to pay the price of a DSWHS if the system is up to standard and technically advanced.

Among the basic drawbacks of the solar marketing policy to date has been the inadequate budget for permanent promotion campaigns, since most manufacturers have been short of funds during the last decade due to sales decrease.

A diffusion barrier observed in Greece -among other European counties, e.g. Austria- is the indifference of local installers for the new solar technology products. This attitude mainly derives from the absence of systematic technical and sales training of craftspeople and the deficiency of appropriate information material for consumers consulting. To be fair, some attempts sponsored by GSIA, ELKEPA (Greek Productivity Centre) and CRES have taken place during the last thirty years, which however were occasional and sporadic.

3.7 Lack of Sate Policy in Favour of Renewable Energy Sources

According to our opinion, another negative aspect concerning the diffusion of DSWHSs -in common with all the Renewable Energy Sources applications- is the unconcerned standpoint of Greek State. Despite the various E.C. funded Operational Programmes (for Energy 1996-1999, for Research and Technology and Competitiveness (2000-2006)) and the number of Laws occasionally including the solar thermal applications subsidization, the State behaviour towards DSWHSs has been groundless and unreliable.

In this context, Greek State has profoundly invested in imported Natural Gas Penetration[19]. Hence, imported natural gas is entering the energy scheme in Greece. Huge investments (co-financed by the EU) in the transmission and distribution network are underway. More precisely, Greece has procurement contracts and is constrained to import annually 2.8 billion m^3 of natural gas from Russia and at least 0.51 billion m^3 from Algeria. The natural gas is commercialised through the Public Gas Corporation (PGC). The sales of PGC for the year 2000 were 1.9 billion m^3 i.e. the 57% of the purchase quotas, while a large portion of these natural gas imports is used for electricity generation, by the State owned PPC (Public Power Corporation). The PGC strongly promotes natural gas utilization in the building sector, replacing electricity for cooking and oil for heating, in order to cover the remaining 43%. Hence, it is almost sure that the intensive promotion of natural gas should impose a negative impact on the further development of solar thermal applications.

On top of this, the Ministries of Development and Environment/Public Works significantly delay the application of the "General Building and Energy Code", which has incorporated the energy design of buildings and the energy saving due to renewable applications. The expected new regulations for energy saving in building were not announced, although the corresponding legislative frame was implemented since 1996.

3.8 Recapitulating

According to several researchers, the impressive DSWHSs diffusion in Greece during the 1980-1994 period has basically been following a demand-driven market mechanism. Nevertheless, despite this fact most researchers of the sector agree that the local market time-evolution was a multi-actor, multi-dimensional and multi-parametric phenomenon. For example it is almost proved that the extent of solar heat usage does not depend on the amount of sunshine received. Additionally, a number of non-strictly market factors have played major roles, either as driving forces or as barriers. The varying sales growth rate per year demonstrates that the DSWHS market development strongly depends on external factors, like existence of financial support and information campaigns. Finally, accomplishment of the Altener Project's ambitious targets may be achievable only upon constant and substantial DSWHS support by the local (Greek) government[3][5].

4. Financial Evaluation of DSWHS

In order to obtain an unambiguous picture of the DSWHS financial attractiveness in Greece one should investigate the expected economic behaviour of a similar system in view of any existing State supported financial incentives.

4.1 Financial Incentives

The incentives for the purchase of a DSHWS were first applied in 1978 (i.e. law 814/78), in the form of income tax reduction, representing 75% of the system cost at that time (1978 rates), in case that the purchase cost did not exceed 10% of the citizen's annual income liable to tax. Later, this amount was slightly modified (decreased to ≈60%) by the law 1473/84. Considering that the above tax reduction had been expressed in constant numerical values (in local currency), the impact of this incentive faded rather fast due to the high inflation rates of that period (1980-90)[29]. During this high inflation period soft loans were also allocated for the purchase of solar systems, covering up to 70% of the system cost.

In 1995, an attempt to support the DSWHS market was made by passing the law 2394/95. According to this law, 75% of the purchase and installation cost of all renewable energy systems is exempted from the individuals' taxable income. Hence, support could obviously originate from legislation and programs fending for the whole renewable energy sector. Even according to the law 2394/95, the final tax deduction strongly depends on the taxable income of the DSWHS owner. Considering that the regular income tax rates are respectively equal to 15%, 30% and 40% (according to the taxable income) and neglecting that any tax return is realized normally one year after the DSWHS purchase, the final subsidization amount is between 11% and 30%, (e.g. γ=0.75x0.40).

Since January 2004, there are no governmental actions supportive to the DSWHSs' purchase by individuals, as the national energy policy is almost exclusively focused on stimulating the imported natural gas penetration in the tertiary sector.

On the contrary, in an attempt to support the purchase of solar thermal systems, the German government has recently[11] announced a 35% grant increase, aiming to double Germany's solar thermal installations by 2006. In this context, solar panels grants for hot water and space heating are increased from 92 to 125 Euro per square meter of collector surface installed. This effort is funded through revenues from the so-called Eco-tax. This continuous and reliable support by the German State is one of the major reasons explaining the flourish situation of the German DSWHS market, despite the limited solar potential of the country. Similar situation also exists in Austria, where on top of the existing grants, the popular use of the thermal solar panels began with the organization of the "do-it-yourself" groups. This new organization encouraged the further spread of DSWHS in the country.

4.2 DSWHS Payback Calculations Model

The economic viability and attractiveness of a DSWHS could be considered on the basis of the system payback period in comparison with the expected service life of the installation. For this purpose one should compare the present value of the total investment cost with the corresponding total savings, both expressed as a function of the operational years of the system.

Thus, using previous analysis by the authors[22][29] the present value of the total operational cost of a DSWHS is given as:

$$C_n = IC_o \cdot \left[(1-\gamma) + m \cdot h_1\right] \tag{1}$$

where:

IC_o is the turnkey cost of a DSWHS, including the ex-works price of the equipment and the installation cost, i.e. connecting parts, pipe insulation materials, transport, labour for mounting the system, etc.

γ is the State subsidy (if any) expressed as a percentage of the DSWHS turnkey cost.

m is the maintenance and operation (M&O) cost coefficient, taking into account the annual repair and maintenance cost, which constitutes expenses for antifreeze, replaced damaged pipes and parts, repaired insulation materials, glass, paint labour cost and other miscellaneous items. Bear in mind that an annual increase of the cost via the M&O mean-annual-inflation-rate "g_m" is incorporated in the tern "h_1" written as:

$$h_1 = \frac{(1+g_m)}{(1+i)} \cdot [1 + \left(\frac{1+g_m}{1+i}\right) + \ldots + \left(\frac{1+g_m}{1+i}\right)^{n-1}] = \frac{1+g_m}{g_m - i} \cdot [\left(\frac{1+g_m}{1+i}\right)^{n} - 1] \tag{2}$$

As it is obvious, the "h_1" term also contemplates the impact of the local market capital cost "i"; see figure (8).

On the other hand, the present value of the total savings "R_n" over an n-years period due to the thermal

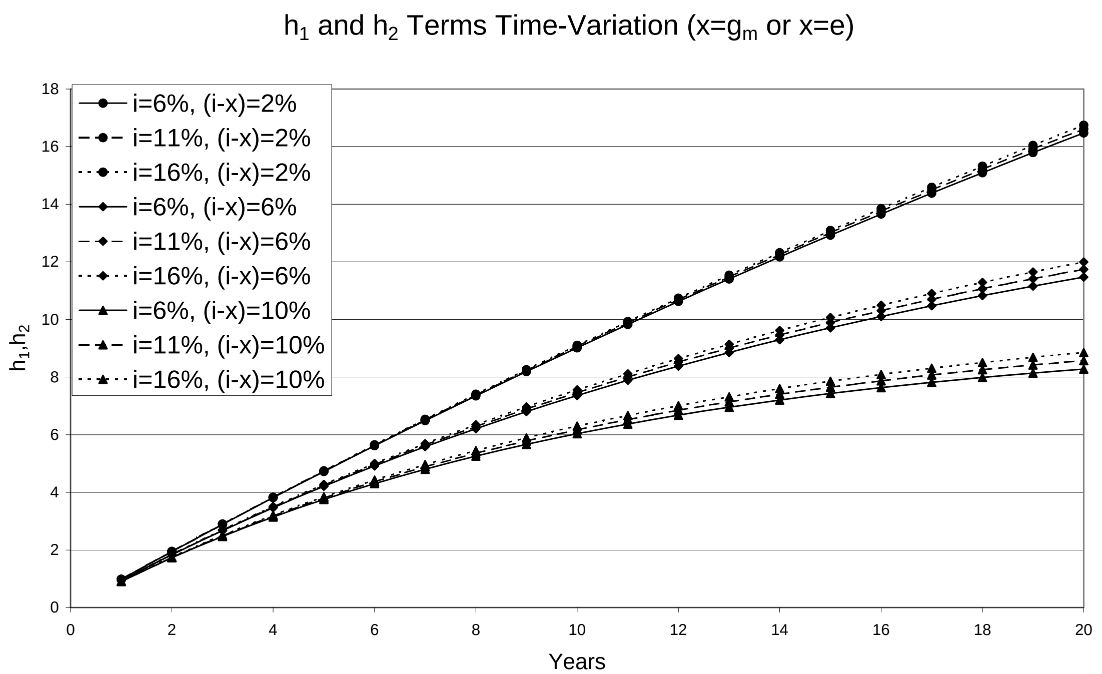

Figure 8: Time Variation of h_1 and h_2 Terms of eqs. (2) and (4)

energy offered by the solar system is given as:

$$R_n = E_o \cdot c_o \cdot h_2 \qquad (3)$$

where:

E_o is the net annual heat output of the installation, assumed constant over the entire operational period of the system (in kWh/year), and
c_o is the present value of the effective cost coefficient of the substituted -by the DSWHS production- conventional energy (in Euro/kWh)

Finally, "h_2" can be written as:

$$h_2 = \frac{(1+e)}{(1+i)} \cdot [1 + \left(\frac{1+e}{1+i}\right) + ... + \left(\frac{1+e}{1+i}\right)^{n-1}] = \frac{1+e}{e-i} \cdot [\left(\frac{1+e}{1+i}\right)^n - 1] \qquad (4)$$

where "e" is the mean annual rate of the substituted conventional heat-sources market price change (i.e. thermal energy price escalation rate) and "i" is the above-mentioned local market annual capital cost, see also figure (8).

The payback period "n^*" of the installation can be calculated by comparing the present value of the investment cost with the corresponding total savings, i.e.:

$$R_n = C_n \quad \text{when } n=n^* \qquad (5)$$

If the predicted payback period is less than the expected system service one, the investment is characterized as financially viable. Besides, the payback period is in inverse proportion to the financial attractiveness of installation.

For the solution of equation (5), in excess of the local market parameters (IC_o, γ, m, h_1, h_2, c_o), one should estimate the annual heat gain of a DSWHS "E_o", according to equation (6), i.e.:

$$E_o = \sum_{i=1}^{365} E_i \qquad (6)$$

For the estimation of daily solar energy gain "E_i" one should ponder over the daily hot water consumption pattern per person[30][31][32] as well as the available solar energy impinging at the selected collector surface[33]. Besides, one cannot ignore the considerable energy heat-losses from the hot water storage tank[34], especially during winter nights for households where all habitants are morning hot water users.

To confront these problems, the authors suggest the following daily solar energy gain calculation model. During the cold season months (e.g. November to April) a rationally sized DSWHS cannot fulfil the daily hot water demand of the consumers (figure (9)), hence the system heat gain is determined by the available local solar potential and the system's total efficiency[35][36], including storage tank heat losses, especially for early morning hot water users. On the other hand, during the hot season periods (e.g. June to September) the available hot water normally exceeds the corresponding demand (figure (9)), considering the relatively high ambient temperature. Hence, in these cases the daily heat gain is usually dictated by the load (hot water) profile[30][31][32][36] of the consumers "Q_i". Therefore, one may write:

$$E_i = \min\{\eta_i \cdot H_i \cdot A_c \ ; \ Q_i\} \qquad (7)$$

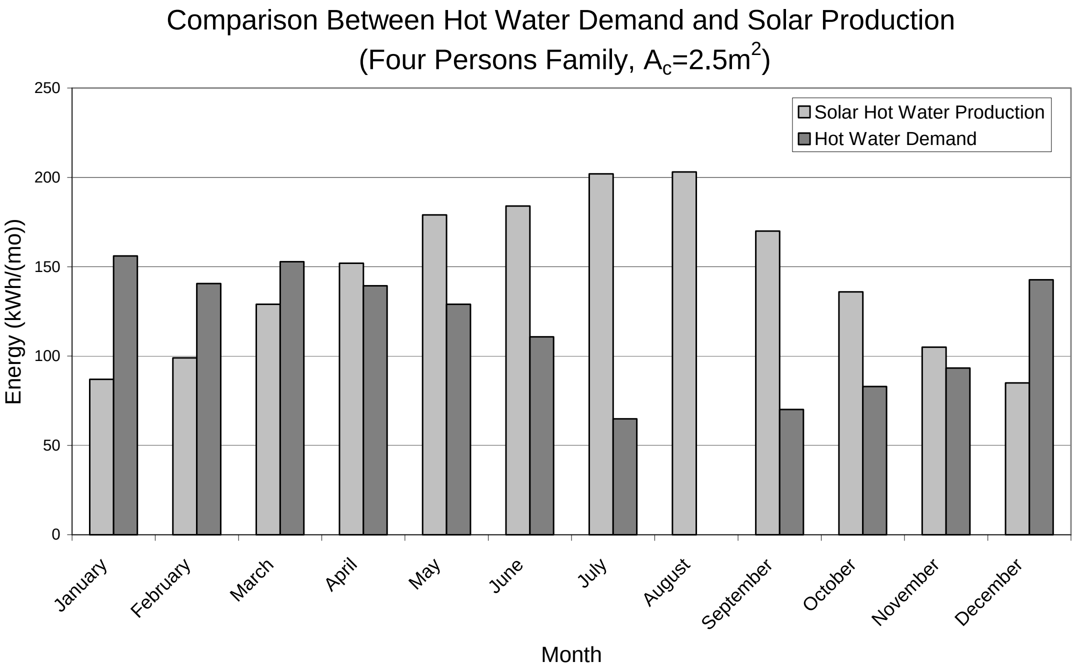

Figure 9: Comparison between Hot Water Demand and Solar Hot Water Production

where "η_i" is the system's daily efficiency and "H_i" is the corresponding solar radiation at the collector surface.

Recapitulating, the annual solar heat production of the system "E_o" can be finally calculated on the basis of the hot water consumption daily/seasonal pattern[31][32], the available solar radiation[37][38] and the solar collector surface and efficiency[35][36].

Introducing the system's annual utilization factor "UF" according to the following equation:

$$UF = \frac{E_o}{H_T \cdot A_C} = \sum_{i=1}^{i=365} \min\left\{ \overline{\eta}_i \cdot \frac{H_i}{H_T}, \frac{Q_i}{\cdot H_T \cdot A_c} \right\} \tag{8}$$

where "H_T" is the total available annual solar radiation per square meter collector's surface received locally, equation (5) finally reads:

$$\frac{IC_o}{A_c} \cdot \left[(1-\gamma) + m \cdot h_1^{(n)}\right] = c_o \cdot H_T \cdot UF \cdot h_2^{(n)} \tag{9}$$

As it is obvious from equation (9) the payback period of a DSWHS depends on:

- The reduced turnkey price of the installation "IC_o/A_c" (in Euro/m^2)
- Any State subsidization, expressed as a percentage "γ" of the initial capital invested
- The annual M&O cost coefficient "m"
- The present value of the effective cost coefficient "c_o" of the substituted -by the DSWHS production- conventional energy (in Euro/kWh)
- The available annual solar energy at the installation location "H_T", and
- The annual utilization factor of the system. It is important to note that "UF" describes the portion of the available solar energy finally used by the consumer, in view of the DSWHS efficiency and the daily/seasonal hot water consumption pattern. According to a large number of consumer profiles and solar radiation combinations tested, the corresponding "UF" value normally varies between 25% and 40%.

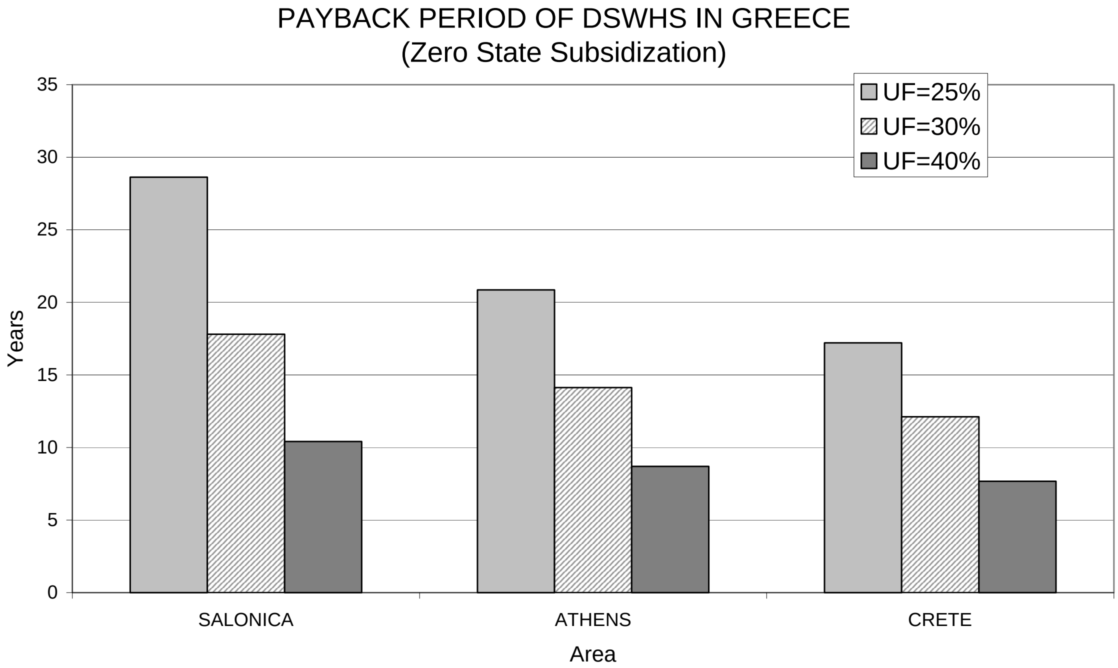

Figure 10: Payback Period of DSWHSs in Greece, without any State Subsidization

Finally, the market capital cost "i", the non solar heat production cost annual escalation rate "e" and the system's M&O cost annual inflation rate "g_m" are also affecting the installation payback period via the "h_1" and "h_2" terms, see also figure (8).

4.3 Payback Calculation Results

The above-presented model is applied to three selected Greek regions (i.e. Salonica, Athens and Crete) representing North, Central and South Greek installations. It should be kept in mind that according to a recent study by CRES[16], 62% of the Greek DSWHS in operation are located in central, 27% in Northern and 12% in South Greece. The necessary numerical data concerning the parameters of equation (9) are given in Table I. More specifically, the reduced turnkey price of a typical DSWHS properly sized for a four-member family (collector surface 2.5m^2, hot water storage tank 150-170lt) is approximately equal to 310€/m^2, while the corresponding effective cost coefficient of the substituted conventional energy is taken equal to 0.080€/kWh$_{th}$. At this point it is necessary to clarify that the selected representative consumer covers 30% of his needs (mainly during winter months when central heating boilers are operating in Greece) using oil, and the rest 70% utilizing an electric heater.

Table I: Nominal Values of the Main Parameters Used in the Payback Prediction Analysis

Parameter	Symbol	Numerical Value	Units	Parameter	Symbol	Numerical Value	Units
Collector Surface	A_c	2.5	m^2	Annual Capital Cost	i	9	(%)
DSWHS Turnkey Reduced Cost	IC_o/A_c	310	€/m^2	Heat Annual Escalation Rate	e	3	(%)
Effective Cost Coefficient	c_o	0.080	€/kWh	M&O Cost Coefficient	m	3	(%)
Reduced Annual Solar Energy	H_T	N. Greece 1544 C. Greece 1730 S. Greece 1882	kWh/m^2	M&O Cost Annual Inflation Rate	g_m	2	(%)

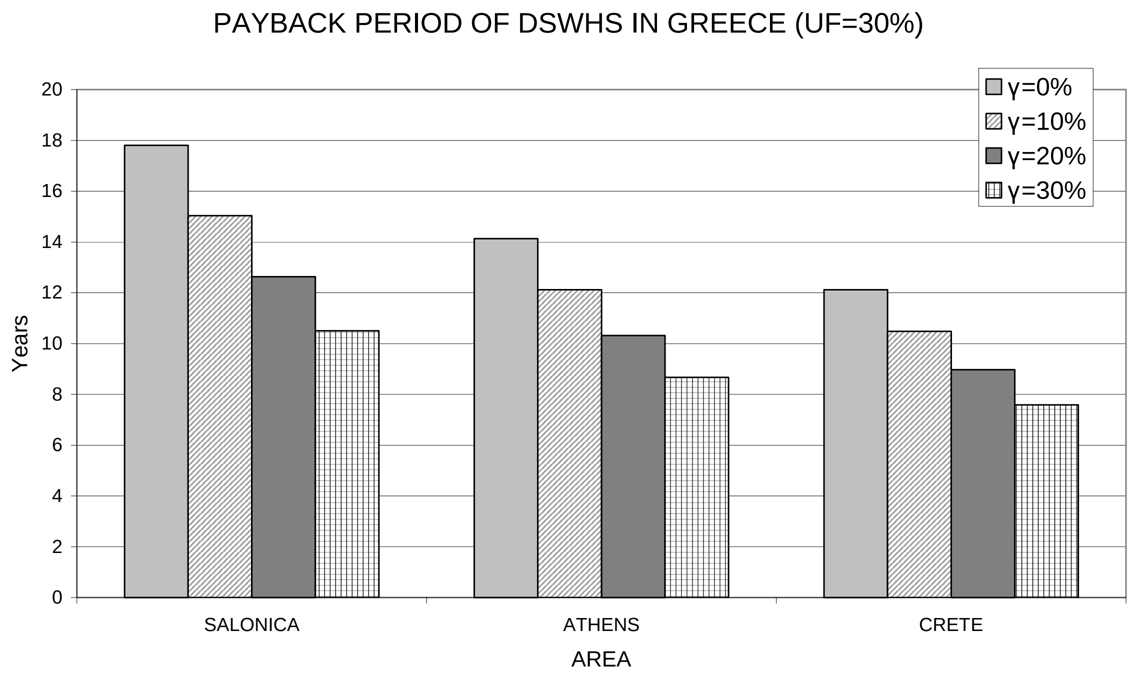

Figure 11: The Impact of Variable State Subsidization on the Payback Period of DSWHS

In figure (10) one has the opportunity to investigate the calculated payback period of a typical DSWHS operating in one of the three representative Greek territories under zero State subsidization (γ=0%), which is the current situation in the local market, for two extreme "UF" values, i.e. 25% and 40% respectively. As it is obvious from the results presented, the expected payback period for the minimum utilization degree scenario in all cases is higher than 17 years, hence almost no DSWHS is financially viable, since the average service period of a contemporary DSWHS is assumed equal to 12.5 years (±3 years standard deviation). This fact is much more evident for Athens major region -estimated payback equal to 21 years- and for Salonica area -estimated payback equal to 28.6 years. Even at maximum utilization of a DSWHS (i.e. UF=40% or 620(kWh/m^2/year) to 750(kWh/m^2/year)) the corresponding investment is marginally viable for North and Central Greece, but in both cases, it cannot be characterized as financially attractive, since the corresponding payback period is 10.4 and 8.7 years respectively. Recapitulating, only 4% of the DSWHS installed in North Greece are expected to have a service period greater than the estimated payback one for a rational utilization factor (i.e. UF=30%), since the calculated payback period is 17.8 years. The corresponding viability percentage is 29.5% for central Greece installations and 55% for North Greece ones. In this context, in case of zero State subsidization, there is a very small possibility for an individual to cover his annual hot water needs by using a DSWHS instead of a conventional oil-fired and electrical heater combination.

In an attempt to estimate the minimum subsidization percentage required to stimulate the competitiveness of DSWHSs in the local market, the former utilization factor is re-evaluated under variable State subsidization percentage, i.e. γ ranges from 0% up to 30%. The calculation results, for all three Greek regions are summarized in figure (11). If one sets the minimum acceptable payback period of a DSWHS equal to 9.5 years (the 75% of the systems installed should operate more than 9.5years without major problems) the necessary subsidization percentage for DSWHSs to be installed in North Greece should be equal to 35%, minimum. The corresponding values for central and south Greece are equal to 25% and 17%. If these subsidization percentage values are not realized, it is almost impossible for an individual to install a DSWHS at his house on the basis of pure financial criteria. This is not a prerequisite for "green" consumers or other "self-build" movements.

5. Proposals-Prospects

According to the above-presented analysis, the solar market in Greece is currently discouraging; despite the abundant solar radiation and the severe environmental and macroeconomic benefits resulting from solar penetration in the domestic energy balance[1][2][3][23][26]. On top of this, the real number of fully operated DSWHSs is almost 50% of those installed since 1980, hence the corresponding active collector surface of the operating systems is only 1,500,000m^2 (or 135m^2 for every 1000 citizens) in comparison with the 3,100,000m^2 reported by several institutions[4][6]; see also figure (5). This last statement complicates the achievement of the E.U. target of 500m^2 solar collectors being in service for every 1000 citizens[5] by 2010.

Regarding the financial viability of contemporary DSWHSs, it is almost obvious than -under the current situation- the solar heat cannot compete with oil and natural gas heat production, in pure financial terms. Only after introduction of the remarkable social and environmental benefits of solar energy in the market competition (e.g. as an initial installation cost subsidization) the DSWHSs may become more cost efficient than the corresponding oil or natural gas based alternatives. The authors strongly support the idea that these "so called solar systems grants" are only a small portion of the avoided social and environmental cost[1][2][3][23][26]. In fact, there is a common agreement among researchers that the above avoided cost presently amounts to 50% of the minimal purchase value of a DSWHS, for a ten-year operating solar system. Hence, the abolition by the Greek State of any financial grants regarding the DSWHSs installations is a partial and unreasonable action encouraging the imported natural gas, jeopardizing the future of domestic solar market and staking survival possibilities of the corresponding local manufacturers.

In an attempt to contribute to the local DSWHSs market recovery, some activities -based on the European Commission's White Paper guidelines- are considered necessary. More specifically:

- ✓ Special attention should be paid to a firm National Policy supportive of the environmental friendly and domestic abundant renewable sources. In this context, the government should include in the energy market the external costs and benefits of all energy resources utilized.
- ✓ Accordingly, progressive marketing strategies should be developed, mostly based on the distribution and sales expansion, along with technical training of installers and craftsmen to facilitate first installation and maintenance.
- ✓ On top of this, additional information is required to raise public awareness both on the environmental benefits and the reliability of new systems with a view to face their early ruined reputation. Besides one should explain the economic advantage of DSWHS in relation to electric heaters.
- ✓ Finally, an effort is also necessary to persuade the decision makers of the building sector about the remarkable prospective of solar systems both in hot water and space heating applications.

As a final comment, the outlook for penetration of new DSWHSs in the local market is rather grim under the current techno-economic situation, especially in view of the natural gas introduction in the urban tertiary sector. Only upon efficient accomplishment of all above activities, in conjunction with a rational incorporation of the external cost in the DSWHSs purchase price, there is a reasonable prospect for local solar thermal market recovery. In addition, Greek islands may establish a prosperous market segment, in view of their excessive electricity production cost and the seasonal hot water demand due to summer tourism.

6. Conclusions

The real situation of local DSWHS market is hereby presented, considering not only the annual number of DSWHS sales but also the current number of active systems in operation. This information is accordingly elaborated in association with the historical evolution of the local solar market with a view to portray the sluggish solar collector market situation during the last decade.

Subsequently, the most important barriers against the DSWHS penetration are demonstrated, including abolition of any financial incentives by the Greek State. In view of the current techno-economic frame, the financial attractiveness of typical DSWHS applications is investigated for representative Greek territories and under variable utilization degree of the available solar potential. According to the results of the proposed feasibility analysis, solar heat cannot compete with oil and natural gas heat production in pure monetary terms, i.e. excluding social and environmental impacts. Only under rational first installation cost subsidization, DSWHS present a payback period remarkably lower than their operational life.

Finally, several activities are anticipated to stimulate the local solar heating market, including improved marketing policy and widely spread information in an attempt to activate people. The present analysis is integrated by analysing the prospects of the local market in view of the existing techno-economic situation, underlining that only the Greek islands actually remain a prosperous market segment for DSWHSs.

Presumably, the local DSWHSs market might keep on stagnating against the global environment and the national economy. The sole outlet of this disadvantageous situation may be a firm and reasonable State support of solar energy applications, together with the hereby-proposed suggestions. Otherwise, the contribution of local DSWHS on the European Union targets for sustainable and environmental friendly development will remain negligible, despite the abundantly available solar potential of the country.

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SOCIAL ATTITUDE TOWARDS WIND ENERGY APPLICATIONS IN GREECE

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Abstract

During the last three years (1999-2002) a significant increase of the existing wind power has taken place in Greece, after a long period (1993-1998) of inactivity. Unfortunately, the largest part of new scheduled installations is concentrated in limited geographical regions, in an attempt to take advantage of the existing electrical network capabilities and the acceptable infrastructure situation. This important concentration of remarkable size wind turbines, suddenly installed in few relatively restricted geographical areas, provoke serious local population reactions, which in some cases lead even to the complete wind power project cancellation. In this context, an extensive study is conducted, concerning the public attitude towards wind energy applications, in several island and mainland Greek territories possessing high wind potential and investment interest. The results obtained significantly declare acceptance for the existing wind parks, being however rather against new installations. More specifically, in Greek islands the public attitude is clearly supportive, while in Greek mainland the public attitude is either divided or definitely against wind power applications. The most troublesome outcome of this survey is the existence of a specific minority that is strongly against wind energy applications, disregarding any financial benefits. Among the primary conclusions drawn, one may underline the necessity of additional public information about wind energy sector.

Keywords: Wind Energy; Social Attitude; NIMBY; Public Survey

1. Introduction

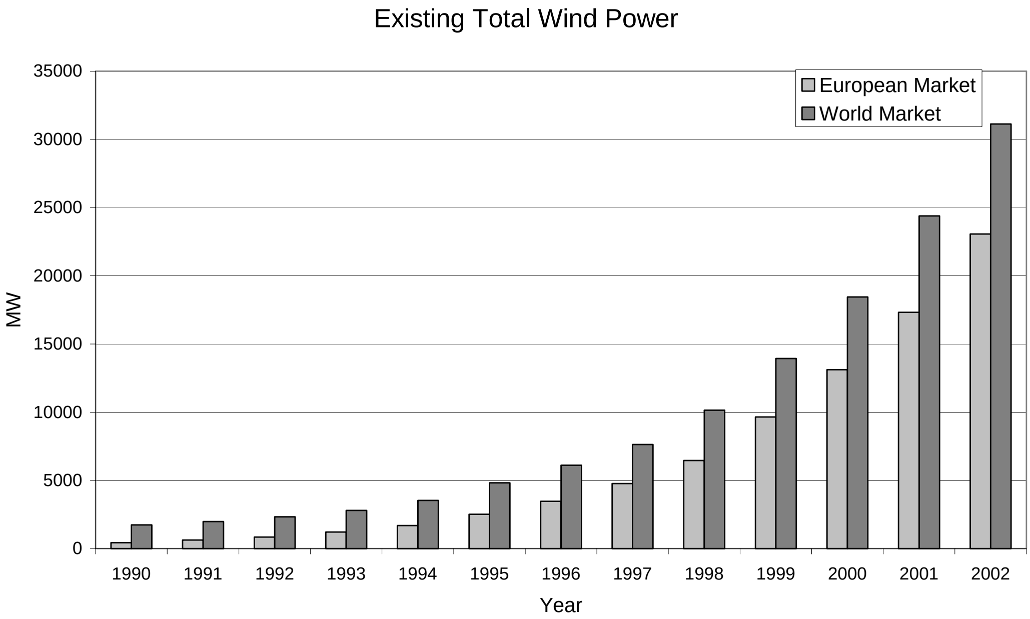

Figure 1: European and worldwide installed wind power

Wind energy is now a mature electricity production technology, constituting not only an economically attractive option to contribute on fulfilling the worldwide constantly increasing energy demand, but also a sustainable energy solution for global development. In this context, wind energy has been the galloping energy sector for electricity production in various European countries[1]. During the last five years, the development rate of installed capacity in individual countries varied between 15% and 75% per year; while the corresponding E.U. mean value of the last decade exceeded the 40%. Thus, the original E.U. target for 4000MW of wind power by 2000 has been almost doubled, while the new European Wind Energy Association target is 40,000MW by 2010 and 100,000MW by 2020. According to the official data[2], another 5870MW of wind capacity has been added up in Europe during 2002, being nearly 1500MW higher than 2001. Thus the total wind capacity in Europe exceeds the 23000MW (figure (1)), producing almost 55TWh/year, equivalent to the annual electricity consumption of 40 million typical consumers.

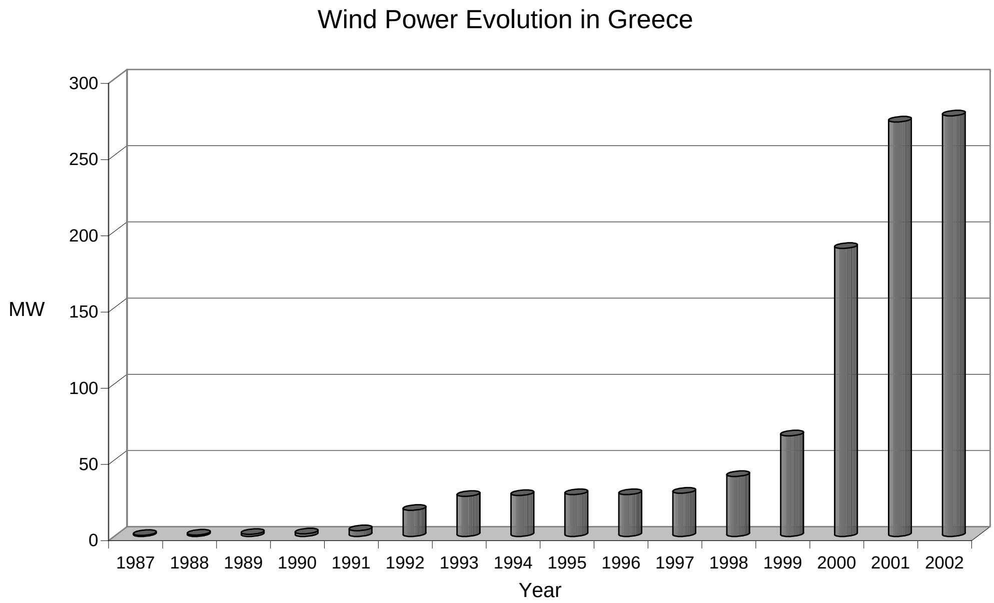

Figure 2: Time evolution of Greek wind power

In Greece, after five years of inactivity -once the 2244/94 law came in force- a significant increase of the existing wind power has taken place during the last three years[3][4][5], pushing the installed wind capacity of our country definitely over 270MW (see figure (2)). On top of that, requests for new wind parks above 11000MW exist in the Ministry of Development, so as to profit from the project total cost subsidization by 30% up 50%. According to the official data, the vast majority of the machines proposed belong to the 500kW to 1MW scale, in an attempt to manipulate the positive scale economy effects[6].

Unfortunately, the largest part of new scheduled installations is concentrated in limited geographical regions (Table I), like Peloponessos and Euboea, in an attempt to take advantage of the existing electrical network capabilities and the acceptable infrastructure situation. More specifically, the existing requests are approximately 3200MW and 2500MW in these two areas respectively. Similarly, as in other European countries, this important concentration of remarkable size contemporary wind turbines, suddenly installed in few relatively restricted geographical areas, provoke serious local population reactions[7]. These reactions in some cases lead even to the complete wind power project cancellation (see also figure (2)), therefore decelerating the current wind energy penetration rate.

2. The Status of Greek Wind Energy Market

According to extensive wind potential studies[8][9], Greece possesses one of the best wind potential in Europe, since the local average wind speeds (at hub height) may overpass the 8÷11m/s, especially in

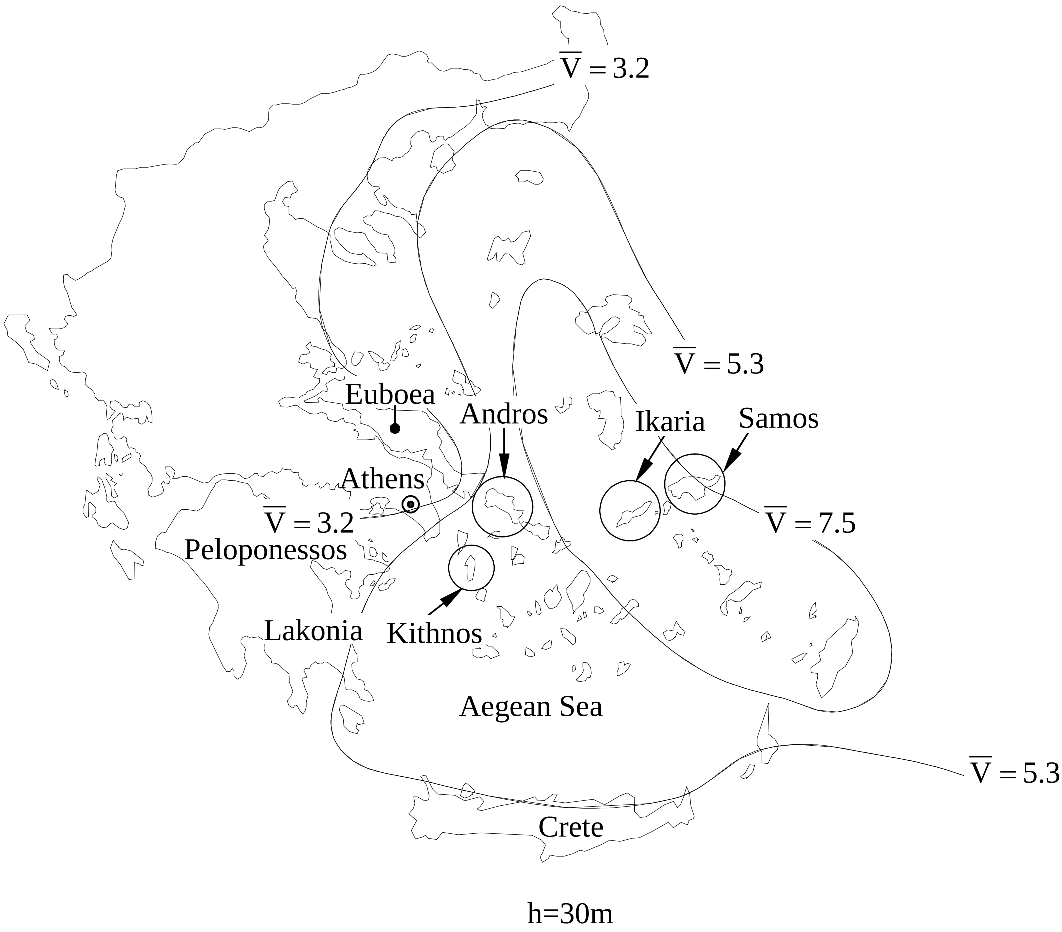

Figure 3: Selected Greek regions for the public survey realization

the Aegean Archipelago and the mainland coasts. At the same time, the electricity production cost for the majority of the remote Greek islands is extremely high, approaching the value of 0.25Euro/kWh, while the fuel cost is responsible for almost 50% of the above-mentioned value[10]. Additionally, Greek dependency on imported fuel (≈70% of its domestic energy consumption is imported) leads to a considerable exchange loss, especially with countries outside the E.U.

For all these reasons, the Greek State has activated its renewable development program since 1982, when the State owned PPC (Public Power Corporation) installed a 5x20kW pilot wind park on Kithnos Island. Since the first pilot wind park of Kithnos was erected, a remarkable number of wind projects were realized, mainly during the 1990-93 and 1999-2001 periods. It is important at this point to mention that PPC -the State owned electricity production and distribution company- had been monopolizing the Greek electricity market, theoretically up to 1994 (law 2244/94) and practically up to February 2001, when the local market liberalization (law 2773/99) officially came in force. In this context, up to mid-98 the vast majority of the existing wind power -142 machines out of 170- belonged to the Greek PPC. However, once the major application problems related to the 2244/94 law for renewable energy sources installations were solved, the private wind parks capacity scaled to 240MW, while at the same period PPC added only two new wind parks (10.5MW), totaling its wind power capacity to 37MW[11]. A supplementary characteristic concerning the new wind parks installed has been their strict concentration in two geographical regions (i.e. East Crete and S. Euboea), while, as it is already mentioned, considerable new installations are being planned for the area of Peloponnesos.

During the last years, the Greek State is strongly subsidizing private investments in the area of wind energy applications[12], either via the 2601/98-development law or the "Energy Operation or the Competitiveness Program" of the Ministry of Development. On top of that, according to the existing

Renewables' Law 2244/94 and the recent Law on local electrical market Deregulation 2773/99[13], the national electrical grid owner is "obliged" to purchase electricity production by wind parks at 90% of the low voltage tariff on islands and 90% of the medium voltage price on the Greek mainland. In addition, ten-year electricity purchase contracts (open for a further ten year extension) are signed between PPC and the private investors in the wind energy sector.

3. Geographical Distribution of Public Reaction Towards Wind Parks

One of the most important topics of the present study is the selection of the areas[14], where the public survey should be realized. In this context, several geographical regions are proposed for the realization of the public survey, (figure (3)). The first area selected is Crete Island. Since 1993, in Crete there have been operating several PPC owned and private wind parks, totaling the installed wind power of the island up to 70MW. Due to the gradual wind power increase and taking into account the urging electricity deficit of the island, the vast majority of Cretans warmly support the idea of creating new renewable energy stations in their region. In this direction some municipalities organize guided tours through the wind parks with remarkable success. As it is clear, Crete presents no real scientific interest, since more than 90% of the inhabitants are supporters of both existing and new wind parks.

Exactly the opposite situation appears in S. Peloponessos, especially in Lakonia area, where a remarkable number of new wind power installations are scheduled (Table I). For various reasons (e.g. opposite financial interests about land usage and political contradiction between the local authorities and the central government) not examined in detail here[7][15], local people -motivated by local authorities- are absolutely hostile to wind parks in their territory, expressing in specific cases even dynamic actions versus individuals or authorities who are trying to introduce wind energy in their area[16]. Under these circumstances, we have no reason to proceed our study in this region.

Table I: New wind power capacity requests in Greece (2002)

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

The next two cases analyzed concern two different wind energy penetration models applying in Greece. Thus during the last three years many large scale (at least for the greek environment) wind farms were created, in S. Euboea, pushing the installed capacity of the region to almost 150MW, which is approximately the 50% of Greek wind power capacity. In this windy area negative attitude towards new wind parks is encountered, mainly due to remarkable wind power concentration in a short time period[7], sending also harmful messages to all over the country.

On the other hand, Samos Island is selected[17] as a representative of the gradual and low intensity wind power penetration strategy. Samos, is a medium-sized island of East Aegean Sea, possessing excellent wind potential. In the island, since 1991, there exist two relatively small PPC wind parks, while quite recently private investors created and have been operating another two medium-sized installations. Although the existing wind parks represent more than 15% of the island peak load, the geographical dispersion of the turbines does not seem to disturb the local population.

Finally, the third part of the present survey took place in various small islands of central Aegean Archipelago (e.g. Andros, Ikaria and Kithnos) where at present moderate wind energy related activity exists. In all these areas possessing excellent wind potential there is a strong interest for new wind power applications, possibly in collaboration with energy storage systems[10][18] (e.g. wind-hydro, battery storage etc.) or desalination plants.

4. Development of the Methodology

In order to investigate the public attitude towards wind energy applications in depth, the Soft Energy Applications and Environmental Protection Laboratory of TEI Piraeus has first scheduled and subsequently conducted[7][14][17] a public survey in several representative Greek territories, presenting wind energy development interest. During the planning phase, emphasis is laid on the following topics:

- ✓ The degree of public knowledge about wind energy applications
- ✓ The public awareness about the environmental and macro-economic impacts of wind energy[19]. Personal annoyance is also recorded
- ✓ The public attitude towards existing and new wind parks, in view of the NIMBY syndrome[7][14]

Table II: Demonstration of the questionnaire used in the present public opinion survey

Question 1	**What do you know about wind energy?**	
Possible Answers	a	It is obtained from the waves of the sea
	b	It is used in the solar heaters
	c	It is obtained from the wind
	d	It is obtained from nuclear plants
	e	I do not know
Question 2	**The wind converters or wind turbines are usually used:**	
Possible Answers	a	in producing electric energy
	b	in marking regions
	c	for aesthetic reasons
	d	for televising purposes
	e	for other reasons
Question 3	**Do you actually agree with the installation of Wind Turbines in your territory?**	
Possible Answers	a	YES, I do
	b	NO, I don't
	c	I would agree if only I had proof of their usefulness
	d	I am not interested in this matter
	e	I have no formed opinion
Question 4	**In case of a new Wind Park installation in your territory:**	
Possible Answers	a	I would not care
	b	I would react on this installation
	c	I might agree, after examining all available data
	d	I have no formed opinion
	e	I would happily agree, being aware of their effectiveness
Question 5	**In case of a new Wind Park installation in your territory:**	
Possible Answers	a	I would not wish to participate, even when it is financially profitable
	b	I would not wish to participate, as I hear it is financially unprofitable
	c	I would ask for further financial data regarding this project
	d	I would wish to participate at any rate, realizing all financial benefits
	e	I am not interested in this matter

The second subject to be clarified is the preparation of this research. According to the existing experience[20][21][22] there are several ways of conducting similar studies, like telephonic interviews, written questionnaires being mailed to a random sample, personal named or unnamed interviews etc. For increasing reliability and due to the country idiosyncrasy this last technique was selected. More specifically, during this survey the questionnaires were completed in the interviewer's sight, while the respondents filled in their name and phone, for confirmation purposes. It is also important to note that all the respondents were living near the existing wind parks (maximum distance 20km), they belonged to groups of various profession and education status, while the 278 of them were men. A pre-selected number of anonymous questionnaires were also completed in specific regions for statistical comparison purposes. The public response was encouraging, since almost one out of two of the persons asked answered the questions eagerly.

The last point to be arranged was the number of interviews needed to draw safe conclusions[23]. As it is obvious, the reliability of the results derived is strongly depending on the size of approved sample used, since the outcome uncertainty is normally decreasing with the square root of the sample size[9]. Due to the geographical diversity of the study and the manpower needed, a sample number in the range of 100 to 150 questionnaires was assumed acceptable, while 50 interviews were set as the lower limit.

For the preparation of the questionnaire a large number of scientists have collaborated, including statistics experts, sociologists and market survey experts. The relative questions to the subject investigated are summarized in (Table II), along with the possible answers. As it is obvious from (Table II), the first two questions asked guarantee that the people being interviewed are familiar with the subject examined. According to the entire sample analyzed (417 questionnaires) 94% of the people interviewed are familiar with the basic wind energy principles (question 1), while only 2% was not sure about the contribution of wind parks in the electrification effort (question 2). Recapitulating, one may clearly state that the samples used have the necessary size to be statistically sound and credible, while the vast majority (≈95%) of the people questioned have quite a good idea about wind energy basic principles and wind power applications. The rest 5% is excluded from further analysis.

5. Results Presentation

After the arrangement of the necessary preconditions, the Soft Energy Applications & Environmental Protection Laboratory staff conducted the above-described public survey in three stages. The first stage is executed in two separate phases (during the 1st and 2nd semester of 2001) and it was focused on the S. Euboea area. The sample of 128 interviews -taken during the period examined- is a representative size to extract statistically safe conclusions. Accordingly, the second stage was concentrated in Samos Island, where almost two hundred (196) local people have been interviewed during 2001 in two separate attempts. Finally, the third stage of the public survey was realized in three different islands of central Aegean Archipelago, the islands of Ikaria, Andros and Kithnos. In these three selected cases the total sample was almost one hundred (93 respondents) while the period examined was between June 2001 and June 2002.

In the present paper emphasis is primarily laid on the analysis of public attitude towards existing and operating wind parks. Using the available information (total sample of 417 respondents) the public attitude is more or less supportive for existing wind turbines, since 51% of the sample is positive and 17% is positive under conditions (figure (4)). This result is in accordance with various public opinion surveys on both sides of the Atlantic[24][25]. More specifically, in all these studies, two-thirds of people polled support the existing wind power stations, which is exactly the case of local market. On the other hand, 16% of the respondents disagree with the existence of wind turbines in his neighborhood, while another 16% (11%+5%) has either no opinion or is not interested about the subject.

The situation is fairly changing in case that new wind parks are scheduled (figure (5)). Although the majority of the respondents is still in favour of new wind parks (39%) and another 20% is positive under conditions, there is an almost 10% difference in comparison with the supporters of existing wind parks. Keep in mind that an almost constant minority (17%) remains negatively expressing versus any wind energy exploitation activity.

This situation is fully supported by the analysis outcome of the answers concerning the last question asked (figure (6)). According to the assessed results 24% of the respondents are eager to participate in new wind energy projects due to expected monetary gains. However, the majority (39%) of the local people require more information about the financial behaviour of similar projects, since PPC administration claims[26] that wind power installations are not economically viable! People disliking

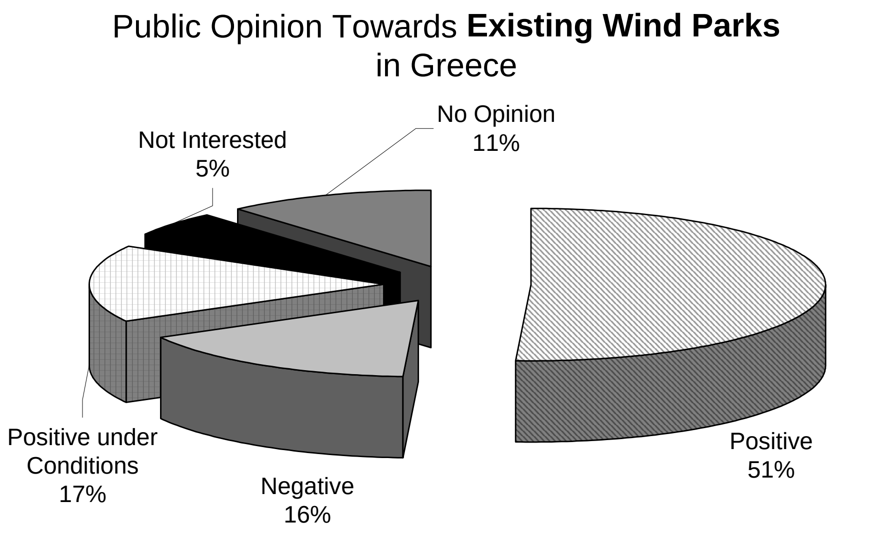

Figure 4: Public opinion results towards existing wind parks

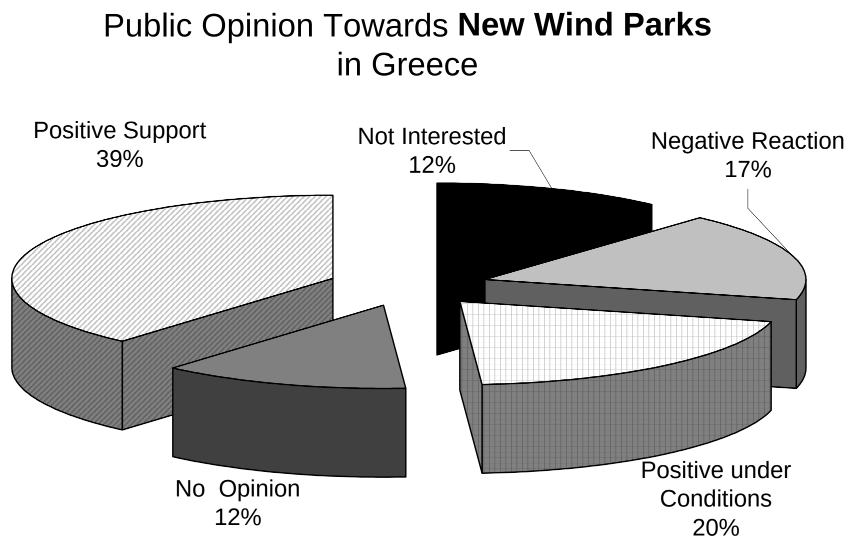

Figure 5: Public opinion results towards new wind parks

wind turbines in their area represent the 18% of the sample, while the vast majority (5/6) of them does not want to participate in new wind parks even under proved financial benefits. Lastly, almost one out of five is not interested in new wind power investments.

6. Discussion of the Results

As already mentioned, the present public survey is conducted in various selected regions, where representative public attitudes are encountered, using information by the local press and the media. Thus, on top of the results demonstrated it is interesting to investigate the geographical distribution of wind energy acceptability degree in Greece.

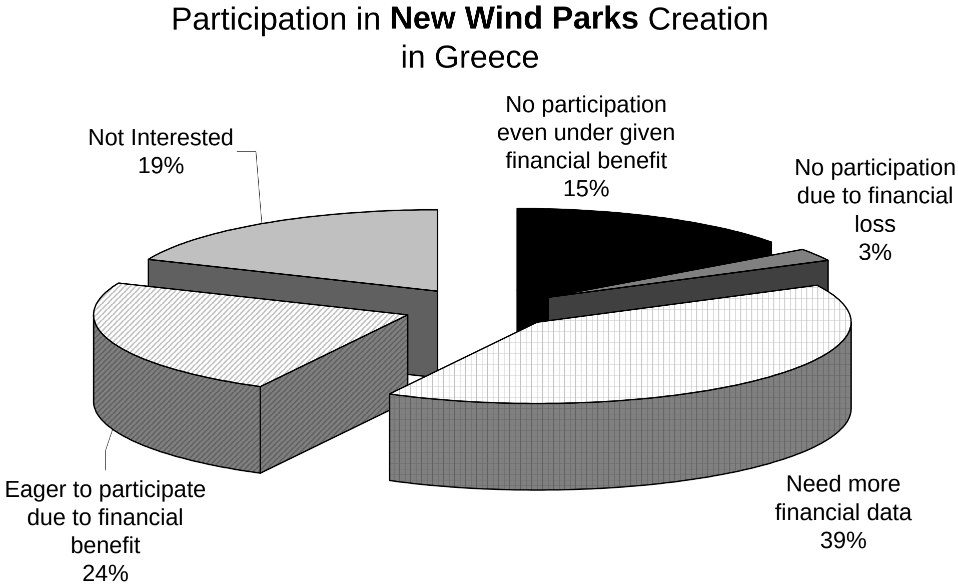

Figure 6: Public attitude towards participation in new wind parks creation

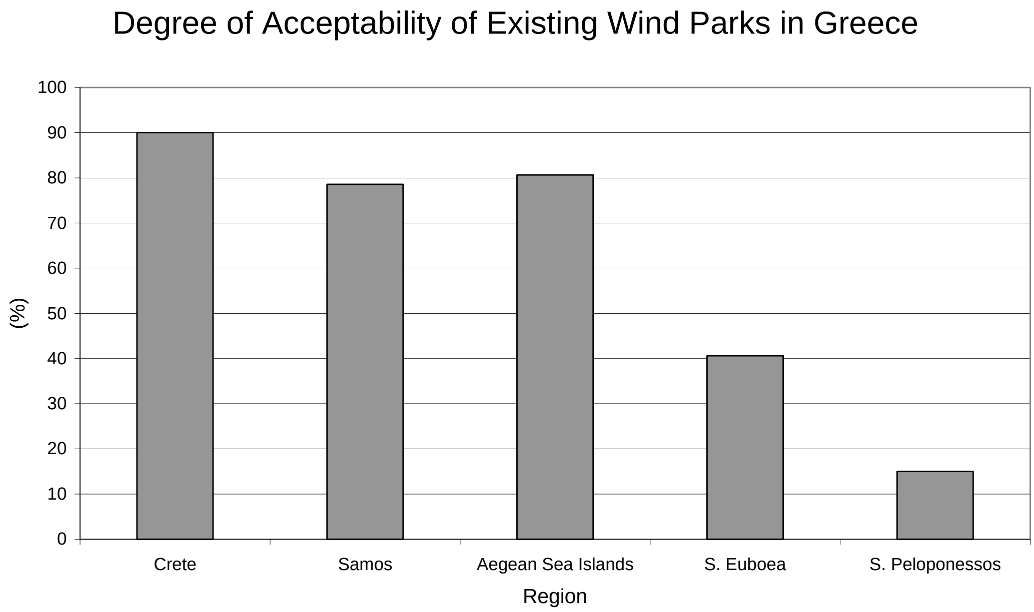

Figure 7: Acceptability degree of existing wind parks throughout Greece

According to the information collected there is a great diversity of the acceptability degree of existing wind parks among the windiest territories of the country (figure (7)). Thus, in almost all islands the existing wind parks are welcome, since the acceptability degree exceeds the 80%. On the other side, in Greek mainland the acceptability degree of operating wind farms is very low, being less than 40% in almost all regions examined.

The situation is getting worse in case that new wind parks are scheduled (figure (8)). In this specific case the wind energy supporters in Greek mainland are hardly one half to one third of people claiming negative reaction against new installations. In the Aegean Archipelago area the degree of acceptability of new wind parks is slightly lower (≈10%) than the one of existing wind parks, a difference that is in accordance with the appearance of NIMBY (Not In My Back Yard) phenomenon[27].

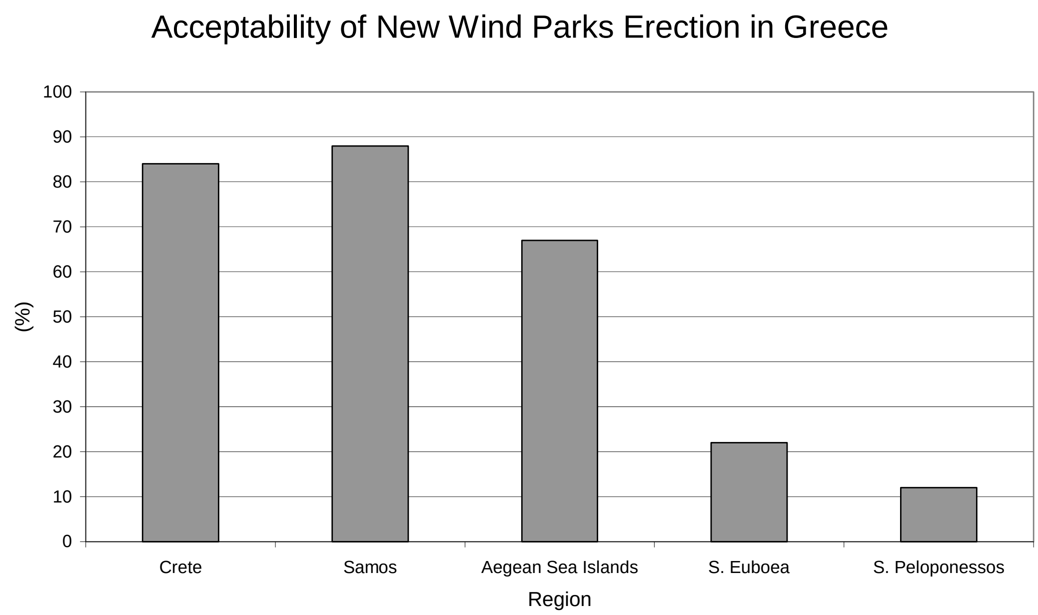

Figure 8: Acceptability degree of new wind parks erection throughout Greece

Taking a closer inspection of the results gathered, one may explain the different attitude between island and mainland territories by considering the following topics:

- In most islands there is a remarkable electricity production deficit[28], especially during the season of summer tourism, impeding the life quality and the economic growth of local societies. This problem does not exist in mainland, since the large thermal power stations provide enough electricity to citizens.
- The introduction degree of wind power applications is quite different in these areas. In most islands there is a gradual penetration of wind turbines[4][11], starting from the early small wind parks of PPC. Only recently a remarkable number of private wind parks has been erected. For the mainland cases, a considerable number of huge machines has been suddenly installed in relatively closed areas, without the appropriate respect for the local scenery aesthetics[29].
- Mainland people are much more conservative in their opinion, being mainly farmers and stock breeders. On the other hand, island people are much more open-minded, since many of them are seamen, traders or they are working in tourism, contacting thus foreign people and meeting new ideas.

7. Conclusions

An extensive study is conducted concerning the public attitude towards wind energy applications, in several island and mainland Greek territories possessing high wind potential and investment interest. The results obtained generally declare significant acceptance of existing wind parks, being however fairly reduced for new installations. More specifically, in Greek islands the public attitude is clearly supportive for existing and new wind turbines, since only a small minority (less than 20%) was negatively expressed versus wind energy applications. On the other hand, in Greek mainland the public attitude is either divided or definitely against wind power applications.

The most troublesome outcome of this survey is the existence of a specific minority that is strongly against wind energy applications, disregarding any financial benefits of all these projects. Bear in mind that legal actions can be induced even by a single person. Subsequently, among the primary conclusions drawn by the sample analyzed one may underline the necessity of additional public information about wind energy sector. This lack of proper information is also reflected in local people unwillingness to participate in new projects, basically due to their uncertainty regarding the financial results of similar ventures, especially in the local socio-economic environment.

In the authors' opinion, a remarkable negative public attitude towards wind energy applications in Greek mainland is encountered, which is not the case in Greek islands. Taking into consideration that most new wind power stations are scheduled for the mainland, if this undesirable situation is not properly analyzed and handled, the future of wind energy applications is questionable.

For all these reasons, the authors believe that the conclusions drawn are very characteristic of the public attitude towards wind power applications in Greece and may be found necessary to everybody related to the local energy planning procedures. Besides, the results obtained may clarify the existing situation and assist Greek society in taking vital decisions regarding the electricity production sector for the next decade, seriously considering the wind energy generation impact on everyday life.

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THE IMPACT OF LOCAL AMBIENT CONDITIONS ON THE ENERGY PRODUCTION OF CONTEMPORARY WIND POWER STATIONS

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Abstract

Wind energy is a mature electricity production technology, since during 2003 the total wind capacity in Europe has exceeded the 25000MW. One of the main problems recently encountered in the local market is the reliable estimation of the instantaneous wind power output of existing wind parks. Up to now, research was focused primarily on the correct prediction of wind speed values. However, according to long-term measurements concerning several operating commercial installations, remarkable deviation may be observed between the officially forecasted and the finally realized wind energy production due to the local environment conditions. In this context, the present work is devoted on investigating the influence of existing ambient conditions on the energy production of contemporary wind energy stations. The results obtained from both experimental and theoretical analysis underline the importance of realistic ambient conditions prediction during the energy yield calculation of commercial wind parks. In the opposite case, deviation up to 20% from the expected wind energy production may appear, strongly questioning the existing wind energy prediction methods and the corresponding power purchase agreement terms undersigned between the wind parks owners and the local electricity utilities.

Keywords: Wind Power; Energy Production; Ambient Conditions; Air Density

1. Introduction

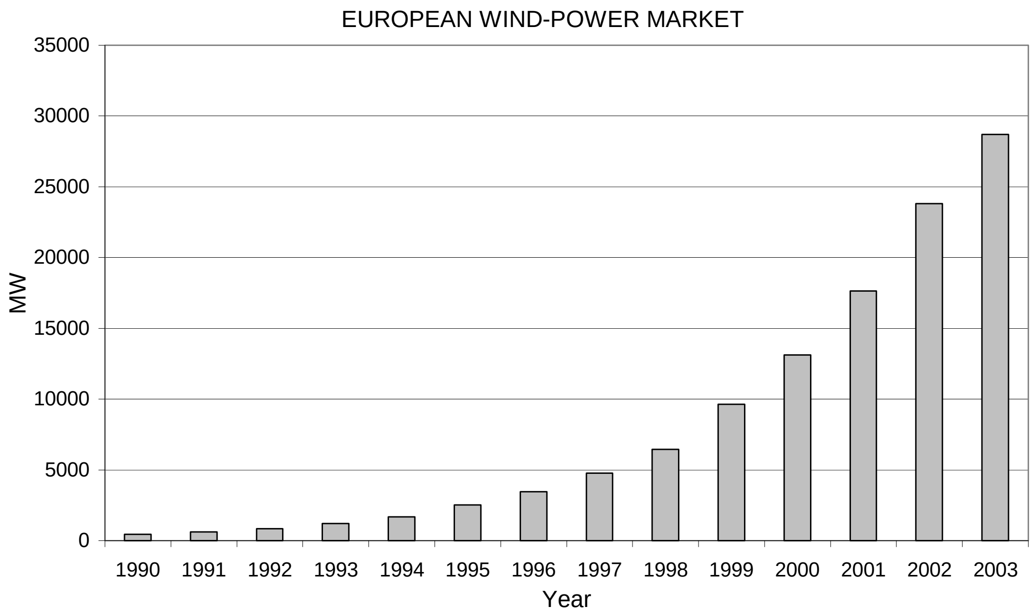

Figure 1: Wind-power time evolution in Europe

Wind energy is considered to be a mature electricity production technology, since during 2003 the total wind capacity in Europe exceeded the 25000MW, figure (1)[1]. In this context, the last four years a substantial wind energy penetration has been noticed in Greece, mainly realized in the mainland. On

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the other hand, new, limited in size, wind parks have been erected at the numerous Greek islands (even the big ones), although their wind potential is clearly better than the one of the mainland[2]. This negative evolution mainly results by the inability of the local weak autonomous electrical networks to absorb the increasing wind generated electrical energy production. In fact, despite the excellent wind potential in the Aegean Archipelago, serious limitation to wind energy penetration is imposed under the restriction that the local grid stability should be protected from production fluctuations[3]. Additional barriers against wind energy penetration in these autonomous electrical grids also exist, due to the stochastic availability of the wind speed, leading to important disharmony between the wind energy production and the electricity demand[3]. As a result, a sizeable wind energy rejection is encountered during the last years in most Greek autonomous electrical networks, leading the wind park owners to remarkable financial losses[4].

In an attempt to realistically simulate the energy performance of existing wind parks, one of the main problems, recently encountered, is the reliable estimation of their instantaneous wind power output. Up to now, research has been focused primarily on the correct prediction of wind speed values. However, according to long-term measurements one may state that local environment conditions have also serious effect on the wind energy production, since the output power of a wind turbine depends on the air density at the wind park location. For example an increase of the air temperature will result in a decrease of the air density and vise versa. In previous work by the authors[5] an almost 20% power decrease was encountered in stall control wind turbines by changing the air temperature from 10°C to 40°C, figure (2). Similarly, in case of pitch control machines there is a remarkable increase of the nominal wind speed value (≈1.5m/s), which accordingly decreases[6] the corresponding energy yield, figure (3).

Hence, the present work is devoted to investigating the influence of existing ambient conditions on the energy production of contemporary wind energy stations. The primary target of the present study is to provide an integrated numerical method able to correctly calculate the energy output of operating wind farms, since according to long-term measurements, remarkable deviation may be observed between the officially forecasted and the finally realized wind energy production due to the local environment conditions (i.e. local temperature, pressure and humidity values).

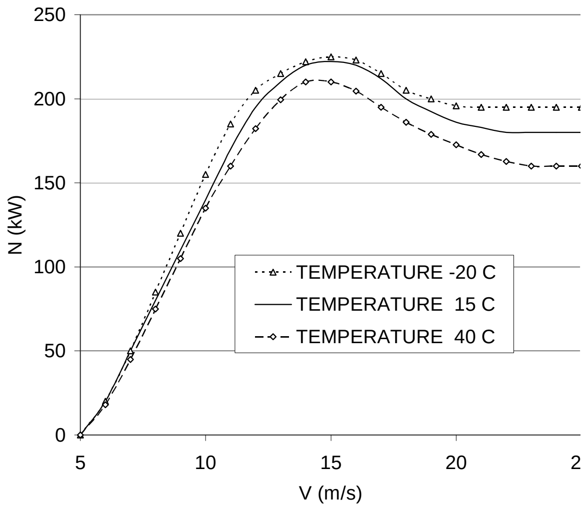

Figure 2: Influence of temperature in stall control wind turbines

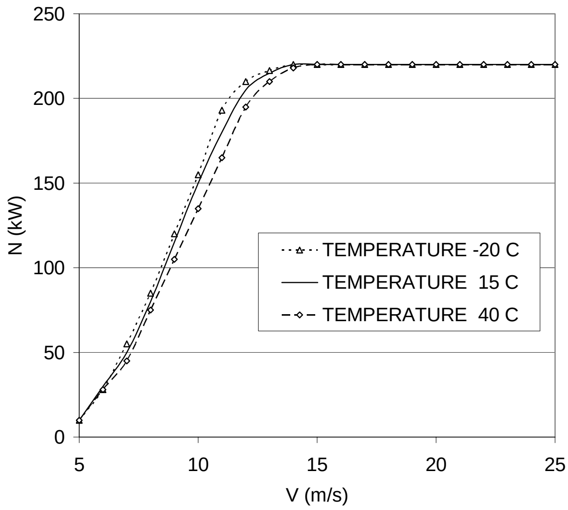

Figure 3: Influence of temperature in pitch control wind turbines

2. Wind power prediction analytical model

The total wind power produced by a wind park of "k" wind turbines in the course of time "t" is the sum of the electricity generation of all wind turbines, i.e.,

$$N_w(t) = \sum_{i=1}^{i=k} N_i(t) \quad (1)$$

The common method used to simulate the output of a wind park is the use of the central anemometer of the installation[7]. In this context one may write:

$$N_w(t) = {}^sN_w(t) \cdot \delta(t) \quad (2)$$

where "${}^sN_w(t)$" is the analytical function describing the power curve of the entire wind park, expressed as a function of the wind speed at hub height, i.e.,

$${}^sN_w(t) = {}^sN_w(V(t)) \quad (3)$$

while "$\delta(t)$" is the Kronecker's delta function taking values either equal to unity (if the wind park is available for operation) or zero, in case that serious malfunctions appear in the specific wind park.

For the calculation of the analytical simulation function "${}^sN_w(t)$" one may use the available large number of measurements concerning the wind power output of the wind park, see for example figure (4), concerning a 10MW wind park located in East Crete. It is important to note that, since the wind speed values are from measurements in the central mast of the wind park, one cannot use these velocity values and the power curve provided by the manufacturer of each wind turbine to reproduce the simulation function "${}^sN_w(t)$". In fact, there is an almost 15% discrepancy between the results given by the direct application of the manufacturers' power curve[6] using the existing wind speed data and the real power output of the wind park.

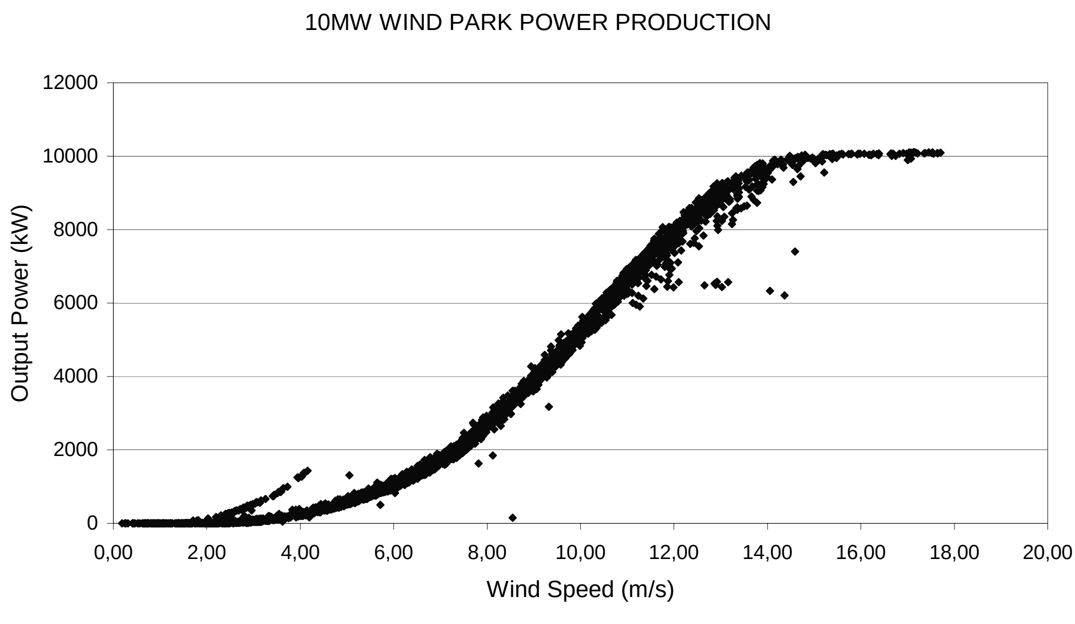

Figure 4: Wind power output of a 10MW wind park located in East Crete

The above calculations of the wind energy production are based on the mean value of the air density during the investigating period, while the resulting power curve is finally normalized for standard day conditions, i.e. air density equal to 1.2215kg/m^3. In order to investigate the effect of the local air conditions the calculations should be repeated with a correction factor "f(t)", which takes into account the time fluctuations "ρ'" of the air density in comparison with the time average value "$\bar{\rho}$" during the operation of the wind park, thus:

$$f(t) = \frac{\rho(t)}{\overline{\rho}} = 1 + \frac{\rho'}{\overline{\rho}} \tag{4}$$

where "ρ(t)" is the instantaneous air density at the wind park's location and "$\overline{\rho}$" is the mean value of the air density for the investigated period. The corresponding air density values "ρ(t)" results from measurements of local temperature "θ" (in Celsius degrees), ambient pressure "p" in Pascal and air relative humidity "w", thus one may write:

$$\rho(t) = \frac{p(t)}{287 \cdot (273 + \theta(t))} (1 + w(t)) \tag{5}$$

The estimation of the wind energy production using the correction factor f(t) is given as:

$$N_w(t) = {}^{s}N_w(t) \cdot f(t) \cdot \delta(t) \tag{6}$$

3. Air density impact on wind power-Theoretical model

For the estimation of the air density impact on the instantaneous wind power output of a typical wind converter one may use the following equation:

$$N = \frac{\rho}{1.2215} N_o(V) \tag{7}$$

where "$N_o(V)$" is the manufacturer standard day power curve. Let "ε" be the total error regarding the air density prediction and "C_ρ" the corresponding relative density error, i.e.

$$C_\rho = \frac{\sqrt{\varepsilon^2}}{\overline{\rho}} \tag{8}$$

Then the corresponding wind turbine power relative error "C_N"[8] is given as:

$$C_N = C_\rho \tag{9}$$

Applying the error transfer analysis on equation (5) we get after several manipulations, that:

$$C_\rho{}^2 = C_p{}^2 + C_{(1+w)}{}^2 + \left[\frac{[\mathrm{aver}(p \cdot (1+w))]^2}{\overline{p}^2 \cdot [\mathrm{aver}(1+w)]^2} \right] \cdot C^2{}_{(273+\theta)} \tag{10}$$

Using the above-described theoretical model, one may clearly state that the relative error on wind turbine output power prediction is practically the sum of the corresponding relative error on ambient pressure, ambient temperature and relative air humidity values. Bear in mind that even in the case that these errors take relatively small numerical values, the energy production of an installation over a given time period is influenced by the numerical integral of the instantaneous values. Hence, the largest the time interval, where the average density value is taken, the biggest the numerical error induced.

4. Application results

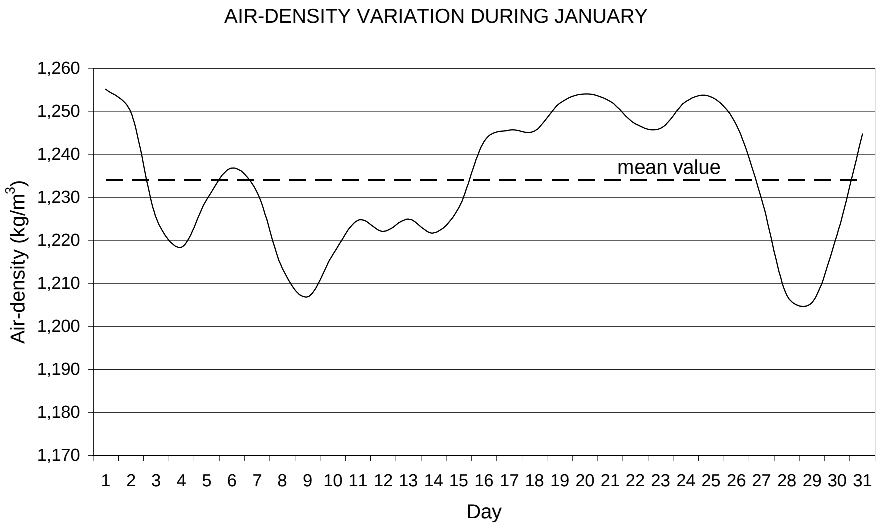

Figure 5: Air-density variation during January

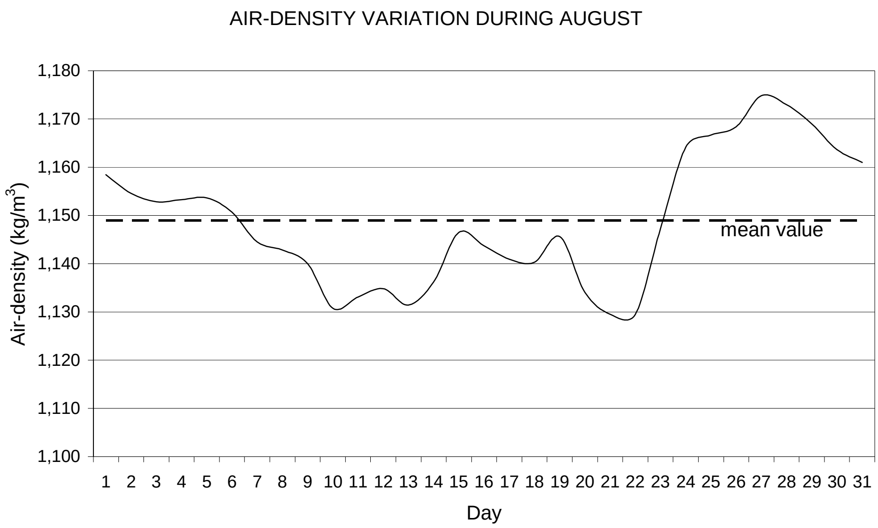

Figure 6: Air density variation during August

The analytical simulation function "$^{s}N_{w}(t)$" is being calculated using the operational data of the wind farm[7]. In this case the calculation of the wind energy production is based on the mean value of the air density during the investigated period. But according to experimental measurements of the ambient parameters, the air density has significant fluctuations during the day both for cold and hot weather. According to figures (5) and (6) the air density between successive days may vary up to ±2.30%, which is an important discrepancy remarkably affecting the accurate energy estimation of a wind park.

Applying equation (3) to the available wind speed data of a selected wind park[7], the energy production is finally estimated. Using, now, the measured wind power absorbed by the local grid one can finally calculate the wind energy rejection (i.e. energy not absorbed by the local electrical network due to grid stability problems). Using the analytical data of air density the energy estimation is recalculated using equation (6). The results obtained are quite interesting, since the total deviation between calculations carried out with and without the air density impact concerning January of 2001 (figure (7)) reaches 24%, a significant value regarding the financial viability of a wind park[4].

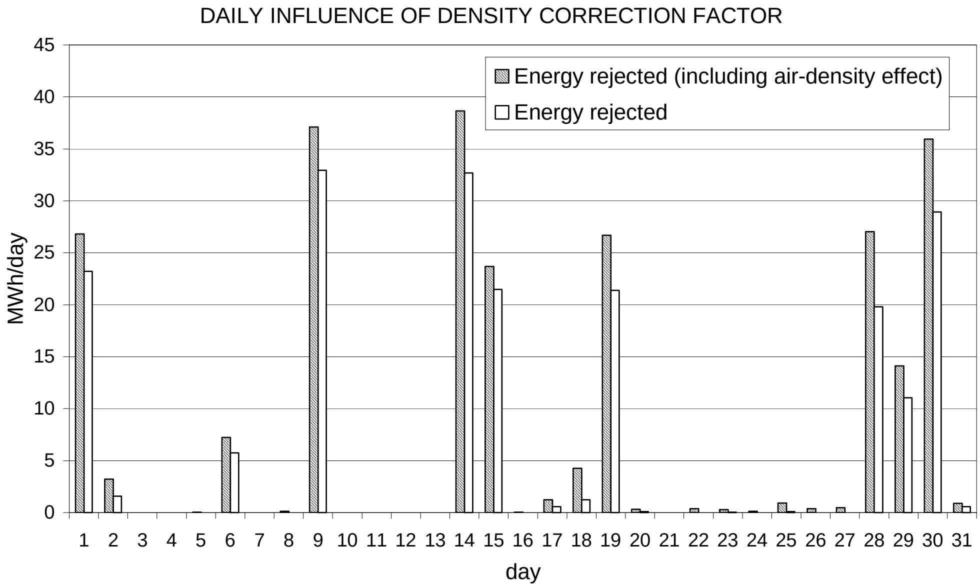

Figure 7: Daily influence of density correction factor in wind power estimation

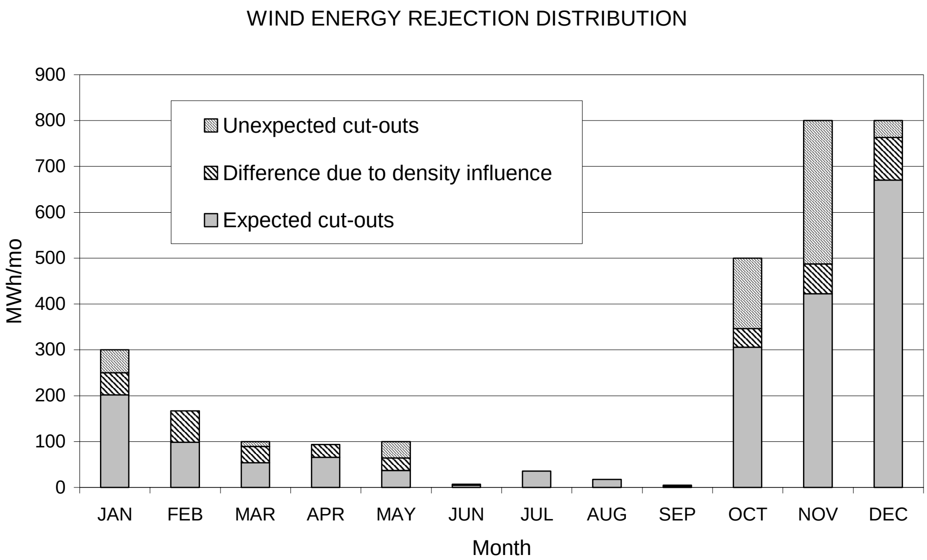

Figure 8: Distribution of wind energy rejection for a 10MW wind park located in East Crete

Subsequently, the proposed analysis can be used to obtain important conclusions regarding the wind energy rejection by the local grid during the entire year. In this context, figure (8) presents the monthly distribution of the rejected wind energy that is dictated by the operator of the local electrical system for the specific wind park of 10MW examined. For the year 2001 and for the investigated wind-park the 65% of the cut-outs realized (figure (9)) are in accordance with the calculations made on the basis of the measured wind speed, while another 14% is explained by including the corresponding measured air density values. Finally, the rest 21% cannot be justified by the existing calculation model, and may be caused by unjustified actions of the system-operator in an attempt to guarantee additional protection of the local network stability[9].

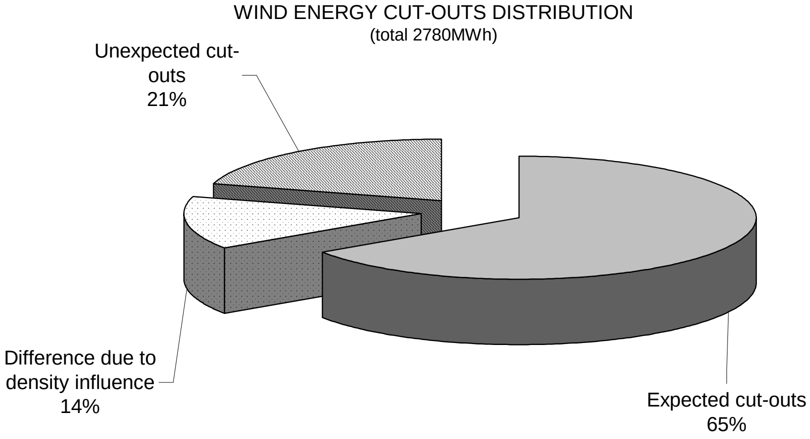

Figure 9: Wind energy rejection distribution during 2001 for a 10MW wind park

5. Conclusions

According to the calculations carried out concerning the investigation of the influence of existing ambient conditions on the energy production of contemporary wind power stations, deviations up to 20% may appear between the theoretical model and the real wind energy yield. In order to analyze this problem, long-term measurements were used concerning existing commercial installations.

In fact, the air density fluctuations may seriously affect the viability of a wind park installation, since the predicted 14% impact on annual wind energy rejection corresponds to almost 400MWh per year of unabsorbed energy production. Using the official wind energy price (72.9€/MWh for the investigated period) defined by the law 2244/94, the negative effect on the income of the specific (10MW) wind park owner is more than 30000€ per year.

Finally the proposed calculation model may be equally well applied on predicting the time distribution of the cutouts imposed to existing wind parks by the local grid operator. The results indicate the importance of the local ambient conditions on accurately estimating the instantaneous wind park output. If the proposed improvement is not taken into account deviation up to 20% from the expected wind energy production may appear, strongly questioning the accuracy of the existing wind energy prediction methods and the validity of the corresponding power purchase agreement terms undersigned between the wind parks owners and the local electricity utilities.

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PART TWO

HYBRID SYSTEMS

- Wind-Hydro
- Stand-Alone Systems

INCOME LOSS DUE TO WIND ENERGY REJECTED BY THE CRETE ISLAND ELECTRICAL NETWORK - THE PRESENT SITUATION

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Abstract

During the last four years a substantial wind energy penetration was encountered mainly in the Greek mainland. At the same time, limited size new wind parks were built in the numerous Greek islands, although their wind potential is clearly higher than the one of the mainland and their wind energy generation could be used to replace electricity produced by diesel engines and gas turbines at moderate and high cost respectively. This negative for the Greek island communities evolution underlines the inability of the local weak autonomous electrical networks to entirely absorb the gradually increased wind energy production. Thus, in the present work special attention is paid to correctly estimate the annual income loss of existing wind parks, due to the wind energy rejection by the autonomous island electrical grids. For this purpose a complete and reliable method is developed, able to realistically calculate the instantaneous wind power production rejected by the local electricity generation system, according to the information provided by the system operator and the wind parks owners. The present analysis is based on extensive time series of real data and measurements. Applying the proposed method to the Crete island network situation, a remarkable amount of wind produced electric energy rejection is predicted for the last three years, which is definitely rising in the course of time. Calculation results are well in agreement with the official monthly wide data provided by the local power utility, in view of the existing power purchase agreement between the private wind power investors and the local network management.

Keywords: Wind Power; Autonomous Electrical Generation Systems; Energy Rejection; Financial Loss; Wind Park; Power Purchase Agreement

1. Introduction

During the last twenty years wind energy has been proven[1][2] 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[3]. This is in accordance with the universal tendency[4] for amplifying the contribution of renewable energy sources to world energy supply, encouraged by the public concern about the environmental protection and sustainability.

In this context, the last four years a substantial wind energy penetration has been noticed in Greece after a long period of idleness[5]. 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[6]. On the other hand, limited in size new 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[7]. This negative policy for the Greek island communities evolution was mentioned (1993) by the authors in their published work[8], underlining the inability of the local weak autonomous electrical networks to absorb the increasing wind generated electrical energy production[9].

In fact, despite the excellent wind potential in the Aegean Archipelago, serious limitation to wind energy penetration is imposed under the restriction that the local grid stability should be protected from production fluctuations[10]. Additional barriers against wind energy penetration in these autonomous electrical grids also exist, due to the stochastic availability of the wind speed, leading to important disharmony between the wind energy production and the electricity demand[10]. As a result, a sizeable wind energy rejection is encountered during the last years in most Greek autonomous electrical networks, leading the wind park owners to remarkable financial losses[11].

In the present study special attention is paid to correctly estimate the annual income loss of existing wind parks in autonomous island electrical grids, due to the incapability of local networks to absorb the entire wind generated electrical energy production. The analysis uses extensive time series data and measurements, while special emphasis is put on realistically estimating the corresponding wind energy rejection. For this purpose the proposed investigation is based on detailed wind speed measurements and wind parks' recorded production figures, concerning the last three years (2000-2002). Accordingly, the energy rejection is compared with the corresponding wind parks' production, in view of the existing official power purchase agreement (PPA) between private wind power investors and the local network management (i.e. Public Power Corporation, PPC). Finally, the calculation results are fairly well in agreement with the monthly wide wind energy rejection values imposed by the local utility (PPC) for the period 2000-2002 on selected typical wind energy producers.

The numerical application case study refers to the island of Crete, which is the biggest Greek island and it actually faces a serious lack of power problem. However, even in this relative big island with a continuously increasing electricity demand and an excellent wind potential, remarkable wind energy rejection is encountered during the last years, erasing the annual income of existing wind power investments[11] and discouraging new investors to proceed in erecting new wind farms[6].

2. Position of the Problem

2.1 Wind Energy Applications in Crete

Crete the fourth largest island in the Mediterranean Sea exhibits very positive wind energy prospects for several reasons, including:

a. Conditions on the island are very windy, as average annual wind speed exceeds 8m/s in numerous locations[12].
b. The road infrastructure of the island is good[6], remarkably improved during the last twenty years.
c. The wind electricity production is purchased by PPC, at a price equal to the small islands' tariff, i.e. at 90% of the consumers' sale price, versus 70% on the Greek mainland[11].
d. The subsidization opportunities are very good, being comparable to the ones valid for the Aegean Archipelago islands, especially after the 2234/94-development law was passed[2].

For all these reasons a remarkable wind power increase was encountered between 1993 and 1999, almost representing the only new wind energy sector activity in the whole country, see figure (1), during that period. Moreover, it was in Crete island that the first Greek private wind park begun its operation in October 1998. In the next two years (1999-2000) significant (≈50MW) wind power capacity amplification took place; see also Table I, pushing the total wind power installed on the island to almost 70MW.

More specifically, in the island exist 12 wind parks (Table I), four of them (16.8MW) belonging to PPC[13] and the rest to private investors (50.5MW) and to local municipalities (3.0MW). Among the facts that one should note is that all the 137 wind turbines of the island belong to the medium-size (300kW-600kW) category, while the vast majority of them (128/137) is found in Lasithi Prefecture, located in the East side of the island, figure (2).

Table I: Existing wind parks in Crete Island (end of 2002)

	Location	**Prefecture**	**Owner**	**Start Up Time**	**Rated Power (MW)**	**Turbines Number**
1	Toplou	Lasithi*	PPC	1993	5.10	17x300kW
2	Toplou	Lasithi	PPC	1993	1.00	2x500kW
3	Toplou	Lasithi	PPC	1995	0.50	1x500kW
4	Xirolimni	Lasithi	PPC	2000	10.20	17x600kW
5	Modi	Lasithi	Private	1998	10.20	17x600kW
6	Chandras	Lasithi	Private	1999	9.90	18x550kW
7	Meg. Vrisi	Heraklion	Private	1999	4.95	9x550kW
8	Achladia	Lasithi	Private	1999	10.00	20x500kW
9	Anemoessa	Lasithi	Private	1999/2000	5.00	10x500kW
10	Krya	Lasithi	Private	1999/2000	10.00	20x500kW
11	Plativolo	Lasithi	Priv.-Munic.	2000	2.50	5x500kW
12	Mare	Lasithi	Municipality	1993	0.5	1x500kW

*Agios Nikolaos (Fig.2) is the capital of Lasithi prefecture.

Due to the favourable wind conditions of the island and the local inhabitants support[14], a considerable number of new wind parks are scheduled to be realized in Crete, since the total capacity of new wind farms' requests submitted to the Greek Regulatory Authority of Energy (RAE) approaches the 400MW[15].

2.2 Crete Island Electricity Generation System

Crete possesses the biggest autonomous electrical network in Greece with an official capacity of 580.9MW. More specifically, the local electrical generation system (EGS) depends almost exclusively upon fuel oil imports. Thus, electricity generation is accomplished by the two thermal power plants located in Chania and Heraklion (Linoperamata), figure (2). The real capacity of the local energy production system is 533MW during winter and approximately 500MW during summer, mainly due to the increased engine cooling requirements.

Accordingly, using official long-term data concerning the Crete EGS[16] for the last decade several

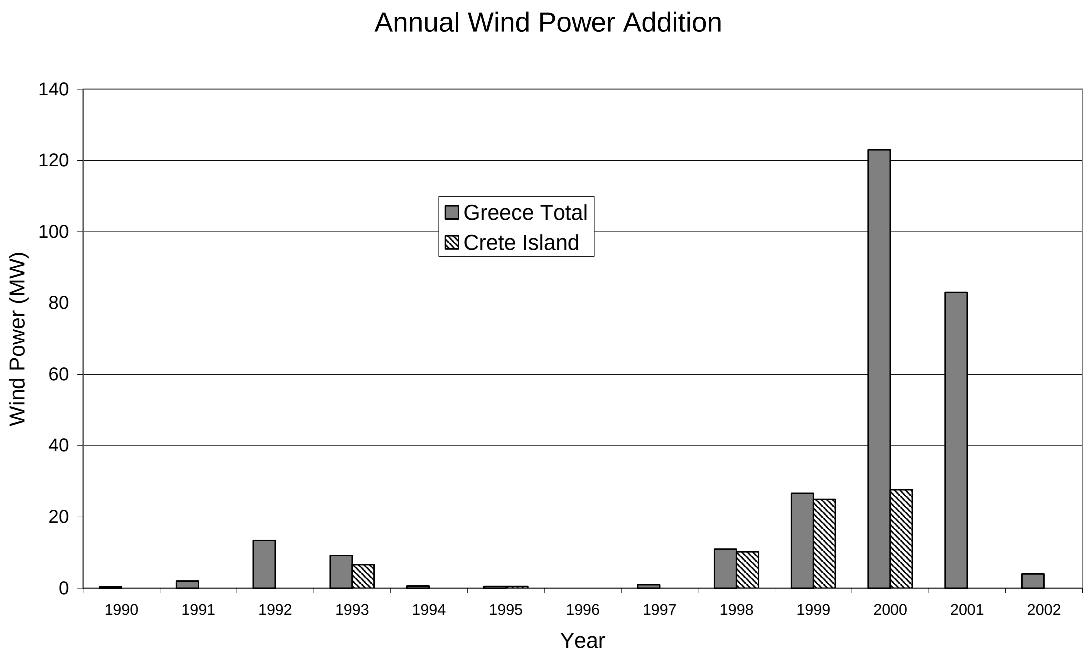

Figure 1: Time evolution of Crete versus total Greece annual wind power increase

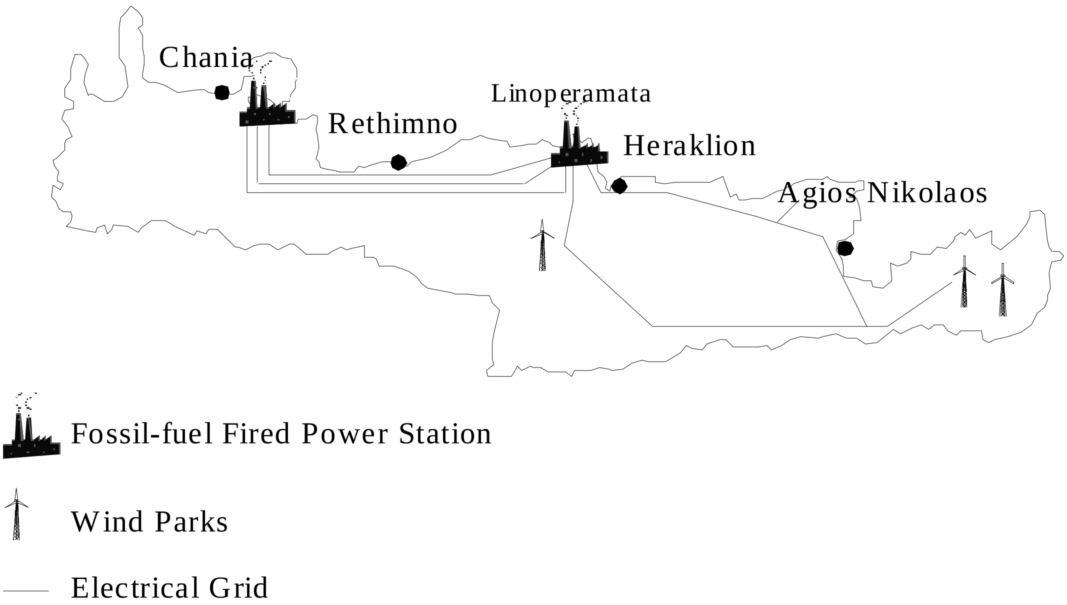

Figure 2: Existing wind farms and fossil-fuel fired power stations location in Crete

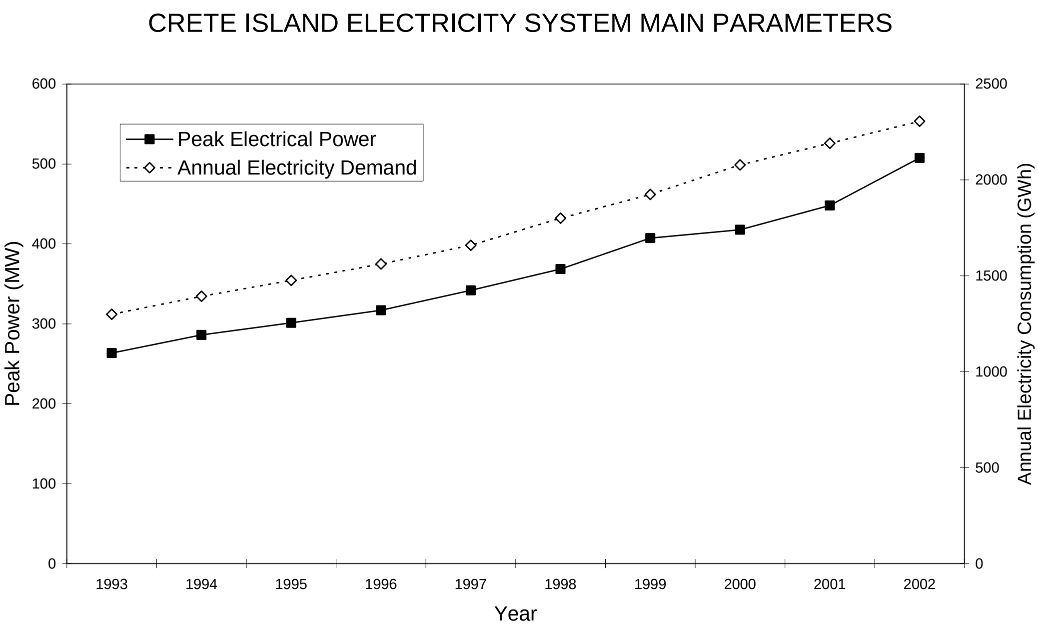

Figure 3: Time evolution of Crete island electricity system main parameters

conclusions may be drawn, i.e.:

- There is a considerable continuous annual electricity consumption increase during the last decade (1993-2002), from 1300GWh to 2300GWh, figure (3).
- The corresponding peak power increase is even much higher, while the peak load demand appearing during August 2002 is 507MW (figure (3)), slightly higher than the official maximum summer capacity of the system.
- Due to the development of the tertiary sector (services, commerce and primarily tourism) a high seasonal variation of electricity demand is encountered during the last years. For example, the mean hourly electricity load profile of the system during August 2002 is almost double the corresponding one of February 2002, figure (4). On top of this, even during low consumption periods (e.g. February

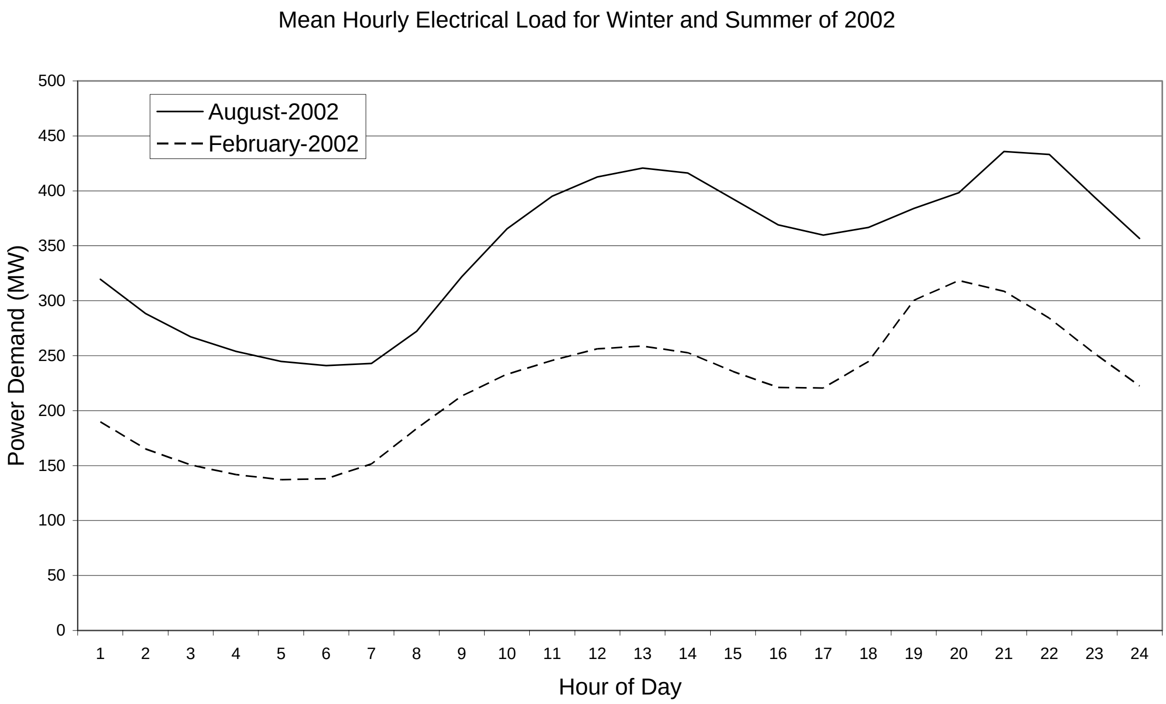

Figure 4: Electrical load comparison for Crete island between February and August of 2002

of 2002), the corresponding load demand is definitely greater than the local EGS technical minimum (i.e. 70-100MW), hence there is almost no possibility of operating the local EGS near or below its minimum capacity.

2.3 The Wind Energy Rejection Problem

According to the information presented, it is almost obvious that there is an urgent need for expanding the EGS limitations with the installation of new power plants. On the other hand, most wind energy investors are quite sceptical about creating new wind farms, while at the same time serious wind energy production rejection is encountered for the currently operating wind farms. On top of that,

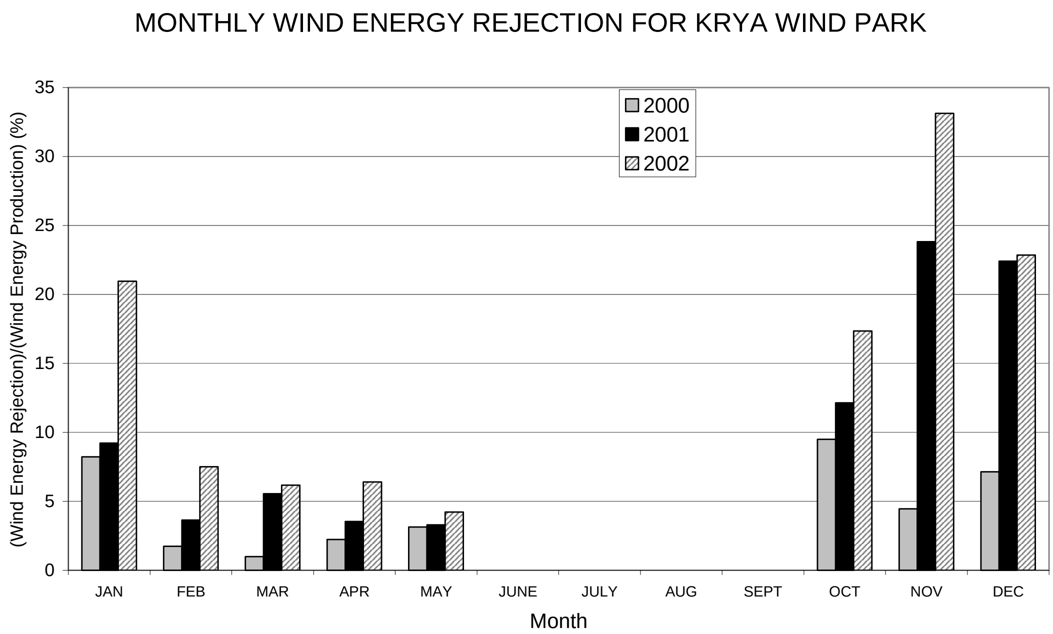

Figure 5: Wind energy rejection as a percentage of Krya wind park (2000-2002) production; monthly-wide distribution

increased wind energy rejection is expected[17] for the near future, especially if additional wind power is going to be installed on the island.

For example, in figure (5) official data is presented concerning the monthly wide wind energy rejection for a specific wind park (line 10 of Table I) and for a 3-year period, as a percentage of the wind energy production of the installation. It is important to mention that for the 2000 almost 3% of the wind park annual yield was rejected, while for 2002 the corresponding percentage is 11%. Besides, one cannot disregard that during winter (i.e. November to January) almost 1/4 of the wind park's production is lost, considerably impairing the financial viability of the investment[2][11]. Similar results are valid for the entirety of existing wind farms of the island, underlining the importance and the size of the problem.

To face this obstacle, in the next section a complete and reliable computational method is devised, able to realistically calculate the wind energy rejection on 10-minutes or on hourly basis, using the operational characteristics of the island's wind farms, the corresponding wind speed values as well as the instantaneous values of wind-based electricity absorbed by the local EGS. The proposed method is accordingly tested versus real wind energy rejection values for the 2000-2002 period in order to validate its accuracy. Finally, using the results of the proposed method one may accurately estimate the annual income loss for every wind power installation in the course of time.

3. Wind Energy Rejection Calculation Method

3.1 Basic Model

For the estimation of the instantaneous wind power rejection "$\Delta N_i(t)$" in the course of time "t", the following information is needed:

- The instantaneous wind power production "$N_w(t)$" of the existing wind parks of the island, assuming zero wind energy rejection. The total wind power production of the system is the sum of the electricity generation of all wind parks (i_{max}=12) of the island (see Table I), i.e.:

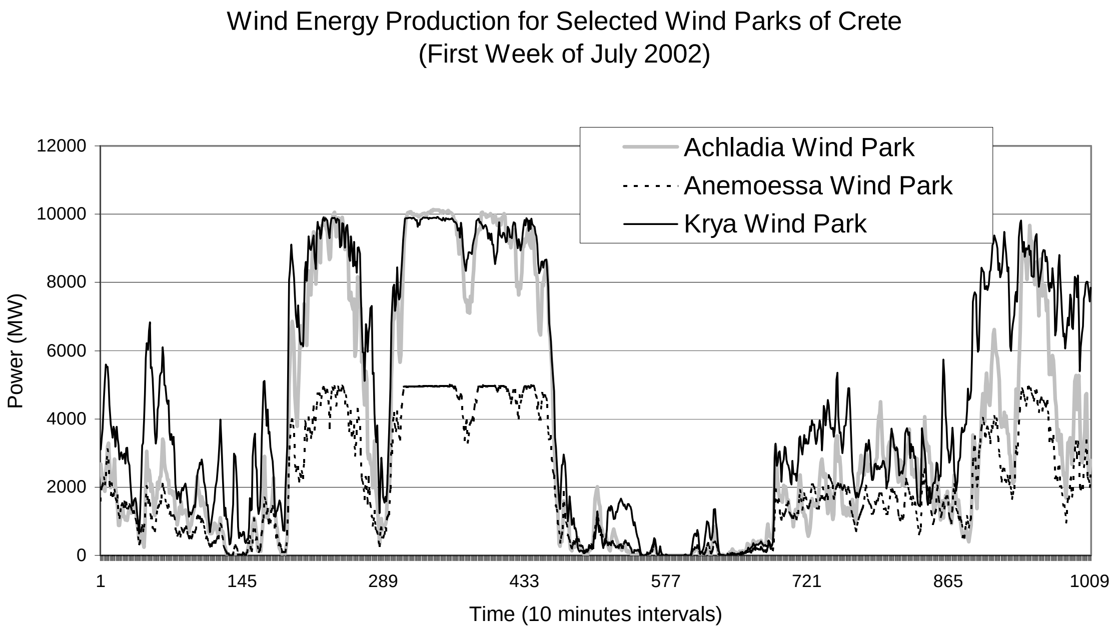

Figure 6: Wind power output of selected wind parks in Crete Island; values taken every 10 minutes

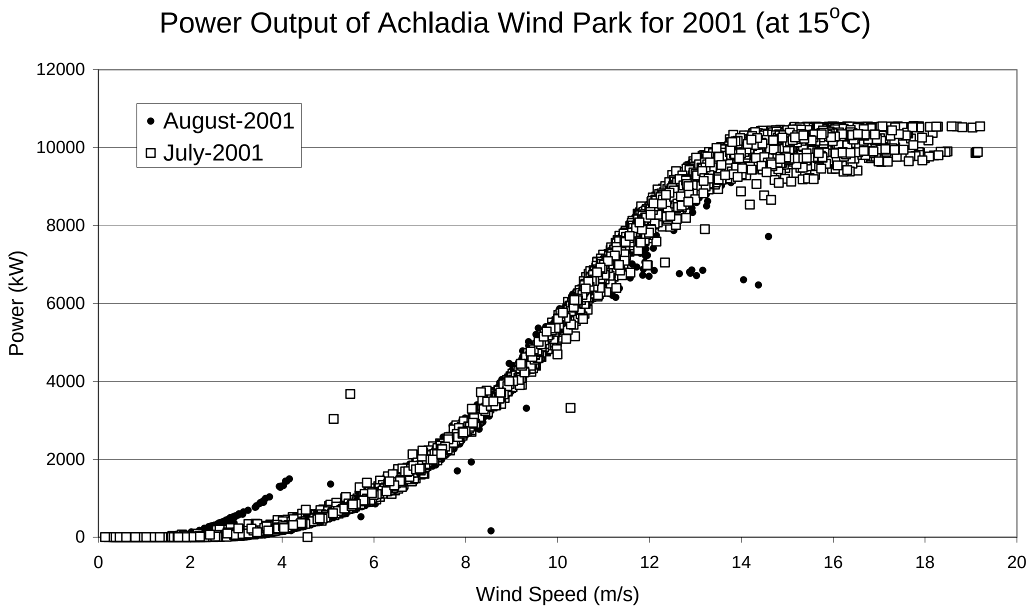

Figure 7: Power versus wind speed measurements for July and August of 2001

$$N_w(t) = \sum_{i=1}^{i=i_{max}} N_i(t) \tag{1}$$

Accordingly, the electricity production of each wind park is expressed as:

$$N_i(t) = \sum_{j=1}^{j=j_{max}} N_{i,j}(t) \tag{2}$$

where "j_{max}" is the number of the wind turbines of each wind park of Table I. In figure (6) one may see the highly variable energy production of three selected wind parks (lines 8-10 of Table I) for a specific time period.

- The wind generated electrical power given finally to the local network (including wind rejection) by each wind park under operation, i.e. "${}^fN_i(t)$"

Hence by definition the wind power rejection "$\Delta N_i(t)$" -for the "i" wind park of Table I- is given by the following relation:

$$\Delta N_i(t) = N_i(t) - {}^fN_i(t) \qquad with\ i = 1, 12 \tag{3}$$

Thus, the main problem for the application of equations (1) to (3) is the fact that the original wind power output of each wind park "$N_i(t)$" is not known, since the existing data concern the final wind energy entering the grid "${}^fN_i(t)$", not showing the wind energy rejected by the local EGS.

3.2 Wind Park Output Simulation

An alternative and practical way to face this obstacle is to simulate the output of each wind park on the basis of the central anemometer of the installation. It is not possible to apply equation (2) because an enormous volume of data is needed for each wind turbine of the island, while some data are not available in detail. In this context[11] one may write:

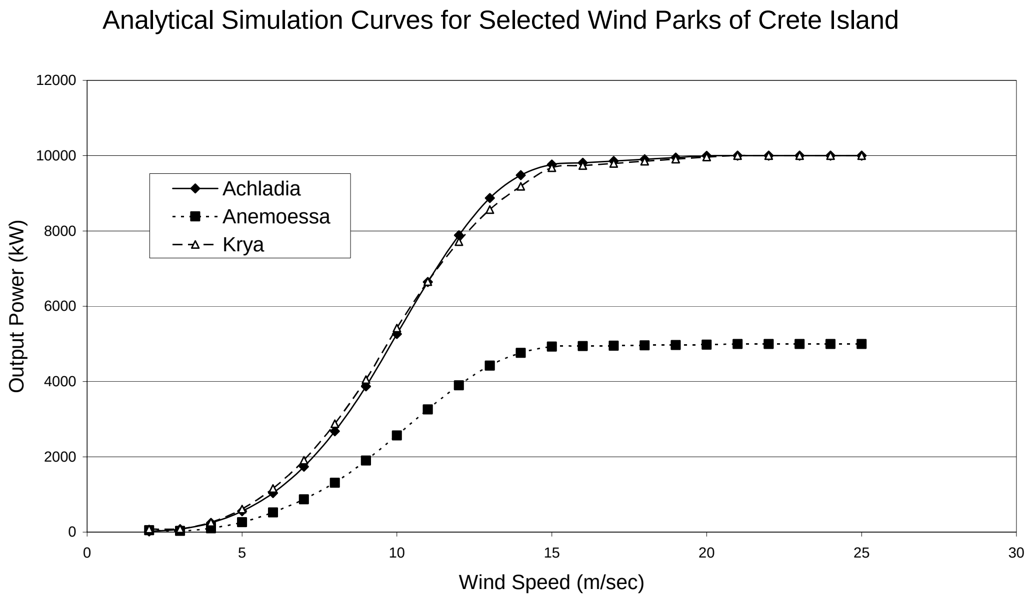

Figure 8: The simulation power curves of wind parks 8-10 of Table I

$$N_i(t) = N_i^s(t) \cdot \frac{\rho(t)}{1.2215} \cdot \delta_i(t) \tag{4}$$

where "${}^sN_i(t)$" is the analytical function describing the power curve of the entire wind park "i", expressed as a function of the wind speed at hub height for standard day conditions, i.e.:

$${}^sN_i(t) = {}^sN_i(V(t)) \tag{5}$$

while "ρ(t)" is the mean instantaneous air density at the wind park location and "$\delta_i(t)$" is the well known Kronecker's delta function taking values either equal to 1 (if the wind park is available for operation) or equal to 0, in case that serious malfunctions appear in the specific wind park. Finally, the air density at standard day conditions is 1.2215kgr/m^3.

For the calculation of the analytical simulation function "${}^sN_i(V)$" one may use the available large number of measurements concerning the wind power output of each wind park during July and August, since no wind energy rejection is taken place in this high electricity demand season, see for example figure (7). Several analytical functions have been tested versus detailed measurements, thus the most suitable ones for the wind parks (8-10 of Table I) and for standard day conditions are presented in figure (8). It is important to note that since the wind speed values are from measurements in the central mast of the wind park one cannot use this velocity and the power curve provided by the manufacturer of each wind turbine to reproduce the distributions of figure (8). In fact there is an almost ±15% discrepancy between the results given by the direct application of the manufacturers' power curves[18] using the existing wind speed data and the real power output of the wind parks.

4. Application Results-Comparison with Existing Data

4.1. Data Preparation

The above-presented method is accordingly applied to estimate the expected wind energy rejection for three selected wind parks (lines 8-10 of Table I), on 10-minutes basis for the 2000-2002 time period. Bear in mind that for this specific time period historical data exist concerning:

- The wind speed values "$V_i(t)$" for every wind park of the island, see for example figure (9)

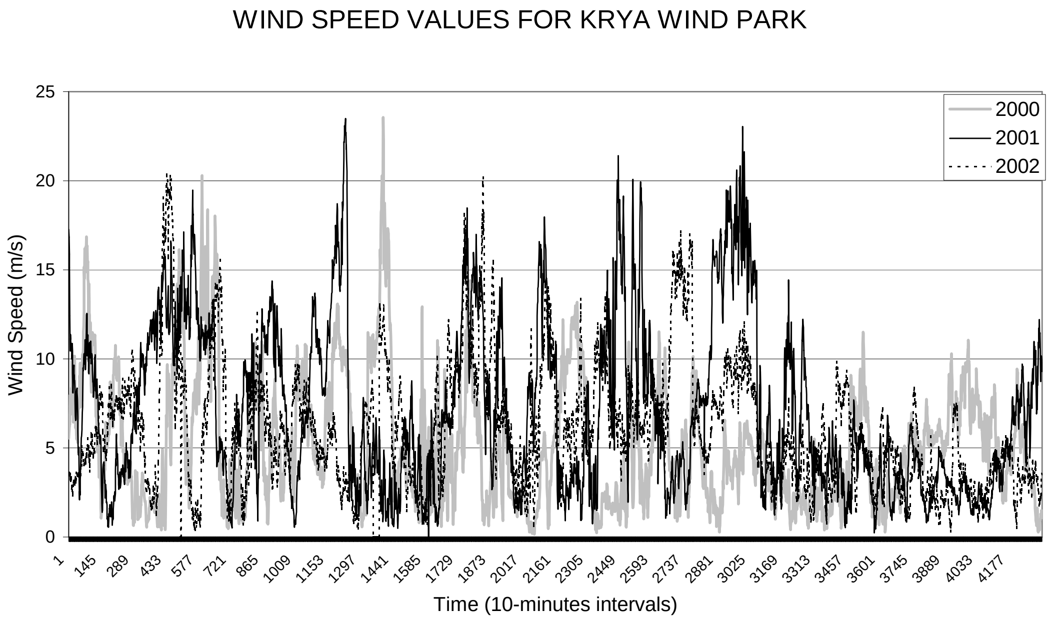

Figure 9: Ten-minutes average wind speed values for selected location during April

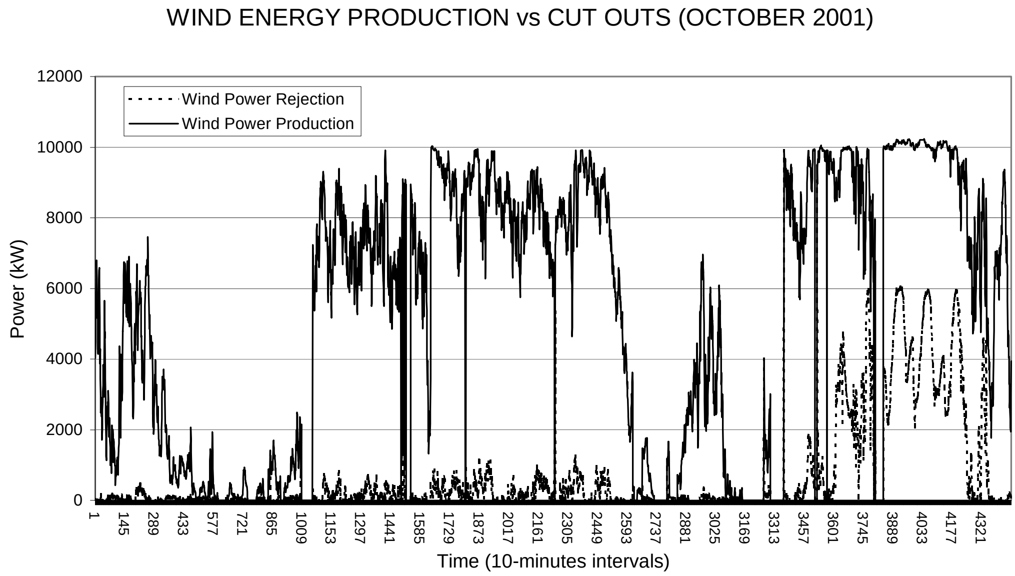

Figure 10: Time-evolution of wind energy rejection for Krya wind park

- The wind power given finally to the local network (including wind rejection) by each wind park under operation, i.e. "$^{f}N_i(t)$"
- The corresponding air density values in kg/m^3, resulting by measurements of local temperature "θ" (in Celsius degrees) and ambient pressure "p" in Pa, since:

$$\rho = \frac{p}{287 \cdot (273 + \theta)} \tag{6}$$

- The technical availability "$\delta_i(t)$" of any wind park investigated in the course of time

4.2 Direct Estimation of Wind Energy Rejection

Subsequently, using equation (3) along with the power curves of figure (8) one can directly estimate the 10-minutes, hourly, daily, monthly and annual wind energy rejection of each wind park for the

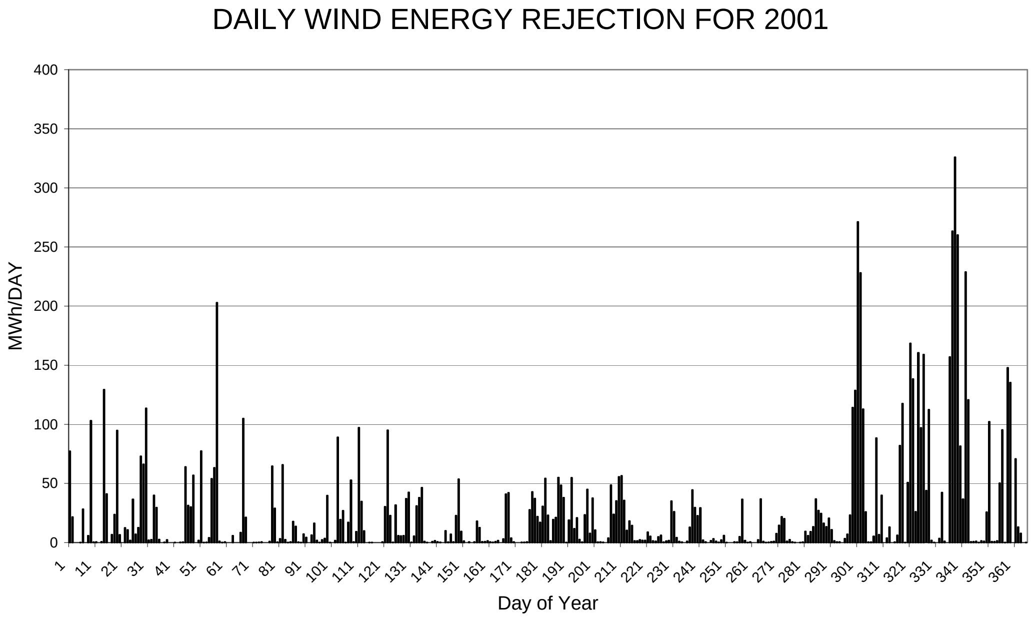

Figure 11: Wind energy rejection of wind parks 8 to 10 of Table I, for 2001

period examined. Applying the direct calculation procedure one can see in figure (10) the wind power rejection in ten-minute intervals for October of 2001 for the wind park (10) of Table I in comparison with the wind power output of the installation, resulting by the corresponding wind speed time-series for the same period[19][20][21]. As it comes out from this figure, significant wind energy rejection has taken place during the last week of the month.

The next two figures (11) and (12) demonstrate the total daily energy cut outs concerning the wind parks (8 to 10) for 2001 and 2002 respectively. It is important to note that for several days of both years more than 200MWh/day are rejected, a value which is equivalent to the daily consumption of a medium size town of 10,000 people.

Finally, in order to support the reliability of the proposed analysis, figures (13), (14) and (15) compare

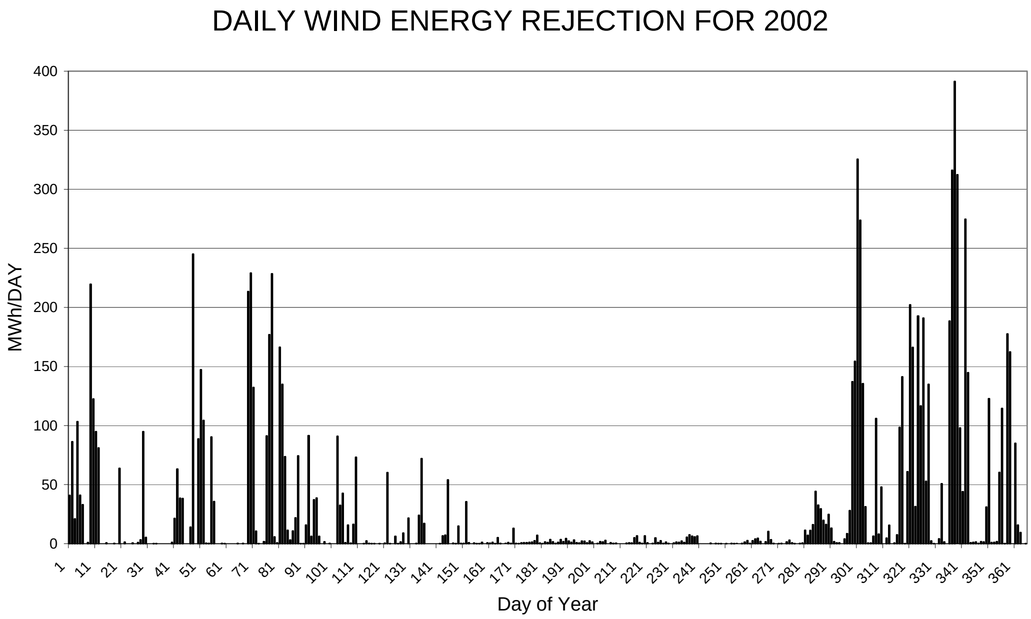

Figure 12: Wind energy rejection of wind parks 8 to 10 of Table I, for 2002

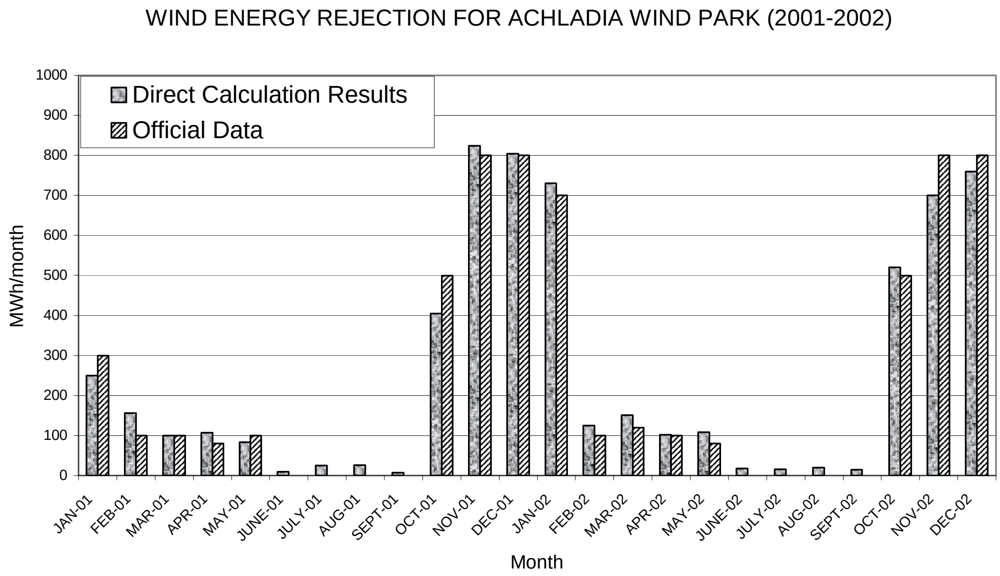

Figure 13: Comparison of calculated and officially reported[16] wind energy rejection on monthly basis; Achladia wind park

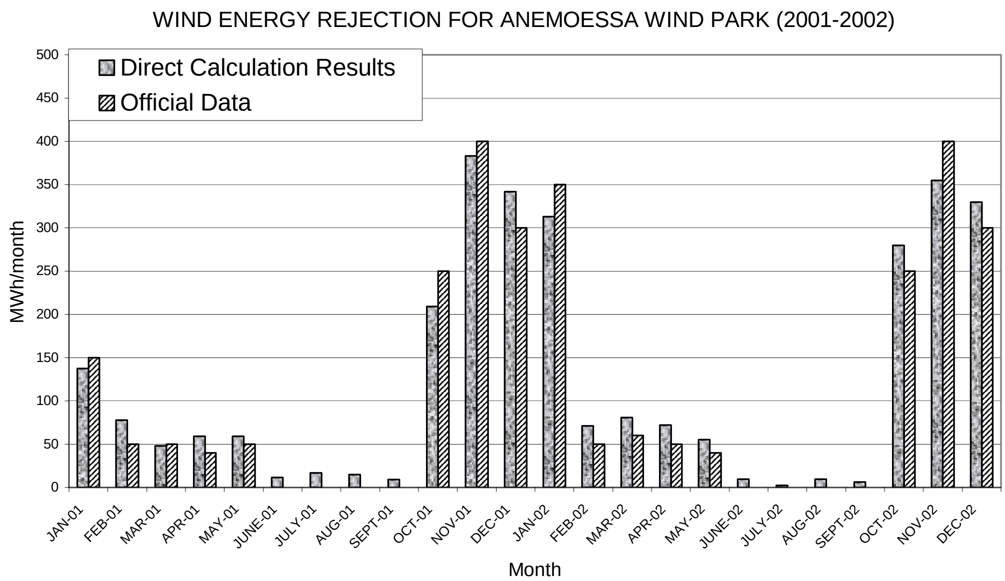

Figure 14: Comparison of calculated and officially reported[16] wind energy rejection on monthly basis; Anemoessa wind park

the calculated wind energy rejection on a monthly basis with the corresponding official rejection values imposed by PPC, which are at the disposal of the owner of the wind parks (8), (9) and (10) for 2001 and 2002. According to the data presented, one may easily conclude that the calculation results represent quite well the reality, while minor discrepancies exist during individual months. For example during February 2001 calculation results overestimate the recorded wind energy rejection, while during November 2002 the wind energy rejection reported by PPC is considerably higher than the corresponding estimated value.

Concluding, on an annual basis estimated wind energy rejection is only 3% higher than the official data provided by PPC and the wind parks owner. As a general conclusion from the above analysis one may clearly state that the developed direct analytical procedure to calculate the original wind park output (i.e. analytical curves of figure (8)) leads to similar results, when compared to the official data.

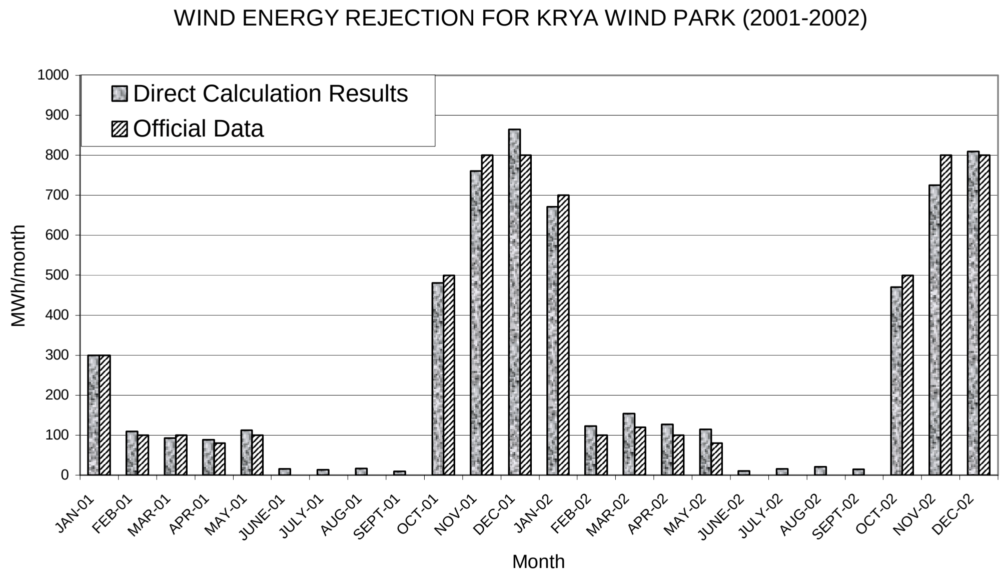

Figure 15: Comparison of calculated and officially reported[16] wind energy rejection on monthly basis; Krya wind park

In this way the analytical curves of figure (8) are thus validated. Consequently, one may use similar equations to simulate the original output of the island's wind parks, without taking into account the wind energy rejection by the local network.

4.3 Discussion of the Results

For practical reasons, emphasis in put on the presentation of estimated values in terms of monthly wind energy rejection values, since the available official data is expressed on monthly basis. Thus, in figures (13) to (15), one can compare the calculation results of the proposed method with the official data for 2001 and 2002, respectively. From this comparison the following conclusions may be drawn:

- There is a remarkable amount of wind energy rejection increase from 2001 to 2002, when at the same time the wind energy potential during 2002 was quite lower than the corresponding one of 2001. As a result, the total wind energy produced during 2002 is less than the 2/3 of the corresponding value of 2001. Hence, the wind energy rejection that marks 2002 amounts to 11% of the corresponding annual production of Crete's wind parks.
- During the cold period (October to March) the calculated monthly value of reduced (per MW of rated power) wind energy rejection is quite significant, varying from 100MWh/(mo.MW) to 200MWh/(mo.MW).
- During summer (June to September) the calculated wind energy rejection is practically zero, which is in accordance with the official recorded values for the months of 2001 and 2002. Any deviation from zero during this period is mainly attributed to the computational numerical noise of the method.
- The calculation results based on the proposed method follow rather closely the official data, although in some cases isolated discrepancies occur. On the average, limited differences between estimated value and official data exist during March to October of both years. On the other hand the November to January calculation results slightly overestimate the official data (by less than 5%).

To get a clear cut picture of the annual wind energy rejection, a summary is shown in Table II of the corresponding results for wind parks (8 to 10 of Table 1) for 2000, 2001 and 2002 respectively. More specifically:

- The second column of Table II shows the annual results of the proposed method
- The third column gives the official data value reported by the local utility
- The fourth column indicates the upper wind energy rejection limit according to the existing power purchase agreement (PPA) signed between the island's wind park owners and the local utility (PPC).

More precisely, for every wind park there is a minimum grid connection time period "Δ_G" per year given by figure (16) as a function of the wind power penetration percentage into the local EGS. The input variable in figure (16) represents the ratio of the rated power of the wind parks of the system divided by the corresponding peak load demand of the previous year.

Table II: Wind energy rejection for wind parks 8 to 10 of Crete Island (in MWh/Year)

Year	Direct Calculation Results	Official Data[16]	PPA Maxium Values	Money Loss (€/MW)
2000	2953	2861	9,891	8,030
2001	7030	6850	14,030	19,990
2002	8384	8230	8,430	24,570

According to the collective information of Table II one may clearly state that direct calculation results agree very well with the available official data on annual basis, since for all three years examined the maximum discrepancy is less than 3%.

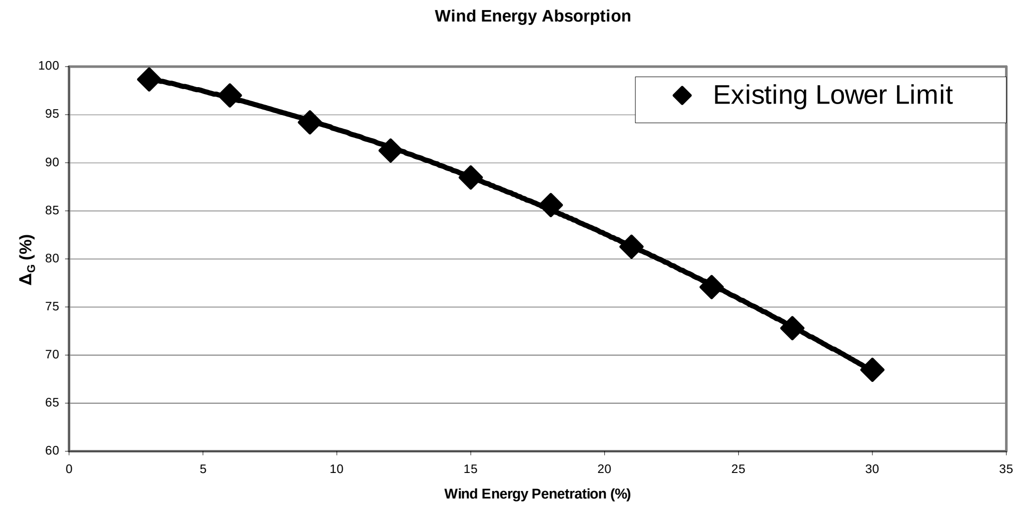

Fig. 16. Minimum wind energy absorption by the Crete electrical network, as a function of the installed wind power

4.4 Income Loss Estimation

One of the most important aspects of the problem investigated concerns the application of the corresponding Power Purchase Agreement (PPA) for the local grid and its economic impact on the feasibility of existing wind power investments. In this context, although during 2000 and 2001 the PPA is not violated by the local utility, during 2002 the official wind energy rejection is slightly below the upper limit dictated by the PPA terms, see figure (16) and Table II.

As a result, the annual financial loss due to this wind energy rejection is quite high, especially during 2002. Using the official value defined by the law 2244/94 and the electricity market price to households[22] the corresponding equivalent wind energy purchase price "c_o" for Crete island is 70.2€/MWh for 2000, 72.9€/MWh for 2001 and 74.6€/MWh during 2002. Subsequently, one may estimate for each wind park "i" the reduced annual income deterioration "δr_i" per MW of installed power "N_i^*" according to the following relation:

$$\delta r_i = \frac{\int_0^{1\,year} \Delta N_i \cdot dt}{N_i^*} \cdot c_o \quad where\ (i = 1,...,12\ \ of\ Table\ I) \tag{7}$$

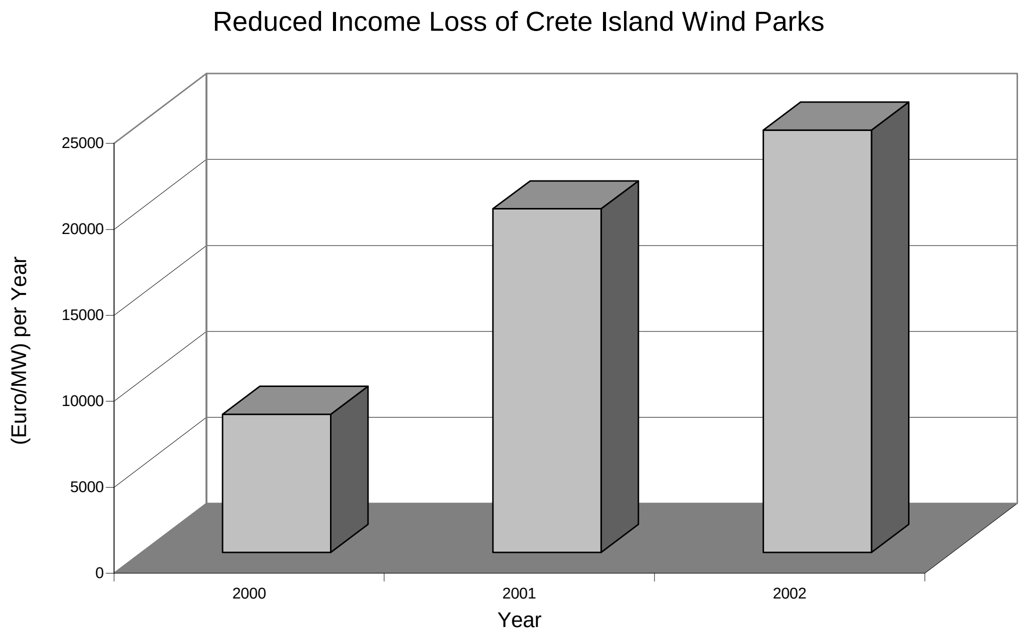

Figure 17: Reduced annual income loss due to wind energy rejection in Crete Island

The application results of equation (7) are also sited in the last column of Table II. More precisely, the corresponding income loss for every wind park of the island is continuously increasing, reaching the considerable value of approximately 25,000€/MW of installed power, figure (17). If this amount continuous to appear in the next years, the financial capacity of all the existing wind parks will be remarkably diminished[2], discouraging also any new investor entering the sector[6][23]. Bear in mind that the annual money loss due to the wind energy rejection by the local EGS represents more than 5% of the capital invested by each wind park owner. Even if this situation remains unaffected, which is rather optimistic, during the next decade, a considerable loss of revenues is expected for any investor in the wind energy sector of Crete island.

5. Conclusions and Proposals

According to the investigation carried out concerning the autonomous electricity generation systems of Greek islands, and specifically that of the island of Crete, a remarkable amount of wind produced electrical energy is rejected during the last three years, with an increased tendency in the course of time. To realistically investigate this problem a new reliable method is developed, in order to estimate the instantaneous wind power rejection by the local EGS according to the information provided by system operator and wind parks owners.

Surely calculation results should be considered reliable, since they are based on detailed long-term data and measurements. More specifically, the proposed method takes into account the wind speed measurements, the wind power forwarded to the local grid and the power curves of each wind park, properly developed using long-term measurements. According to the results obtained, the present method describes fairly well the officially recorded wind electric energy rejection time evolution.

Finally, the obtained calculation results are compared with the maximum permitted annual wind energy rejection dictated by the existing PPA. In any case the existing PPA seems not to be violated by the local utility authority, although during 2002 wind energy rejection reaches the upper limit of this agreement. As a result, that year, wind energy investors lost almost 25,000€ per MW of installed power, an amount which is quite higher than the ones of the years 2000 and 2001.

Summarizing, current practice seems quite irrational that, despite the considerable electricity deficit of most Greek islands, Crete included, a significant amount of wind energy rejection takes place at the same time. This situation is going to be worsening during the next years, especially if new wind power units will be installed at the island. From the up to now obtained results one may suggest the utilization of an appropriate energy storage system like an hybrid water pumping-small hydro power station in combination with the existing or new erected wind parks. However, an extensive computational examination of the wind energy rejected is needed -for a ten to twenty years period- along with a detailed cost-benefit analysis. These are the scientific domains requiring a further research and are currently under investigation.

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ENERGY BALANCE ANALYSIS OF A STAND-ALONE PHOTOVOLTAIC SYSTEM, INCLUDING VARIABLE SYSTEM RELIABILITY IMPACT

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Abstract

Official statistics estimate that almost two billion people have no direct access to electrical networks, 500,000 of them living in European Union and more than one tenth of them in Greece. An autonomous photovoltaic system is one of the most interesting and environmental friendly technological solutions for the electrification of remote consumers or entire rural areas. The primary objective of this current study is to determine the optimum dimensions of an appropriate stand alone photovoltaic system, able to guarantee the coverage of remote consumers energy demand located in typical Greek territories using long-term measurements, under the restriction of minimum initial cost. Accordingly, the impact of acceptable reliability level on the stand-alone photovoltaic system energy behaviour and initial cost is also examined. Finally, special emphasis is laid on the detailed energy balance analysis of selected stand-alone photovoltaic system configurations, on an hourly basis at least. According to the results obtained, a properly sized stand-alone photovoltaic system is a motivating prospect for the energy demand problems of numerous existing isolated consumers all around Greece.

Keywords: Stand-Alone System; Optimum System Sizing; Photovoltaic System; Energy Balance; Reliability Level

1. Introduction

Energy and especially electricity is considered to be a substantial element of contemporary societies, like fresh water and clean air. However, official statistics estimate[1] that almost two billion people have no direct access to electrical networks, 500,000 of them living in European Union and more than one tenth of them in Greece[2]. Afar from decision centres and having limited political influence, isolated consumers are usually abandoned, facing a dramatically insufficient infrastructure situation[3][4]. Their importance, however, is not based on simply techno-economic criteria but mainly on social or even national survival reasons.

An autonomous photovoltaic system (PVS) is one of the most interesting and environmental friendly technological solutions for the electrification of remote consumers[5][6][7] or entire rural areas[8]. For this purpose, a properly sized small photovoltaic generator is necessary to exploit the available solar potential producing useful electrical energy. Thus, as a contribution to life quality amelioration of several isolated habitants, an integrated solution based on an energy autonomous stand-alone photovoltaic system has been elaborated by the authors[9][10] during the last five years.

Therefore, the initial objective of this current study is to determine the optimum dimensions of an appropriate stand alone photovoltaic system, able to guarantee the coverage of remote consumers energy demand located in typical Greek territories using long-term measurements. For this purpose, extended measurements are taken into account, including low and high solar radiation years, in order to realistically determine the appropriate size of a stand-alone photovoltaic system.

At this point, it is important to mention that the zero-load rejection constraint is a very strict one, leading to storage devices over sizing. Hence, it is actually replaced by a 99% or 95% system reliability condition (i.e. the system is annually out of power for 88h to 440h). In this context, the impact of acceptable reliability level on the energy balance and the stand-alone photovoltaic system initial cost is also examined.

Finally, special emphasis is laid on the detailed energy balance analysis of the selected configurations, since the proposed methodology has the ability to investigate the energy behaviour of any stand-alone photovoltaic system on an hourly basis at least. On top of that, interesting energy production results are also included, concerning annual and monthly-wide distributions.

2. Proposed Solution for the Energy Fulfilment Problem of Remote Consumers

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 local market survey a representative weekly electricity consumption profile[11][12][13] is adopted, being also depended on the year period analysed (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 Hellenic Statistical Agency[5][9]. More precisely, the numerical load values vary between 30W (refrigerator load) and 3300W.

Thus, the annual electricity consumption -on an hourly basis- is the first input of the present analysis, while full particulars of the electricity consumption profile is presented in the application results of chapter 4. Additionally, the corresponding solar radiation and ambient temperature are also necessary to integrate the energy balance calculations. 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.

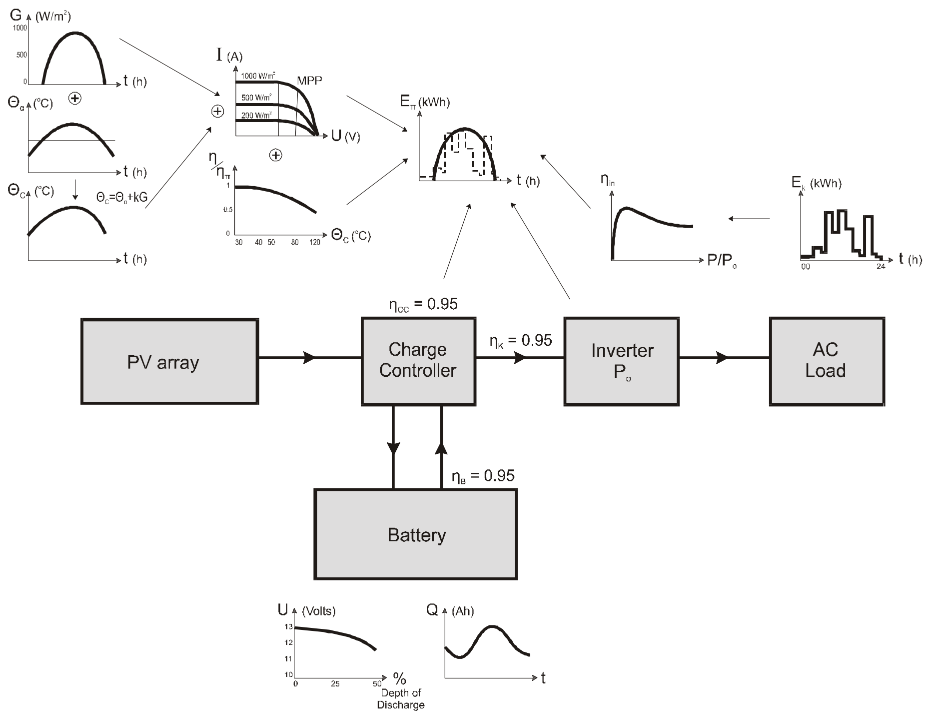

Figure 1: Proposed Autonomous PVS Configuration for Remote Consumers

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

i. A photovoltaic system of "z" panels ("N_o" maximum power of every panel) properly connected (z_1 in parallel and z_2 in series) to feed the charge controller to the voltage required
ii. A lead acid battery storage system for "h_o" hours of autonomy, or equivalently with total capacity of "Q_{max}", operation voltage "U_b" and maximum discharge capacity "Q_{min}" (or equivalently maximum depth of discharge "DOD_L")
iii. A DC/AC charge controller of "N_c" rated power, charge rate "R_{ch}" and charging voltage "U_{CC}"
iv. A DC/AC inverter of maximum power "N_p" able to meet the consumption peak load demand

where "N_p" is the maximum load demand of the consumption, including a future increase margin (e.g. 30%). The proposed safety margin is based on a long term analysis of local electrical parameters[14], indicating that the Greek electricity consumption increase has approximated 4% per annum, while the maximum (peak) load increase of the mainland electrical grid is much more abrupt (6%). Hence, since the proposed system has an operational life of at least twenty years, it is assumed reasonable to take into consideration a five-year forecast of the expected electricity consumption.

As mentioned above, the main scope of the present work is primarily to estimate the appropriate dimensions of a stand-alone PVS for every remote consumer examined and subsequently to evaluate the complete system energy behaviour. The two governing parameters used during the optimisation procedure are the number "z" and the rated power "N_o" of each photovoltaic panel used and the battery maximum necessary capacity "Q_{max}". To confront similar problems, a computational algorithm "PHOTOV-III" is developed. This specific numerical code (see Chapter 3 for more details) is used to carry out the necessary parametrical analysis on a given time step (e.g. on an hourly) energy production-demand basis.

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

$$z_{init} = E_{tot} \big/ (8760 \cdot CF \cdot N_o) \qquad (1)$$

where "E_{tot}" is the system annual electricity consumption, increased by 20% to take into account future changes[14] and "CF" is the photovoltaic station capacity factor.

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

$$Q_{init} = \frac{h_{min} \cdot E_{tot}}{8760 \cdot \eta_s \cdot DOD_L \cdot U_b} \qquad (2)$$

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

Subsequently, for each "z" and "Q_{max}" pair the "PHOTOV-III" algorithm is executed for all the time-period selected (e.g. one month, six-months, one year or more) and emphasis is laid on obtaining zero-load rejection or desired reliability level operation. More precisely, for every time point investigated, the system energy demand is compared to the photovoltaic generator energy production, including inverter and power line loss. The photovoltaic generator output is defined by the solar radiation at the selected tilt angle "β", the ambient temperature and the manufacturer power curve (I-U). Thus, during the long-lasting operation of the proposed stand-alone system, the following situations may appear:

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

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

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

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

$$h_{max} \leq (1-R)\cdot 8760 \qquad (3)$$

where "h_{max}" is the maximum annual number of hourly load rejection of the PVS.

Next, the number of photovoltaic panels is increased and the calculations are repeated. Thus, after the integration of the analysis a (z-Q^*) curve is predicted under a specified reliability level restriction.

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

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

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

3. Best Configuration Choice

As already mentioned, during the last years a fast and reliable numerical algorithm "PHOTOV-III " has been created[5][9], able to investigate in details the energy behaviour of stand-alone photovoltaic systems for a selected time period. The main steps of this algorithm are:

i. For every region analysed, select a "z" and "Q_{max}" pair, see equations (1) and (2).
ii. 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.
iii. 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 ii). Otherwise, proceed to step (iv).
iv. 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 (ii). 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 (i).

Following the integration of the energy balance analysis, a (z-Q^*) curve is predicted under a given reliability level "R_{min}" restriction. More specifically,

$$R_{min} = 1 - \frac{h_{max}}{8760} \tag{5}$$

To get an unambiguous picture, keep in mind that for every pair of (z-Q^*) the stand-alone photovoltaic system is energy autonomous for the period investigated, excluding a small period of "h_{max}" hours per annum. Finally, the optimum pair may be selected from every (z-Q^*) curve, on the basis of the minimum first installation cost criterion.

In this context, the initial cost "IC_o" of a photovoltaic stand-alone system can be approximated as:

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

where "C_{PV}" is the photovoltaic modules ex works cost, "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[9][15], one may finally get:

$$IC_o = \zeta \cdot z \cdot Pr \cdot N_o \cdot (1+f) + c_b \cdot Q_{max} + a + b \cdot z \cdot N_o \tag{7}$$

where "ζ" is a function of "z" (i.e. $\zeta=\zeta(z)$), expressing the scale economies for increased number of photovoltaic panels utilized. In the present case ($z \approx 100$) ζ is taken equal to one. Subsequently "P_r" is the specific buy-cost[16] of a photovoltaic panel (generally $P_r=P_r(N_o)$) expressed in Euro/kW_p. Similarly, "c_b" is slightly dependent (Euro/Ah) on battery capacity. Thus for the local market -after a market survey[17] concerning lead-acid batteries of 24V- the following semi-empirical relation may be used:

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

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[18] of a stand-alone photovoltaic system is a function of "z" and "Q_{max}" if "N_o" is defined, thus one may write:

$$IC_o = IC_o(z, Q_{max}) \tag{9}$$

Hence, by using the initial cost function (equation (7)) it is possible to estimate for any reliability level (z-Q^*) curve the minimum initial cost solution, which guarantees a specific acceptable number "h_{max}" of hourly load rejection per annum of the remote consumer for the time-period examined.

On top of 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:

$$IC_{IN} = (1-\gamma) \cdot IC_o \tag{10}$$

4. Application Results

The present analysis is focused on an island location -Zakinthos island-, with remarkable solar potential medium-low wind speeds, where long-term solar radiation and ambient temperature measurements are available by PPC[19]. Zakinthos is a medium-sized island (39000 habitants. area of 434km^2), located near (SW) Peloponnese at the South Ionian Sea, latitude 37.3° and longitude 20.7°. The topography of the island is typically Ionian, i.e. gentle slopes, low mountains and remarkable vegetation. As already mentioned the area possess high solar potential, see figure (2), since the annual solar energy per square meter exceeds the 1600kWh. More specifically in figure (2) one may observe the monthly solar energy profiles for the best, worst and medium quality year, on the basis of the experimental data. As it is clear from the data collected, there is a remarkable difference between the "best" solar potential year and the "worst" one, which cannot be disregarded.

Using the "PHOTOV-III" numerical algorithm for various PV panel tilt angles, one has the opportunity to estimate the corresponding stand-alone PVS configuration for the selected three years (high, medium, low solar potential) and for the same region, see figures (3) to (5). In these figures the constant initial cost curves are also drawn, including a 50% State subsidization. According to the results obtained, the optimum (minimum initial cost) configuration is realized when the panel tilt angle varies between 45 and 60 degrees. For comparison purposes, figure (6) presents the energy autonomous PVS configurations for all three years investigated and for β=45° and β=60°. The results of figure (6) are in accordance with the solar potential data of figure (2), while a remarkable difference between the proposed solutions is encountered (photovoltaic system size and initial cost), for the three representative years examined, although all cases concern the same area.

As it is obvious from the results, the minimum initial cost solution is realized for the same "β" angle, while there is a considerable size and initial cost discrepancy of the proposed photovoltaic system between the best and the worst solar potential case, leading to more than 10000Euro initial cost increase, excluding State subsidization.

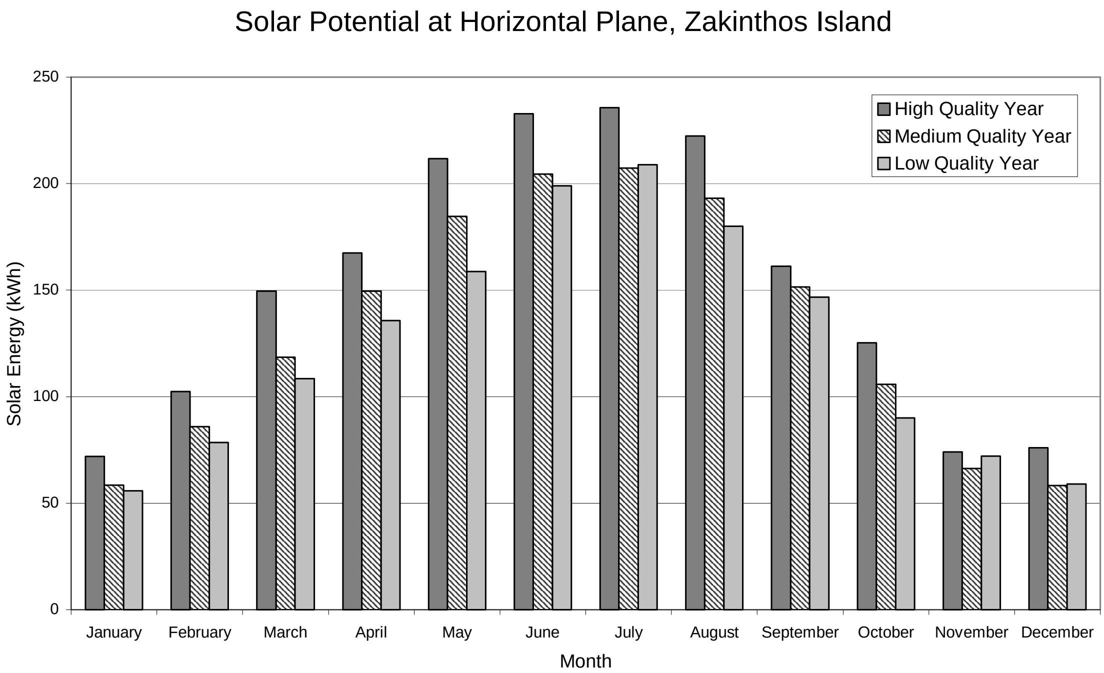

Figure 2: Experimental Solar Potential Values for Zakinthos Island

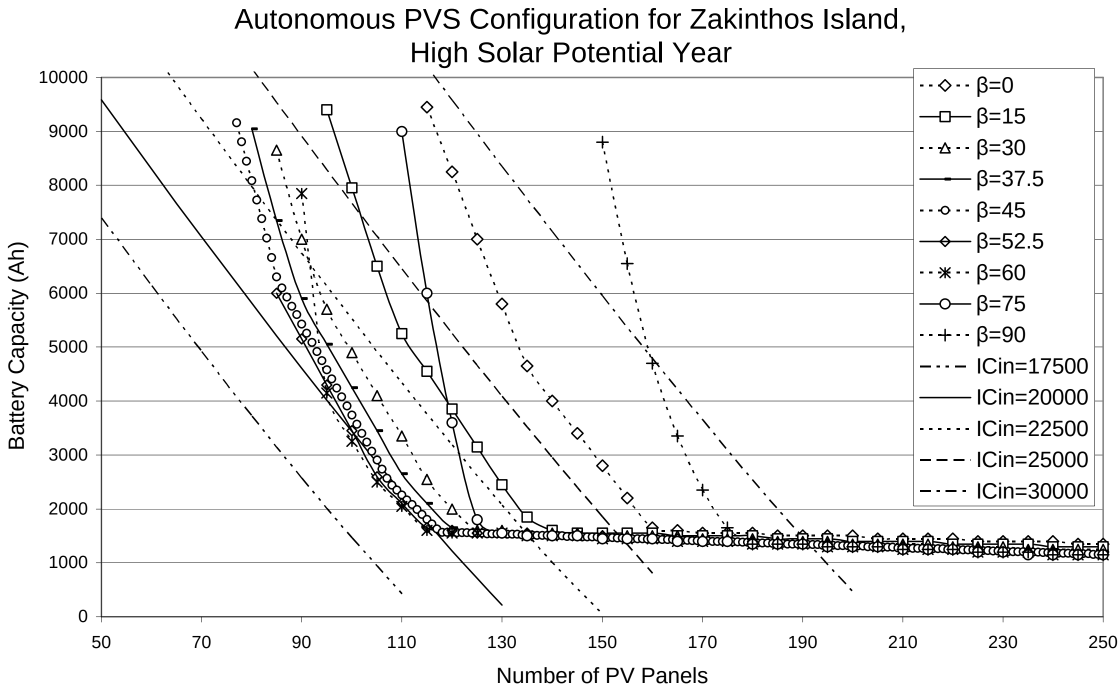

Figure 3: Optimum Stand-Alone PVS Configuration for Zakinthos Isl, High Solar Potential Year

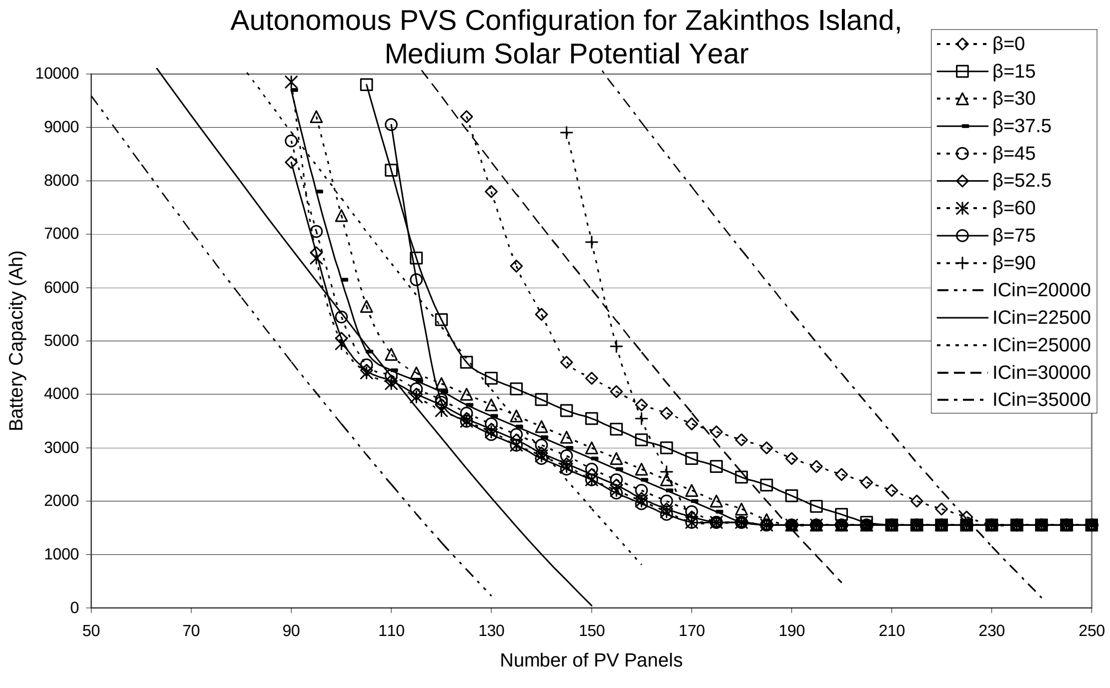

Figure 4: Optimum Stand-Alone PVS Configuration for Zakinthos Isl, Medium Solar Potential Year

More specifically, an almost 15% photovoltaic panel number increase, see Table I, is necessary to guarantee the system energy autonomy for the worst solar potential year in comparison with the best one. The solar potential quality, however, actually influences the battery bank capacity, which for the medium and the worst solar potential years becomes almost double than that of the best year. On the other hand, for the medium solar potential year the optimum PV panel number turns out to be less than the best year one.

Table I: Optimum Configuration for a Stand-Alone Photovoltaic System at Zakinthos Island

Solar Potential Quality	(z) PV Panel Number	Q_{max} (Ah)	ICo (Euro)
Best Year	105	2500	39100
Medium Year	100	4950	43650
Worst Year	120	5000	49400

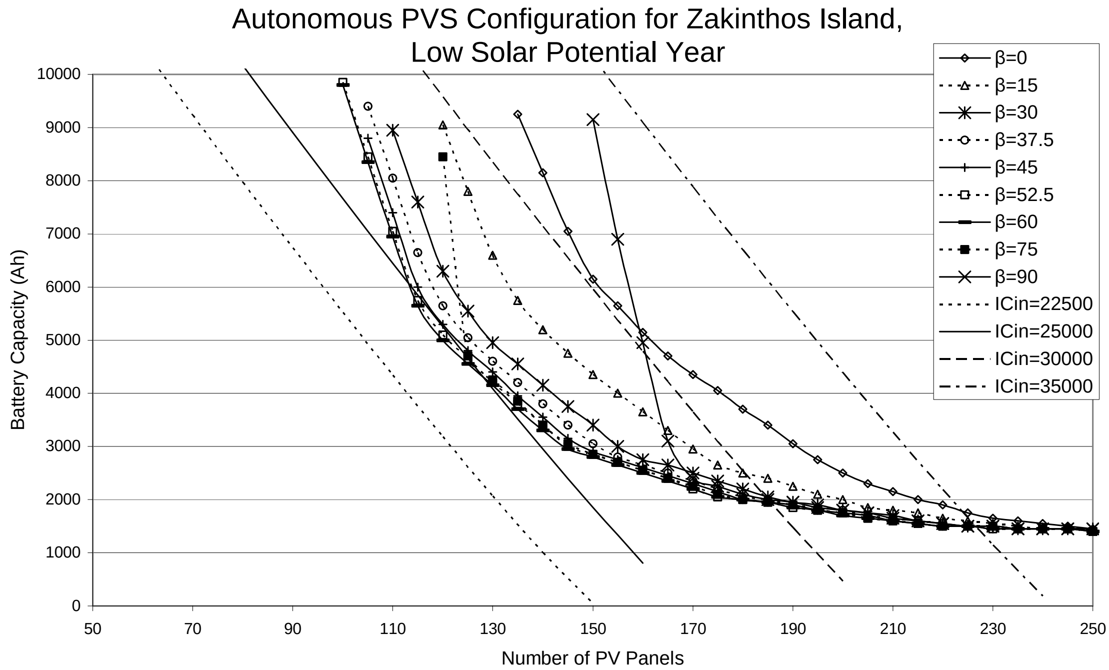

Figure 5: Optimum Stand-Alone PVS Configuration for Zakinthos Isl, Low Solar Potential Year

Finally, it is interesting to compare the minimum initial cost variation with the panel tilt angle for the three representative years selected, figure (7). For all the three years examined the minimum initial cost is achieved for "β" taking values between 52.5° and 60°. Besides, there is a remarkable initial cost variation with the time period investigated even for the same region. This variation can be explained on the basis of measured solar potential values, see figure (2), and it strongly questions the reliability of pure theoretical models, used to simulate the energy production of a photovoltaic system, in order to define the necessary configuration of a stand-alone installation.

Recapitulating, one may state that -in an attempt to predict the minimum initial cost configuration of a stand-alone photovoltaic system- the selected time period strongly influences the system size. However, one may use the medium solar potential quality year data to define the optimum configuration, if the minimum acceptable reliability restriction can be violated in a certain degree.

5. The Influence of System Reliability on the System Sizing

The reliability of a stand-alone energy production system is usually expressed either using the number of hourly load rejections during a given time period (e.g. one year period) or in term of loss of load probability "LLP". Therefore the no-load rejection case -or equivalently the LLP=0 value- corresponds to a total energy autonomy of the system during the complete time period examined.

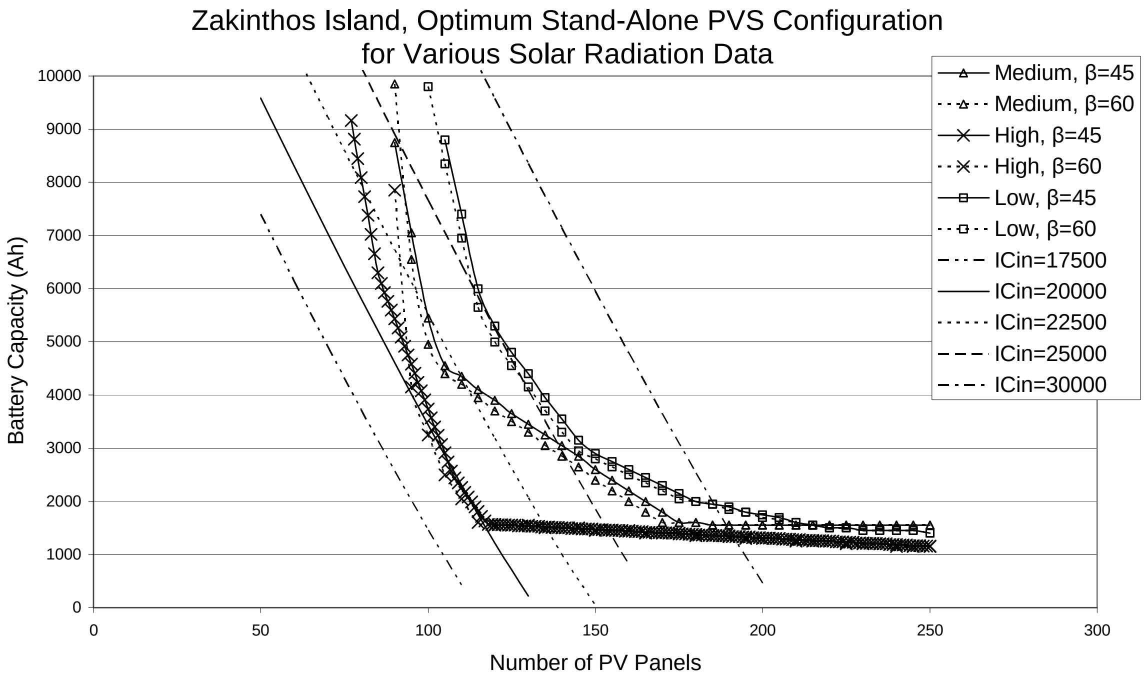

Figure 6: Comparison of Optimum PVS Configurations for Representative Solar Potential Years, Zakinthos Island

In an attempt to clarify the impact of the acceptable reliability on the stand-alone system size main parameters (i.e. "z" and "Q_{max}") the "PHOTOV-III" algorithm is applied for the high and the low quality solar potential year (β=60°), accepting zero, nine (9), forty four (44), eighty eight (88), one hundred and seventy six (176) or four hundred forty (440) load rejections per annum. More precisely, the corresponding "LLP" values are 0, 0.001, 0.005, 0.01, 0.02, and 0.05 respectively, while the equivalent reliability values are 100%, 99.9%, 99.5%, 99%, 98% and 95%.

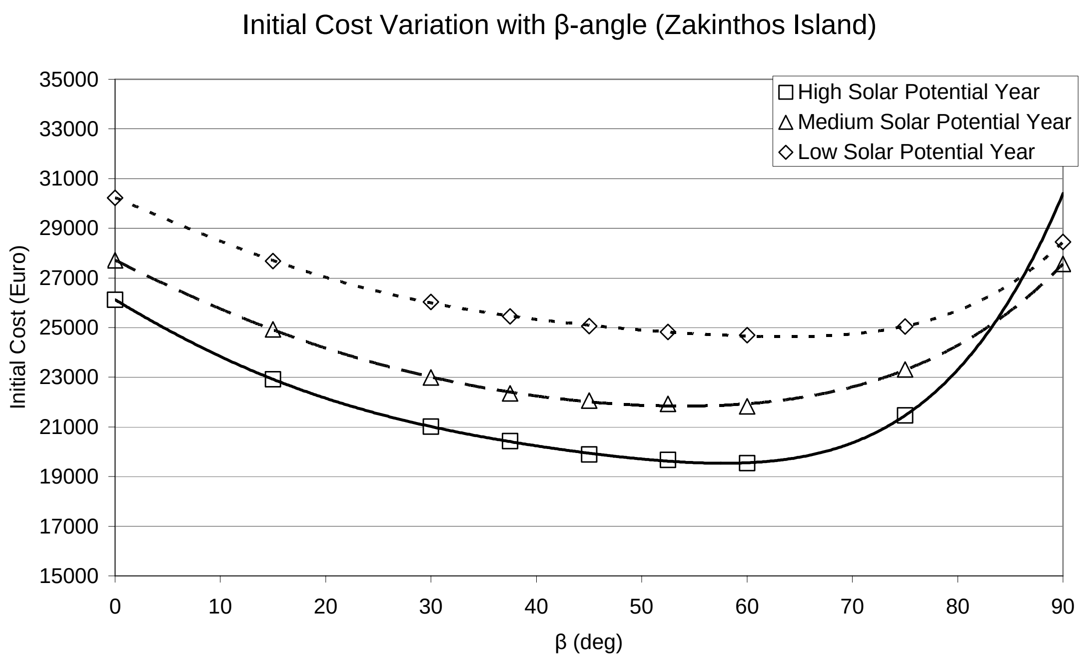

Figure 7: Comparison Between the Initial Cost (State Subsidization Included) of a PVS

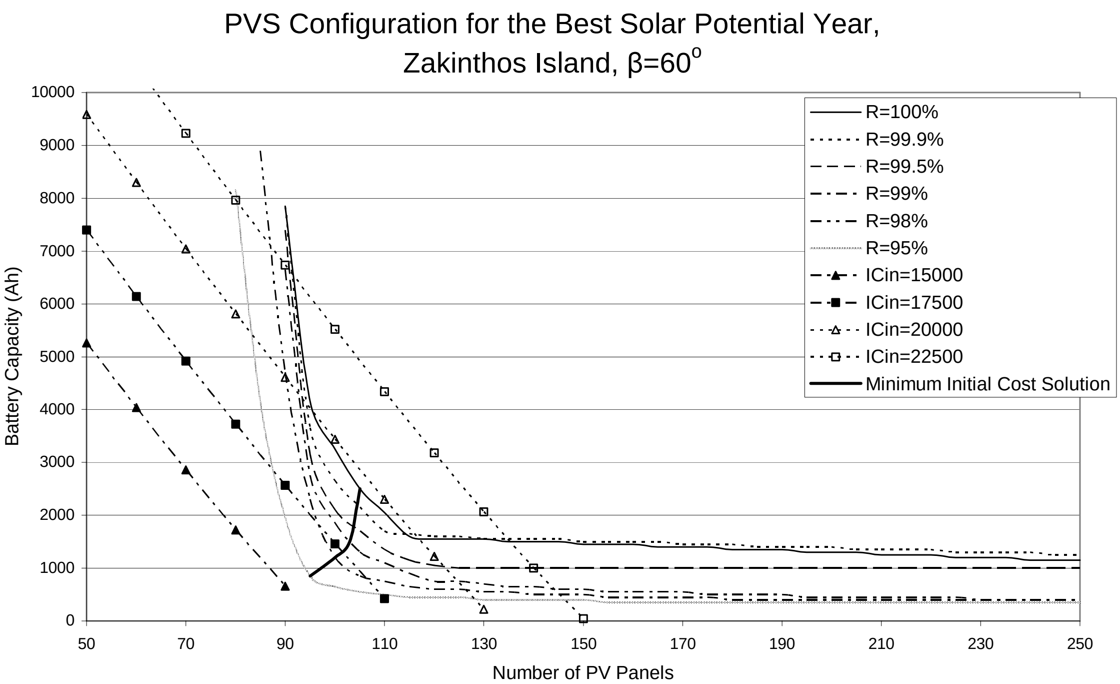

Figure 8: The Relation between the Configuration of a Stand-Alone PVS and the Initial Cost (*50% Subsidization Included*), for variable Reliability Values; Zakinthos Island

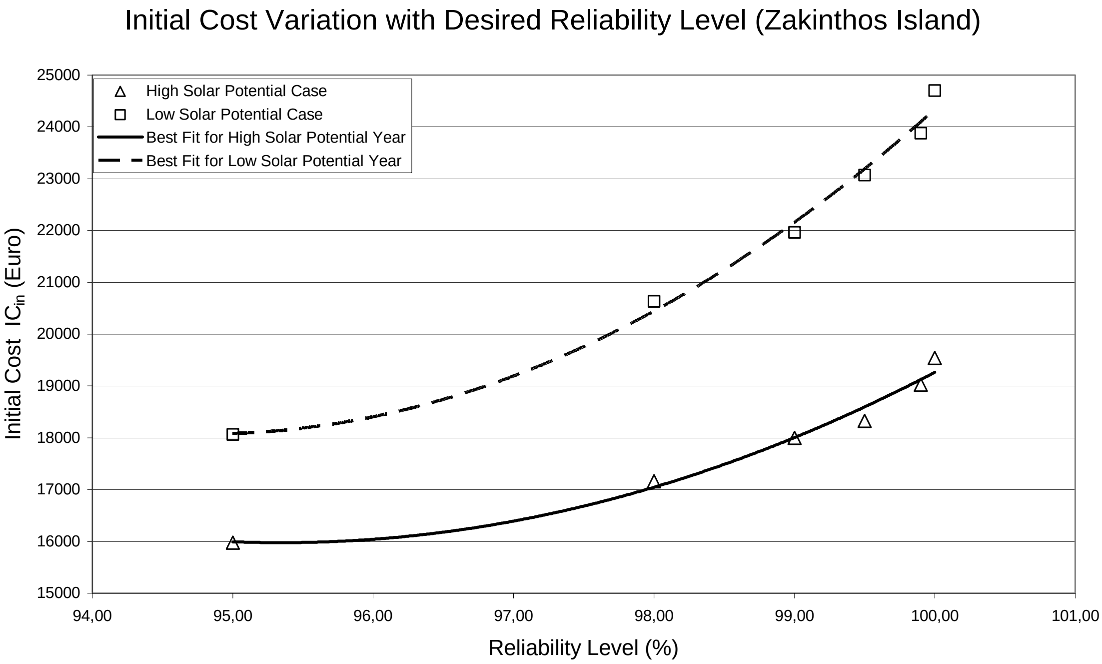

Figure 9: The Impact of Desired Reliability on the Initial Cost of a PVS

Consequently, the proposed system configuration combinations that guarantee the desired system reliability are presented in figure (8), along with the corresponding constant "IC_{IN}" curves for the high solar potential year investigated. On top of that, the minimum initial cost points are predicted and represented in the same figure by the "minimum IC_{IN} solution" curve. As it is obvious from these results, a remarkable battery size diminution is encountered up to R=99%, since the corresponding optimum "Q_{max}" value tends to 1300Ah, in comparison with the almost 2500Ah for the zero-load rejection case. For lower reliability level cases, the PV panel number is slightly decreased in

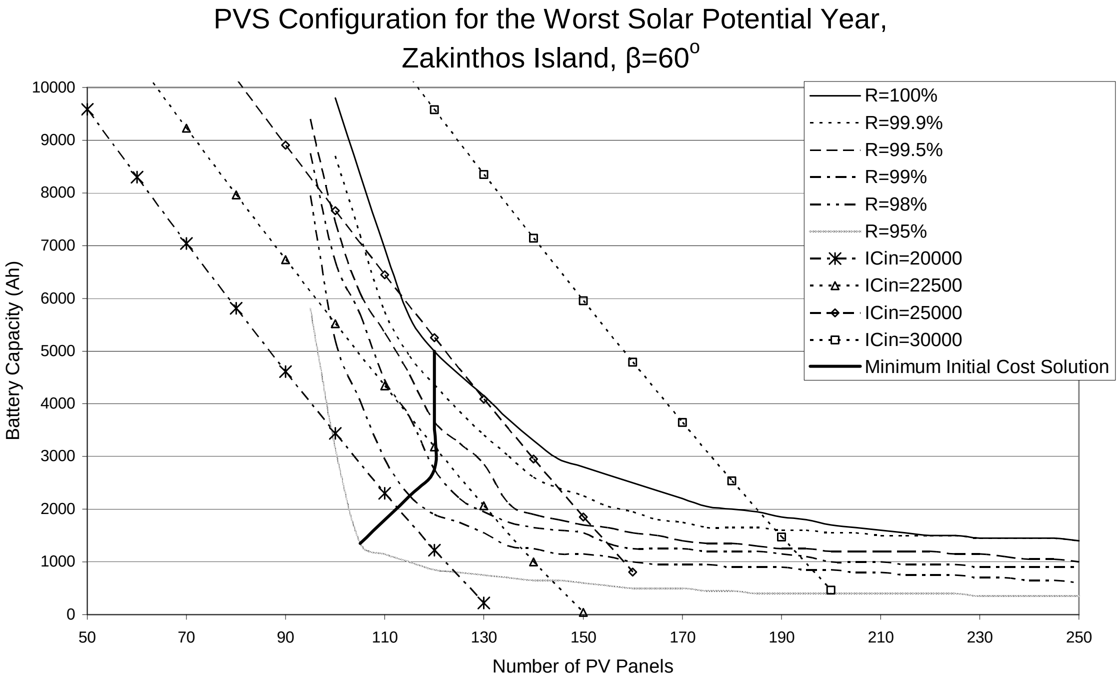

Figure 10: The Relation between the Configuration of a Stand-Alone PVS and the Initial Cost (*50% Subsidization Included*), for variable Reliability Values; Zakinthos Island

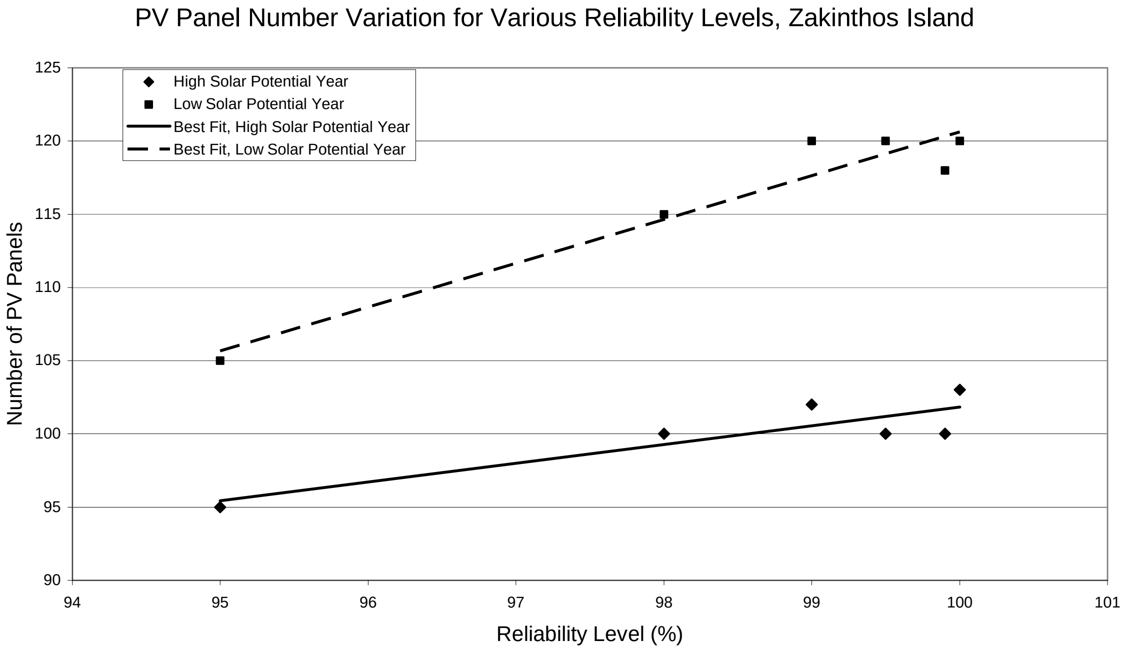

Figure 11: The Impact of Desired Reliability Level on the PV Panel Number Requested

combination with a remarkable battery capacity diminution. Similarly, the minimum cost solution is decreased -figure (9)- from 39000Euro (5.4kW, 2500Ah-no load rejection case) to 36000Euro (5.4kW, 1300Ah) for 99% reliability and to 32000Euro (4.8kW, 850Ah) for 95% reliability.

Subsequently, a low solar potential year is investigated using the above-described method. The calculation results are given in figure (10), along with the corresponding constant initial cost and the "minimum IC_{IN}" curves. In this specific case, the influence of a permitted small number (i.e. 10 or 90) of load rejections is more pronounced than the previous case on the corresponding (z-Q_{max}) curve.

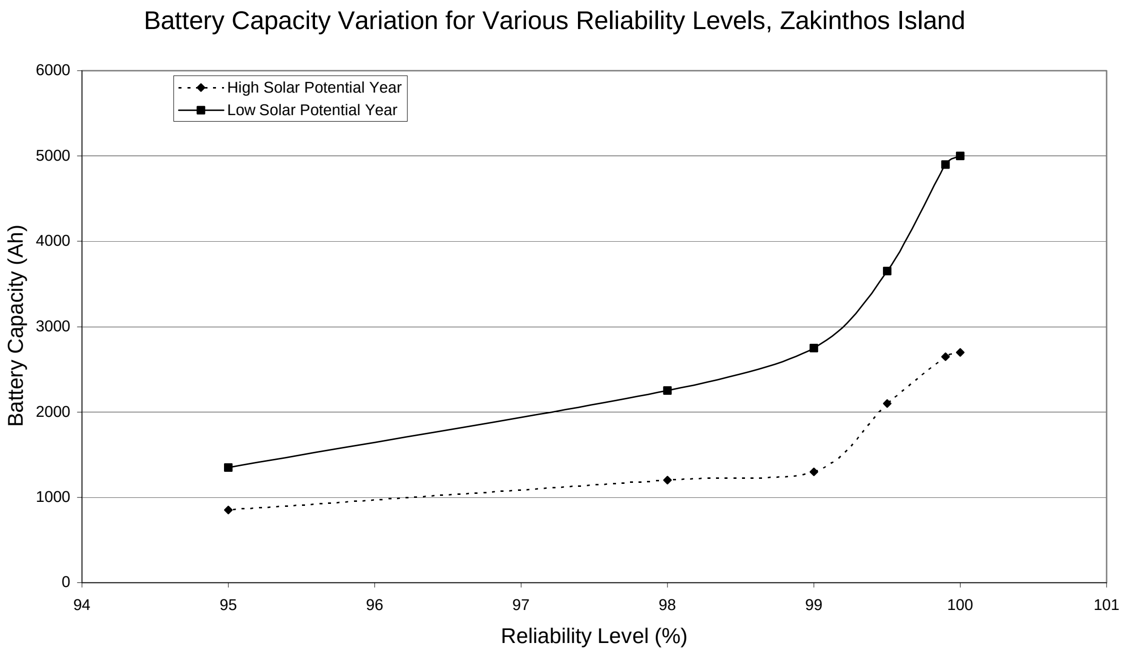

Figure 12: The Impact of Desired Reliability Level on the Battery Bank Capacity of a PVS

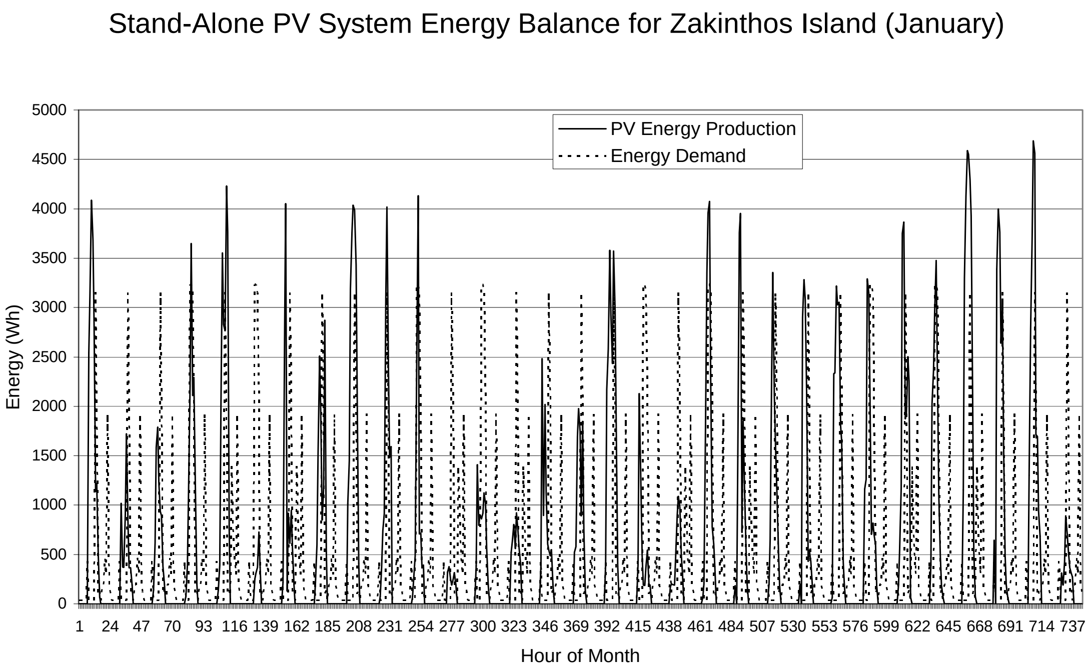

Figure 13: Energy Balance of a Stand-Alone PVS during January at Zakinthos Island

Thus, by increasing the number of acceptable load rejections of the stand-alone system, a remarkable (≈50%) diminution of the battery capacity required takes place. For lower reliability level values, a significant reduction of the stand-alone system photovoltaic panel number is observed, i.e. from 120 to 95, along with a remarkable battery capacity decrease. At the same time, the minimum initial cost solutions -figure (9)- show considerable cost diminution, since by accepting R=99% instead of the no-load rejection solution, the reduction on the system first installation cost is approximately 4500€ (or ≈10%).

Recapitulating, the replacement of the zero load rejection constraint by a 99% system-reliability-value mainly influences, figures (11) and (12), the stand-alone PVS battery capacity, while the corresponding PV panel number is slightly decreased. On the other hand, for lower reliability values (up to 95%) there is a linear PV panel diminution, accompanied by a similar battery capacity decrease. Besides, the battery capacity value modification is more important in years of low solar potential than in high solar potential ones.

6. Energy Balance of a Stand-Alone PVS

As already stated, one of the main targets of the present study is to extensively analyse the energy balance of the proposed autonomous PVS for the complete time period investigated. To get a representative picture of the proposed system behaviour, figure (13) presents a typical winter month (January) energy balance profile for the medium solar potential year, resulting from the operation of the minimum initial cost configuration under the no-load rejection restriction.

To get a clearer picture, the autonomous PVS worst week energy balance is given in figure (14), along with the corresponding battery bank "DOD" values. Using the available solar radiation measurements, a two-days low energy production is encountered, leading to a significant battery "DOD" increase. Generally speaking, the battery bank charge condition is quite low for the entire week, achieving "DOD" values of the order of 65%.

Accordingly, the photovoltaic system energy balance is evaluated -figure (15)- for two different reliability values (R=100% and R=95%) on a monthly basis. Keep in mind that the R=100% solution is based on z=120 PV panels, while the R=95% configuration uses only 105 panels, Table I. Thus, using the calculation results, the maximum energy surplus appears during spring and autumn, since during summer the remote system energy consumption is remarkably increased to cover the air conditioning loads. Another interesting conclusion drawn is that there is a remarkable system components-related energy-loss (i.e. DC/AC inverter, battery charge controller etc.), which represents the 12% to 14% of the system total energy production, see figures (16) and (17). Besides, for the R=95% case the photovoltaic system energy production cannot completely satisfy the remote

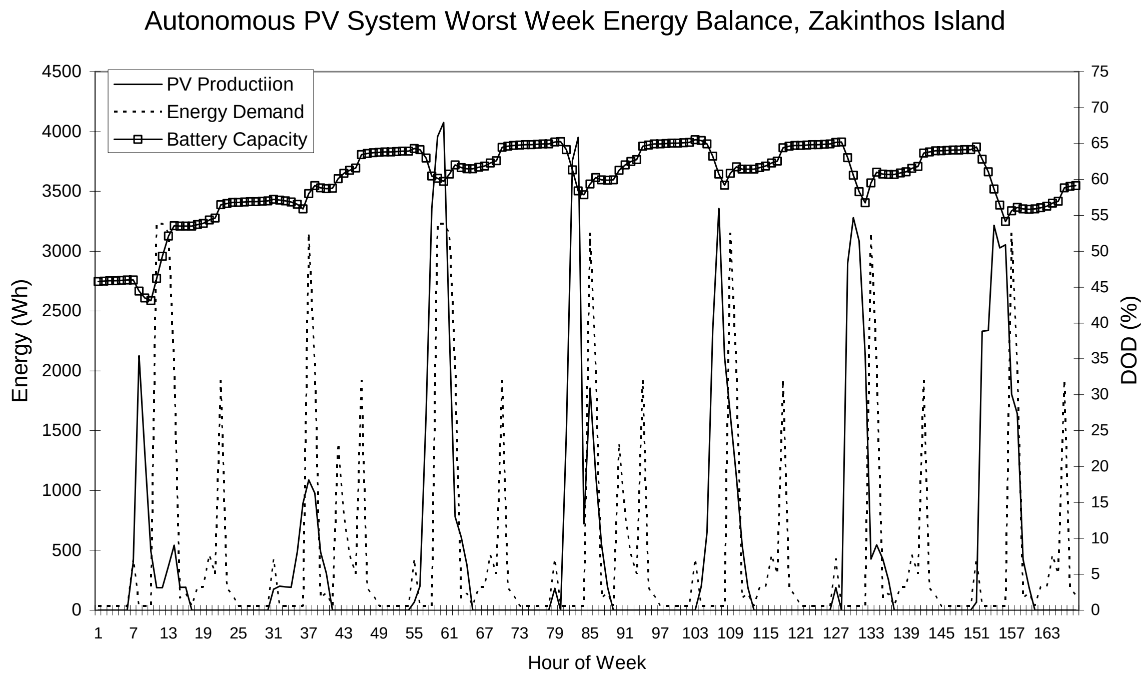

Figure 14: Energy Balance and Battery Status of a Stand-Alone PVS during the Worst Week of a Typical Solar Potential Year, Zakinthos Island

consumer energy demand (i.e. for January) or can hardly cover the system load (e.g. December). On the other hand, the system energy surplus is definitely less than the R=100% configuration.

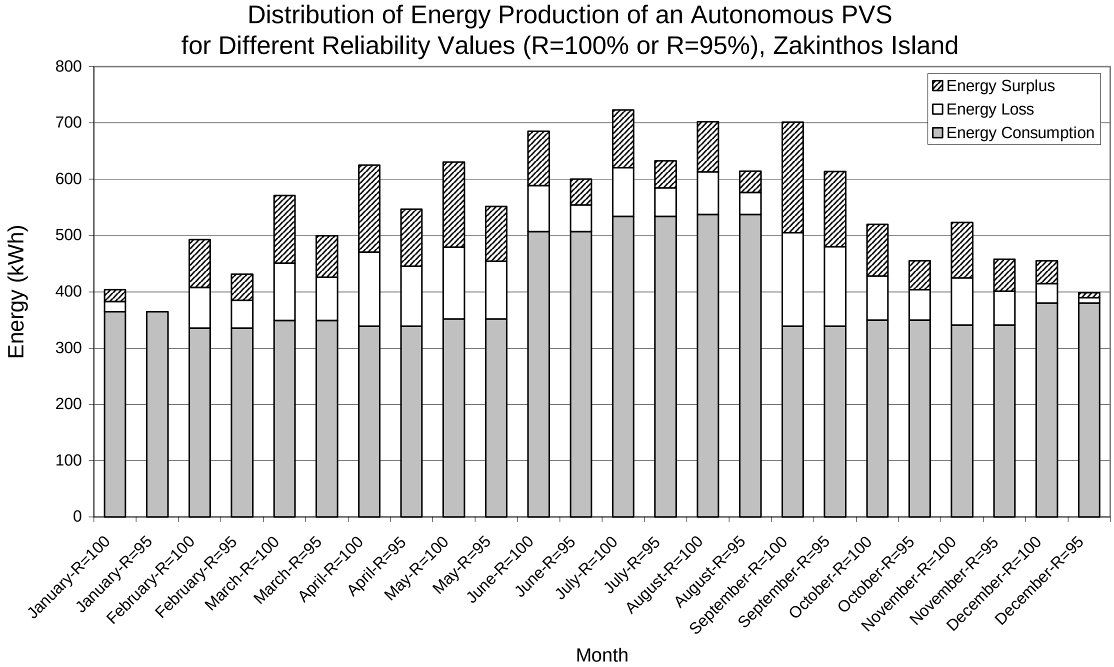

Figure 15: Energy Production Analysis of a Stand-Alone PVS at Zakinthos Island

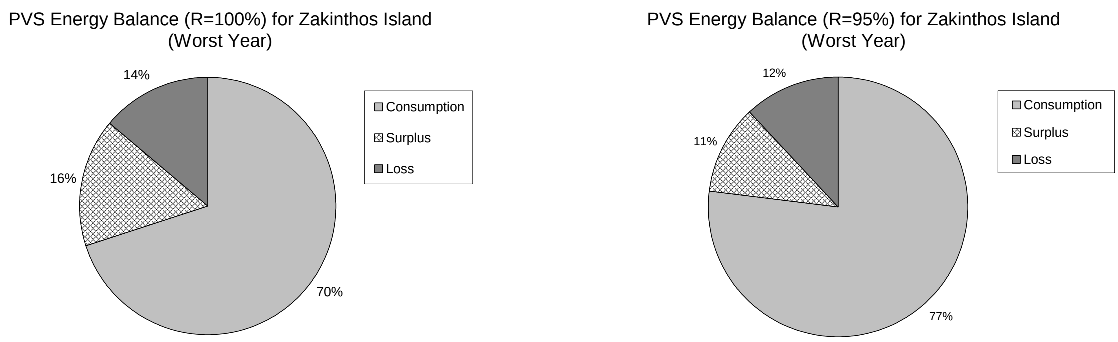

Figure 16: Annual Energy Balance of a Stand-Alone PVS at Zakinthos Isl for Variable Reliability Levels

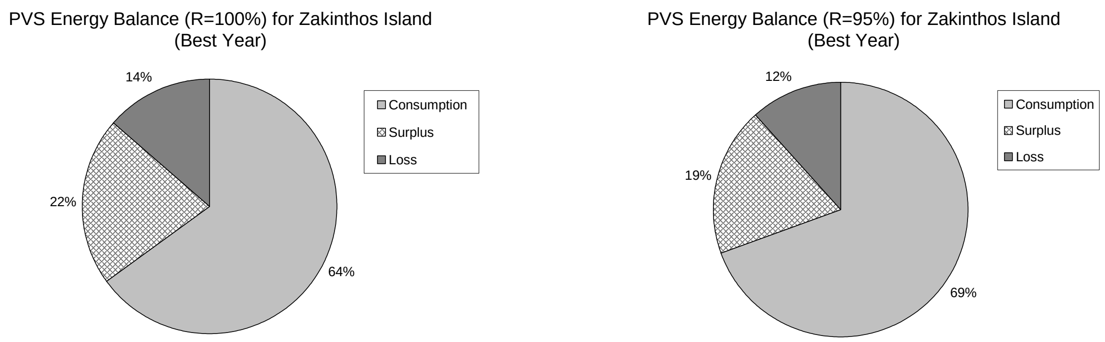

Figure 17: Annual Energy Balance of a Stand-Alone PVS at Zakinthos Isl for Variable Reliability Levels

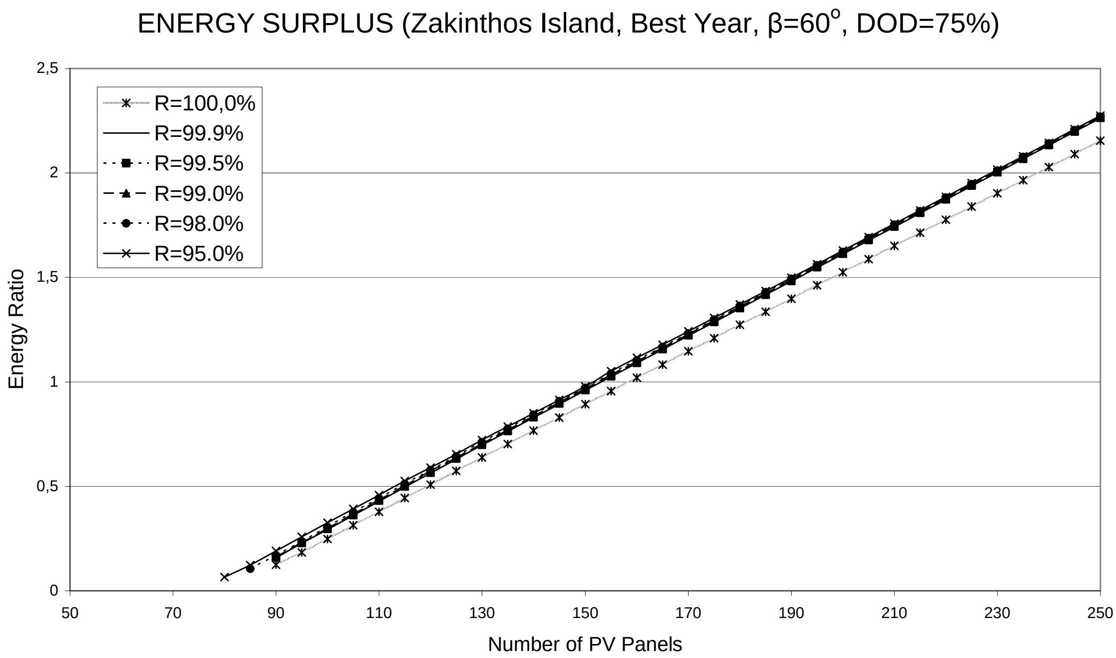

Figure 18: Energy Surplus (*expressed as a function of annual energy consumption*) versus Panel Number, of a Stand-Alone PVS for Variable Reliability Levels

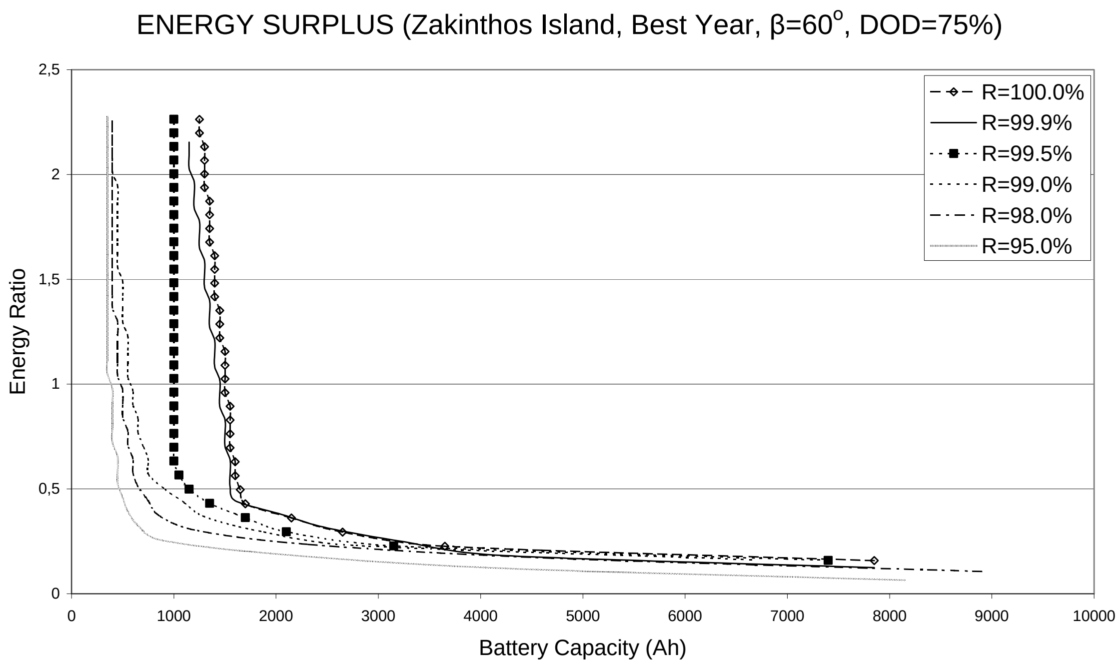

Figure 19: Energy Surplus (*expressed as a function of annual energy consumption*) versus Battery Bank Capacity, of a Stand-Alone PVS for Variable Reliability Levels

This conclusion is clearly supported by inspecting figures (16) and (17), where the minimum initial cost photovoltaic system annual energy balance is demonstrated for R=100% and R=95%, for the "worst" and for the "best" solar potential year respectively. Thus, the system energy surplus is 16% for R=100% and low solar potential year, dropping to 11% for R=95%. On the other side, an almost 22%

energy surplus is predicted for R=100% and high solar potential year, which is decreased to 19% for the R=95% solution.

Using the results of the present study, one may state that the photovoltaic system energy surplus is linearly increased with the PV panel number used, figure (18), while the minimum energy surplus is realized for the R=100% configuration, for the same "z" value. On the contrary, there is a significant energy surplus decrease as the photovoltaic system battery capacity is slightly increased, figure (19). This battery capacity increase mainly depends on the desired reliability level. After this rapid decrease region, the energy surplus is fairly influenced by the battery bank size, being however linearly decreased.

7. Conclusions

The optimum configuration of a stand-alone photovoltaic system is defined for a typical Greek island, using extensive solar potential data. The results obtained are based on experimental long-term measurements and operational characteristics by the proposed system components manufacturers. According to the results presented, there is a remarkable system size and initial cost discrepancy between the best and the worst solar potential year, strongly questioning pure theoretical models used to simulate the operational behaviour of PVS.

Subsequently, the desired PVS reliability level considerably affects the necessary system battery capacity, especially up to R=99%. For lower reliability values the battery capacity decrease is milder. At the same point, there is an almost linear PV panel diminution as the acceptably system reliability decreases from 100% to 95%. Recapitulating, a remarkable initial cost diminution is encountered as system reliability value drops from 100% to 95%.

Finally, an extensive energy balance analysis is carried out for several stand-alone PVS configurations. Detailed results on an hourly, monthly and annual basis are demonstrated, for variable system reliability levels and representative solar potential time-series. According to the results obtained, the 2/3 of the photovoltaic generator production is finally transferred to the consumption, while 12% to 14% is the system components energy loss.

Consequently, the energy balance behaviour of a stand-alone photovoltaic system applied at a representative remote consumer case for a long time period, along with its high reliability and low maintenance competitive advantage -in comparison with other available alternatives- outline the proposed solution as a motivating prospect for the energy demand problems of numerous existing isolated consumers. On top of that, using the above-described methodology, one has the opportunity to select the desired stand-alone photovoltaic system long-term reliability level, appreciating at the same time the necessary capital to be invested.

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PARAMETRIC INVESTIGATION CONCERNING DIMENSIONS OF A STAND-ALONE WIND POWER SYSTEM

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Abstract

A detailed parametrical analysis is carried out concerning the optimum sizing of a stand-alone wind power system, used to ensure the electricity supply of several remote consumers. This study initially analyzes the impact of the available wind potential quality on the dimensions of the main system components. Accordingly, the influence of the specific wind power curve -utilized on the proposed configuration sizing- is also examined. In addition, the system minimum acceptable reliability contribution is investigated on determining the minimum cost stand-alone system dimensions. Finally, the consumer size effect is taken into consideration during the best choice selection process. Thus, by incorporating the proposed parametrical analysis results in an appropriate decision taking procedure, a significant reduction of the system dimensions may be realized, leading to a remarkably diminished first installation cost.

Keywords: Wind Power; Optimum Sizing; Stand-Alone; Wind Potential

1. Introduction

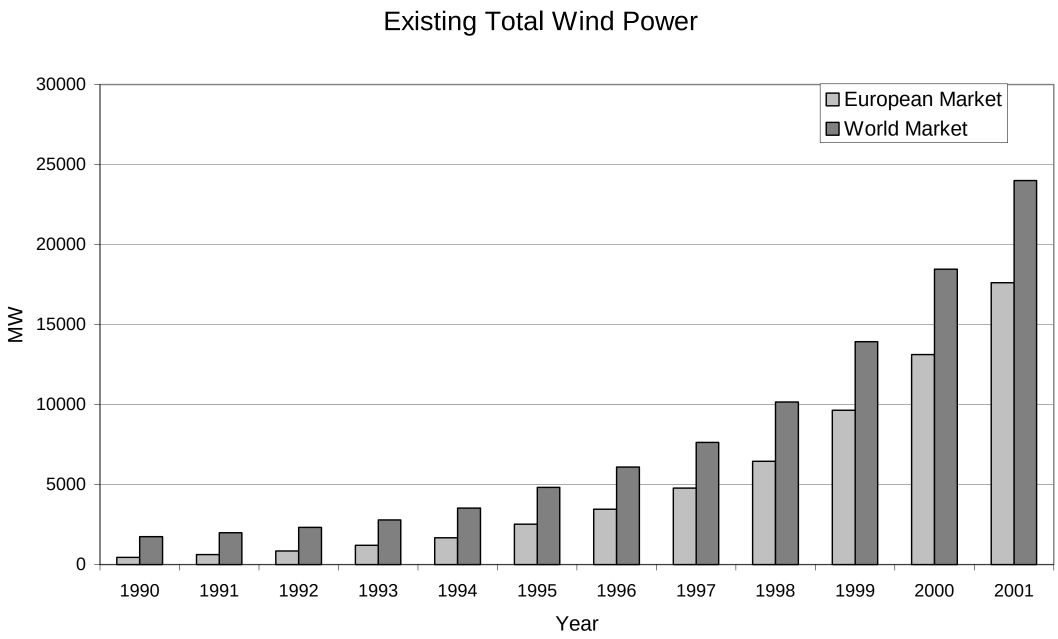

Figure 1: Wind power time evolution in Europe

During the last ten years, an astonishing increase of wind energy contribution on the European electrification sector has been encountered[1], mainly based on the approximately 40,000 medium and large-sized wind turbines installed all over Europe, figure (1). On the other hand, small-micro (less than 15kW) wind converters are also instrumental in providing electricity (figure (2)) to the isolated consumers. As a matter of fact, small wind turbines are able to produce only a few MWh per year.

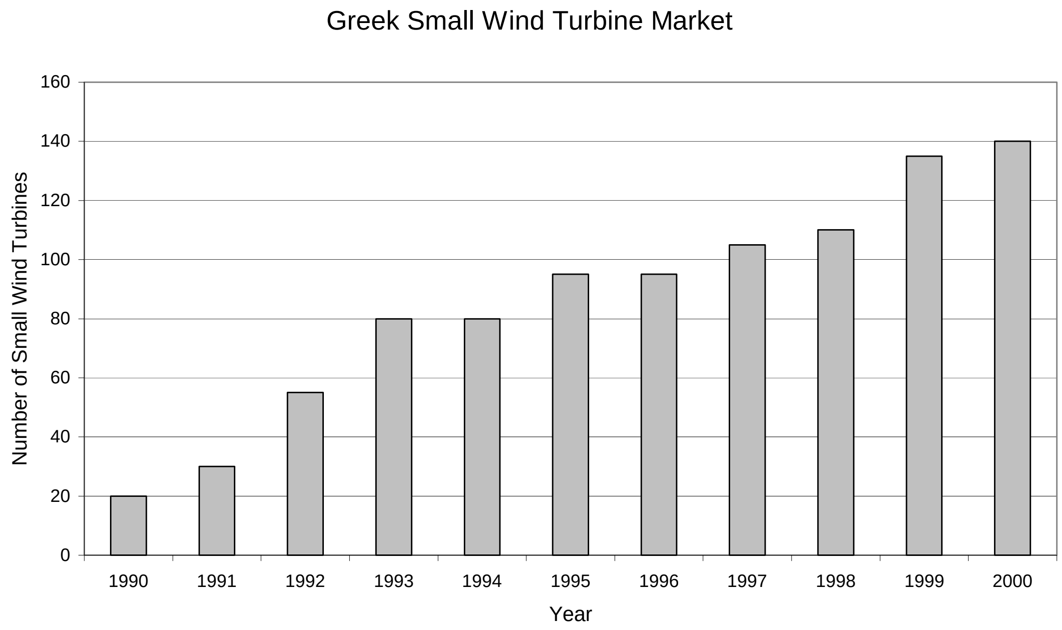

Figure 2: Small wind turbines annual sales in Greece

Figure 3: Wind potential map for Aegean Sea area at 30m height

However, even this limited -in absolute terms- contribution does make a big difference in upgrading standards of living in the remotest parts of the planet.

More precisely, according to rough estimates[2] a significant number (≈500,000) of isolated consumers are spread all over Europe, including country houses, inaccessible farms, shelters, telecommunication stations, small islands, light houses etc. Additionally, a remarkable number (≈50,000) of remote consumers can be found[3][4] throughout the Aegean Archipelago region, a remote Hellenic area possessing[5] an outstanding wind potential, figure (3). Unfortunately, the absence of electrical network in their major area or the prohibitively high connection cost -due to large distances and peculiar topography- force these remote consumers to use small diesel-electric generators in an attempt to hardly cover their urgent electrification needs.

An interesting solution to similar electrification problems, based on a stand-alone wind power system, has recently been proposed[6][7] providing energy autonomy to remote consumers, especially in medium-high wind potential locations. In previous works, the optimum size of such a stand-alone system has already been defined for a specific Aegean Sea island, by using a properly developed[6] numerical code (WINDREMOTE-II) able to elaborate the presented[5] long-term wind speed and meteorological data of the investigated area.

In the present study, an integrated parametrical analysis is carried out in order to investigate the impact of several important factors on the optimum size of the proposed isolated system, such as the wind potential quality, the power curve type of the wind turbine used, the remote consumer's size, along with the minimum acceptable system reliability. The results obtained may guide all consumers interested in deciding the appropriate solution to their electrification problem, according to the specific characteristics of their installation.

2. Proposed Solution

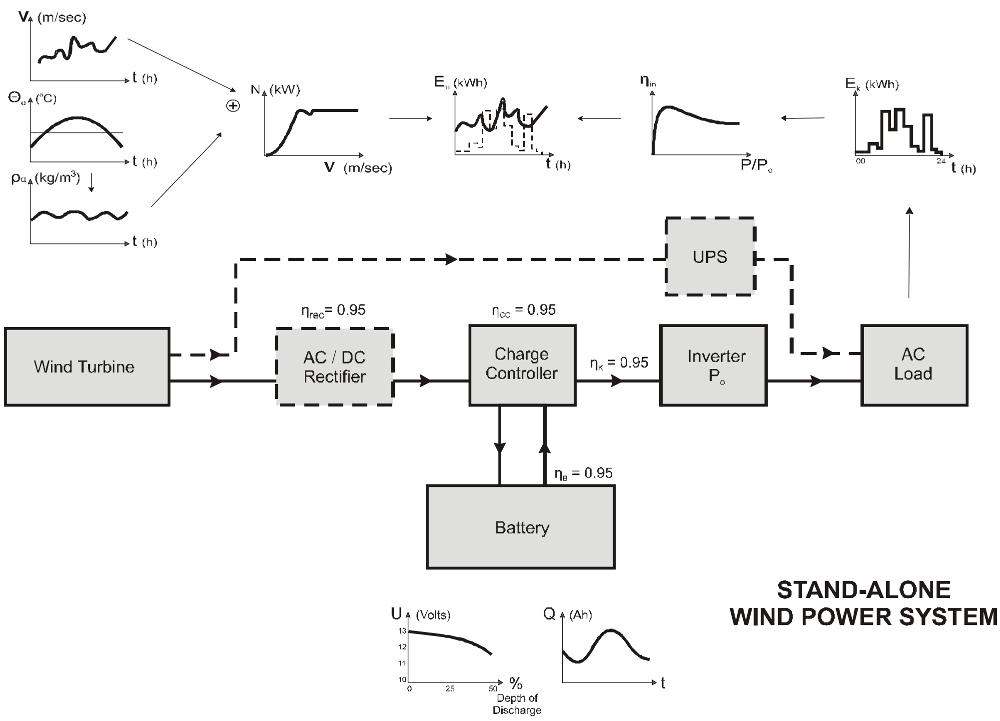

Figure 4: Proposed stand-alone wind power system

The proposed by the authors[6][7] stand-alone system (figure (4)) comprises a small wind converter of rated power "N_o" (i.e. $N_o \leq 20kW$) feeding -via a UPS of similar nominal power- the AC load of the system. In case that the electricity demand is inferior to the corresponding wind turbine production, the energy surplus is first rectified from AC to DC and then stored to a battery row (maximum capacity "Q_{max}", maximum depth of discharge "DOD_L" and operation voltage "U") via a battery charge controller. Finally, in cases that the wind energy production cannot fulfill the load demand, a DC/AC inverter is used to transform the battery output in order to meet the system electrical requirements.

Summarizing, the proposed stand-alone wind power system is based on:

i. A small wind converter of "N_o" kW and specific power curve "N=N(V)" for standard day conditions

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"

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"

v. A UPS of "N_p" kW, frequency of 50Hz, autonomy time "δt=2-5min" and operational voltage 220/380Volt

vi. A DC/AC inverter of "N_p" kW, frequency of 50Hz and operational voltage 220/380Volt

The main system dimensions (i.e. wind turbine rated power "N_o" and battery size "Q_{max}") are defined using the WINDREMOTE-II algorithm developed by the authors[6][7], while the inverter maximum power is directly related to the consumption peak load demand "N_p"[8].

More precisely, for every region analyzed during a given time period "Δt" (e.g. one year) specific initial "N_o" and "Q_{max}" values (i.e. "N_{init}" and "Q_{init}") are selected[7], with:

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

where "E_{tot}" is the system annual electricity consumption (increased by 20% to include future changes) and "CF" the capacity factor[9] of the installation.

Accordingly, "Q_{init}" is given as:

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

depending on the minimum acceptable hours of energy autonomy of the system "h_{min}". Keep in mind that "η_s" is the efficiency of the storage branch, used to feed the consumption (including inverter efficiency and power line loss). Accordingly, for every time point of the year the energy consumption is compared with the corresponding wind energy production, resulting by the available wind potential, the air density and the wind turbine power curve.

In cases of energy deficit, the battery storage system is assumed responsible to cover the additional energy demand via the inverter. If the battery is near the upper "DOD" limit, the no-load rejection condition is to be violated, thus the battery capacity should be increased by a specific "ΔQ" value, while the complete calculation restarts from the beginning of the year.

After the integration of the calculation, a (N_o-Q_{max}) curve has been predicted. For each pair of (N_o-Q_{max}) values belonging to this curve, the energy autonomy of the remote system is ensured for the entire time period (e.g. one year) investigated.

Finally, the optimum (N^*_o-Q^*_{max}) values are predicted according to a first installation cost analysis[10], also using the initial cost "IC_o" function developed by he authors, i.e.:

$$IC_o = \left(\frac{a}{b + N_o^x} + c\right) \cdot N_o * (1 + f) + c_b(Q_{max}) * Q_{max} + A(N_p) + B * N_o \tag{3}$$

where the first RHS term of equation (3) describes the wind turbine exworks price and the balance of the plant cost[11], the second term represents the battery system initial cost, while the last two terms depend on the rest electronic equipment purchase price, being a function of the system peak load demand "N_p" (e.g. inverter) and the wind turbine rated power "N_o" (e.g. rectifier, charge controller). The numerical values of all variables in equation (3) are summarized in Table I.

Table I: Proposed Values for the First Installation Cost Parameters of equation (3)

	Variable	Range	Proposed Value	Comments
a	Wind Turbine Cost Coefficient		$8.7x10^5$	$N_o \leq 100kW$
b	Wind Turbine Cost Coefficient		621	$N_o \leq 100kW$
c	Wind Turbine Cost Asymptotic Value	600-900Euro/kW	700	$N_o \leq 100kW$
x	Wind Turbine Cost Exponent	1.95-2.1	2.05	$N_o \leq 100kW$
f	First Installation Cost Coefficient	0.15-0.45	0.15	$N_o \leq 30kW$
B	Electronic Equipment Cost Coefficient	350-400Euro/kW	380Euro/kW	$3kW \leq N_o \leq 50kW$
c_b	Battery Purchase Cost Coefficient	$c_b = 5.0377 / Q_{max}^{0.0784}$		$5000Ah \leq Q_{max} \leq 100000Ah$
A	Electronic Equipment Cost Coefficient	$A = 483.57 \cdot N_p^{0.917}$		$5kW \leq N_p \leq 50kW$

3. Wind Potential Impact on System Sizing

The existing wind potential quality in one candidate region is one of the most important parameters defining the main dimensions of similar stand-alone wind power installations. More precisely, in figure (5) the well-known[12] Weibull wind potential parameters (i.e. "C" is the wind speed normalizing factor and "k" is the corresponding shape factor) are presented for several regions analyzed and for three different years of operation. According to figure (5) data, Andros island (presented with points A-1, A-2 and A-3) undoubtedly possesses the best wind potential of the cases analyzed, while the Kea island (points Ke-1, Ke-2 and Ke-3) presents the lowest annual mean wind speed values "$\overline{V}$", considering that "$\overline{V}$"≈0.9C[13]. In the same figure, the wind potential data for Kithnos (i.e. K-1, K-2 and K-3) and Naxos (i.e. N-1, N-2 and N-3) islands are also included.

Subsequently, in figure (6) the no-load rejection curves (N_o-Q_{max}) are summarized for all cases investigated, i.e. four (4) separate areas are examined for three (3) successive years. Bear in mind that every combination on each of those (N_o-Q_{max}) curves guarantees one year's energy autonomy for the investigated region. Accordingly, by using equation (3) and Table I, the minimum initial cost point - represented by the symbol "•"- is estimated for every curve presented. These specific (N_o^*-Q_{max}^*) combinations not only guarantee energy autonomy for an entire year, but get it accomplished with the minimum possible initial cost.

Representing in figure (7) the optimum battery capacity values "Q_{max}^*" as a function of the mean wind speed value of the regions investigated "C" or "$\overline{V}$", one may state that the quality of the available wind potential strongly influences the optimum battery size. More specifically, the battery capacity is remarkably increased as "C" values are decreased. This general tendency is also statistically validated (figure (7)), since the corresponding "R^2" coefficient approaches the 75%. A parallel attempt is made to similarly relate the wind turbine size "N_o" and the mean wind speed value "C" (or "$\overline{V}$"). Unfortunately, such an analytical correlation is not statistically validated with the required confidence, since $R^2 \leq 50\%$.

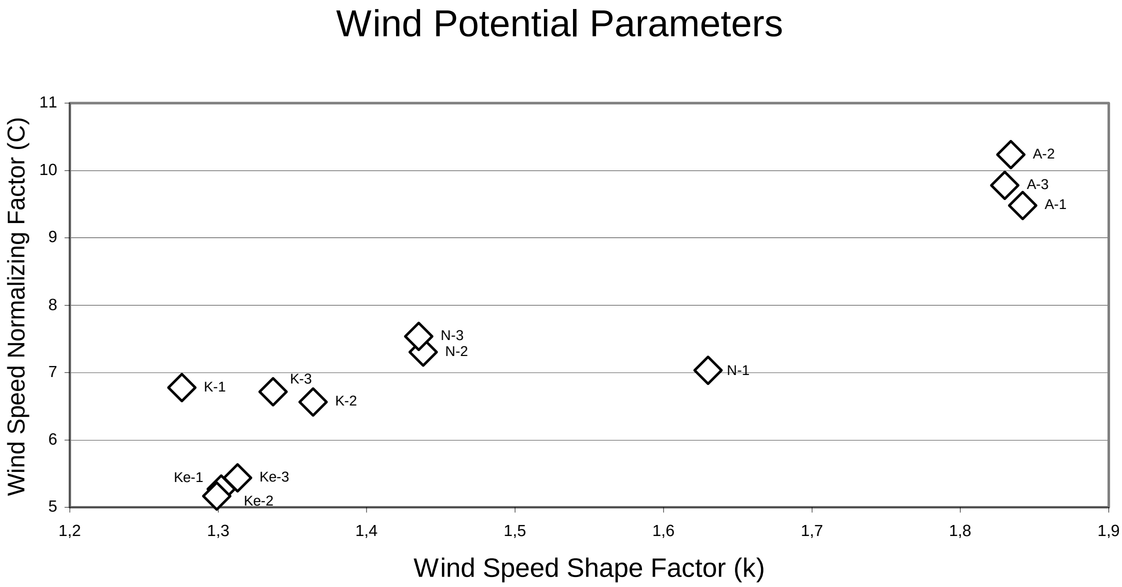

Figure 5: Wind potential variables (c, k) values of the areas analyzed

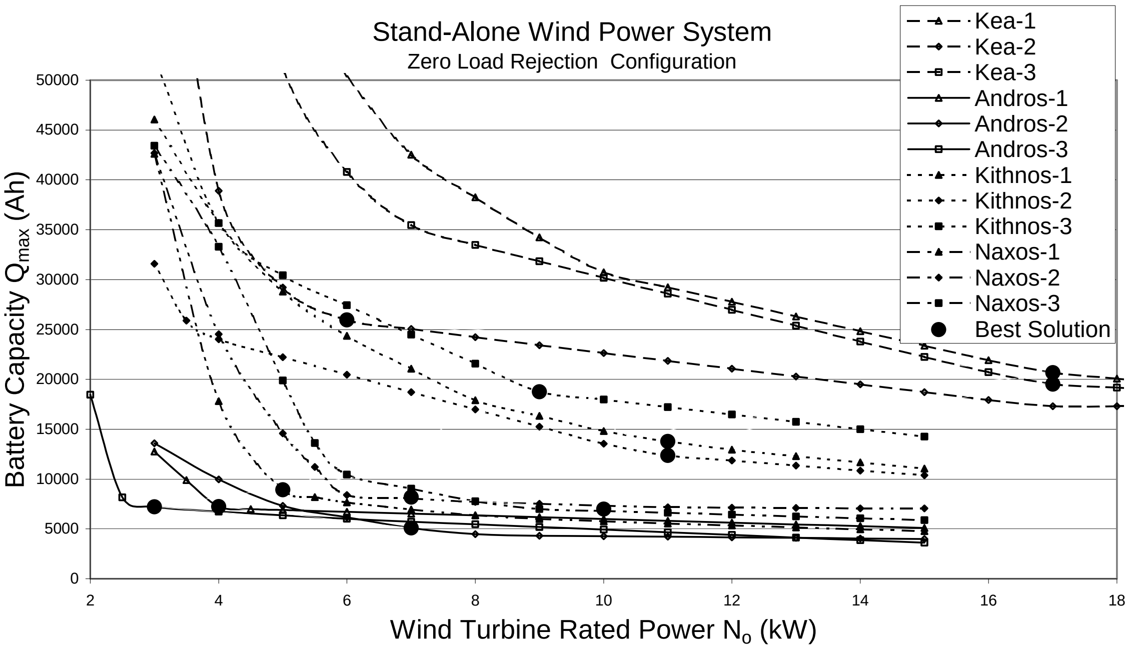

Figure 6: Wind potential impact on a stand-alone wind power system sizing

In this context and after analyzing the results of figure (6) in view of the data of figure (5), one may conclude that the wind speed shape factor "k" value does not seem to influence systematically the values neither of "Q_{max}" nor of "N_o", although both parameters decline as "k" value increases.

Recapitulating, as a general rule, the proposed stand-alone wind power system dimensions are significantly reduced as the quality of the available wind potential is ameliorated. Of course, such a systematic correlation is statistically validated, only for the battery size-mean annual wind speed relation. This undesirable result can be attributed either to the limited number of cases analyzed or to the fact that the ("C" and "k") parameters are not sufficient to accurately describe[14] the quality of the available wind potential of an area. Therefore, additional wind potential information should be

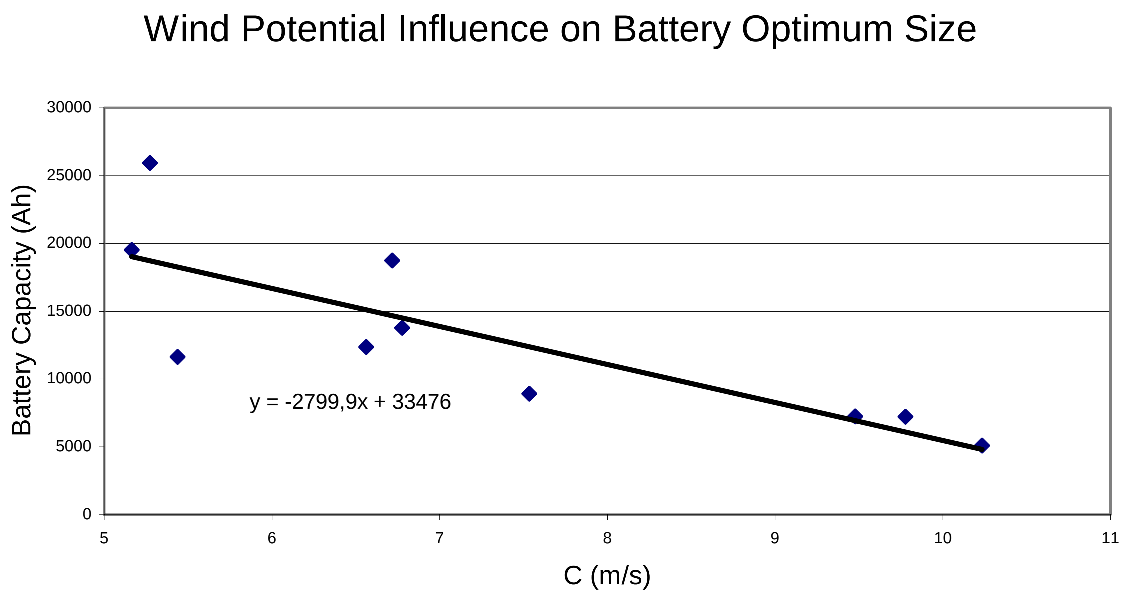

Figure 7: Wind potential influence on the battery optimum size of a stand-alone system

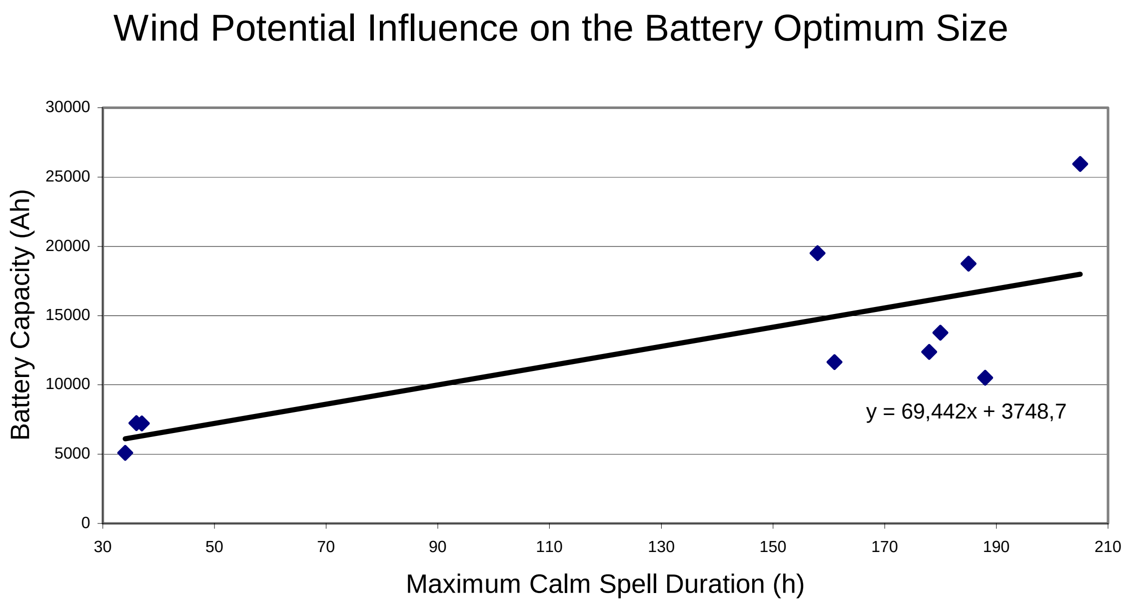

Figure 8: Maximum calm spell duration impact on the battery optimal size

included in the proposed analysis, regarding the maximum calm spell of each region for every year examined. Subsequently, an attempt is made to correlate the maximum calm spell duration "h_{max}" (in hours) to the optimum "Q_{max}" and "N_o" values predicted. According to the calculation results, no correlation between "N_o" and "h_{max}" exists, while on the other hand "Q_{max}" and "h_{max}" correlate with statistically acceptable quality, see also figure (8). As it is obvious from figure (8), the battery capacity of a stand-alone wind power system is significantly increased as the maximum calm spell duration of a region is amplified.

4. The Impact of Wind Turbine Power Curve on System Sizing

After an extensive survey[15][16][17] concerning the wind converters availability in European and international market, a remarkable number of machines have been found, covering the 3 to 20kW

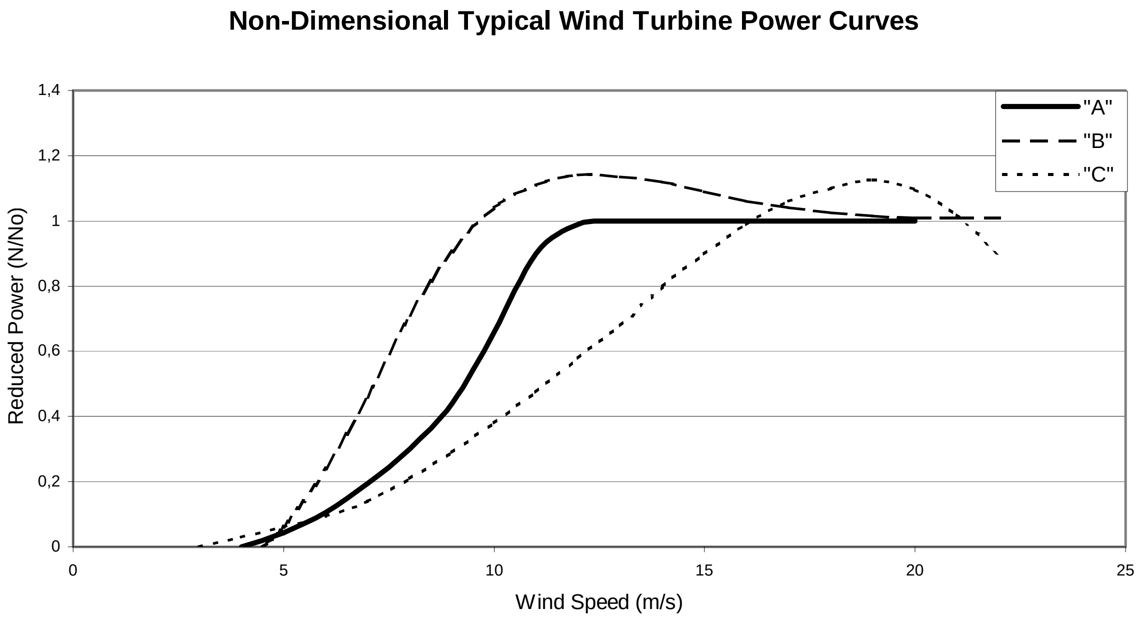

Figure 9: Reduced wind turbines power curve types used in the present analysis

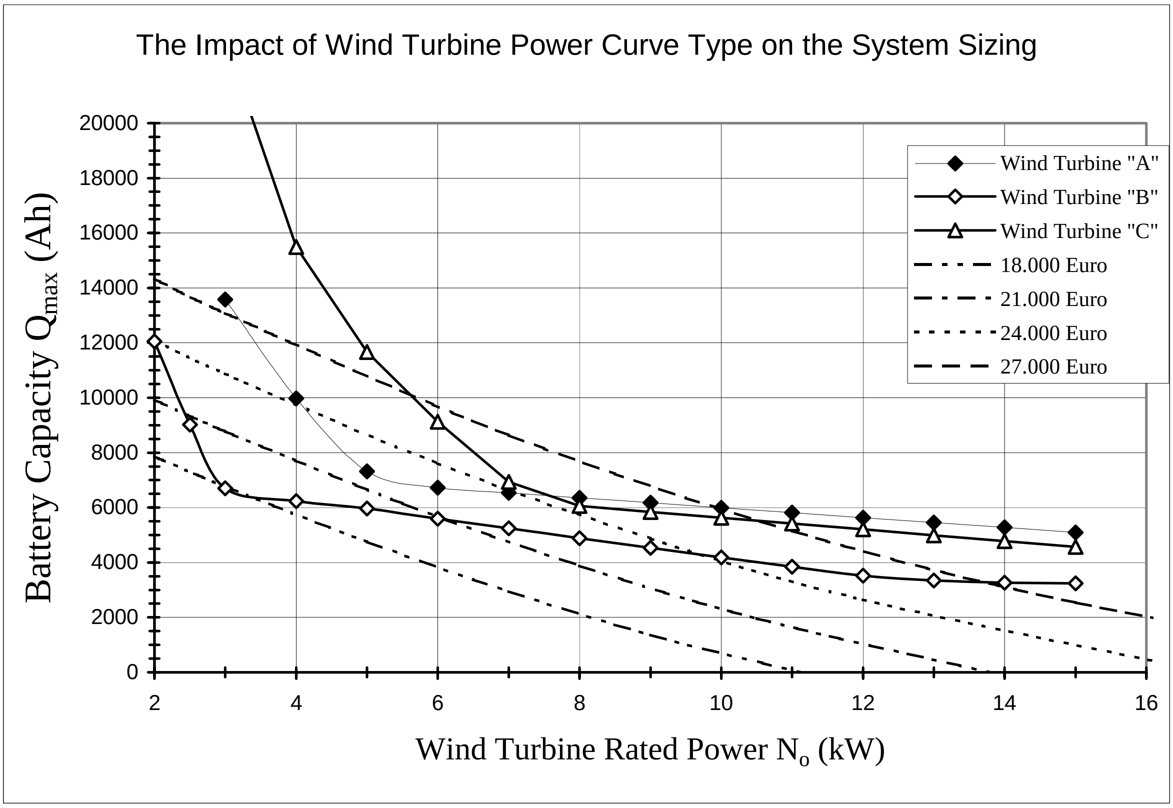

Figure 10: The impact of wind turbine power curve type on the stand-alone system sizing

power range. From technical data provided by their manufacturers, several types of power curves are observed. Heading towards the analysis independence from the wind turbine rated power, the reduced power values ("$N/N_o(V)$") versus wind speed "V" at hub height is used. Subsequently, three of the most representative wind turbine power curve types have been selected, figure (9), and accordingly used in order to investigate the impact of the power curve type on the stand-alone system dimensions. The manufacturers of these three wind turbines used give the same rated power (e.g. N_o=5kW).

Finally, in this comparative study, four-year wind potential data of Andros Island have been chosen for the application of "WINDREMOTE-II" algorithm.

Subsequently, the (N_o-Q_{max}) no-load rejection curves are summarized in figure (10), for the three power curve types tested. As it results from figure (10), the power curve "B" leads to the smallest battery capacity for all the nominal power range analyzed. On the other hand, the power curve "A" gives quite lower battery size than the power curve "C" for rated power values up to 7kW. Further to this value, the power curve "C" is combined with smaller batteries (than "A") so as to guarantee the no-load rejection operation of the system.

The above described results can be explained according to the wind turbines power curves distribution of figure (9), since the wind turbine "B" gives the highest output, especially for wind speed values up to 10m/sec, representing the majority of wind speed measurements in all areas investigated. Additionally, the wind turbine "A" generates an output higher than "C" for wind speed values almost up to 16m/s.

Finally, the optimum system size (3kW, 6700Ah, 17900€) using wind turbine "B" is quite lower than the one (5kW, 7300Ah, 22000€) resulting from the utilization of wind turbine "A", while the wind turbine "C" imposes quite large system dimensions (7kW, 6950Ah, 24500€). Thus, the system initial cost is remarkably reduced from wind turbine "C" to wind turbine "B". More precisely, considerable money savings result (≈6500€ or 25%) by adopting the wind turbine "B" instead of wind turbine "C", while wind turbine "A" also leads to almost 4000€ higher first installation cost compared to wind turbine "B".

Recapitulating, the influence of the wind turbine power curve type on the sizing of a stand-alone wind power system is of a great importance. Indeed, for the same site of implantation and same energy consumption profile, the fact of choosing a power curve identical to type "C" rather than type "B" leads to more than doubled nominal power values, although the battery capacity is not remarkably affected. Thus, during the size definition process of the proposed system, the wind turbine nominal power and the battery storage capacity are not sufficient to define the optimum system configuration, since the wind turbine power curve distribution strongly affects[18] the energy behaviour and the initial cost value of the system.

5. The Influence of System Reliability on the System Sizing

The reliability of a stand-alone energy production system is usually expressed either using the number of hourly load rejections[10] during a given time period (e.g. four year period) or in term of loss of load probability "LLP"[18]. Therefore the no-load rejection case or equivalently the LLP=0 value corresponds to a total energy autonomy of the system during the complete time period examined.

In an attempt to clarify the impact of the acceptable reliability on the stand-alone system size main parameters (i.e. "N_o" and "Q_{max}") the "WINDREMOTE-II" algorithm is applied for a high and a medium quality wind potential case, accepting zero, ten (10), fifty (50), one hundred (100), two hundred (200) or five hundred (500) load rejections per annum. More precisely, the corresponding "LLP" values are 0, 0.001, 0.005, 0.01, 0.02, and 0.05 respectively, while the equivalent reliability values are 100%, 99.9%, 99.5%, 99%, 98% and 95%.

Consequently, the proposed system configuration combinations that guarantee the desired system reliability are presented in figure (11), along with the corresponding constant "IC_o" curves for the high wind potential region investigated. On top of that, the minimum initial cost points are predicted and represented in the same figure by the "best points" curve. As it is obvious from these results, a remarkable battery size diminution is encountered up to 50 annual load rejections, since the corresponding optimum "Q_{max}" value tends to 2000Ah in comparison with the almost 4200Ah for the zero-load rejection case. For higher load rejection cases, a remarkable wind turbine rated power

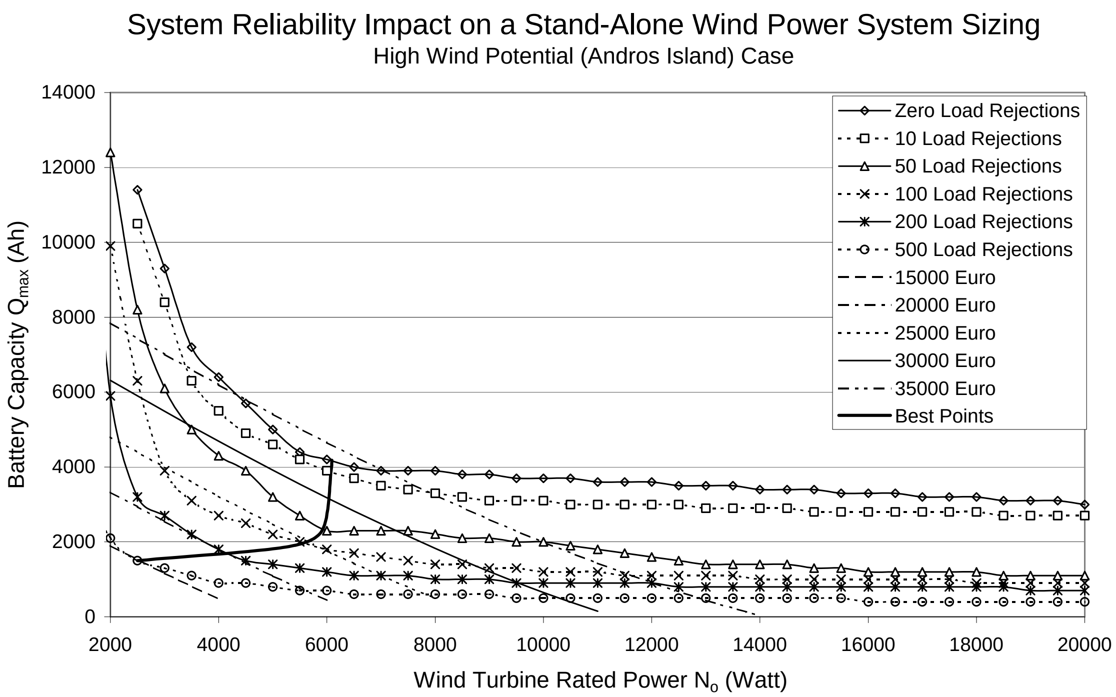

Figure 11: The impact of acceptable reliability level on a stand-alone wind power system sizing, high wind potential region

diminution is encountered, while the battery capacity seems practically unaffected. Similarly, the minimum cost solution is decreased from 34000Euro (6kW, 4200Ah-no load rejection case) to 24000Euro (5.5kW, 2000Ah) for 99% reliability and to only 15000Euro (2.7kW, 1800Ah) for 95% reliability.

Subsequently, a medium-high wind potential area is investigated (i.e. Kithnos island) for a 4-year period using the above-described method. The calculation results are given in figure (12), along with the corresponding constant initial cost and the "best point" curves. In this specific case, the influence of a permitted small number (i.e. 10 or 50) of load rejections is limited on the corresponding (N_o-Q_{max}) curve, since the resulting curves almost coincide to the no-load rejection ones. Increasing the number of acceptable load rejections of the stand-alone system by a factor of ten (i.e. R=99%), a remarkable (≈40%) diminution of the battery capacity required takes place. For higher annual rejection numbers a significant reduction of the stand-alone system wind turbine power is observed, i.e. from 11kW to 7kW. At the same time, the minimum initial cost solutions represented by the "best points" curve shows considerable cost diminution, since by accepting 100 annual load rejections (R=99%) instead of the no-load rejection solution the reduction on the system first installation cost is approximately 18000€ (or ≈25%).

Recapitulating, the replacement of the zero load rejection constraint by a 99% system-reliability-value mainly influences the stand-alone system battery capacity, while the corresponding wind turbine size remains almost unaffected. On the other hand, for lower reliability values (up to 95%) there is a considerable wind turbine size diminution. Besides, the battery capacity value modification is more important in areas of high wind potential (≈60%) than in medium-high wind potential cases (≈40%).

6. The Impact of Consumer Size on the System Sizing

The last parameter analyzed in the present study is the remote consumer size, while the hourly distribution of the load demand remains constant. More precisely the available numerical values of the hourly electricity demand[7] is multiplied by an appropriate integer factor "λ" (e.g. λ=1,2,3 or 4)

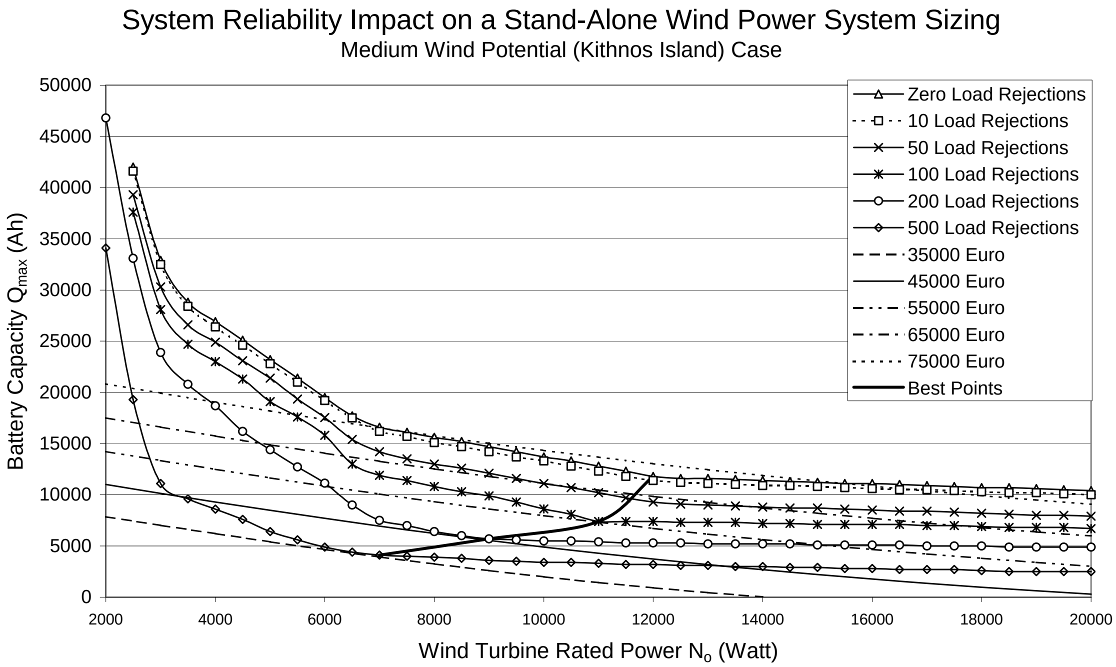

Figure 12: The impact of acceptable reliability level on a stand-alone wind power system sizing, medium wind potential region

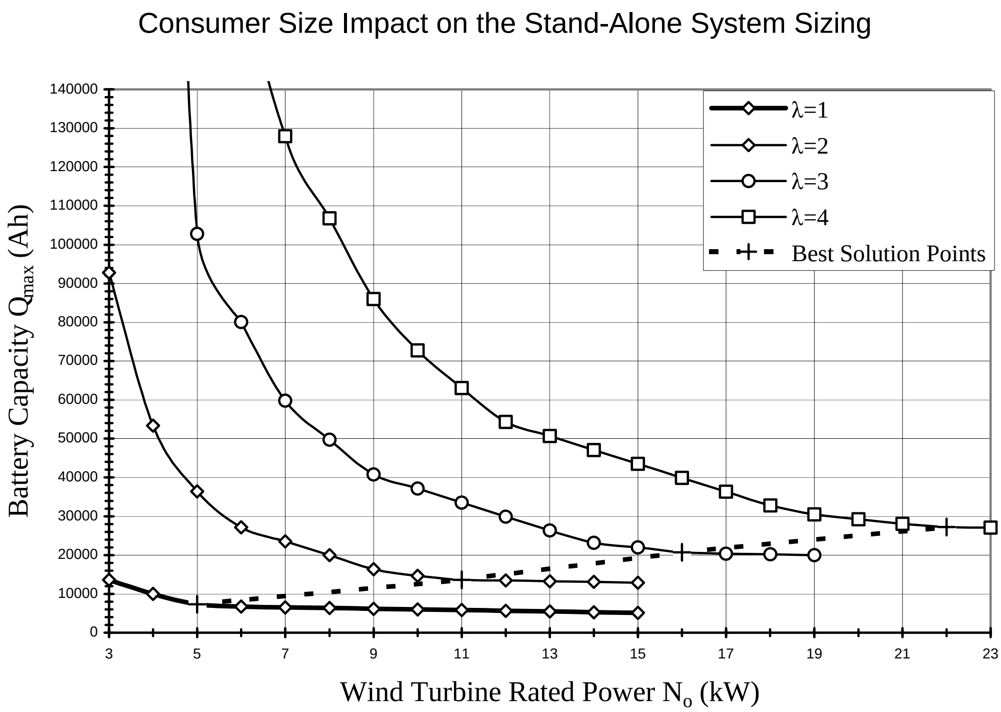

Figure 13: The impact of consumer size on the stand-alone system sizing

representing the existence of one to three additional consumers, exactly similar to the initial one, which concurrently covers their electrification needs from the stand-alone wind power system under investigation. In this specific case, additional attention should be paid, since the UPS and the inverter rated power is also modified by the introduction of the "λ" coefficient, see also Chapter Two.

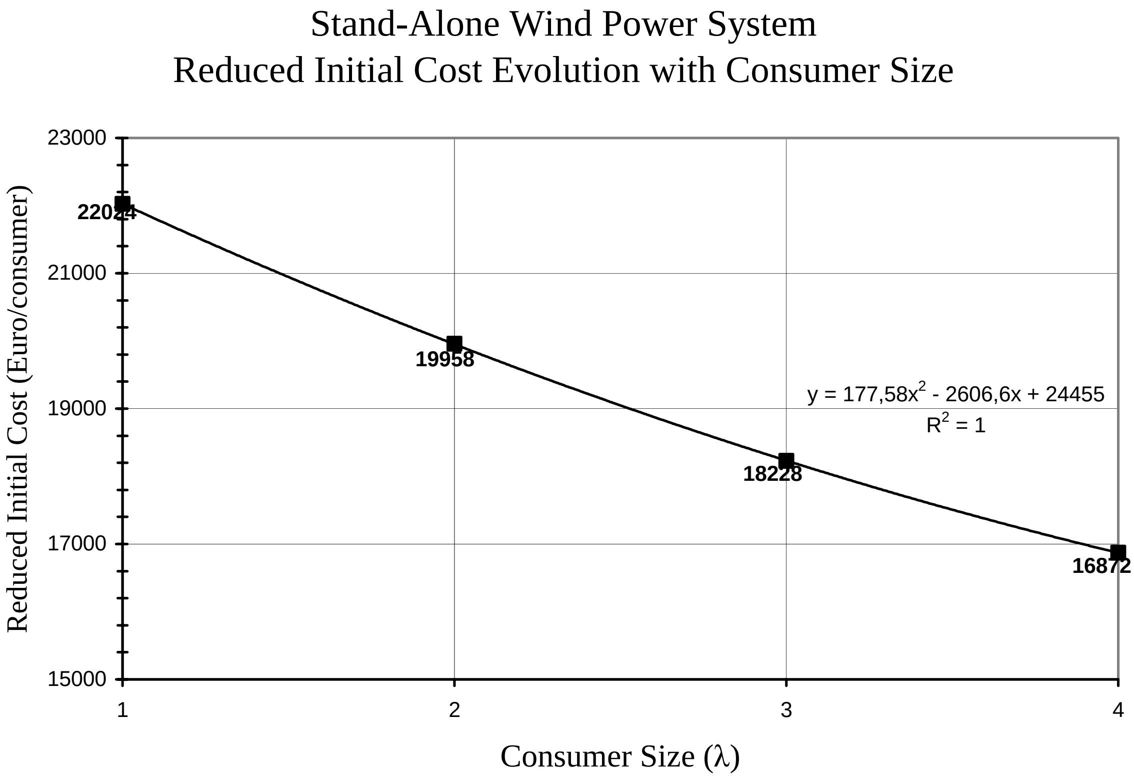

Figure 14: Reduced (per consumer) initial cost variation versus consumer size

Applying the "WINDREMOTE-II" algorithm to these four different energy consumption profiles for a high wind potential region, the calculation results are sited in figure (13). As it is clear from these data, the required battery capacity -to guarantee no-load rejection for the period examined- is significantly increased as the "λ" value also increases. Thus, the asymptotic "Q_{max}" value for λ=4 is almost 5.5 times higher than the single consumer corresponding one. On top of that, the minimum wind turbine size is remarkably increased also, as "λ" increases; in order to obtain practically realized solutions (i.e. $Q_{max} \leq 50000Ah$).

Finally, in figure (13) the minimum initial cost configurations (best points) are also given for comparison purposes. It is interesting to mention that the optimum "N^*_o" and "Q^*_{max}" values increase almost linearly with the consumption size coefficient value "λ". On the other hand, the per-family reduced first installation cost (i.e. "IC_o/λ") of the proposed stand-alone system is not constant, but it decreases with the number of consumers sharing the same installation, figure (14).

Recapitulating, one may support that the consumers’ number-increase significantly enlarges the required battery capacity of the proposed stand-alone system, if the rated power of the wind turbine used remains constant. However, the optimum system configuration demands an analogous to the consumer number wind turbine size increase, accompanied by a modest increase of the corresponding battery size. On the other hand, the inverter and UPS rated power closely follows the increase of the system peak load demand. One of the important aspects -that should be reconsidered in a future research effort- is the expected diversification of the separate consumers electricity demand profile, leading to a remarkable energy consumption profile time shift in comparison with the single consumer load demand. In this way, the discontinuous hourly electricity demand of a single consumer is gradually transformed to a continuous smooth curve like the one describing the hourly electricity consumption of various small islands[4] of Aegean Sea (e.g. Agios Efstratios, Anafi, Megisti etc, where 50 to 70 families are living).

7. Conclusions

An extensive parametrical study was carried out concerning the main stand-alone wind power system dimensions, used to fulfill the electricity requirements of numerous remote consumers all around the small Greek islands. During this study, the impact of the wind potential quality, the wind turbine used power curve type, the desired system reliability and the size of the consumer on the proposed stand-alone system sizing are investigated.

According to the results obtained, the system battery capacity required is remarkably reduced as the corresponding annual mean wind speed increases or the maximum calm spell duration decreases. Subsequently, the wind turbine size also seems to shrink with the amelioration of the available wind potential quality. On the other hand, the wind turbine rated power is considerably affected by the specific wind turbine power curve distribution adopted, while the corresponding battery size is fairly influenced.

Accordingly, the diminution of the minimum acceptable system reliability initially influences the system battery capacity, especially for high wind potential regions, while for additional system reliability diminution a significant (≈50%) wind turbine size reduction is encountered. Finally, the increase of the consumer number sharing the same stand-alone energy production system leads to a linear increase of both wind turbine and DC/AC inverter rated power, along with a fair battery capacity enlargement. As a result, the specific (per consumer) initial cost of the proposed system is remarkably reduced as the consumer number is multiplied, due to well-known scale economy effects.

The proposed stand-alone wind power solution is found to be one of the best alternatives to meet the electricity demand of isolated consumers, especially in regions with medium-high wind potential. Therefore, considering the above presented piece of information, it is possible to select the optimum size of an appropriate stand-alone wind power system, able to ensure the desired electricity supply reliability, on a minimal initial cost basis. Hence, the above-mentioned guidelines may contribute to significantly reducing the system dimensions, leading thus to a considerable money saving.

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PART THREE

FEASIBILITY EVALUATION

- Hydro Power
- Desalination Plants
- Solar Systems

TECHNO-ECONOMIC EVALUATION OF SMALL HYDRO POWER PLANTS IN GREECE: A COMPLETE SENSITIVITY ANALYSIS

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Abstract

Hydropower has by far been the most mature renewable energy resource used for electricity generation in our planet. Recently, the investors' interest was whipped up by the mass development of small hydropower (SHP) stations, as they are most prosperous for additional hydropower penetration in developed electricity markets. In Greece, the increasing interest for building SHP stations got off the ground since 1994. Ever since, an enormous number of requests keep piling up in the Greek Regulatory Authority of Energy and the Ministry of Development, with the object of creating new SHP stations of total capacity over 600MW. The present work is concentrated on the systematic investigation of the techno-economic viability of SHP stations. The study is concluded by a sensitivity analysis properly adapted for the local market financial situation, in order to enlighten the decision makers on the expected profitability of the capital to be invested. According to the results obtained, the predicted internal rate of return (IRR) values are greater than 18% for most SHP cases analysed. Finally, as per the sensitivity analysis carried out, the installation capacity factor, the local market electricity price annual escalation rate and the reduced first installation cost are found to be the parameters that mostly affect the viability of similar ventures.

Keywords: Small Hydro Power Stations; Electricity Generation; Cost-benefit Analysis; Sensitivity Analysis; Hydro turbines

Nomenclature

C	total cost of the installation (€)
CF	capacity factor of the installation (%)
c	electrical energy price (€/kWh)
c_N	power reimbursement per month (€/kW/mo)
d	diameter of the penstock used (m)
E	electricity generation by the proposed SHP station (kWh)
e	electricity price annual escalation rate (%)
e_N	electrical power compensation annual escalation rate (%)
FC	fixed maintenance & operation cost of the SHP station (€)
f	first installation cost coefficient (%)
f(Q)	probability density function describing the available water potential (%)
g	gravity acceleration (m/sec^2)
g_m	maintenance & operation cost annual inflation rate (%)
H	total head of the hydro turbines used (m)
h	hydrostatic head of the installation (m)
IC_o	SHP station turnkey cost (€)
IRR	internal rate of return of the installation (%)
i	return on investment index (%)
L	length of the penstock used (m)
m	fixed maintenance & operation cost coefficient (%)
N	power output of the SHP station (kW)
N_o	rated power of the hydro-turbines used (kW)
NPV	net present value of the investment

n	service period of the installation (years)
Pr	reduced ex-works price of the installation (€/kW)
p	investment revenues fraction transferred directly to local municipalities (%)
Q	volume rate of the hydro turbine (m^3/sec)
Q_b	water bleedings for auxiliary services (m^3/sec)
Q_e	minimum flow rate of the river, for ecological protection reasons (m^3/sec)
Q_r	river flow rate (m^3/sec)
R	total revenues of the investment (€)
t	time (sec)
VC	variable maintenance & operation cost of the SHP station (€)
W_o	water annual fees (€)
w	water fees annual escalation rate (%)
Y	residual value of the investment (€)
z	number of turbines used
γ	State subsidization percentage (%)
Δ	technical availability factor of a small hydro power station (%)
δH_f	total hydraulic loss of the system (m)
ζ	local loss coefficient for the water circuit of the SHP station
η	total efficiency of the SHP plant (%)
λ	friction loss coefficient for the water circuit of the SHP station
ξ	specific cost coefficient of civil engineering works (%)
ρ	water density (kg/m^3)
Φ	annual tax on profit (€)
ω	mean power coefficient of the installation (%)

1. Introduction

Hydropower has by far been the most mature renewable energy resource used for electricity generation, providing almost 1/5 of our planet electricity consumption[1]. In Greece, several -mostly large- hydroelectric plants[2] are in operation, exceeding 3100MW of electrical power. Recently, the investors' interest was whipped up by the mass development of small hydro power stations[3], being in accordance with the E.U. target to increase small hydro capacity by 4500MW (50%) before the year 2010.

In this context, it is important to mention that small hydro power (SHP) plants are the most prosperous way for additional hydro power penetration in European electricity market, considering that most large-scale opportunities have either been already exploited or face serious contradictions by local societies as environmentally unacceptable[4]. On the other hand, SHP units usually operate as "run-of-river" systems, thus any dam or barrage used is quite small, not really disturbing the water flow rate. Although to date there is no internationally agreed definition of SHP plants size, the officially size in the local electricity generation market is set equal to 10MW maximum (law 2244/94).

In Greece, an increasing interest for building SHP stations got off the ground since 1994, after the 2244/94 law was voted, permitting private investors to build and operate their own electricity generation stations based on renewable energy sources. In the last five years a fair number of SHP plants were established by individuals and local municipalities[2][5], while at the same time an enormous number of requests keep piling up in the Greek Regulatory Authority of Energy (RAE) and the Ministry of Development, with the object of creating new SHP station over 600MW.

The present work is concentrated on the systematic investigation of the techno-economic viability of SHP stations in Greece. The proposed analysis takes into account previous work on this field[6][7][8], along with available information concerning the local hydro potential[9]. Accordingly, the impact of the governing techno-economic parameters on the financial behaviour of SHP plants is analysed[10]. This study is concluded by a sensitivity analysis properly adapted for the local market financial situation, in order to enlighten the decision makers on the expected profitability of the capital to be invested.

2. Analytical Simulation of Small Hydropower Stations Energy Production

Hydro-turbines transform the water potential (mainly high pressure) into mechanical shaft power, which is finally converted to electricity[11][12]. The electrical power "N" available of every turbine used is proportional to the product of total pressure head "H" and volume rate "Q" of penstock, thus one may write:

$$N = \eta \cdot \rho \cdot g \cdot H \cdot Q \tag{1}$$

where "η" is the total efficiency of the turbine (including the electrical generator), see for example figure (1), "ρ" is the water density and "g" is the gravity acceleration. Bear in mind that the hydro-turbine head results from the hydrostatic head "h" of the waterfall and the total hydraulic loss "δH_f", both lengthwise and local ("λ" and "ζ" are the corresponding loss coefficients) when the water circuit is used for energy production. More precisely,

$$H = h - \delta H_f \tag{2}$$

and

$$\delta H_f = (\lambda \cdot \frac{L}{d} + \zeta) \cdot \frac{8 \cdot Q^2}{g \cdot \pi^2 \cdot d^4} \tag{3}$$

with "L" the length and "d" the diameter of the penstock used.

The energy production over a time period "T" (e.g. one year) of a SHP station based on "z" hydro-turbines of rated power "N_o" (generator loss is included) is given as:

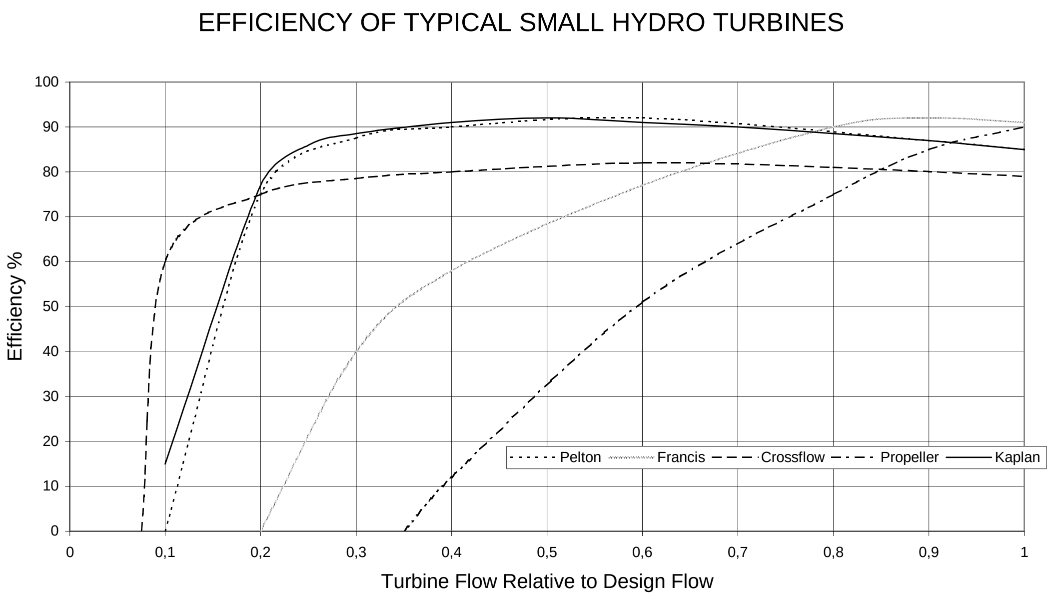

Figure 1: Efficiency curves of typical small hydro turbines

$$E = \sum_{j=1}^{z} \int_{o}^{T} N_j(t) \cdot dt \quad (4)$$

or equivalently as:

$$E = 8760 \cdot z \cdot CF \cdot N_o - \delta E \quad (5)$$

where "CF" is the corresponding capacity factor of the installation and "δE" describes the line transmission and transformer loss as well as any self-consumption of the power station on annual basis. More specifically "CF" can be expressed as the product of the mean technical availability factor "Δ" and the mean power coefficient "ω" of the installation, i.e.:

$$CF = \Delta \cdot \omega \quad (6)$$

The mean power coefficient, expressing the yearly-averaged energy production during an hour per kW of nominal power of the station, is defined by the following equation, i.e.:

$$\omega = \int_{0}^{\infty} \frac{N(Q)}{N_o} \cdot f(Q) \cdot dQ = \int_{Q_{min}}^{Q_{max}} \frac{N(Q)}{N_o} \cdot f(Q) \cdot dQ \quad (7)$$

In equation (7) "f(Q)" is the probability density function describing the available water potential (flow-rate) and "Q_{min}" and "Q_{max}" are the minimum and maximum working flow rates of the hydro turbine used. By integrating the probability density function one may obtain[9] the well-known flow-rate duration curve "$G(Q_o)$", since:

$$G(Q \geq Q_o) = \int_{Q_o}^{\infty} f(Q) \cdot dQ = 1 - \int_{0}^{Q_o} f(Q) \cdot dQ \quad (8)$$

It is important to underline that the water flow-rate through the turbine is not exactly the river flow-rate "Q_r", because a minimum flow-rate "Q_e" should remain in the river for reasons of conservation, while one should also consider water channelling for irrigation or agricultural purposes, i.e. "Q_b". Thus one may write:

$$Q = Q_r - Q_e - Q_b \quad (9)$$

Recapitulating, the following relation is valid for the power output of a SHP plant:

$$N = \begin{Bmatrix} 0 & Q \leq Q_{min} \\ N(Q) & Q_{min} \leq Q \leq Q_{max} \\ N_o & Q_{max} \leq Q \end{Bmatrix} \quad (10)$$

In addition, natural river flow is highly variable; given that most rivers exhibit pronounced seasonal variation in their flow (see figure (2)). Remarkable efforts were undertaken[13] in an attempt to present a generalized model able to predict a stream flow-rate duration curve. However, long-term measurements -if obtainable- should be preferred.

Recapitulating, one may estimate the annual electricity yield of a SHP plant using equation (5), the operational characteristics of the selected hydro-turbines and the river flow-rate probability density or duration curve. The net energy output of the station should make an allowance for the technical availability and the electric power consumed by the auxiliary systems of the plant.

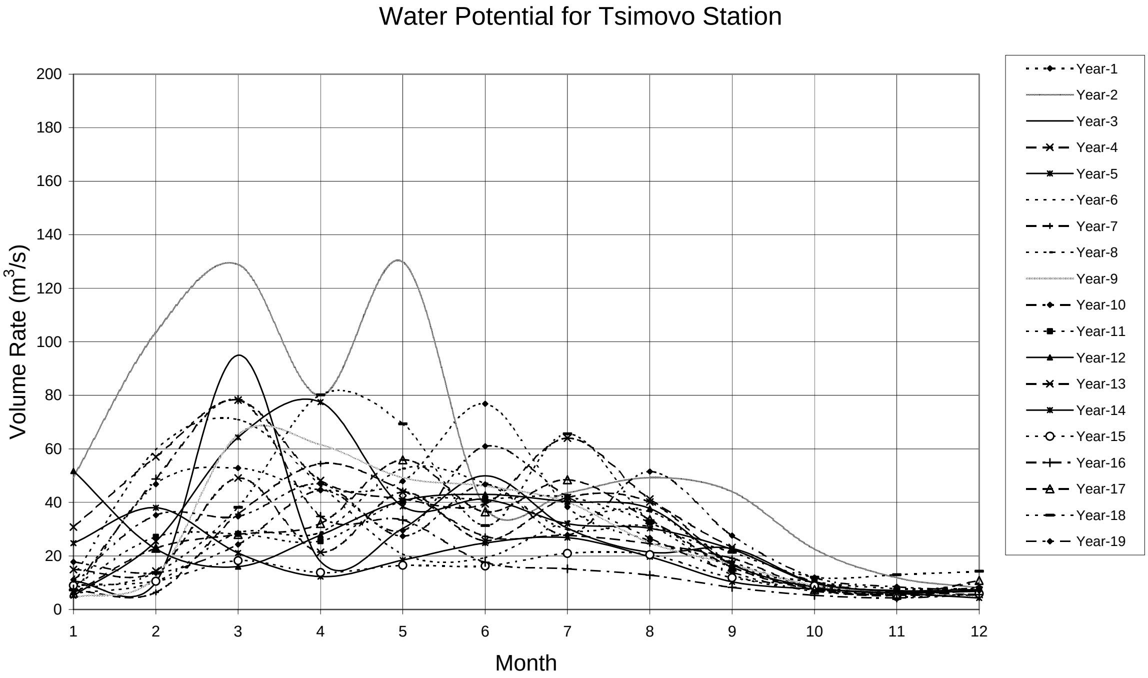

Figure 2: Water potential long-term variation for Tsimovo SHP station

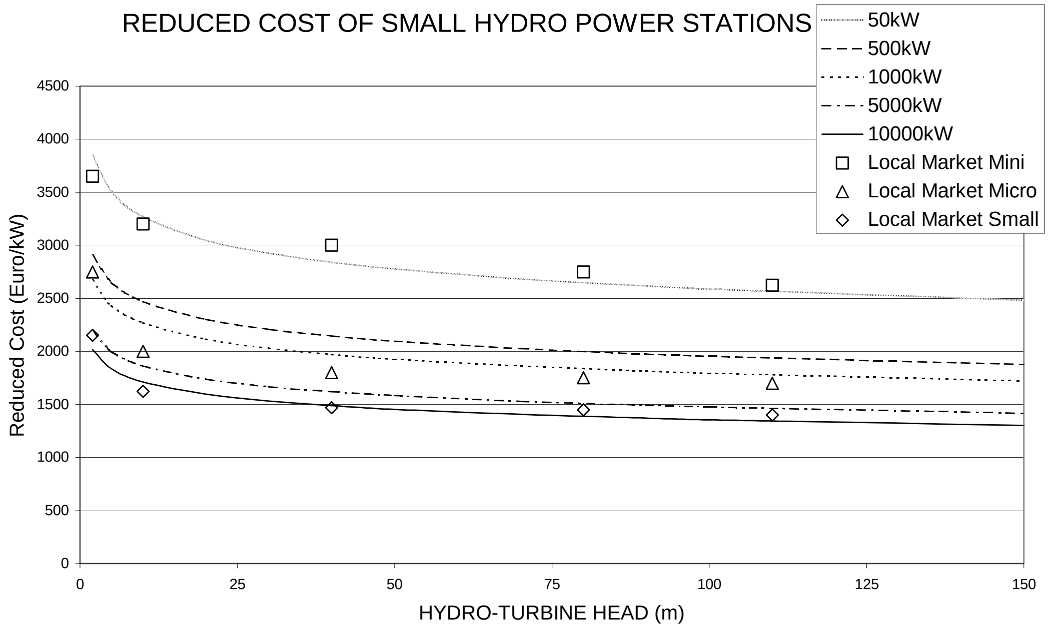

Figure 3: Specific cost of small hydro power plants

3. Cost-Benefit Analysis of a Small Hydro Power Station

According to previous analysis by the authors[14][15], the present value of the investment cost of a SHP installation (after n years of operation) is a combination of the initial cost and the corresponding maintenance and operation cost. The initial cost includes the market price of the electromechanical equipment (usually ex-works), the civil engineering activities and the corresponding balance of plant cost. Thus one may write:

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

where the specific (reduced) ex-works price "Pr" (€/kW) of the SHP is given as:

$$Pr = Pr_1 + Pr_2 \tag{12}$$

Keep in mind that "Pr_1" describes the electro-mechanical equipment reduced cost, being mainly a function of the hydro turbine nominal power and the corresponding head (see also figure (3)), hence one may write:

$$Pr_1 = \frac{b_o}{N_o^{b1} \cdot H^{b2}} \tag{13}$$

with b_o=3300€, b_1=0.122 and b_2=0.107.

On the other hand, "Pr_2" describes the specific cost of civil engineering works, including infrastructure, land purchase, dam construction, weir and intake, water canal, forebay tank, penstock etc. Unfortunately, it is not possible to simulate the "Pr_2" value, since it depends on the local situation of every specific site. More specifically, the characteristics of topography, geology, road access and local electricity grid of each site have such an influence that each project becomes a prototype. So, the risk of the budgetary deviations is quite high. Generally speaking, according to the experience[1][2][5][7][8][11][13][14] of a remarkable number of local installations, "Pr_2" can be expressed as:

$$Pr_2 = \xi \cdot Pr_1 \tag{14}$$

with "ξ" taking values between 0.8 and 2.0. The higher "ξ" values appear in cases of dam construction (usually earthen) and long penstock utilization.

Finally, "f" expresses the installation cost (e.g. electrical interconnection cost, access tracks, development cost etc.), which is given as a fraction (f≈5%-10%) of the "Pr" (or "Pr_1").

The maintenance and operation (M&O) cost can be split into the fixed maintenance cost "FC" and the variable one "VC". Expressing the annual fixed M&O cost as a fraction "m_1" of the electromechanical equipment ex-works price plus a fraction "m_2" of the civil engineering work cost and assuming an annual increase of the total cost equal to "g_m", the present value of "FC" is given as:

$$FC_n = (m_1 \cdot Pr_1 + m_2 \cdot Pr_2) \cdot N_o \cdot \frac{(1+g_m)}{(1+i)} \cdot \left[1 + \left(\frac{1+g_m}{1+i}\right) + \ldots + \left(\frac{1+g_m}{1+i}\right)^{n-1}\right] + W_o \cdot \sum_{j=1}^{j=n} \left[\frac{1+w}{1+i}\right]^j \tag{15}$$

where "i" is the investment discount rate (or interest rate)[16]. Bear in mind that the last part of equation (15) expresses water fees "W_o" (rarely applied), including an annual cost escalation rate equal to "w".

The variable maintenance and operation cost[10][15] mainly depends on the replacement of "k_o" major parts of installation, which may have a shorter lifetime "n_k" than the complete power station. Using the symbol "r_k" for the replacement cost coefficient of each "k_o" major part (e.g. electrical generator, rotor blades etc), the present value of "VC" term can be expressed using the following relation:

$$VC_n = IC_o \cdot \sum_{k=1}^{k=k_o} r_k \cdot \sum_{l=1}^{l=l_k} \left\{ \left[\frac{(1+g_k) \cdot (1-\rho_k)}{1+i} \right]^{l \cdot n_k} \right\} \tag{16}$$

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

$$l_k = \left[\frac{n-1}{n_k}\right] \tag{17}$$

Note that "g_k" and "ρ_k" respectively describe the annual change of price and the corresponding technological improvement level for the "k-th" major component of the hydropower station.

Finally, the present value of the total investment cost "C_n" of the SHP installation after n years of operation reads:

$$C_n = (1-\gamma)\cdot IC_o + FC_n + VC_n \tag{18}$$

where "γ" is the subsidy percentage by the Greek State or the E.U. According to the existing 2601/98 development law or the current National Competitiveness Program of the Ministry of Development, a 40% subsidy is provided to private investors in the area of small hydropower applications countrywide.

Subsequently, the total savings over an n-year period -resulting from the operation of a SHP station- are mainly due to the energy production sold to the national electrical grid. In addition, there is a monthly compensation for the power added to the local network. On the other hand, according to the current[17] legislation frame (Law 2773/99), a supplementary amount from the investment revenues is directly transferred to local municipalities, defined as their fraction "p" ($p \approx 2\%$-3%). Thus, the present value of the total SHP station income (operating for n years) is given as:

$$R = E\cdot c\cdot(1-p)\cdot\sum_{j=1}^{j=n}\left[\frac{1+e}{1+i}\right]^j + (\sigma\cdot\sum_{j=1}^{12}N_{max_j})\cdot c_N\cdot(1-p)\cdot\sum_{j=1}^{j=n}\left[\frac{1+e_N}{1+i}\right]^j \tag{19}$$

where "c" and "c_N" respectively are the energy price (€/kWh) and the power reimbursement per month (€/kW/mo). Also "e" and "e_N" are the corresponding electricity price and electrical power compensation annual escalation rate. Finally, "N_{max}" is the maximum output power of the station for every month of the year and "σ" is the average power contribution factor of the SHP to the local grid, defined by the 2244/94 law, i.e. $\sigma=0.7$.

Comparing the present value of the total investment cost and the corresponding total revenues, one has the ability to estimate the net present value of the investment "NPV" after n years of operation, i.e.:

$$\begin{aligned} NPV_n = & -1+\gamma-\frac{m_1\cdot Pr_1+m_2\cdot Pr_2}{(Pr_1+Pr_2)\cdot(1+f)}\frac{a_m\cdot(1-a_m{}^n)}{1-a_m}-\sum_{k=1}^{k=k_o}r_k\cdot\sum_{l=1}^{l=l_k}\left\{\left[\frac{(1+g_k)\cdot(1-\rho_k)}{1+i}\right]^{l\cdot n_k}\right\}-\frac{W_o}{IC_o}\cdot\frac{a_w\cdot(1-a_w{}^n)}{1-a_w} \\ & +\frac{E\cdot c}{IC_o}\cdot\frac{a_e\cdot(1-a_e{}^n)}{1-a_e}+\frac{(\sigma\cdot\sum_{j=1}^{12}N_{max_j})\cdot c_N}{IC_o}\cdot\frac{a_N\cdot(1-a_N{}^n)}{1-a_N}+\frac{Y_n/IC_o}{(1+i)^{n^*}}-\sum_{j=1}^{j=n}\frac{\Phi_{(j)}/IC_o}{(1+i)^{n^*}} \end{aligned} \tag{20}$$

where:

$$a_m = \frac{1+g_m}{1+i},\quad a_N = \frac{1+e_N}{1+i},\quad a_e = \frac{1+e_e}{1+i},\quad a_w = \frac{1+w}{1+i} \tag{21}$$

In equation (20) "$\Phi_{(j)}$" describes the tax paid only during the "j" year, mainly due to the revenue of the previous year. According to the Greek tax-law, the "$\Phi_{(j)}$" depends on the law-defined tax-coefficient (e.g. 35%), the net cash flow of the "j-1" year, the investment depreciations, as well as the financial obligations of the enterprise[16]. In the following, the impact of taxation will be explicitly presented on the evaluation results of a SHP station investment.

Similarly, "Y_n" represents the residual value of the investment, owing for the most part to amounts recoverable at the "n" year of the project life (e.g. value of land or buildings, scrap or second hand value of equipment, etc.), along with the experience gained and the corresponding technological know-how.

As acknowledged, the internal rate of return "IRR" of an investment operating during an n-year period is predicted by setting the "NPV" equal to zero, thus we get:

$$IRR = i^*, \quad \text{when} \quad NPV(i^*) = 0 \tag{22}$$

For the estimation of "IRR" an "expert type" numerical code has been devised, based on the iterative solution of the non-linear break-even equation (20). Additionally, the developed algorithm has the ability not only to check the economic viability of SHP stations, but also to predict the modifications of the "IRR" due to changes in values of the main techno-economic parameters.

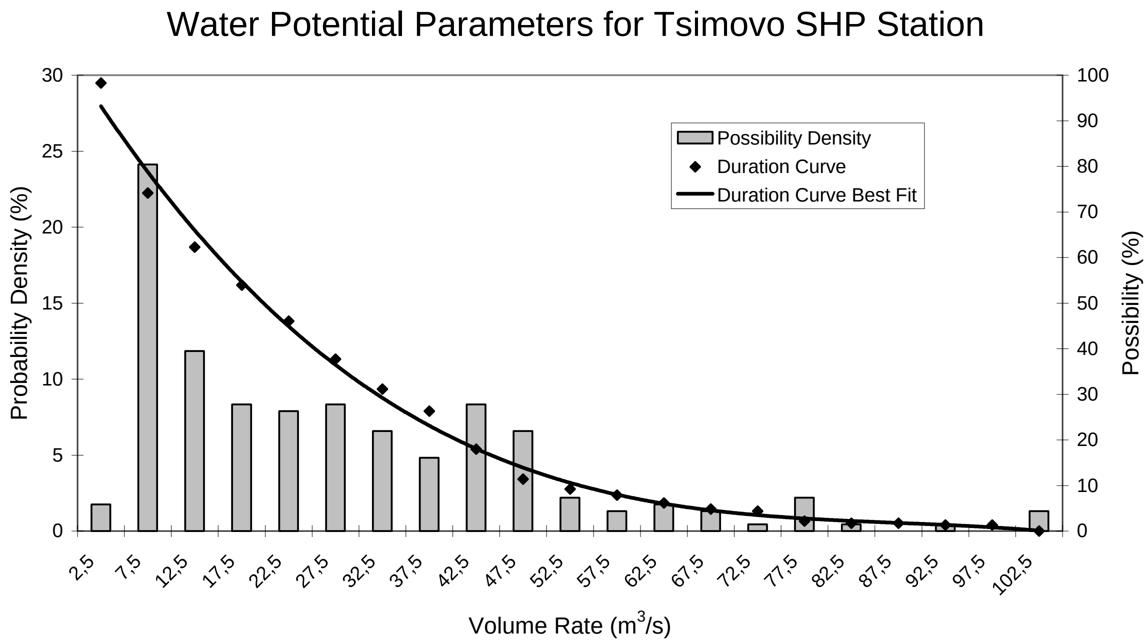

Figure 4: Main water potential parameters of Tsimovo SHP station for a 20-years period

4. Application Results

The above-described analytical method is used to analyse a representative case in the mainland of Greece, concerning the installation of a new small hydro power station. The case investigated is a typical "run-of-river" plant, exploiting the significant flow rate of Aracthos River, using a small artificial hydrostatic head of 27m. In this specific case, the utilization of one to three Kaplan S-type hydro turbines is examined, taking into account the large flow rate and the low head available.

4.1 Calculation of Energy Production

More precisely, a SHP plant is under development in Tsimovo Bridge near Ioannina town of Epirus prefecture, using the Aracthos river flow rate. In order to estimate the expected mean annual energy production of the station, 20-years water-potential data (on an hourly basis) are contemplated.

According to figure (2), the mean annual flow rate varies between 15m^3/sec and 38m^3/sec, excluding the unusually extreme data of the 2nd year investigated. Applying a statistical analysis on the available measurements (on an hourly basis), it is possible to estimate the 20-years long-term probability density profile of the available water potential (figure (4)), along with the corresponding duration curve.

On the basis of the data analysed, 25% of the available flow rate measurements are between 5m^3/sec and 10m^3/sec, while only 2% of the data exceed the 80m^3/sec. Besides, a very small part (only 1.8%) of data are below the 5m^3/sec, while a fairly constant probability density distribution appears for flow rate values between 15m^3/sec and 50m^3/sec.

Using the information of figure (4) and the analysis of section 2, one may estimate the expected long-term mean power coefficient, on the basis of two similar Kaplan S-type hydro turbines, i.e. the corresponding capacity factor numerical value is almost 46.7%. Thus, the proposed installation is based on 2x5MW hydro turbines with nominal flow rate of 22m^3/sec and design head equal to 27m. The total flow rate selected (2x22m^3/sec) validates the general rule of thumb applicable for SHP, i.e. the most economic beneficial SHP volume rate is about twice the 50% flow rate of the river under investigation. The expected mean annual yield is 38,400MWh and the mean power contribution to the local grid is 4.7MW.

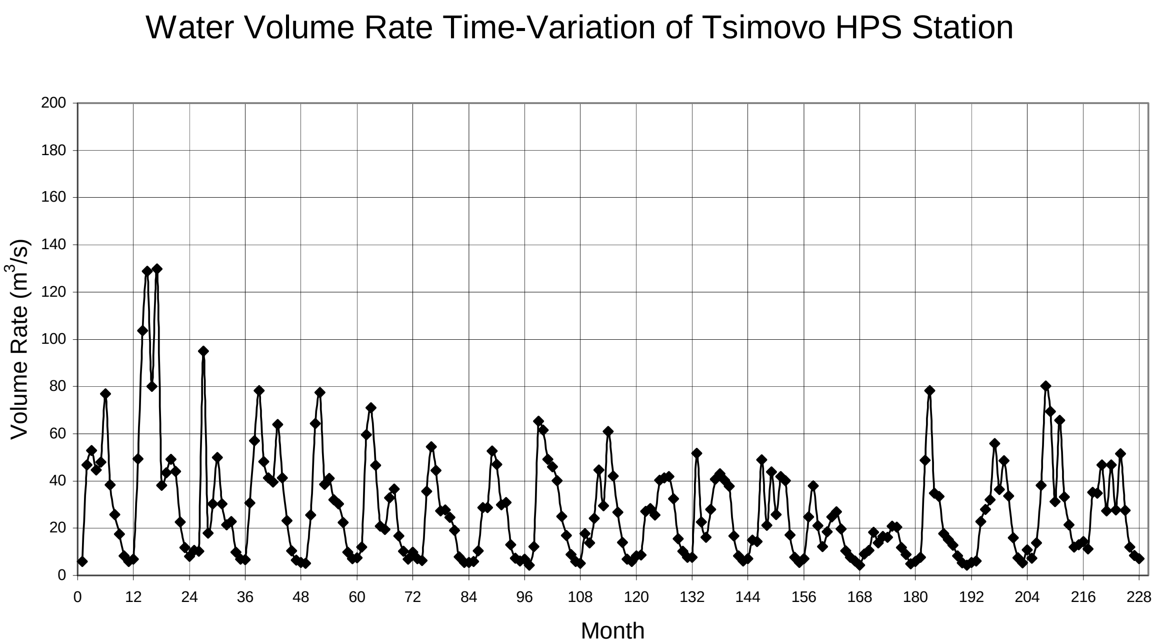

Figure 5: Time-evolution of Tsimovo SHP station water volume rate

In an attempt to increase the reliability of the proposed analysis, the river flow rate time series, figure (5), for the entire period analysed is taken into consideration. Hence, using equations (1) and (4), it is possible to estimate the annual energy production of the installation for the 20-years time period examined (see figure (6)). According to the calculation results, the expected annual energy production varies between 20,000MWh (for the worst year of the twenty-year period) and 70,000MWh (for the best year). The corresponding long-term average energy yield (including the technical availability impact and the station energy self-consumption) is approximately 38,500MWh, which is almost identical to the value given by equations (5) to (7). Summarizing, as it is obvious from the calculation results presented, the mean annual energy production of the SHP station under investigation is equal to 38,500MWh.

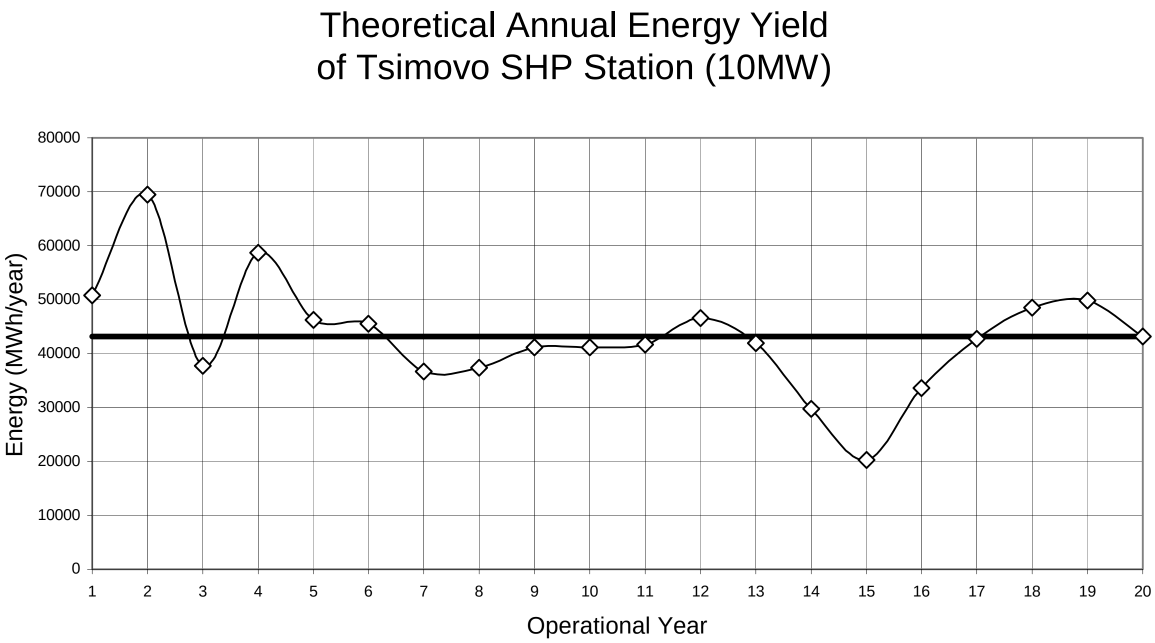

Figure 6: Time-evolution of annual electricity yield of Tsimovo (10MW) SHP station

4.2 Cost-Benefit Analysis

Before presenting the calculation results concerning the financial behaviour of a representative SHP installation, it is important to define the central values of the governing parameters of the problem. These values should be representative for the techno-economic situation of the local market[15][17] for the next 10 to 20 years. After extensive research, the following values are selected for the main parameters of the problem; see also Table I.

Table I: Central values of the governing parameters

Parameter	Numerical Value	Units	Parameter	Numerical Value	Units
N_o	5000	kW	i	8	(%)
H_o	27	m	e	3	(%)
Q_o	22	m^3/sec	g_m	3	(%)
z	2	-	m_1	2.5	(%)
Pr	1500	€/kW	m_2	1.5	(%)
CF	46.7	(%)	c	0.0606	€/kWh
Δ	95	(%)	c_N	1615	€/MW/mo

- ✓ The SHP station analysed is based on two (2) hydro turbines of rated power N_o=5000kW, mass flow rate 22m^3/sec and nominal head 27m. The number of turbines used is one of the parameters of the problem, while the total station power should not exceed the 10MW.
- ✓ The turnkey price of the SHP station is realistically described by equations (11) to (14) and figure (3).
- ✓ The annual mean capacity factor of the installation is assumed equal to 0.467, being a realistic value for the site selected, (see figure (6)), while the corresponding technical availability parameter is taken as Δ=0.95.
- ✓ The maintenance and operation cost factors "m_1" and "m_2" are taken equal to 2.5% and 1.5% respectively, while the corresponding terms related to the variable maintenance cost are chosen from published documents referred to long-term operation of SHP all over Europe[1][9][11].
- ✓ The mean long-term annual electricity price escalation rate is assumed equal to e=3%, a value based mainly on historical records[15].

✓ The mean maintenance and operation cost annual inflation rate is assumed equal to g_m=3%, in view of the fact that a target value for the local economy concerning the inflation ratio is 2%.
✓ The corresponding capital cost value is taken equal to i=8% a reasonable value in comparison with the local market investment opportunities and the corresponding investment risk, while the loan amortization period is set equal to five (5) years.
✓ The corresponding price for the electricity production sold to the national grid is determined by the law 2244/94, according to the tariffs of the Greek Public Power Corporation[17], and it is assumed equal to 0.0606€/kWh, while the corresponding monthly power compensation is 1615€/(kW.mo).
✓ No water fees are taken into consideration in the present survey, i.e. W_o=0.

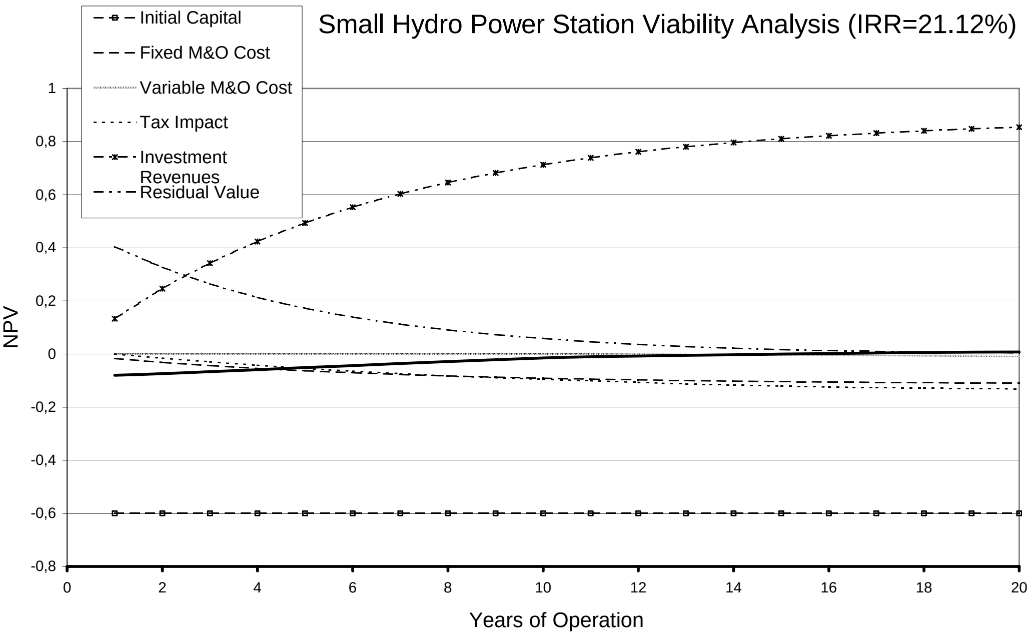

Figure 7: Viability analysis of a SHP station-IRR prediction

Subsequently, the net present value distribution of the Tsimovo SHP station may be estimated by using equation (20) as a function of the operation time horizon of installation. For this purpose, several investment discount rate values are tested so as to nullify the investment "NPV" in course of time. For example, the selected discount cost value zeroing the "NPV" after 15 years of operation is 21.12% (see figure (7)). Thus the corresponding 15-years "IRR" value of the investment is 21.1%, a quite good value in comparison with the local market current annual inflation rate (3.5%). A closer inspection of figure (7) data emphasizes the dominant role of the station's annual savings compared with the investment cost -being however slightly decelerated in the course of time- due to the discounting factor impact. At the same time, the present value of the investment residual value is gradually decreasing, practically approaching zero bordering on n=20years, while -as expected- the M&O cost is gradually increasing with time. On top of this, the residual value esteemed during the calculations of the present section is assumed equal to 50% of the logistic current value of the enterprise in order to incorporate possible investment liquidation problems.

In an attempt to obtain a clarified picture of the financial behaviour of the station under examination, an additional analysis is carried out, using a quite lower discount rate value, i.e. i=10%. According to the results achieved (see figure (8)), the SHP station NPV becomes positive from the 2nd year of operation, underlining the economic attractiveness of the investment. As in the previous case, the variable M&O cost impact is quite small, which is not the case for the corresponding fixed one. In addition, one cannot disregard the taxation impact on the NPV -being higher than the SHP station total M&O cost effect. Finally, by comparing figures (7) and (8), it is almost obvious that when high "IRR" values are imposed there are no additional gains from the long operation of the station, since the corresponding "NPV" remains almost constant. On the other hand, by setting the "IRR" value near the market capital cost (6%-8%), one may expect significant gains from the long-term operation of the station.

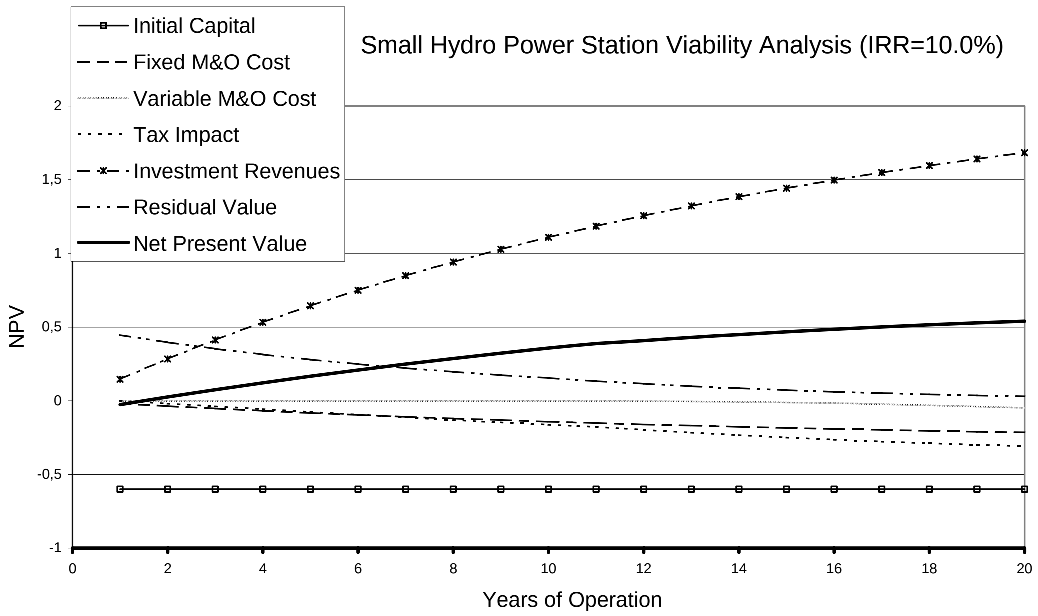

Figure 8: NPV variation for a selected SHP station in the course of time

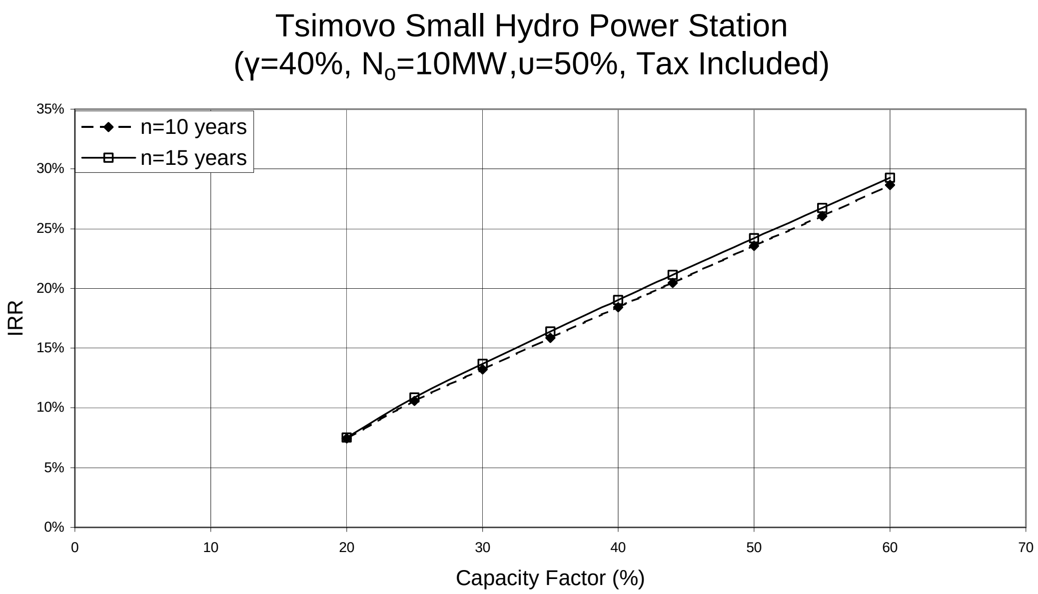

Figure 9: The impact of capacity factor on the IRR distribution of a SHP station

5. Parametrical Analysis of the Financial Behaviour of a Small Hydro Power Plant

In the following, the impact of the key parameters on the "IRR" value of a SHP plant in Greece is examined in the course of time (i.e. years of operation).

5.1 Capacity Factor

As stated above, the capacity factor value of a SHP plant depends on the water potential of installation site and on the power curve of hydro turbine utilized. Additionally, the technical availability of the power station also influences the exact "CF" value. The dominant impact of "CF" on the "IRR" value of a SHP investment may be observed in figure (9). More precisely, there is an almost positive linear relation between "IRR" and "CF" values (i.e. 0.5% "IRR" amelioration for every 1% "CF" increase), which is almost independent of the operation time, especially for low "CF" values. On top of that, for "CF" values exceeding 30% -which is a very conservative value- the ten-year and fifteen-year "IRR" value respectively exceed 14% and 13.5%, a rather motivating financial efficiency of similar risk energy production installations.

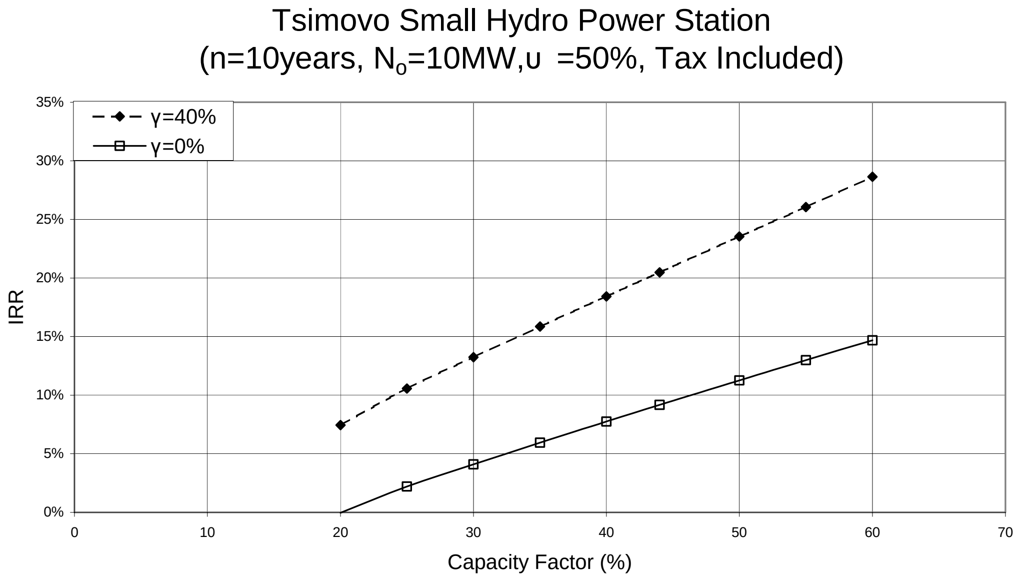

Figure 10: The combined impact of capacity factor and State subsidization percentage on the IRR distribution of a SHP station

Subsequently, the combined impact of the "CF" value and the subsidization percentage on the "IRR" value of a typical SHP investment may be examined in figure (10). As in the previous figure, the positive linear relation between "IRR" and "CF" is revalidated. However, the slope of the "IRR-CF" curve in case of State subsidization is higher than in case of no-subsidization. This outcome is quite unexpected; as one may assume that realization of low capacity installations need further financial support than those of high water potential regions.

5.2 Number of Hydro Turbines Used

The next parameter investigated is the number "z" of hydro turbines used, under the precondition that the total rated power of the installation should be equal to 10MW. Three cases are hereby examined, based on employment of one, two or three hydro turbines, operating under the same total head and variable volume rate; see Table II.

Table II: Technical characteristics of the small hydropower station configurations

Configuration	A	B	C
Number of Turbines	1	2	3
Nominal Volume Rate	$44m^3/s$	$22m^3/s$	$14.7m^3/s$
Total Power	10MW	10MW	10MW
Minimum Volume Rate	$4.4m^3/s$	$2.2m^3/s$	$1.47m^3/s$
Mean Power Coefficient	0.474	0.492	0.465
Technical Availability	0.95	0.95	0.95
Capacity Factor	0.451	0.467	0.441
Theoretical Annual Yield	39500MWh/y	40950MWh/y	38650MWh/y
Annual Energy Production	37000MWh/y	38400MWh/y	36250MWh/y

According to the calculation results, see also section 2, the maximum annual energy yield of the installation is realized for two 5MW hydro turbines. On the other hand, there is a fair first installation cost amplification, as the number of machines used is also increasing. Applying all above in the financial analysis model for the investment evaluated, the "IRR" variation -with the number of turbines used for 10 year and 15 years of the SHP plant operation- may be observed; see figure (11). According to the results presented, the usage of one or two hydro turbines maximizes the "IRR" value of the installation, while the utilization of the third turbine leads to "IRR" value decrease by almost 3%. Since the "IRR" value is almost the same for z=1 and z=2, other criteria -like improved reliability, uncomplicated maintenance process etc- should also be considered, in order to decide on the optimum hydro turbines number.

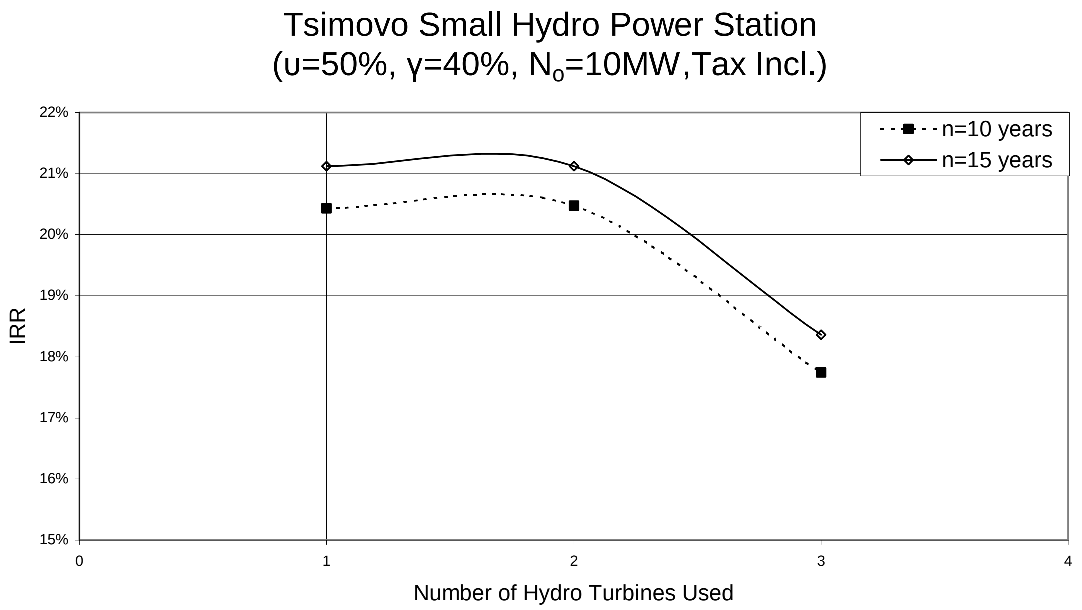

Figure 11: The impact of turbines number on the IRR distribution of a SHP station.

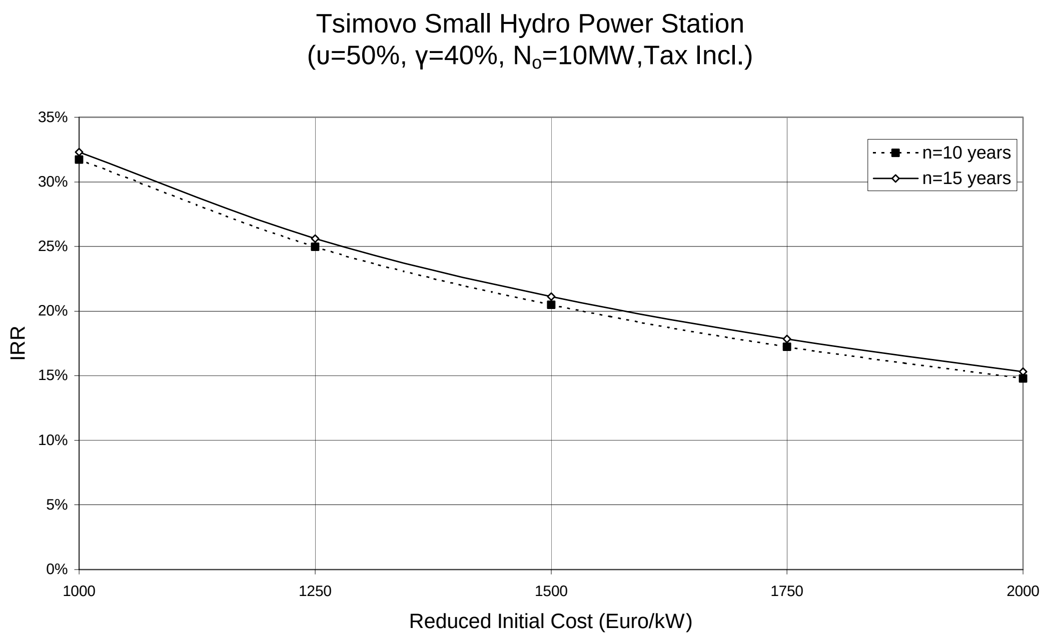

Figure 12: Initial cost impact on the IRR distribution of a SHP station

5.3 Turnkey Cost

The initial investment cost (turnkey cost) includes the ex-works price of the required equipment and the corresponding balance of the plant cost. Application of new technological achievements and economies of scale reduce the price of a SHP installation. Besides, the installation head is in inverse proportion to the water volume required for a given power produced; therefore smaller and low-cost equipment is required. However, high head sites are usually disposed in mountainous areas of low population density and poor infrastructure. In similar cases, long electricity transmission distances to the main consumption centres nullify any profits of remote high head SHP stations.

Applying a wide range of reduced initial investment cost values (i.e. from 1000€/kW to 2000€/kW), see also figure (3), "IRR" appears to be intensely decreasing as the "Pr" value increases, see figure (12). However, the "IRR" value of the proposed investment exceeds 15% after 10 years of uninterrupted operation, even at a 2000€/kW turnkey cost value. Finally, the years of operation hardly affect the "IRR" value (≈0.5%) for the entire "Pr" value range analysed.

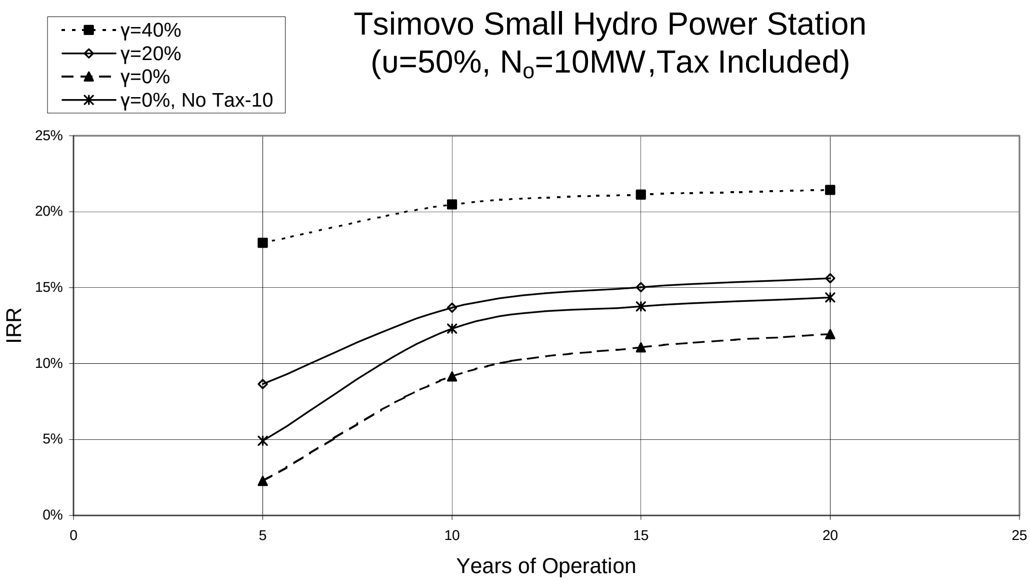

Figure 13: State subsidization impact on the IRR distribution of a SHP station

5.4 Subsidization Impact

During the last twenty-year period, the E.U. and the corresponding country members remarkably subsidize investments in the energy production sector, under the precondition of clean energy production, i.e. utilization of renewable energy sources[17][19][20]. In Greece, all SHP applications are currently subsidized by 40% of the initial capital invested, while this value formerly was 50%[21]. In several other E.U. countries, it is not the initial capital but the energy production price that is financially supported, in an attempt to guarantee enduring and regular operation of the power station. Bear in mind that this subsidization amount is only a portion of the evaded environmental and macro-economic outlay and benefits from the operation of renewable energy production stations instead of fossil fuel fired plants[19].

Indicative of figure (13), the "IRR" distribution is enhanced in cases of initial cost subsidization comparatively to the no-subsidized ones. This disparity is almost 15% for the first years of operation of the power station, being slightly decreased to 10% for long-term operation of the investment. A closer inspection of figure (13) may also affirm the following:

a. Apart from subsidization, the "IRR" value of the investment is above 10% for operation exceeding eleven years, including taxation and assuming residual value equal to 50% of the logistic-official value.
b. The "IRR" value in all cases increases every year of operation, independently of the subsidization value "γ".
c. The "IRR" increase descends as "γ" ranges from 0-20% rather than from 20% to 40%.

The same figure also introduces the "IRR" profile versus years of operation, in case that the second subsidization option of the law 2601/98 is adopted. More precisely, according to the 2601/98 law, investors have the alternative to refuse the 40% subsidization of the initial investment cost, erect the plant on their own (using loan capitals) and instead to operate the enterprise tax-free for a decade. As it becomes obvious from figure (13), such an option leads to significantly lower "IRR" values (14.5% maximum value) than the initial capital subsidization, explaining thus the inefficiency of this latter alternative.

5.5 Electricity Price Escalation Rate

The term "electricity price escalation rate" is hereby used to describe the annual rate of change of the electrical energy (and power) market prices, as according to the existing legislative frame (Laws 2244/94 and 2773/99) the electricity generated by the SHP stations is finally sold to the local network at a price directly related to the corresponding retail price. More specifically, for private investors of the electricity generation sector the buy-back rate is set equal to 90% of the utility's domestic consumer tariff (for autonomous island grids) and to 90% of the utility's mid-voltage (or commercial) price in the mainland of Greece.

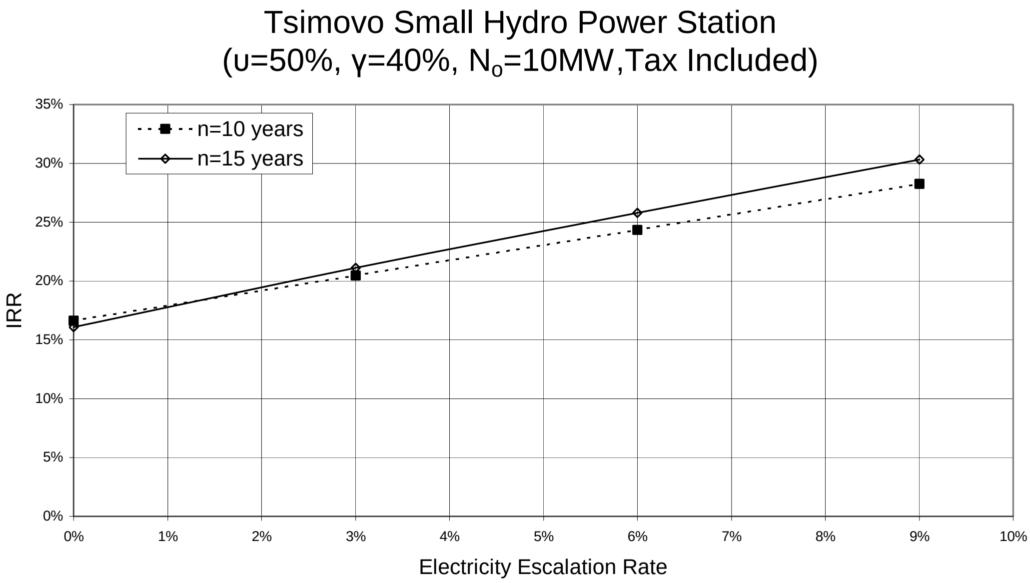

Figure 14: Electricity price escalation rate impact on the IRR value of a SHP station

As expected, figure (14) demonstrates that the "IRR" value is significantly increasing with the electricity price escalation rate. More precisely, there is an almost linear positive relation between "IRR" and "e", leading to 1.5% "IRR" rise as "e" increases by 1%. Similar to previous cases, the impact of operational years is limited, although more intense than the one shown in figures (9) and (12).

5.6 Maintenance and Operation Cost Inflation Rate

The inflation rate expresses the tendency of everyday life cost to increase in the course of time. Thus, the M&O cost inflation rate "g_m" describes the annual escalation of the M&O cost, in view of the annual changes of labour cost and the corresponding spare parts. Generally speaking, M&O cost inflation rate follows the market inflation rate tendency, being usually one or two percentage units lower[15].

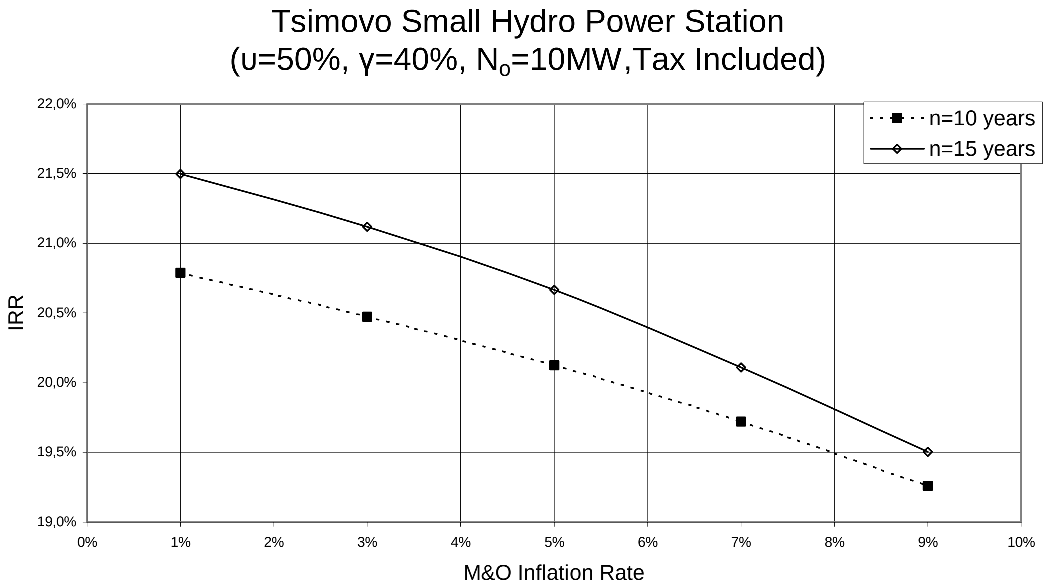

Figure 15: Inflation rate influence on the IRR distribution of a SHP station

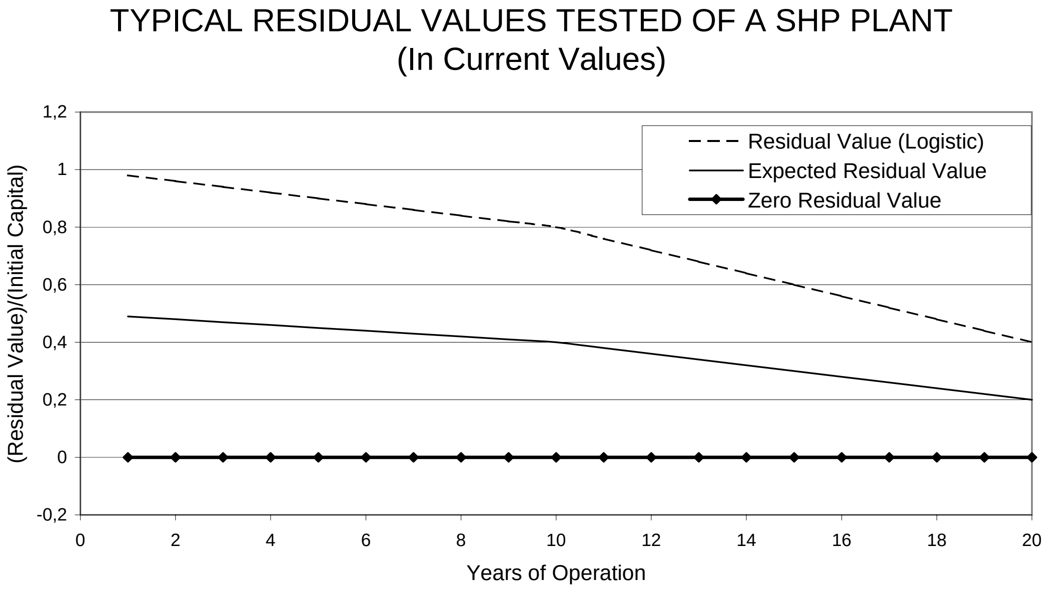

Figure 16: Typical residual value profiles of a SHP station with time

In this context, M&O cost inflation rate has a negative and relatively small direct influence on the "IRR" value of a SHP plant, figure (15), since an almost 8% change of "g_m" practically imposes a 2% on the 15-year "IRR" value and an 1.5% on the 10-year "IRR" value decrease.

5.7 Investment Residual Value

As already mentioned, the residual value of an investment after n years of operation considers the current value of the installation. This numerical value is usually predicted using at first logistic methods (based on depreciation models and taking into account the financial obligations of the enterprise) and then qualitative estimations regarding the experience gained and the corresponding technological know-how transfer that cannot easily be quantified. Additionally, the impact of investment residual value is normally investigated after the 5-th year of operation, given that five years is the normal loan amortization period.

In the present analysis, three typical residual value profiles versus time are utilized; figure (16). The first distribution assumes a time variation of the investment residual value, given as a ratio to the initial capital invested "υ", resulting from the enterprise logistic balance-sheet historical data, with the exception of every component that cannot be easily quantified (e.g. experience, know-how, etc.). Bear in mind that the terms presented are in current values; hence their present value should regard the corresponding depreciation factor. The second profile is equal to the former one multiplied with one half (½). This case is analysed in order to look into difficulties related with the liquidation process of a SHP enterprise. It is worth mentioning that similar enterprises cannot easily be sold in Greece, due to lack of relative experience.

Finally, the last prospect examined assumes zero residual value of investment, independently of the years of operation. Such an extreme situation may be the case of either granting the installation to local municipalities or abandoning the plant for various reasons. To be more realistic, in case the investment is subsidized, the law does not permit change of the enterprise's capital stock before a decade of operation.

In this context, the impact of investment residual value on the corresponding "IRR" distribution versus time may observed; see figure (17). According to the results presented, the impact of different residual value distributions is important for the first decade of operation. After this period, the "IRR" profiles converge, almost independently of the residual model adopted, especially after the 15-th year of operation. Additionally, the investment "IRR" value is remarkably increasing with time as "υ" varies between 0 and 0.5. On the other hand, the "IRR" values are decreasing with time if "υ" is equal to the case (i) distribution, due to the impact of the first installation cost subsidization. Finally, in any case the "IRR" value is above 20% for 10 years of operation of the investment under investigation, while the residual value of the investment is in proportion to the corresponding "IRR" value.

5.8 Taxation Impact

According to the existing tax-law, every energy production company pays an amount per annum, mostly attributable to the gains of the previous year. This amount depends on the law defined tax coefficient "φ", the investment revenue, the annual maintenance and operational cost, the debt repayment method, the investment depreciations etc.

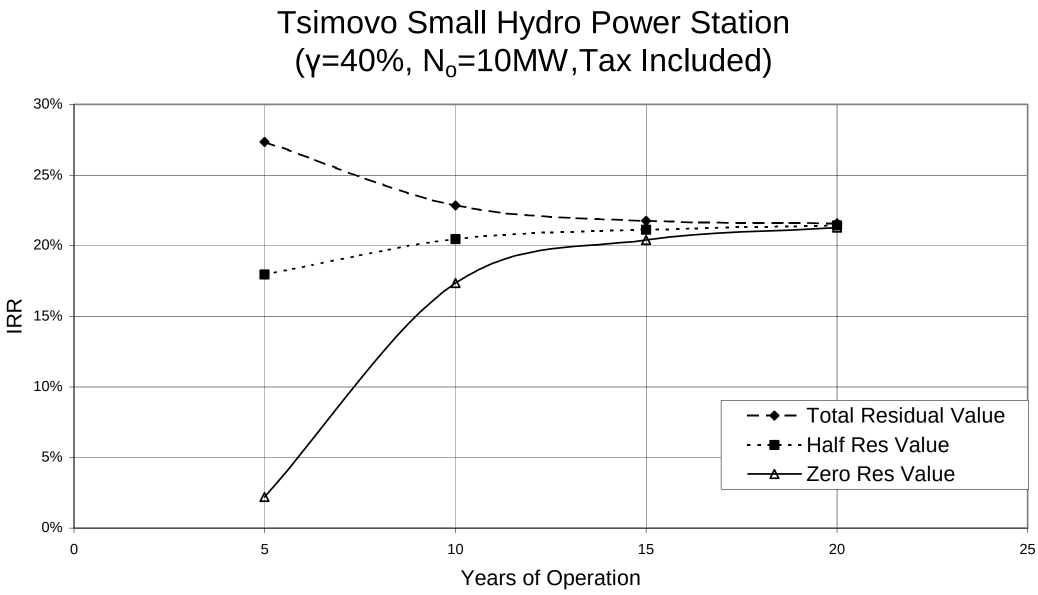

Figure 17: Operation years and residual value impact on the IRR distribution of a SHP station

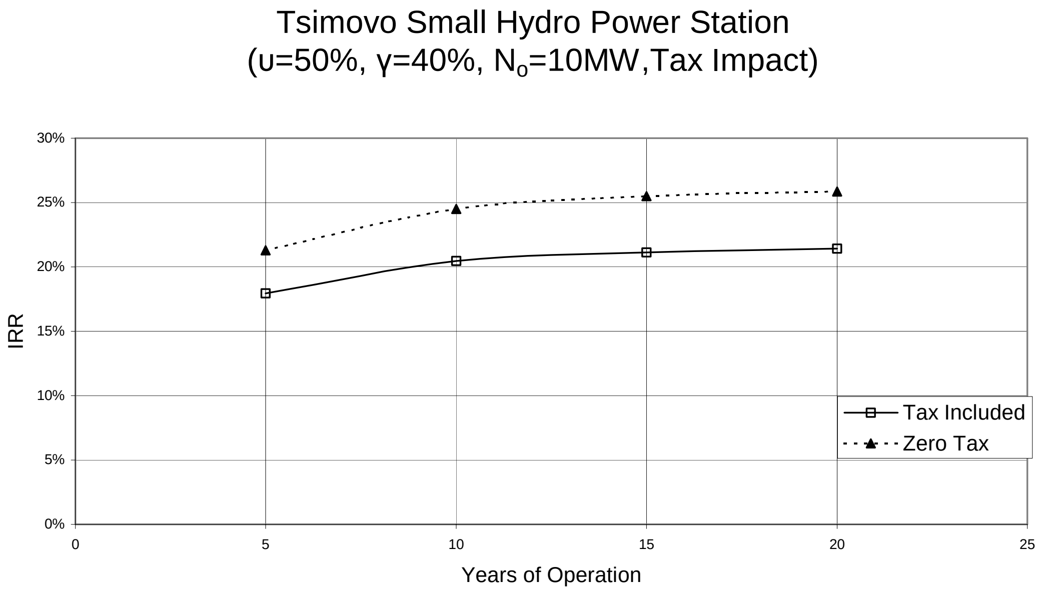

Figure 18: Tax Impact on the IRR distribution of a SHP station

As most other countries, Greek State exercises several investment taxation alternatives in order to encourage new ventures based on either local or international capitals. For this purpose, several tax coefficient values -ranging from 0% up to 35%- are applied. Thus, figure (18) states that although the taxation does not change the "IRR" versus time distribution (as the residual value does), it reduces the corresponding "IRR" values from 3% for a 10-years operation period up to almost 5% for longer service period of the power plant.

Table III: Small hydro power station cost-benefit assessment. Sensitivity analysis results.

Parameter	Range of Values	Impact on IRR	Relative Change*
CF	20%-60%	Linear Positive	(+0.5%)/(1%)
z	1-3	Parabolic	-
Pr	1000€/kW-2000€/kW	Negative (Hyperbolic-Linear)	(-17%)/(1000€/kW)
γ	0%-40%	Positive	(+10%)/(40%)
e	0%-9%	Linear Positive	(1.5%)/(1%)
g_m	1%-9%	Negative (Linear-Parabolic)	(1.5%-2%)/(8%)
υ	0%-100%	Positive	(5%-2%)/(100%)
φ	0%-35%	Negative	(4%-5%)/(35%)

* *In case of two values, the first is for 10-years and the second for 15-years of operation*

Recapitulating, one may classify the impact of all above-analysed parameters on the "IRR" value of a SHP (see Table III) as follows:

✓ The installation capacity factor and the electricity price escalation rate affect the "IRR" value of the investment quite positively

✓ The State subsidization and the residual value of the examined power station undeniably influence quite positively the corresponding "IRR" value

✓ The impact of the first installation (reduced) cost increase on the "IRR" value is strongly negative

✓ The maintenance & operation cost inflation rate and the tax coefficient increase affect the financial viability of the investment in a negative way

✓ The number of the hydro turbines used in the plant, given the maximum rated power, imposes a parabolic distribution of the corresponding "IRR" value, providing the opportunity to select the optimum configuration of a SHP station.

6. Conclusions

An extensively thorough techno-economic analysis is hereby presented, concerning the small hydropower installations in Greece, together with the most important parameters of the problem. The method applied is based on a well-elaborated theoretical model, on long-term measurements and real market techno-economic information. For this purpose, a numerical code is developed in an "expert-type mode", in order to predict the resulting "IRR" values of any similar type investment under variable external conditions. On top of this, this numerical tool is used to carry out a comprehensive sensitivity analysis, so as to demonstrate the impact of the main techno-economic parameters on the behaviour of a SHP venture for ten or fifteen years of operation.

According to the results obtained, the predicted "IRR" values of a SHP installation are greater than 18% for most cases analysed, in comparison with the local economy inflation rate of 3.5% and with the corresponding market annual capital cost of 6-8%. Subsequently, the "IRR" value maximizes after ten to fifteen years of operation. It is also worth mentioning the insignificant "IRR" amendment upon increase of the installation service period; a fact that undermines the long-term operation of similar applications mainly due to the current subsidization practice. This fact is contradicting the established international opinion that hydropower plants are generally characterized as long-term investments.

The sensitivity analysis provides clear evidence that the installation capacity factor, the annual escalation rate of local market electricity price and the reduced first installation cost are the parameters that mostly affect the viability of a SHP station. Finally, the current subsidization scheme is definitely necessary to encourage similar investments, leading however in several peculiarities. For example, the current first installation cost subsidization status principally supports installations with high capacity factor values instead of sites possessing lower hydraulic potential, although latter cases need further financial support to be realized.

Summarizing, several opportunities for sequence of small hydropower plants developments subsist in the mainland of Greece, which -if properly designed and realized- should lead to considerable profits, contributing in the country's independency from imported oil and accomplishing the Kyoto protocol obligations.

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RENEWABLE ENERGY DESALINATION PLANTS FOR THE GREEK ISLANDS, TECHNICAL AND ECONOMIC CONSIDERATIONS

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Abstract

For the majority of the Greek islands, the water resources are quite restricted, limiting the economic development of the local societies. To face the increased potable water requirements, more than 2,500,000m^3 of clean water is transferred annually to these islands at a cost approaching the value of 7€/m^3. On the other hand, the final cost of the locally produced water from renewable energy sources (RES) based desalination plants is expected to be quite lower than this value. In this context, the main purpose of the present study is to examine the economic viability of several representative desalination plant configurations based on the available renewable energy sources, using an integrated cost-benefit analysis. In the proposed analysis, all the cost parameters of the problem are taken into consideration, including the capital cost of the desalination plant, the annual maintenance and operation cost, the energy consumption cost, the local economy annual capital cost index and the corresponding inflation rate. The calculation results obtained definitely support the utilization of RES based desalination plants, as the most promising and sustainable method to satisfy the fresh, potable water demands of the small-medium sized Greek islands at a minimal cost, without disregarding the considerable environmental and macro-economic benefits.

Keywords: Desalination; Renewable Energy Sources; Greek Islands; Water Resources; Production Cost; Cost-Benefit Analysis

Nomenclature

c_D	imported from the local network electricity purchase cost (€/kWh)
c_e	electricity production cost of the proposed hybrid station (€/kWh)
c_w	desalinated water production cost of the proposed hybrid station (€/m^3)
d_w	desalinated water autonomy of the island (number of days)
E	annual electricity generation by the proposed hybrid station (kWh)
E_D	imported energy from the local network (kWh)
e_D	imported energy price annual escalation rate
e_E	produced energy cost annual escalation rate
FC^{ep}	fixed maintenance & operation cost of the electricity generation station
FC^{w}	fixed maintenance & operation cost of the desalination plant
f_x	auxiliary function concerning parameter "x", see also equation(16)
g^m	maintenance & operation cost annual inflation rate
h_1	reverse osmosis desalination plant reduced cost (€/m^3)
h_2	water storage reservoir specific cost (€/m^3)
IC_i	total installation cost of component "i" of the proposed hybrid station (€)
IC_o	autonomous hybrid system total initial cost (€)
i	return on investment index
i'	local market capital cost
m	electricity generation maintenance & operation cost coefficient
n	service period of the installation
p_e	electricity price in the local market (€/kWh)
UF	desalination plant utilization factor (equation14)

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.*

V_o	desalination plant daily capacity (m^3/day)
V_{st}	water storage reservoir volume (m^3)
V_t	annual desalinated water production (m^3)
w	water price annual escalation rate
α	invested own capital fraction (%)
β	invested loan capital fraction (%)
γ	State subsidization percentage (%)
ε_{DP}	specific electricity consumption of the desalination plant (kWh/m^3)
ξ	desalination plant maintenance & operation cost coefficient

1. Introduction

The seawater desalination industry has installed a total water production capacity approaching 30 million cubic meters of fresh water per day, in some 12,500 plants over the past 30 years. In the course of the last ten years, new plant installation has averaged about 1,200,000 cubic meters per day annually. This activity represents about $1.5 billion in equipment sales or about $3 billion in total capital cost for installed plants on annual basis[1].

Seawater desalination methods may be classified[2] into those involving a phase transition (distillation methods) and the so called membrane methods, such as reverse osmosis (RO). In terms of capacity, the majority of installed systems continue to be distillation technology, although recently reverse osmosis technology increases its worldwide contribution. More precisely, multi-stage flash distillation and RO represent about 86% of the total distillation capacity. Bear also in mind that RO is commercially available in a range of sizes and has much lower specific power consumption than the average one[3]. On top of that, the RO seawater desalination solution is found to be the best alternative, especially for applications in remote, often off-grid, areas with small and medium local water demand, such as islands or isolated villages in coastal areas[4].

Up to now, desalination systems using Renewable Energy Sources (RES) as their energy input source is scarce and of limited capacity. They only represent about 0.02% of the total desalination capacity[5]. However, there are significant financial and social benefits of using RES for desalination, especially in remote regions with water deficit[6]. This interest is reflected in several works that appear lately in the literature, dealing with technological issues and the economic, social and environmental impacts of the RES driven desalination plants[7][8][9].

2. Current Water Supply Status in the Greek Islands

The Aegean Archipelago islands are located at the southeastern part of Europe, figure (1). The main characteristics of these islands are the dry Mediterranean climate and the relatively long distance from the mainland, resulting to an economic development deficit with the rest E.U. regions. For the vast majority of these islands the water resources are quite restricted, thus deteriorating the life-quality level of the habitants[10]. 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 sometimes even ten times more than the normal, figure (2). 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 the 50%÷80% of the fresh-water needed is transferred at a very high cost.

The best solution to the islands water supply problem depends on a number of parameters, such as the water needs and their time and quantity distribution during a year, the infrastructure of the island, its size and morphology, the economic activities, the population and its seasonal fluctuation, as well as the extent of the water shortage. The problem has been studied extensively in the past years[1][11][12][13][14] and various short, medium and long term solutions have been proposed and -some of them- implemented, such as:

Figure 1: Cyclades and Dodecanese complex islands presenting water deficit

- The construction of new surface water reservoirs, combined with water refineries, as well as the efficient operation of the existing water reservoirs
- The construction of new water dams
- The construction of new desalination plants, since significant progress has been achieved in the cost reduction of the desalinated water
- Transportation of water from other neighbouring islands or from mainland (Athens), but only in cases where other methods cannot be applied
- Improvement of the island’s infrastructure, e.g. the replacement of the water supply networks in order to eliminate water loss
- Collection of the rainwater in domestic or public water cisterns
- Construction of a second parallel water supply network for uses that do not require high quality of water
- Waste water treatment and reuse of the treated water effluence for secondary uses (irrigation, cleaning, construction works, harbours, etc.)
- Appropriate pricing policy and rational demand management

The above mentioned various solutions to the water shortage problem differ in suitability, difficulty and capital cost. A serious consideration that needs to be taken into account is the reliability of the proposed solution to guarantee the water supply of the island for a long time horizon. In this context, one of the most widely considered solutions in the Aegean Archipelago region is the construction of water reservoirs that are always combined with water treatment plants (approximate turnkey cost of 1.5 to 3 million €). The water reservoirs have almost no operating cost and are a long term, sustainable solution to the water shortage problem, which however require significant precipitation and suitable land and soil. Unfortunately, during the last forty years a remarkable (approximately 20mm per year) precipitation decrease is encountered[15] for the area under investigation, see also figure (3).

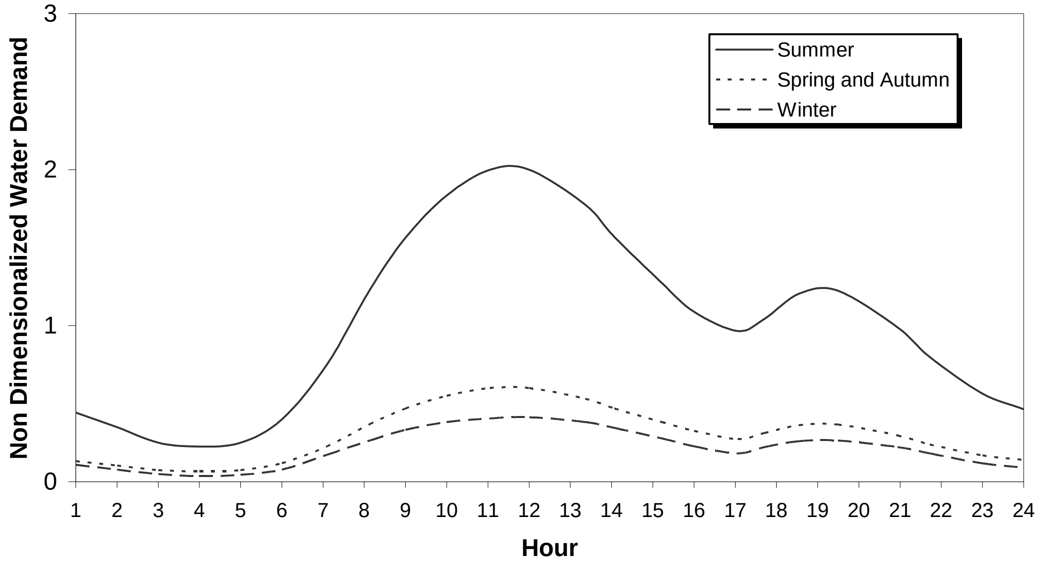

Figure 2: Typical daily water demand profile for a remote island

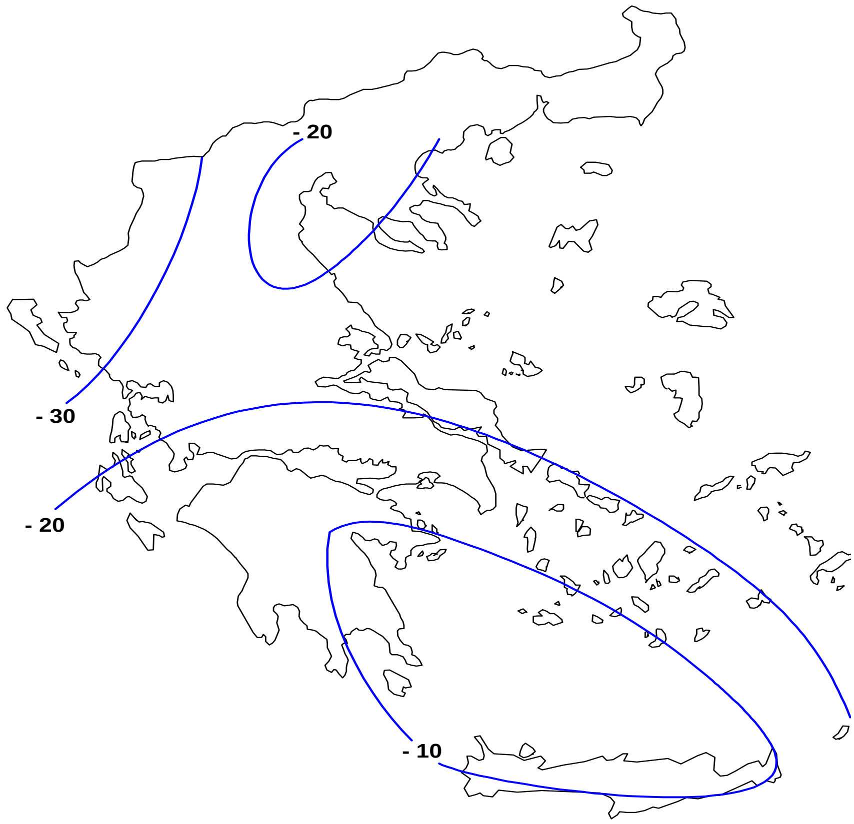

Figure 3: Spatial distribution of the decreasing precipitation trend in Greece

Another alternative solution that has already been implemented in various cases is the construction and operation of desalination plants. The operating cost of current-technology desalination plants is still important, mainly due to their high energy consumption and the cost of the membranes replacement in the case of RO systems. Therefore, one of the main issues for the viable operation of these plants is to reduce their total energy cost. At this point one may take into consideration the possibility of utilizing the energy surplus by already operating or under development electricity generation stations based on

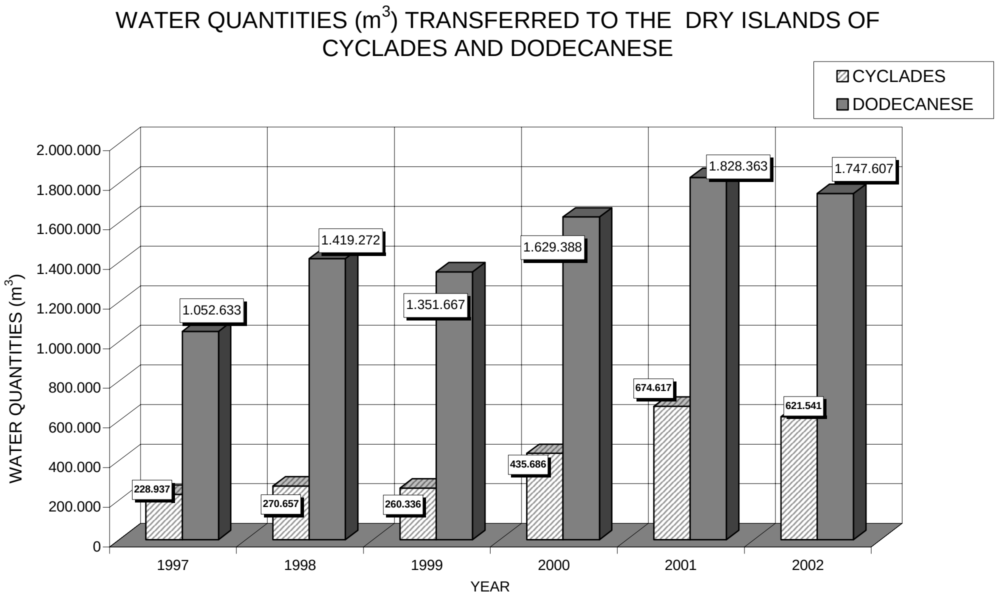

Figure 4: Quantities of water (m^3 per year) transferred to the dry islands of Cyclades and Dodecanese during the period 1997-2002[19]

Renewable Energy Sources exploitation, not absorbed by the local autonomous electrical networks especially during low consumption periods[16][17][18].

Until now, most of the water demand of the small Greek islands is covered by the water transportation with water carrying boats. Today, water is officially transported to eleven (11) Cyclades islands and nine (9) Dodecanese islands.

In the Tables I and II the official data[1][19] concerning the water transportation to the above mentioned (20) islands is shown for the 1997-2002 period. Accordingly, in figure (4) one may examine the time evolution of the total transferred water quantity for Cyclades and Dodecanese complex islands respectively. As it is obvious from the data analyzed, there is a considerable water import increase in both areas, thus the current total water needs are officially estimated (2002) to be almost 2,500,000m^3 per year in comparison with the 1,300,000m^3 needed during 1997. Additionally, the specific islands investigated may be divided in three categories on the basis of their average summer season daily water deficit. It is important to note that the summer average water demand is approximately three times higher than the corresponding annual value, figure (2). More specifically,

- The first group contains islands with summer average daily water deficit between 1000 and 2500m^3/d. According to Tables I and II these islands are the islands of Koufonisi, Kimolos, Tinos, Milos, Lipsi, Megisti, Nisiros, Patmos, Simi and Halki.
- In the second group of 100 to 250m^3/d average summer daily demand, one may include the following islands: Amorgos, Heraklia, Shinousa, Folegandros, Sikinos, Thirasia and Agathonisi.
- Finally, the third group (average summer daily demand between 10 and 25m^3/d) includes the islands of Donousa, North Kalimnos and Pserimos. In this category one may incorporate several other small islands not appearing separately in Tables I and II, since their import limited water quantities from their neighboring bigger islands.

Table I: Quantities of water (m^3 per year) transferred in 11 Cyclades islands during the period 1997-2002[19]

ISLAND	YEAR 1997	1998	1999	2000	2001	2002
AMORGOS	59.721	62.012	72.400	39.824	56.200	51.778
KOYFONISI	68.540	83.992	77.241	86.136	91.439	84.245
KIMOLOS	41.585	53.089	48.055	72.011	88.431	81.474
HERAKLIA	15.231	19.457	22.729	26.705	35.628	32.825
SHINOUSA	23.640	35.731	10.067	34.160	41.673	38.394
FOLEGANDROS	20.220	16.376	29.844	37.359	48.481	44.667
TINOS	-	-	-	110.143	105.112	96.842
SIKINOS	-	-	-	29.348	42.699	39.540
THERASIA	-	-	-	-	24.211	22.906
DONOUSA	-	-	-	-	880	-
MILOS	-	-	-	-	139.863	128.859
TOTAL	**228.937**	**270.657**	**260.336**	**435.686**	**674.617**	**621.541**

Table II: Quantities of water (m^3 per year) transferred in 9 Dodecanese islands during the period 1997-2002[19]

ISLAND	YEAR 1997	1998	1999	2000	2001	2002
AGATHONISI	8.892	15.558	21.388	25.941	33.361	31.887
LIPSI	77.770	94.168	79.600	105.607	166.533	159.177
MEGISTI	72.927	108.161	125.420	135.491	150.594	143.942
NISIROS	117.491	131.410	153.760	235.093	259.245	247.795
PATMOS	253.616	311.599	380.319	482.367	606.788	579.987
SIMI	521.350	591.378	451.245	515.450	433.193	414.059
CHALKI	0	166.264	138.761	126.006	169.258	161.782
NORTH KALIMNOS	587	734	1.174	3.081	2.348	2.244
PSERIMOS	-	-	-	352	7.043	6.732
TOTAL	**1.052.633**	**1.419.272**	**1.351.667**	**1.629.388**	**1.828.363**	**1.747.607**

According to the international experience, the water transportation method is applied in cases that no other solution seems feasible and the possibilities for water supply from drilling have been exhausted. On top of that, this solution has definitely temporary character and it is one of the most expensive methods. Despite the above mentioned disadvantages, this solution is adopted by the Greek State at the present. More specifically, the Ministry of Aegean funds[19] the water transportation, allocating a very significant part of its budget to this activity. The cost of transferred water for the Cyclades islands is 7.3€/m^3+VAT, while for Dodecanese complex the corresponding value is 4.1€/m^3+VAT (2003 prices). Take into consideration that the cost difference encountered may be attributed to the fact that the water is transferred in Cyclades islands from the Water and Sanitary Company of Athens network, while the water in Dodecanese complex is mainly transferred from Rhodes island[19][20], see also figure (1).

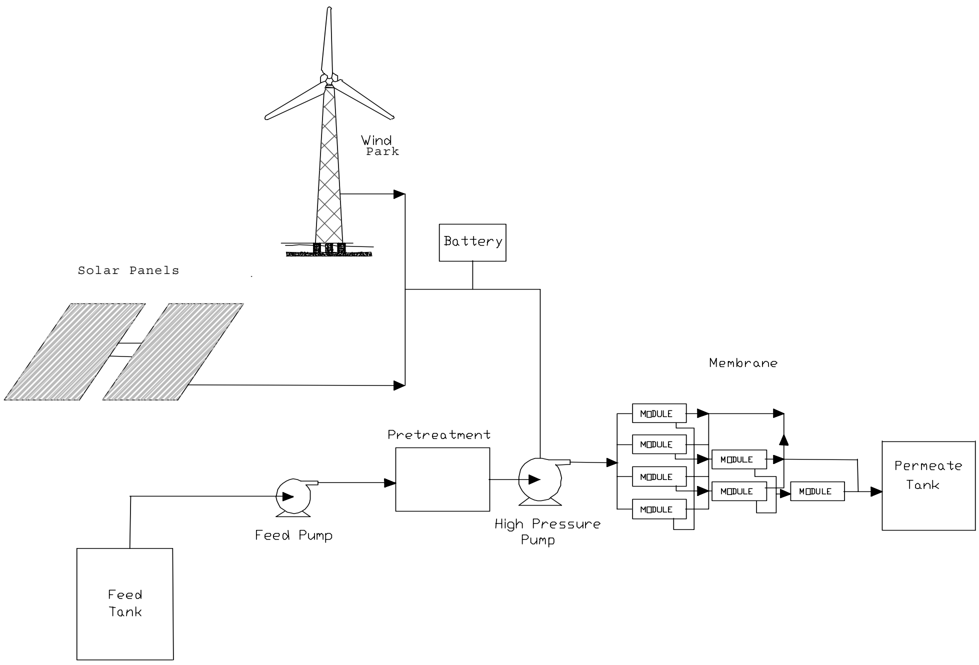

Figure 5: Schematic presentation of an integrated electricity and water production system for remote islands

Recapitulating, a sustainable solution of the water shortage problem for a significant time horizon must be able to guarantee water supply sufficiency in each island, without dependency from external conditions.

3. Proposed Solution

In an attempt to solve this serious problem, several alternative solutions have been elaborated, according to which fresh-water supply for an island community is based on a combination of a wind converter and a photovoltaic plant, while additional electrical energy is bought from the existing autonomous electrical network or from an existing backup diesel generator. In all these cases, the wind turbine or the photovoltaic station was almost exclusively used to feed the existing RO plant and only the excess of energy -not used by the RO station- was sold to the grid[11][12]. Moreover, in several cases, electrical energy is directly bought from the local grid to cover the energy demand of the desalination plant.

In the present alternative, the fresh water production activity belongs to an integrated solution for the energy and clean water demand problem of a remote society[10], on the basis of an hybrid energy production station, see figures (5)-(6). By adopting the proposed formulation, not only the electricity demand problem is solved but also the fresh water can be produced at a minimal cost.

More specifically, the proposed solution is based on a wind-photovoltaic and small hydropower station used to cover the electricity demand of a remote community on the basis of the available RES potential. A properly sized[21] energy storage system (e.g. a water pumping station, a battery bank etc.) is used to match the variable electrical energy demand with the practically unpredictable electricity generation by the RES production stations. In addition, during the low electrical energy consumption periods of the day, electricity is forwarded to the desalination plant. In the extreme case of zero electricity production by the RES stations (including the existing energy storage devices), the corresponding energy demand is covered by the existing thermal power units (mainly diesel generators).

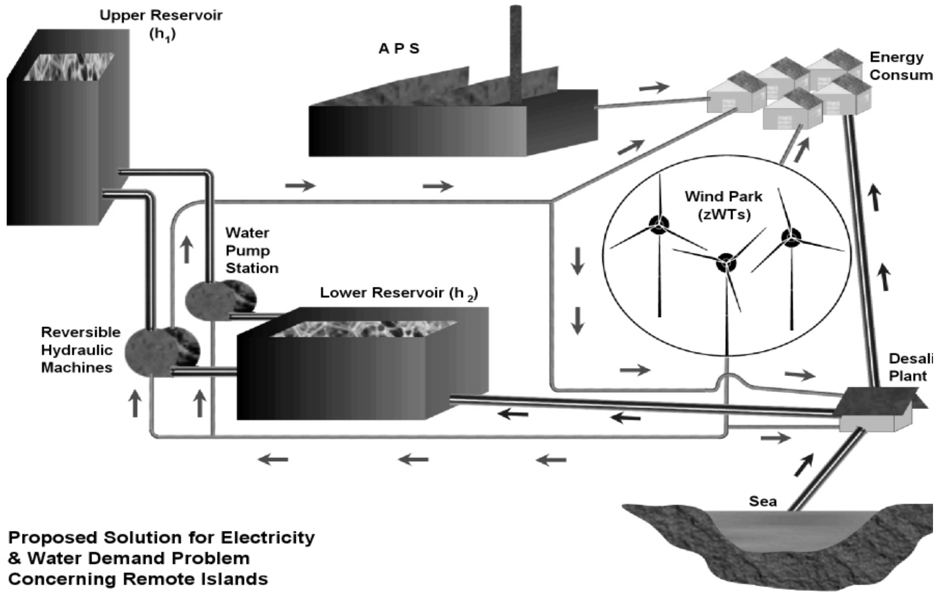

Figure 6: Schematic presentation of an integrated electricity and water production system for remote islands

Accordingly, the economic viability and attractiveness of several desalination plant configurations -based on the reverse osmosis technique- is examined, using an integrating cost-benefit analysis[6]. During the proposed analysis, all the governing parameters of the problem are taken into consideration, including the first installation cost of the desalination plant, the annual maintenance and operation cost, the energy consumption cost, the local economy capital cost and the corresponding inflation rate[22][23][24].

As mentioned above, the fresh water marginal production cost is strongly depended on the energy input cost of the desalination plant. In cases that the energy demand is covered by the energy surplus of an autonomous renewable energy station (i.e. the necessary energy is practically donated to the habitants), a remarkable decrease of clean water production cost is encountered. However, in the present analysis the electrical energy consumed by the desalination plant is charged according to the existing national price list for industrial users.

4. Cost Model Development

4.1 Investment Cost

The future value (after –n years of operation) of the investment cost of a combined energy and clean water production installation is the sum of the initial installation and the corresponding maintenance and operation (M&O) cost, both expressed in current values[6][22].

The initial investment cost "IC_o" includes the market price of the energy production station "I_{EP}", based mainly on renewable energy production equipment (i.e. wind turbines, small hydro-turbines, photovoltaic panels) along with the corresponding installation cost. Additionally, the desalination plant's initial cost "IC_{DP}" should also be taken into account. In both initial cost values, energy and clean water storage systems' costs are also included, along with the corresponding cost of the necessary control devices. In cases that an APS (autonomous power station) is employed as a stand-by system, its initial cost value should also be added. Consequently, the turnkey price "IC_o" of the combined electricity- desalinated water production system is given as:

$$IC_o = IC_{EP} + IC_{DP} \quad (1)$$

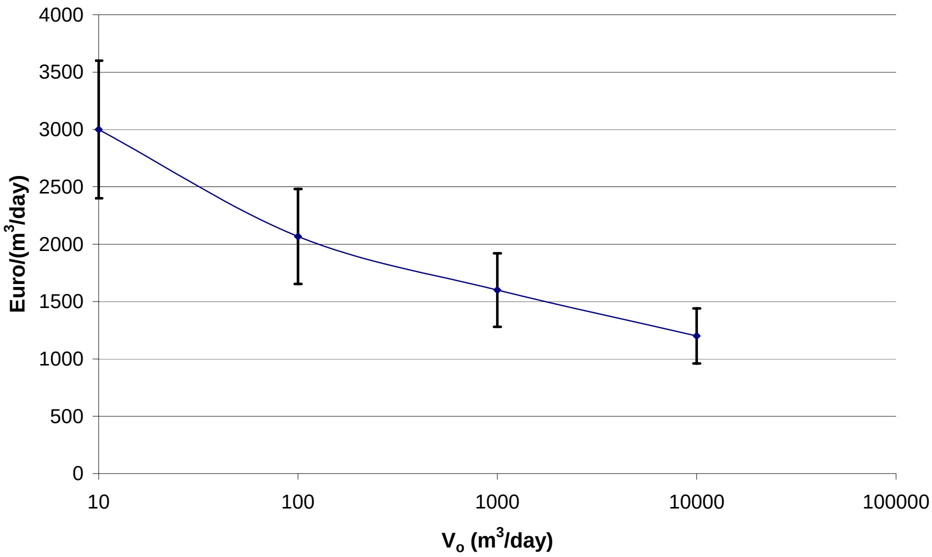

Figure 7: Reduced first installation cost of an RO desalination plant

where:

$$IC_{EP} = IC_{WP} + IC_{PV} + IC_{HP} + IC_{SS} + IC_{CD} + IC_{D} \quad (2)$$

and

$$IC_{DP} = IC_{PP} + IC_{st} \quad (3)$$

More details concerning the initial cost of a wind park "IC_{WP}", a small hydro-power station "IC_{HP}", a photovoltaic station "IC_{PV}", a diesel station "IC_{D}", an energy storage system "IC_{SS}" and the corresponding control devices "IC_{CD}" can be found in references[22][23][24][25] respectively. As it is logical, some terms may not appear in the RHS of equation (2), e.g. $IC_{HP}=0$ in case that no hydropower station exists.

Similarly, the initial cost of an RO desalination plant "IC_{PP}" can be expressed (after a market survey)[6] as a function of the nominal per day water production capacity "V_o", thus one gets:

$$IC_{PP} = h_1 \cdot V_o \quad (4)$$

with $h_1=h_1(V_o)$ given in figure (7).

Also, the corresponding investment cost for the desalinated water storage reservoir "IC_{st}" can be estimated[26] as:

$$IC_{st} = h_2 \cdot V_{st} \quad (5)$$

with $h_2=h_2(V_{st})$ is given in figure (8).

In cases that the desalination plant uses the lower reservoir of a wind-hydro station (see figure (6)) or any existing natural dams and lake-tanks[13] are exploited, the "IC_{st}" term is practically eliminated.

Summarizing, the future value of the initial investment cost[22] can be expressed as:

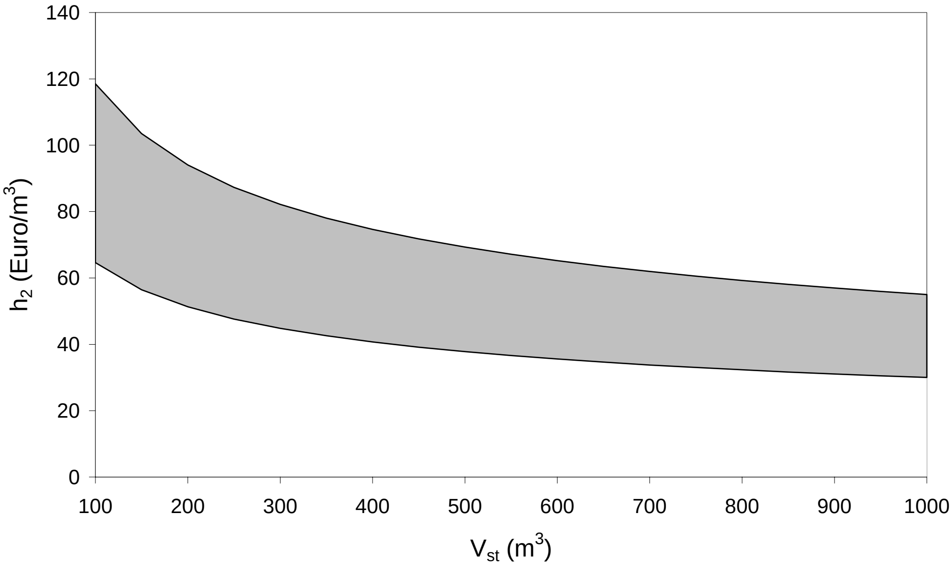

Figure 8: Reduced investment cost for a water storage reservoir

$$IC_n = \alpha \cdot IC_o \cdot (1+i)^n + \beta \cdot IC_o (1+i')^n \tag{6}$$

where:

$$\alpha + \beta = 1 - \gamma \tag{7}$$

and "γ" is the subsidy percentage by the Greek State. According to the existing Greek Development Law (2601/98), renewable energy and desalinated water production investments are supported with a 40 percent subsidy, for all over the country. The first term of the RHS on equation (6) describes the invested capital "$\alpha.IC_o$" future value ("i" return on investment index), while the second term expresses the corresponding cost (" $i^{/}$ " capital cost) of the loan capital, "$\beta.IC_o$".

Accordingly, the maintenance and operation (M&O) cost can be split into the fixed maintenance cost "FC_n" and the variable one "VC_n". The variable M&O cost mainly depends on the replacement of some major parts of the installation, with shorter lifetime than the complete installation. This term becomes important only for long service period of the installation. For simplicity reasons, the variable M&O cost is not explicitly analyzed here. Furthermore, during the first years of operation the corresponding term is incorporated in the fixed M&O cost[27].

More precisely, the annual fixed M&O cost of the energy production system can be expressed as a fraction "m" of the corresponding initial capital invested (assuming also an annual increase of the cost equal to the M&O cost annual inflation rate "g^m"[22]) plus the energy purchase value by the existing thermal power station (belonging to the local electrical utility). Thus, one gets for the future value "FC_n^{ep}":

$$FC_n^{ep} = m \cdot IC_{EP} \cdot (1+i)^n \cdot \sum_{j=1}^{n} \left[\frac{1+g^m}{1+i} \right]^j + E_D \cdot c_D \cdot (1+i)^n \cdot \sum_{j=1}^{n} \left[\frac{1+e_D}{1+i} \right]^j \tag{8}$$

with "E_D" the imported electricity production quantity by the local APS and "c_D" the corresponding current price. Keep also in mind that "e_D" is the electricity price average escalation rate (usually coincides to the fuel escalation rate).

On the other hand, the corresponding annual fixed M&O cost of the desalinated water production plant is given on the basis of the annual desalinated water production volume, using the coefficient "ξ" in €/m^3 (an annual increase "g^m" is also included), plus the annual energy consumption "$\varepsilon_{DP} \cdot V_t$" cost value "$c_e$". More precisely, we get:

$$FC_n^w = \xi \cdot V_t \cdot (1+i)^n \cdot \sum_{j=1}^{n} \left[\frac{1+g^m}{1+i}\right]^j + \varepsilon_{DP} \cdot c_e \cdot V_t \cdot (1+i)^n \cdot \sum_{j=1}^{n} \left[\frac{1+e_E}{1+i}\right]^j \quad (9)$$

where "V_t" is the annual desalinated water production (m^3), "ε_{DP}" is the specific electricity consumption (kWh/m^3) of the desalination plant and "e_E" is the electricity production cost average escalation rate. It is noticed that the value of the specific energy consumption term depends on the applied desalination technology.

4.2 Electricity and Desalinated Water Production Cost

Taking into account the analysis presented by the authors[28], concerning the current electricity marginal production cost, one gets the following equations under the condition that the net present value of the investment becomes zero (NPV=0) after n* years of operation, i.e.:

$$c_e = \frac{\left\{\alpha + \beta \cdot \left(\frac{1+i'}{1+i}\right)^{n^*} + m \cdot \sum_{j=1}^{n^*} \left[\frac{1+g^m}{1+i}\right]^j\right\} \cdot IC_{EP} + E_D \cdot c_D \cdot \sum_{j=1}^{n^*} \left[\frac{1+e_D}{1+i}\right]^j}{E \cdot \sum_{j=1}^{n^*} \left[\frac{1+e_E}{1+i}\right]^j} \quad (10)$$

where "E" is the average annual electricity generation by the integrated hybrid energy production station.

Applying the same analysis for the present value of the desalinated water production cost, we derive the following equation:

$$c_W = \frac{\left[\alpha + \beta \cdot \left(\frac{1+i'}{1+i}\right)^{n^*}\right] \cdot IC_{DP}}{V_t \cdot \sum_{j=1}^{n^*} \left[\frac{1+w}{1+i}\right]^j} + \frac{\xi \cdot \sum_{j=1}^{n^*} \left[\frac{1+g^m}{1+i}\right]^j + \varepsilon_{DP} \cdot c_e \cdot \sum_{j=1}^{n^*} \left[\frac{1+e_E}{1+i}\right]^j}{\sum_{j=1}^{n^*} \left[\frac{1+w}{1+i}\right]^j} \quad (11)$$

where "w" is the clean water cost annual escalation rate.

The resulting calculated value should accordingly be compared with the corresponding market price of the water in each island as to investigate the financial viability of the proposed solution.

5. Application Results

In order to obtain a clear-cut picture of the islands desalinated water production problem, the idea of operating the renewable energy station under the precondition to fulfill the energy requirement of a desalination plant is investigated. In case that the electricity demand is not completely covered by the renewable power system, the energy deficit "E_D" is covered by the operation of the island's APS[10].

Since the investment is mainly based on the desalinated water production revenues, non-special attention is given to minimize the renewable energy production cost "c_e" at this study. According to numerous analyses[22][23][24][28] the renewable energy marginal production cost is only a fraction of the corresponding market price "p_e", i.e.:

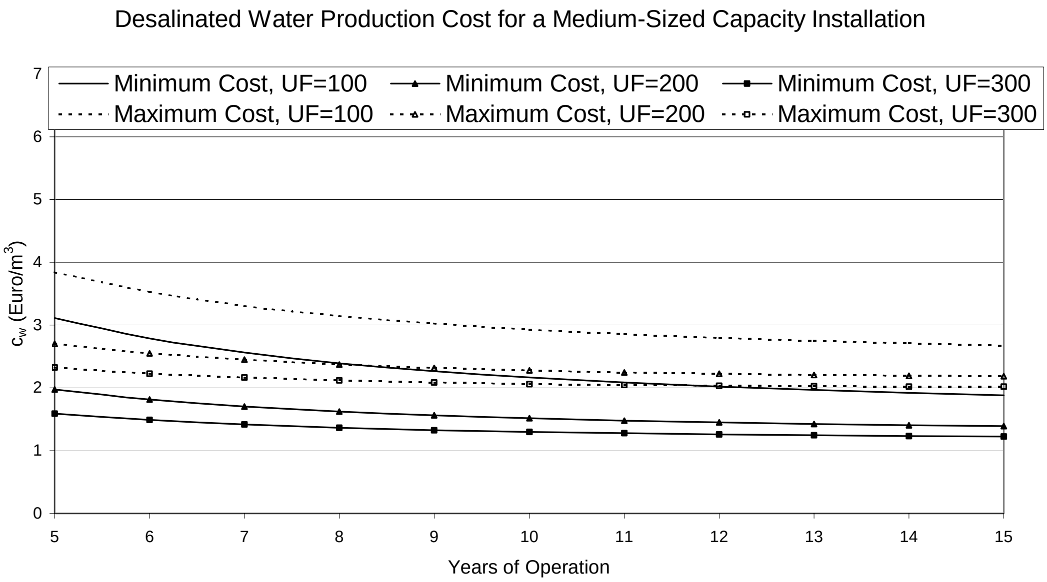

Figure 9: Water production cost for medium-sized capacity installations

$$c_e = \lambda \cdot p_e \qquad (\lambda \leq 1.0) \tag{12}$$

However, one may accept that generally speaking $c_e \rightarrow p_e$.

Using equation (12), one may get for the water production cost that:

$$c_W = \frac{(1-\gamma)}{f_w} \cdot \left\{ \frac{h_1}{UF} + h_2 \frac{d_w}{365} \right\} + \frac{\xi \cdot f_g}{f_w} + \frac{\varepsilon_{DP} \cdot \lambda \cdot p_e \cdot f_e}{f_w} \tag{13}$$

assuming that for an enterprise operating for the social benefit, the return on investment index should be equal to the corresponding market capital cost, i.e. i=i'.

Additionally, the desalination plant utilization factor "UF= V_t / V_o " can be written as:

$$UF = \frac{V_t}{V_o} = \sum_{l=1}^{l=365} \frac{V_l}{V_0} \leq 365 \tag{14}$$

expressing the number of days that the specific desalination plant operates at full capacity. For example, in cases of summer operation only, the desalination plant operates no more than 100 days per year, thus UF=100. On the contrary, for constant desalinated water production operation during the entire year, the corresponding "UF" value tends to the value of 365, but practically never exceeds the value of 300.

Similarly, the water storage reservoir volume "V_{st}" can be expressed as:

$$\frac{V_{st}}{V_t} = d_w \cdot \frac{V_t / 365}{V_t} = \frac{d_w}{365} \tag{15}$$

where "d_w" expresses the number of typical days that the selected reservoir guarantees clean water autonomy of the system, without the operation of the desalination plant.

Finally, one may write:

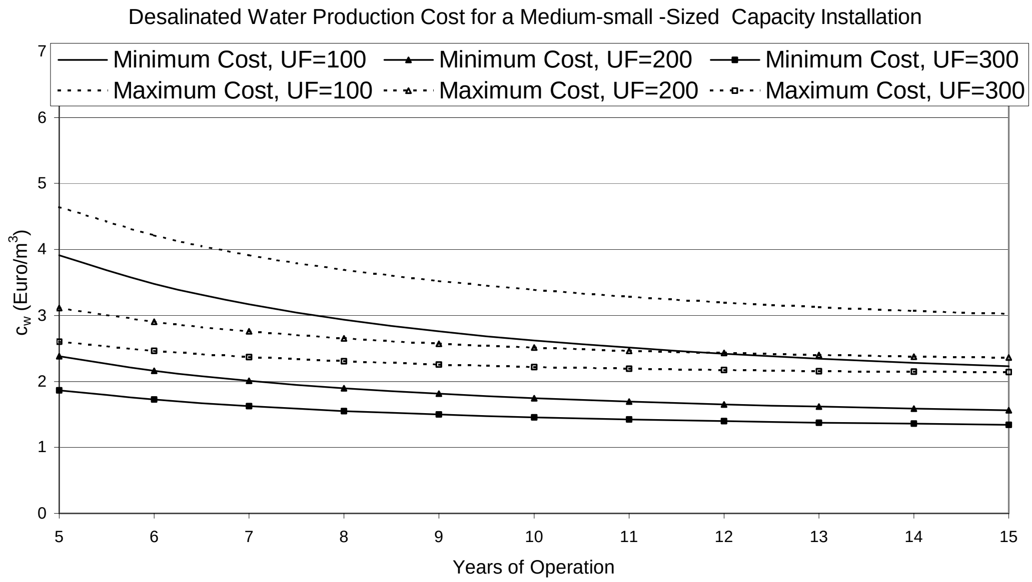

Figure 10: Water production cost for medium-small-sized capacity installations

$$f_x = \sum_{j=1}^{n}\left[\frac{1+x}{1+i}\right]^j = \frac{1+x}{1+i}\cdot\left(1+\frac{1+x}{1+i}+...+\left[\frac{1+x}{1+i}\right]^{n-1}\right) \qquad (16)$$

with x=g; x=e and x=w.

The proposed analysis is subsequently applied for a medium-sized capacity installation (V_o=1000÷2500 m^3/d), a small capacity installation (V_o=100÷250 m^3/d) and a very small one (V_o=10÷25 m^3/d). The calculation results for each category are summarized in figures (9)-(11) respectively for various combinations of input energy and maintenance & operation cost and several "UF" values. More specifically, for the calculations carried out, the parameters of equation (13) take the values of Table III. In figures (9)-(11), the maximum production cost results using the maximum "ε" and "ξ" values of Table III, while the corresponding minimum production cost analysis takes into account the minimum "ε" and "ξ" values.

Table III: Typical Numerical Values of the Main Parameters of the Proposed Analysis

α	γ	i	p_e	λ	g^m	ε	e	ξ	d_w	w	UF
0.3	0.4	5%÷15%	0.041 €/kWh	1	4%	8÷20 kWh/m^3	4%	0.45÷0.65 Ecu/m^3	1	0%÷6%	100,200,300

According to the results obtained:

- There is a remarkable production cost decrease (between 1€/m^3 and 1.8€/m^3) with the years of operation of the proposed investment, especially realized between the fifth and the tenth year of operation.
- The scale of the total annual consumption (medium or small size island) strongly influences the water production cost. For example the maximum production cost for a small capacity installation is almost 2€/m^3 higher than the corresponding production cost of a medium size one.
- The impact of the utilization factor "UF" on the production cost is dominant, especially in the range of 100 and 200 full days of operation per year. Hence, for 5 years of operation the water production cost drops by almost 2€/m^3 (1.1€/m^3 for medium-sized capacity installations) if the utilization factor increases from 100 to 200 days per year.

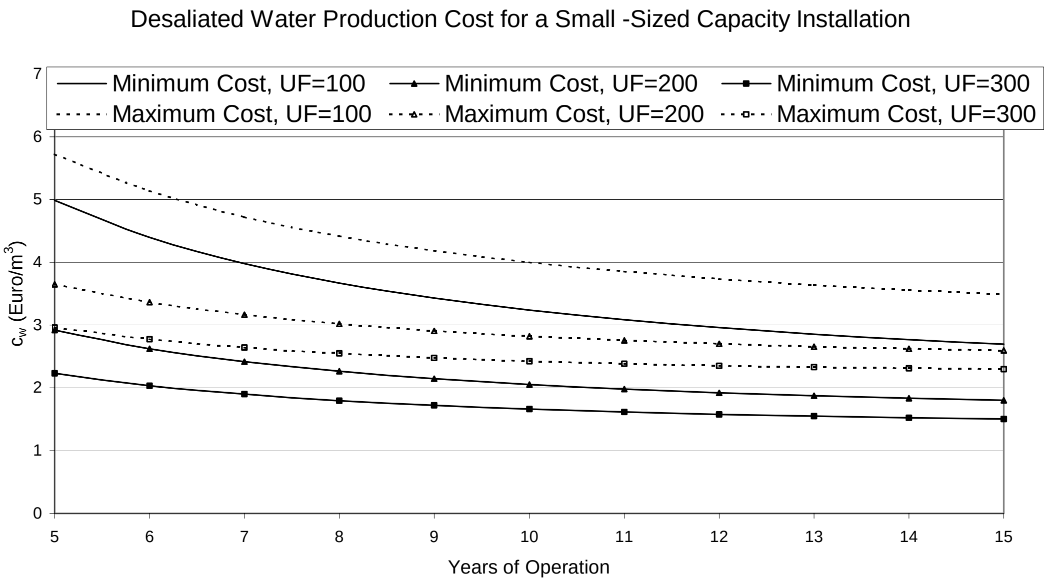

Figure 11: Water production cost for small-sized capacity installations

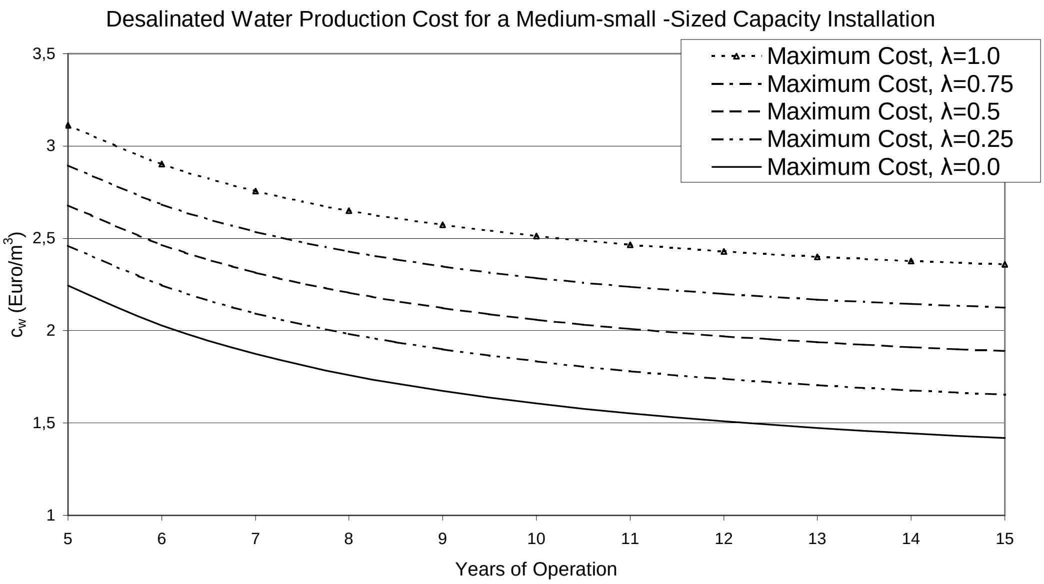

Figure 12: Electricity pricing impact on water production cost in remote islands

- A significant production cost decrease may be realized by decreasing the specific M&O cost "ξ" and the reduced electrical energy consumption "ε" of the installation.
- In any case, the marginal production cost of the proposed solution is less than 7.3€/m^3 (current price of the imported water for Cyclades islands) and generally less than 4.1€/m^3, which is the official price of clean water for Dodecanese complex.
- On top of that, by accepting a rational service life of the installation (e.g. 10 years) and a fair UF value (UF≈200), the corresponding water production cost is between 1.5-2.3€/m^3 for medium sized capacity installations and 2.0-2.8€/m^3 for small size consumers, even if the purchase price of imported electricity is 100% charged to the desalination plant operational cost.

In this context, the decrease of the electrical energy cost (decreasing λ value) implies a considerable water production cost reduction, figure (12). More specifically reducing by 25% the input energy cost, the corresponding maximum water production cost reduction varies between 0.2 and 0.25€/m^3. Finally, in case that "λ=0" (the electrical energy is donated to the desalination plant, e.g. energy

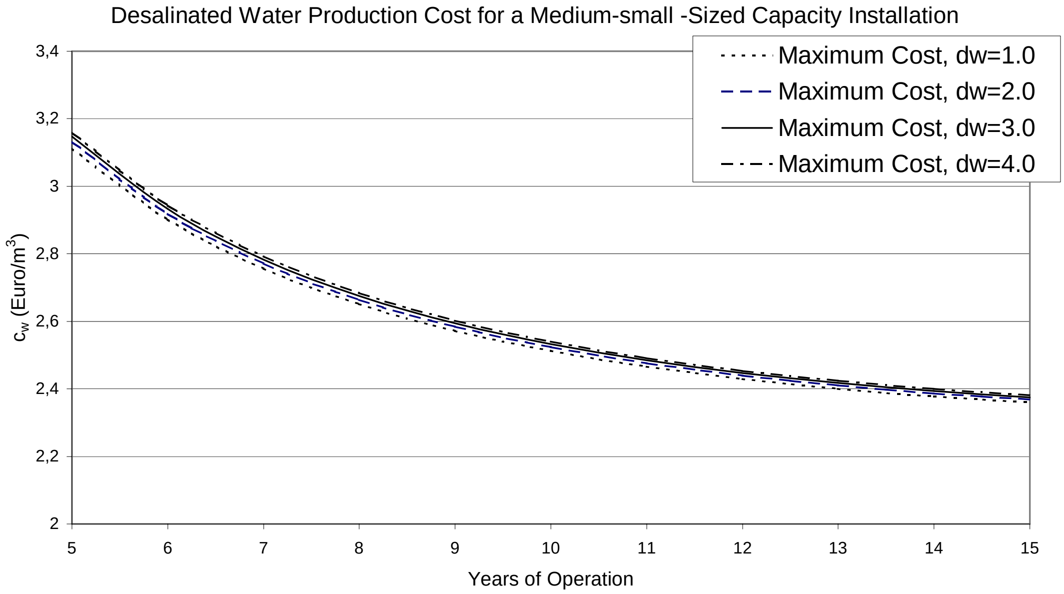

Figure 13: Water storage size impact on water production cost in remote islands

surplus of the electricity production system), the corresponding water maximum production cost decrease is between 30% for a short term to 40% for a long-term operation, figure (12).

On the other hand, the size of the water reservoir for the produced clean water storage seems not to remarkably affect the desalinated water production cost, figure (13). Even by quadruplicating the volume of the water reservoir (i.e, the days of autonomy of the system), the corresponding water cost is increased rather slightly (≈0.03€/m^3). However, one cannot easily create large water reservoirs due to the limited area available in most small-medium size islands.

Subsequently, applying the above presented cost-benefit model for a medium-small-sized capacity installation V_o=100m^3/day and for various typical values of capital cost "i", we get the calculation results appearing in figure (14), as a function of the installation's service life. The numerical values of all other parameters are given in Table III. As expected, there is a remarkable impact of the market capital cost on the maximum water production cost values. More specifically, by changing 1% the market capital cost the corresponding water production cost change is 0.04€/m^3.

Finally, one has the opportunity to investigate the influence of the water production cost annual escalation rate on the present value of the water production cost. As it comes out from figure (15), by keeping constant the water production cost, the corresponding long-term operation value tends to 2.7€/m^3. On the contrary, if a 6% annual escalation value is permitted, then the corresponding water maximum production cost present value tends to 1.8€/m^3, for a 15 years service life of the proposed desalination configuration.

6. Conclusions

An integrated cost-benefit analysis, concerning the desalinated water production cost for remote islands, using renewable energy sources and reverse osmosis desalination techniques, is presented. According to the proposed solution, the desalinated water production activity belongs to an integrated solution for the energy and clean water demand problem of an autonomous community. For this purpose, the solution obtained should guarantee the clean water sufficiency of the remote community at a rational production cost, definitely lower than the current water market price in the same region.

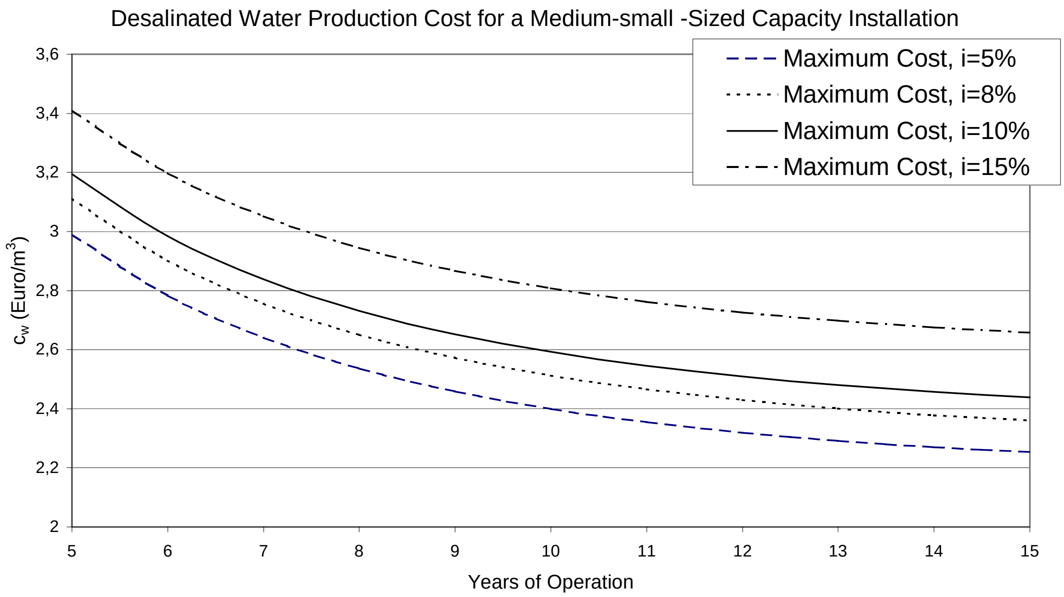

Figure 14: Capital cost impact on water production cost in remote islands

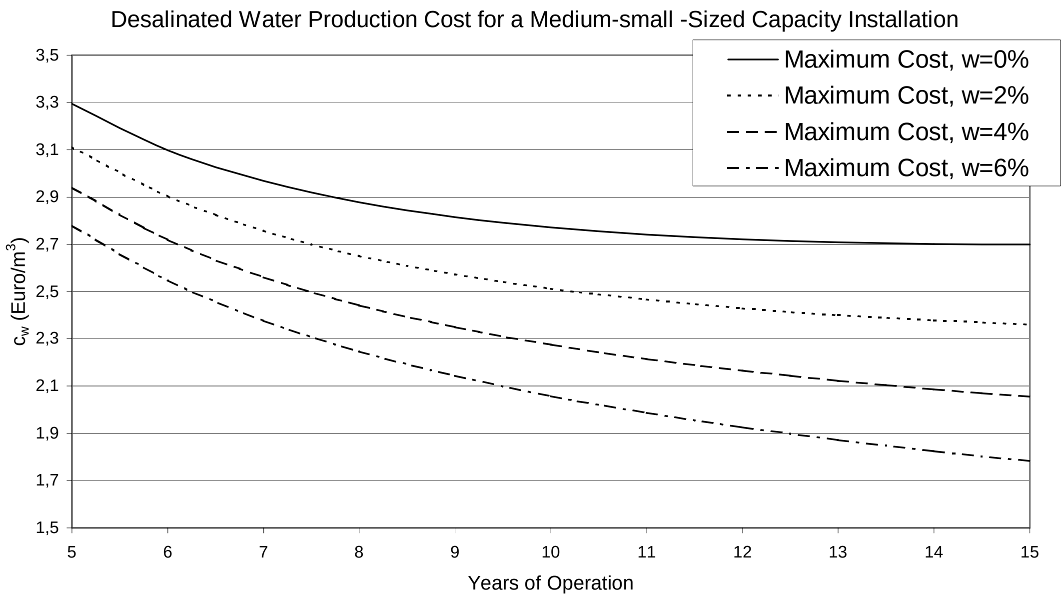

Figure 15: Water price annual escalation rate impact on water production cost

According to the results obtained, concerning several typical configurations of the proposed solution, the resulting maximum water production cost is less than 2.5€/m^3 for medium sized capacity installations and inferior to 3.5€/m^3 in very small ones. These cost values are remarkably reduced with the increase of the unit’s service life, while there is a significant potentiality for additional cost reduction by careful maintenance and operation of the system and by an appropriate energy management of the installation. Bear in mind that the electricity consumption cost of the desalination plant strongly influences the desalinated water production cost. On top of this, the increase of the utilization factor of the selected desalination plant decreases the corresponding water production cost considerably. Furthermore, the economic performance of the integrated system is improved in the case that the energy demand of the desalination plant is covered by the surplus of the energy produced by the RES power station.

It is therefore proved that the implementation of alternative water supply solutions, such as desalination plants integrated with appropriate RES technologies, can contribute significantly to the sustainable solution of the water shortage problem, as it is justified in the present work. Hence, the authors believe that the proposed solution, in addition to its significant sustainability features, is economically competitive to any other clean water production solution for the Greek islands, thus enabling the supply of the local communities with an adequate amount of water at a minimal cost. Thus, by adopting the proposed analysis, it is possible to accelerate the economic development of the small societies of the Aegean Archipelago, improving -at the same time- the life quality level of the habitants.

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FEASIBILITY ANALYSIS OF DOMESTIC SOLAR WATER HEATING SYSTEMS IN GREECE

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Abstract

The excessive usage of fossil fuels has world-widely caused chain environmental consequences. An interesting solution to this problem is the systematic exploitation of available renewable energy sources, including solar energy. Greece is located in a major geographical region with an abundant and reliable supply of solar energy, even during the winter. In as much, one cannot disregard the significant dependency of the country on imported fuels, since almost 70% of its domestic energy consumption is covered by oil and natural gas imports. Despite the relative local sun abundance, during the last ten years the local solar collectors market illustrates a sluggish behaviour, in comparison with the impressive numbers of sales during the 1980-90 decade. At a first glance, such an occurrence characterizes a controversy. In an attempt to find a rational explanation of this peculiar situation, an integrated cost-benefit analysis is carried out taking into consideration the vast majority of the parameters affecting solar thermal energy production cost. The resulting numerical values are then compared with the corresponding ones coming from alternative hot-water production techniques. Accordingly, a quite extensive sensitivity analysis is carried out, in order to demonstrate the impact of the main techno-economic parameters on the fiscal behaviour of contemporary solar hot water production systems. The results obtained not only explain with sufficient accuracy the current local market situation but also demonstrate the specific actions that if realized they may boost solar collector sales in the corresponding local market.

Keywords: Solar Collector; Cost-Benefit Analysis; Solar Hot Water Production; Sensitivity Analysis; Solar Thermal Market; Utilization Factor

1. Introduction

The excessive usage of fossil fuels has world-widely increased carbon dioxide concentration, which in turn is to be blamed for the more often encountered extreme weather conditions and other chain environmental consequences. In this context most E.U. citizens believe that environmental degradation does not necessary has to be the compensation and the price paid for economic growth. An interesting bilateral solution to this problem could be the systematic exploitation of available renewable energy sources, including solar energy[1][2].

It is widely accepted that Greece possesses an excellent solar energy potential according to existing long-term measurements, as seen in figure (1). More specifically, Greece is located in a major geographical region (SE Mediterranean area) with an abundant and reliable supply of solar energy, even during the winter. This is the reason of the impressive increase of solar collector sales in Greece during the 1980-90 decade[3]. On the other hand, one cannot disregard the significant dependency of Greece on imported fuels (i.e. oil and recently natural gas). More precisely, almost 70% of the country's domestic energy consumption is covered by fossil fuel imports during the last twenty years[4], a fact that leads to a considerable loss of currency and unbalanced trade-off, especially when this trading takes place with countries outside the E.U.

Despite the mild local weather conditions and sun abundance, both suitable for the exploitation of solar collectors, local solar industry market has gone through a sluggish sales period during the last

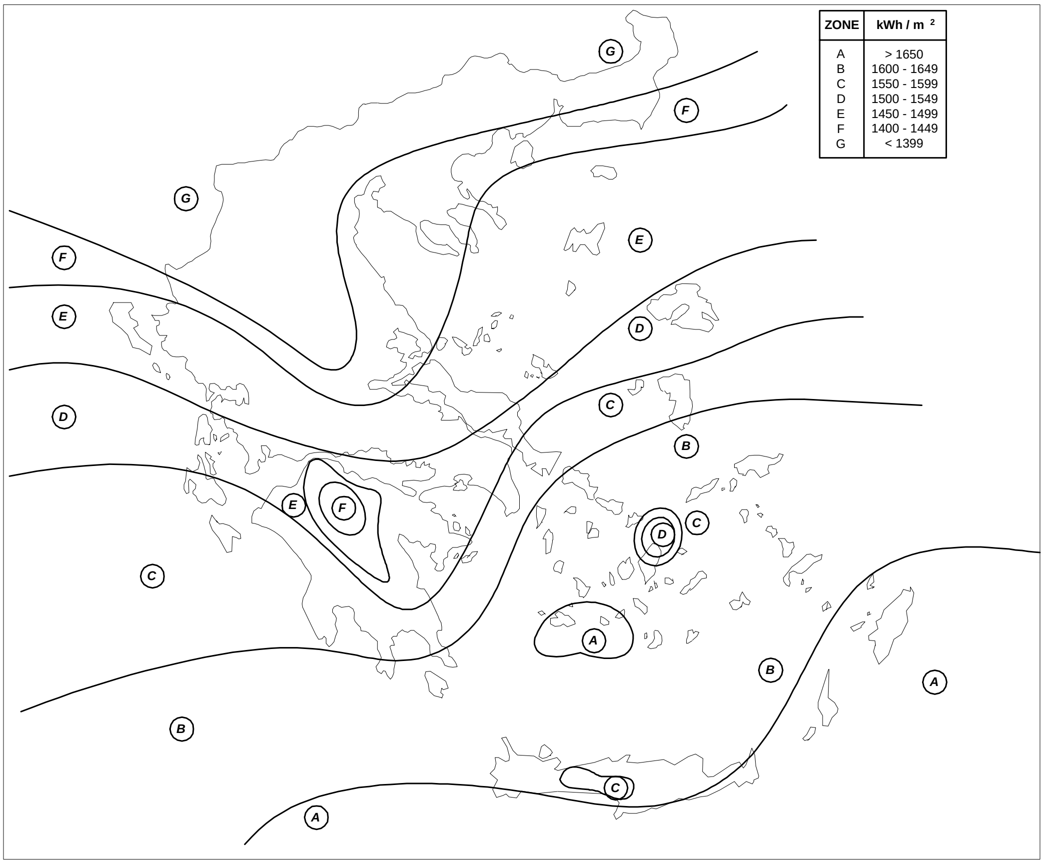

Figure 1: Solar potential zones in Greece[8]

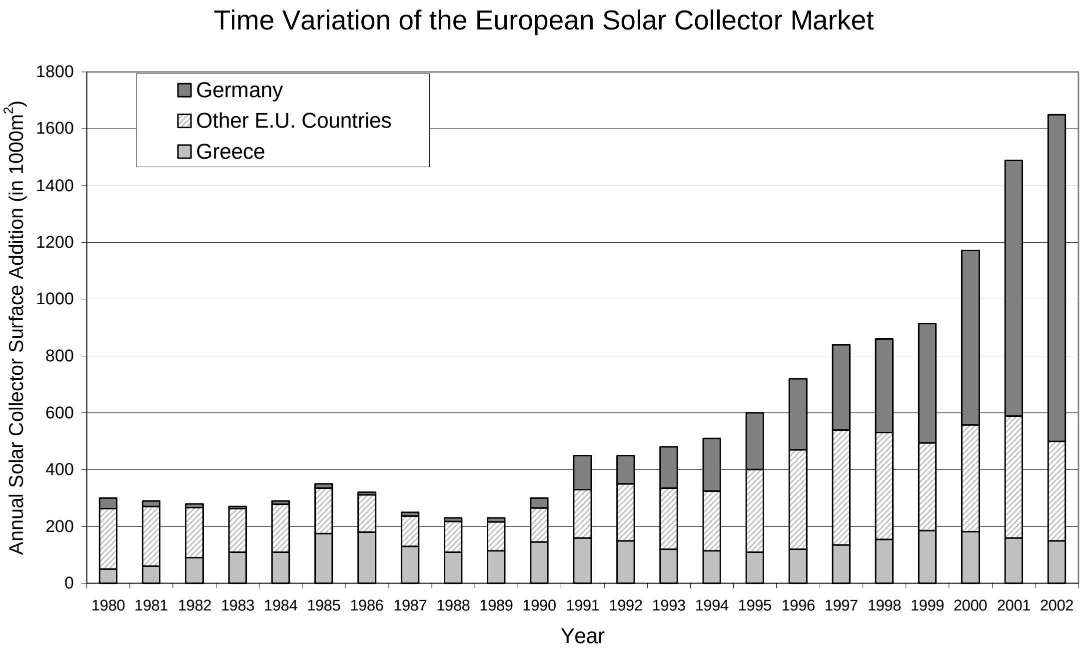

Figure 2: Time series of the variation of annual solar collector addition in Europe

few years[5][6], while electric water heaters continue to flourish. This situation by itself characterizes a controversy. On one side, a continuously declining initial investment cost evolution in constant terms along with an improved production quality is reported. On the other side, a sales and interest rate decrease is testified concerning the domestic solar water heating systems (DSWHS), being in contradiction with the thriving dynamic solar market of Germany and Austria, figure (2). Unfortunately, during the last decade, the solar collector local market annual sales are almost stable, slightly varying between 120,000m^2 and 160,000m^2 of solar collector surface. At this point, it is important to mention that a remarkable portion of these annual sales is related to the replacement of old-fashioned or completely out of order systems installed in the early 80s. According to estimations[6], for the last ten years, less than 50,000 new systems are annually installed in Greece, fairly contributing to the realization of the E.U. target of 500m^2 solar collectors for every 1000 citizens[3].

In an attempt to explain the reason why this strange decline in sales has occurred, an integrated cost-benefit analysis is carried out taking into consideration the vast majority of the parameters affecting solar thermal energy production cost. The resulting numerical values are accordingly compared with the alternative hot-water production techniques. The results obtained not only explain, with sufficient accuracy, the current local market slowdown but also demonstrate the specific actions that if realized they may boost DSWHS local market sales.

2. Cost-Benefit Analysis

Solar hot water systems are devices that utilize sun's energy to directly heat water providing it to households, hotels, factories and other recipients[7]. Such systems typically incorporate[8] a roof-mounted solar collector, an insulated hot water storage tank and a hydraulic heat transport system with sensors and controls, figure (3). A solar collector receives solar irradiance and converts it into heat. The main work is done by an absorber plate, which is often painted mat black or coated with a special "selective" coating. To minimize heat losses the collector is thermally insulated and has a transparent cover made of special glass or plastic. Hot water is circulated to and from the storage tank by means of a circulation pump, or by gravity as in the "thermosyphonic" systems (the latter being the most commonly used in Greece). Such a system may provide more than 2/3 of the annual hot water demand, while a conventional heat source (such as a gas-oil boiler, or an electric heater) provides the rest.

The economic viability and attractiveness of a DSWHS could be founded by computing the solar-

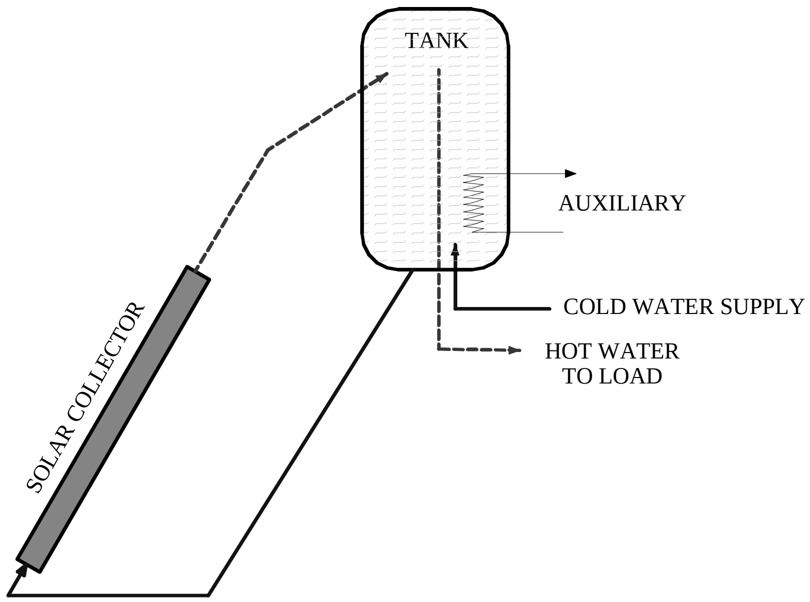

Figure 3: Schematic presentation of a typical DSWHS

thermal energy production cost value, and then compare the results obtained with the corresponding

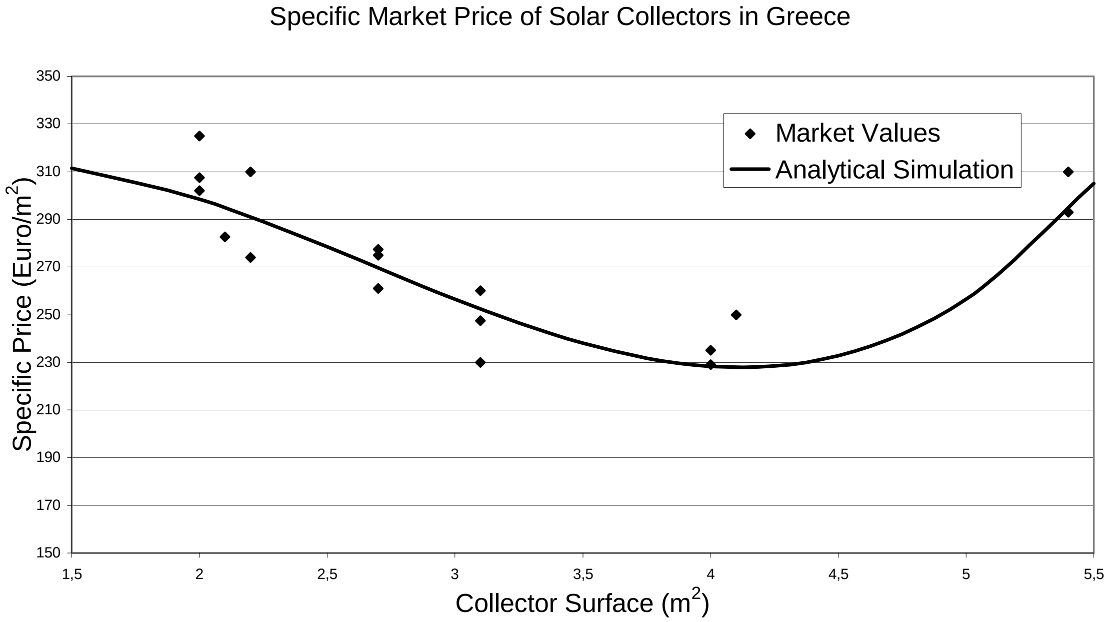

Figure 4: Solar collectors specific market price in Greece (end of 2002)

energy market prices of the other available alternative solutions, like electric heater, gas-oil boiler etc.

The future value of the total investment cost of a DSWHS after n years of operation "C_n" is a combination[9] of the initial installation cost "IC_n" along with the corresponding maintenance and operation cost "FC_n", both quantities expressed in current values. Thus, one may write:

$$C_n = IC_n + FC_n \tag{1}$$

where

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

and

$$FC_n = m \cdot IC_o \cdot \frac{(1+g_m)}{(1+i)} \cdot [1 + \left(\frac{1+g_m}{1+i}\right) + ... + \left(\frac{1+g_m}{1+i}\right)^{n-1}] \cdot (1+i)^n \tag{3}$$

In equation (2) "IC_o" is the turnkey cost of a DSWHS, given as:

$$IC_o = Pr \cdot A_c + f \cdot Pr \cdot A_c = Pr \cdot A_c \cdot (1+f) \tag{4}$$

where "f" expresses the installation cost coefficient. In the present analysis the DSWHS installation cost is expressed as a fraction (f≈3%-10%) of the ex-works price of the equipment (i.e. $Pr.A_c$) and it normally includes connecting parts, pipe insulation materials, transport, labour for mounting the system, etc. "Pr" is the specific ex-works price (Euro/m^2) of the system. The problem of finding the specific cost of a DSWHS is a multivariable one. In practice however the two most important parameters are the collector area "A_c" and the storage tank capacity "V", see figures (4) and (5). Thus one may write:

$$Pr = Pr(A_c, V) \tag{5}$$

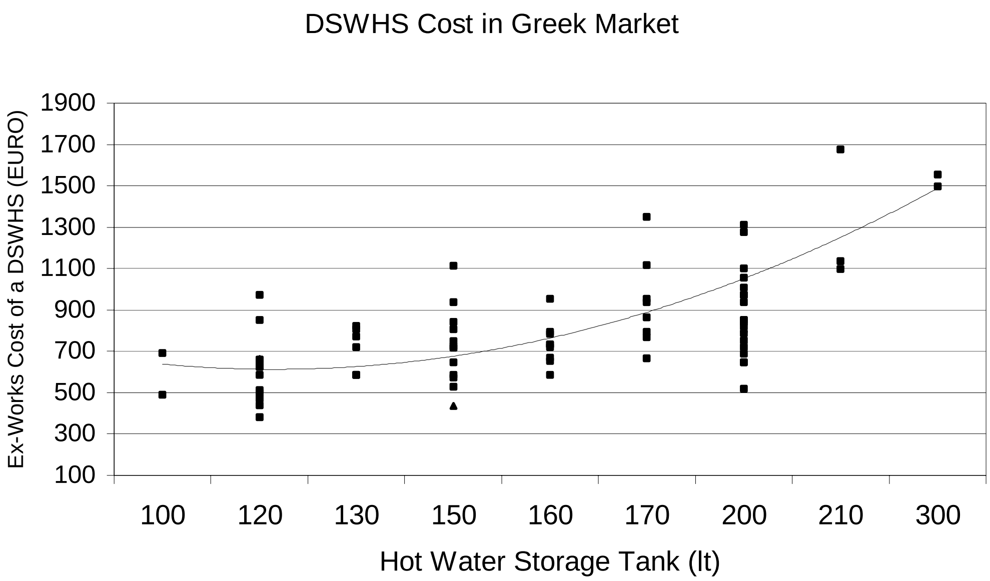

Figure 5: DSWHS ex-works price in Greece (end of 2002)

Accordingly, "δI" is the State subsidy (if any) amount concerning the DSWHS purchase cost, e.g. tax deduction, etc, given as:

$$\delta I = \gamma \cdot IC_o \tag{6}$$

The maintenance and operation (M&O) cost "FC_n" includes the annual repair and maintenance cost, which constitutes expenses for antifreeze, replaced damaged pipes and parts, repaired insulation materials, glass, paint labour cost and other miscellaneous items. During the present analysis "FC_n" is expressed as a function of the initial cost "m", taking also into account an annual increase of the cost via the M&O mean annual inflation rate "g_m". In the early systems the "m" value exceeded 10%, while for the contemporary systems this value has dropped to 3%-5%. Finally, "i" is the mean annual capital cost of the local economy.

On the other hand, the total savings "R_n" (in current values) over a n-years period due to the thermal energy offered by the solar system are given as:

$$R_n = E_o \cdot c_o \cdot \frac{(1+e)}{(1+i)} \cdot [1 + \left(\frac{1+e}{1+i}\right) + ... + \left(\frac{1+e}{1+i}\right)^{n-1}] \cdot (1+i)^n \tag{7}$$

where:

E_o is the net annual heat output of the system, assumed constant over the entire operational period of the system (in kWh/year)

c_o is the present value of the effective cost coefficient of the substituted -by the DSWHS production- conventional energy (in Euro/kWh)

e is the mean annual rate of the substituted conventional heat-sources market price change (i.e. thermal energy price escalation rate)

The effective cost coefficient value "$c_o^{(n)}$" after –n years of operation of the solar system can be predicted by equating the future value of the investment cost with the corresponding total savings, i.e.:

$$R_n = C_n \tag{8}$$

After several algebraic manipulations, equation (8) reads in view of equations (1) through (7):

$$c_o^{(n)} = f_1 \cdot [(1-\gamma) + m \cdot f_2] \cdot x \tag{9}$$

where

$$x = \frac{IC_o}{E_o} \tag{10}$$

It is important to note that "f_1" and "f_2" both take into account the impact of the thermal energy escalation rate and the local market capital cost as well as, the M&O cost annual inflation rate and the local market capital cost respectively. Therefore, the expressions of "f_1" and "f_2" should be written as:

$$f_1 = \frac{1}{\frac{1+e}{e-i} \cdot [\left(\frac{1+e}{1+i}\right)^n - 1]} \tag{11}$$

$$f_2 = \frac{1+g_m}{g_m - i} \cdot [\left(\frac{1+g_m}{1+i}\right)^n - 1] \tag{12}$$

Substituting equation (4) into equation (10) one gets:

$$x = \frac{Pr \cdot (1+f)}{E_o / A_c} = \frac{Pr \cdot (1+f)}{\varepsilon_o} \tag{13}$$

where "ε_o" is the collector's reduced annual heat production, that is the annual solar heat production per square meter of collector surface (kWh/year.m^2), i.e.:

$$\varepsilon_o = \frac{E_o}{A_c} \tag{14}$$

Summarizing, the solar heat production cost present value after n-years of operation of a DSWHS is given as:

$$c_o^{(n)} = f_1 \cdot [(1-\gamma) + m \cdot f_2] \cdot \frac{Pr \cdot (1+f)}{\varepsilon_o} \tag{15}$$

The above computed value should be compared with the present value of the superseded conventional heat source used to produce hot water, "c^*". In Greece, solar energy usually substitutes either diesel oil or electricity. Recently, a remarkable natural gas penetration in the local tertiary sector is under way. Hence, generally speaking, hot water may be produced by using either oil-natural gas (mainly during the cold months), or electricity. Setting as "ξ" the energy fraction covered by oil and natural gas, the corresponding specific cost of the non solar produced thermal kWh "c^*" is expressed as:

$$c^* = \xi \cdot c_f + (1-\xi) \cdot c_{el} \tag{16}$$

where "c_f" and "c_{el}" are the specific cost of producing a kWh of heat using oil/natural gas and electricity, respectively.

Therefore, if

$$c_o^{(n)} \le c^* \tag{17}$$

then the proposed DSWHS is financially viable, leading to total gains, for the n-years expected service period (present values) "$G_o^{(n)}$" expressed as:

$$G_o^{(n)} = \left(c^* - c_o^{(n)}\right) \cdot n \cdot E_o \tag{18}$$

Hence, the corresponding expression of the benefit to initial cost ratio "BCR"[9] becomes:

$$BCR_n = \frac{G_o^{(n)}}{(1-\gamma) \cdot IC_o} = \frac{\left(c^* - c_o^{(n)}\right) \cdot n}{(1-\gamma) \cdot x} \tag{19}$$

3. Application Results

Before the application of the above presented cost-benefit model one should define the specific ex-works price of a DSWHS along with the corresponding reduced annual heat production value. As already mentioned, the problem of finding the specific cost of a DSWHS is a multivariable one. In practice however, except for the manufacturer's brand name, the other two most important cost conforming parameters are the collector area and the storage capacity. Generally speaking "Pr" depends mainly on the collector area "A_c" and the hot water storage capacity "V".

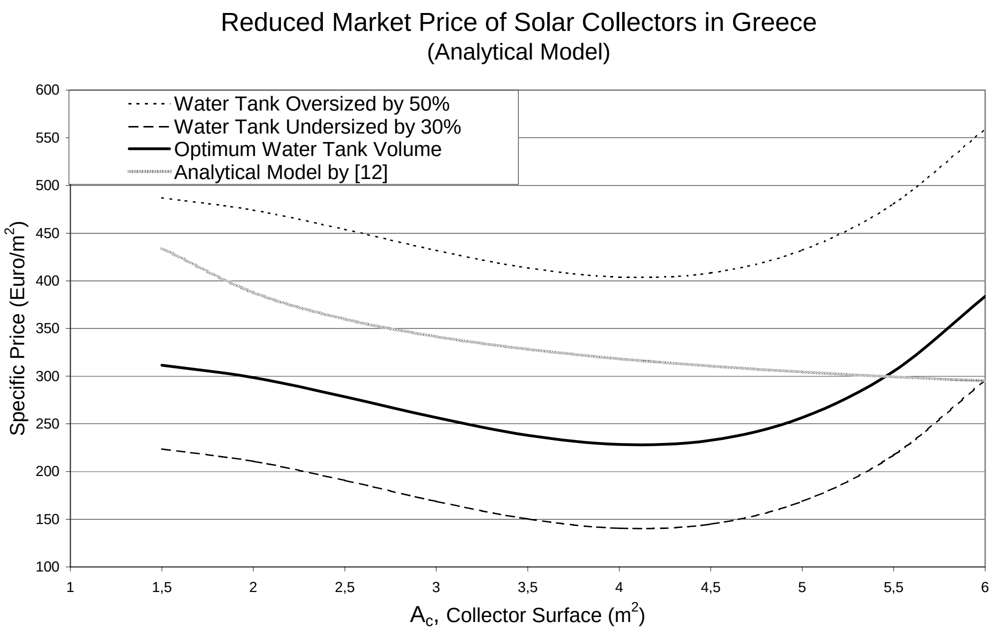

Figure 6: Proposed analytical model concerning the DSWHSs reduced price

3.1 Specific Price of a DSWHS

In previous cost-benefit analysis publications[10][11] relatively constant specific cost values have been considered, ranging from 210€/m^2 up to 380€/m^2. In an earlier but more detailed cost-benefit study[12] the proposed form of equation (5) was validated. However, the relation proposed does not incorporate the negative scale economies for relatively high collector surface systems, which are not widely used in Greece. Instead, this early model takes into consideration the positive scale-economies and the hot water storage volume ratio relative to the corresponding collector surface area.

Subsequently, based on the results of an extensive market survey (1996-2003) throughout Greece[13][14] the following expression may be used, see also figure (6):

$$P_r(A_c, V) = 7.085 \cdot A_c^{\,3} - 56.83 \cdot A_c^{\,2} + 107.5 \cdot A_c + 5.85 \cdot \left(\frac{V}{A_c} - 55\right) + 254.2 \qquad (20)$$

Equation (20) is valid for, 1.5 $m^2 \leq A_c \leq 6.0 m^2$ and $40(lt/m^2) \leq (V/A_c) \leq 85(lt/m^2)$.

Using the data gathered, one may support that for a rationally selected DSWHS the specific ex-works price varies between 230€/m^2 and 300€/m^2, while the corresponding turnkey prices should range between 250€/m^2 and 330€/m^2. From the outcome of the sensitivity analysis explained in the next section, the impact of the exact value of the turnkey price is vital for the viability of a DSWHS. That's why one should insist on establishing the correct numerical value of this parameter.

On top of this, researchers are in agreement with the results of the present market survey that during the last decade the turnkey prices of DSWHS in Greece have been remained almost steady in constant values. Therefore, no remarkable price differences are encountered during the seven years long market survey, a result that is also supported by [11] and [15].

3.2 Reduced Annual Heat Production of a DSWHS

The next parameter to be defined according to equation (15) is the collector's reduced annual heat production "ε_o". More specifically, the annual heat gain of a DSWHS "E_o" can be estimated as:

$$E_o = \sum_{i=1}^{365} E_i \qquad (21)$$

For the estimation of daily solar energy gain "E_i" one should take into consideration the daily hot water consumption pattern per person as well as the available solar energy impinging at the selected collector surface[16]. Besides, one cannot ignore the considerable energy heat-losses from the hot water storage tank, especially during winter nights for households where all habitants are morning hot water users.

Until recently "ε_o" is assumed constant, e.g. equal to 576kWh/(m^2.year)[11], or equal to 600-650kWh/(m^2.year)[10]. Haralambopoulos et al.[12] used a quite interesting approach, based also on experimental measurements. One of the most interesting outcomes of this research is that the mean annual efficiency of a rationally sized DSWHS is between 35% and 50% and almost independent of the inclination (tilt angle) of their collector's surface. However, one should realize that the solar heat gains calculation model does not take into consideration the daily, or more practically the seasonal hot water demand variations[17][18][19]. For example, during the summer time period a considerable amount of solar energy is available, which normally over-fulfils the corresponding hot-water demand. Nevertheless, this amount of energy may be partially or totally remained unutilised if the DSWHS owners are away from home, i.e. for summer vacations, which is the case for most city dwellers.

To confront these problems, the authors suggest the following reduced heat calculation model. During the cold season months (e.g. November to April) a rationally sized DSWHS cannot fulfil the daily hot water demand of the consumers, hence the system heat gain is determined by the available local solar potential and the system's total efficiency, including storage tank heat losses, especially for early morning hot water users. In these cases one may write:

$$E_i = \eta_i \cdot H_i \cdot A_c \qquad (22)$$

where for the system's energy daily efficiency "η_i" estimation one may use equally well the data given in [12].

On the other hand, during the hot season periods (e.g. June to September) the available hot water normally exceeds the corresponding demand, taking also into account the relatively high ambient temperature. Hence, in these cases the daily heat gain is usually dictated by the load (hot water) profile[17][18][19] of the consumers "Q_i".

Recapitulating, the reduced annual solar heat production of the system "ε_o" can be finally calculated using the following relation:

$$\varepsilon_o = \sum_{i=1}^{i=365} \min\left\{\overline{\eta}_i \cdot H_i , \frac{Q_i}{A_c}\right\} \tag{23}$$

This is done on the basis of the hot water consumption daily/seasonal pattern[17]18][19], the available solar radiation[20][21] and the solar collector surface and efficiency. According to a large number of consumer profiles and solar radiation combinations tested, the corresponding "ε_o" value varies between 300 and 700kWh/(m^2.year).

3.3 Financial Subsidization of DSWHS

The incentives for the purchase a DSHWS were first applied in 1978 (i.e. law 814/78), in the form of income tax reduction, representing the 75% of the system cost at that time (1978 rates), in case that the purchase cost did not exceeded the 10% of the citizen's annual income liable to tax. Later, this amount was slightly modified (decreased to ≈60%) by the law 1473/84. Taking into consideration that the above mentioned tax reduction was expressed in constant numerical values (in the local currency), the impact of this incentive became ineffective rather fast due to the high inflation rates of that period (1980-90)[22]. During this high inflation period soft loans were also allocated for the purchase of solar systems, covering up to 70% of the system cost[15].

In 1995, an attempt to support the DSWHS market was made by passing the law 2394/95. According to this law, the exemption of 75% of the purchase and installation cost of all renewable energy systems from the individuals taxable income is anticipated. Hence, it is obvious that the only support could come from legislation and programs supporting the whole renewable energy sector. Even according to the law 2394/95, the final tax deduction strongly depends on the taxable income of the DSWHS owner. Taking into consideration that the existing income tax rates, for the majority of taxpayers, are equal to 15%, 30% and 40% respectively (according to the taxable income) and neglecting that any tax return is realized normally one year after the DSWHS purchase, the final subsidization amount is between 11% and 30%, (e.g. γ=0.75x0.40).

Currently, (actually, since January 2004), there are no governmental actions supporting anymore the DSWHSs' purchase by individuals, since the national energy policy is almost exclusively focused on stimulating the imported natural gas penetration in the tertiary sector.

3.4 Service Period Impact on the DSWHS Competitiveness

Using the above-presented information, one could go ahead and calculate the effective cost coefficient variation as a function of the DSWHS service life for selected representative regions of Greece. For this purpose the available long-term solar radiation data based on measurements are taken into consideration[8][20][21] concerning the North, Central and South Greece, see figure (7). It should be kept in mind that according to a recent study by CRES[23], 62% of the Greek DSWHS in operation are located in central, 27% in Northern and 12% in South Greece.

It is also important to note that the contemporary DSWHSs' service life is estimated around 15 years, although the early systems manufactured in the '80s present quite lower life-span. For this case

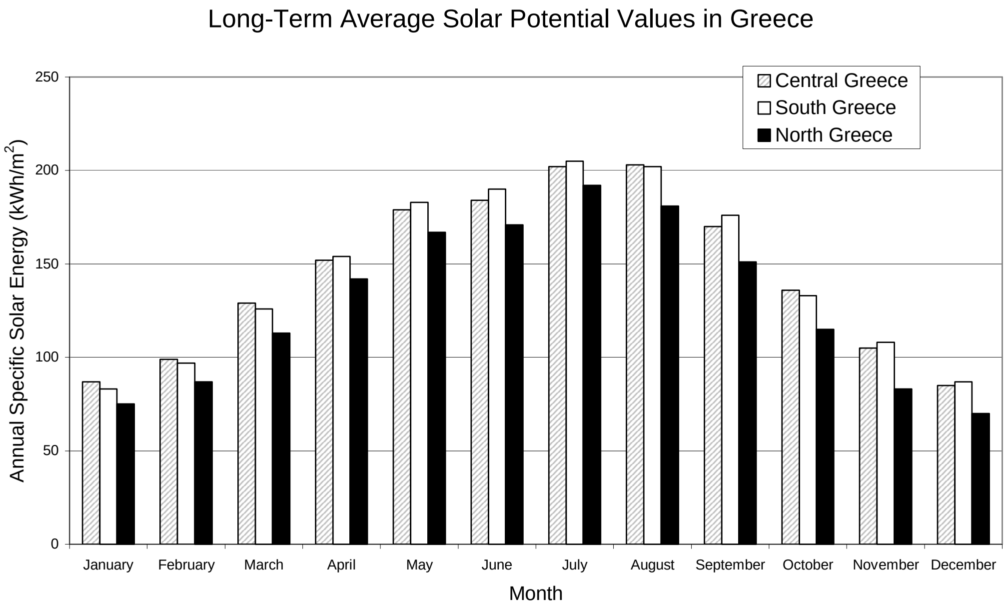

Figure 7: Monthly solar potential profile in Greece

ESIF[24] estimates the life expectancy of typical Greek manufactured DSWHSs to be around 10 years, while CRES/GSIA (GSIA, i.e. Greek Solar Industry Association) of experts assume average life-span equal to 15 years for the earlier (before 1985) installations and up to 20 years for the ones produced after 1996[10][11][25].

Table I: Nominal Values of the Main Parameters Used in the Present Cost-Benefit Analysis

Parameter	Symbol	Numerical Value	Units	Parameter	Symbol	Numerical Value	Units
Collector Surface	A_c	2.5	m^2	Annual Capital Cost	i	9	(%)
DSWHS Specific Price	Pr	300	€/m^2	Heat Annual Escalation Rate	e	3	(%)
First Installation Cost Subsidization Percentage	γ	0-30	(%)	M&O Cost Annual Inflation Rate	g_m	2	(%)
DSWHS Service Period	n	10 or 15	years	M&O Cost Coefficient	m	3	(%)
First Installation Cost Coefficient	f	3	(%)	Heat Oil Fraction	ξ	30	(%)
Reduced Annual Solar Energy	H_T	1730	kWh/m^2	Electricity-Heat Cost	c_e	0.095	€/kWh
Reduced Annual Heat Production	ε_o	690	kWh/m^2	Oil-Heat Cost	c_f	0.050	€/kWh

In figure (8) one may examine the solar hot water production cost variation for a typical DSWHS (see Table I) operating in Central Greece (where Athens and its vicinity) as a function of service period of the installation, for cases with zero and maximum available (30%) subsidization. According to the results from the calculations, solar heat cost is remarkably reduced with the years that the DSWHS stays in operation, especially during the first eight (8) years. Moreover, there is a significant solar heat

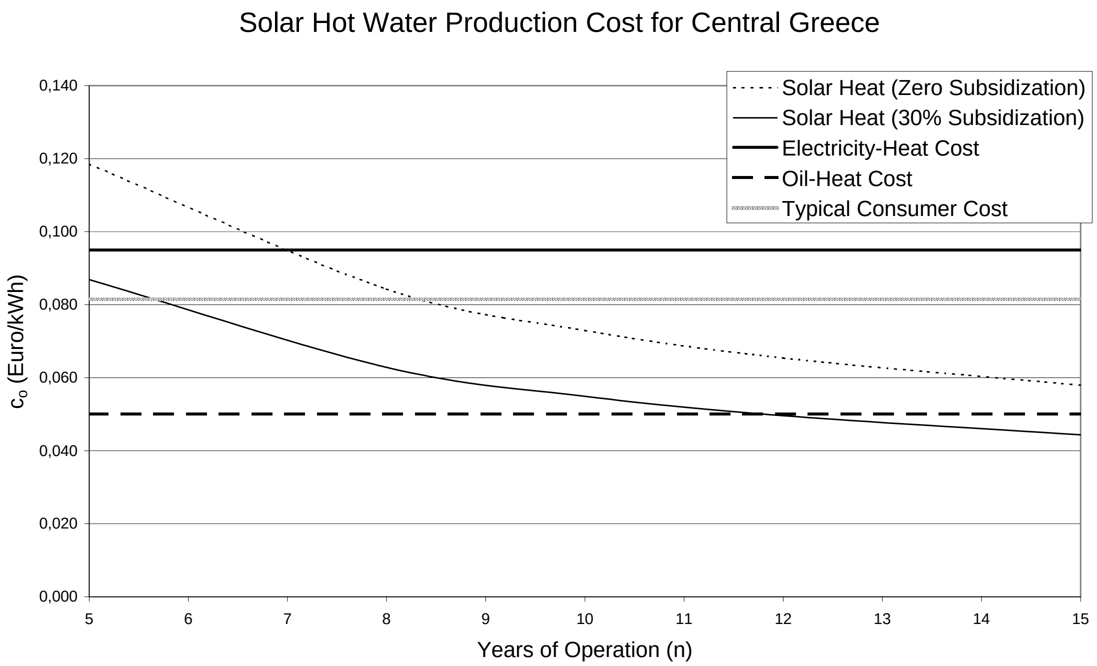

Figure 8: Solar hot water production cost variation with DSWHSs years of operation in Central Greece

cost reduction in systems with 30% subsidization (approximately 0.03€/kWh), which is slightly decreasing with the system operational time.

In the same figure one may compare the present value of the solar hot water production cost with the corresponding value by an electric heater or an oil-fired central boiler, operating with total efficiency estimated at 95% and 75%, respectively[12]. According to the results obtained the proposed operation scheme of a DSWHS cannot be financially matched when compared with an oil-fired water heating central system, independent of its operation period, when no State subsidization is considered. Only when the maximum subsidization is taken into account, the corresponding pay-back period is slightly less than twelve years. On the other hand, DSWHSs are definitely more cost effective than the typical commercial electric heaters, presenting a pay-back period equal to seven years in cases without, and less than four years in cases with 30% first installation cost subsidization.

Similar results are also available for a typical DSWHS located in North Greece (as in Salonica major area) or in South Greece (i.e. the island of Crete), figures (9) and (10). One should bear in mind that the available annual solar energy is more than 10% higher in the South than in the North part of Greece, figure (7). However, for the N. Greece, DSWHSs seem to have no possibility to be less cost effective than oil-fired water heating systems (even with 30% subsidization). Quite opposite, for both areas, North and South, the expected payback period in relation with electric water heating is less than eight (8) and seven (7) years respectively, without any external financial subsidization. As far as the initial installation cost subsidization is concerned, the corresponding payback diminution regarding DSWHSs operating throughout Greece is almost three (3) years for cases of maximum subsidy in comparison with installations without State contribution.

3.5 Critical Discussion of the Results

At this point one should clarify two important points. First, DSWHSs are not, economically speaking, in a favourable situation when compared to the fossil fired water heating systems. This happens, basically, because the Greek State keeps down the cost of electricity (the Public Power Corporation, PPC, was under State control up to 2001) and oil (by imposing lower taxation) relatively constant (in current terns) for a long period of time, in an attempt to control local market inflation rate. As a result, prices paid for electricity throughout 2000, expressed in constant terms (inflation free), are almost

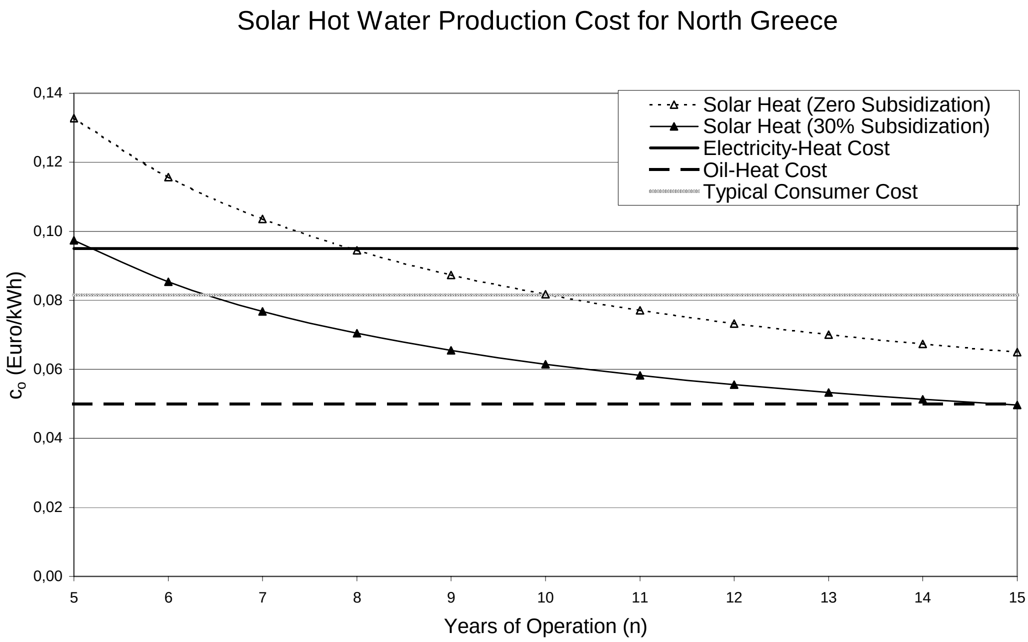

Figure 9: Solar hot water production cost variation with DSWHSs years of operation in North Greece

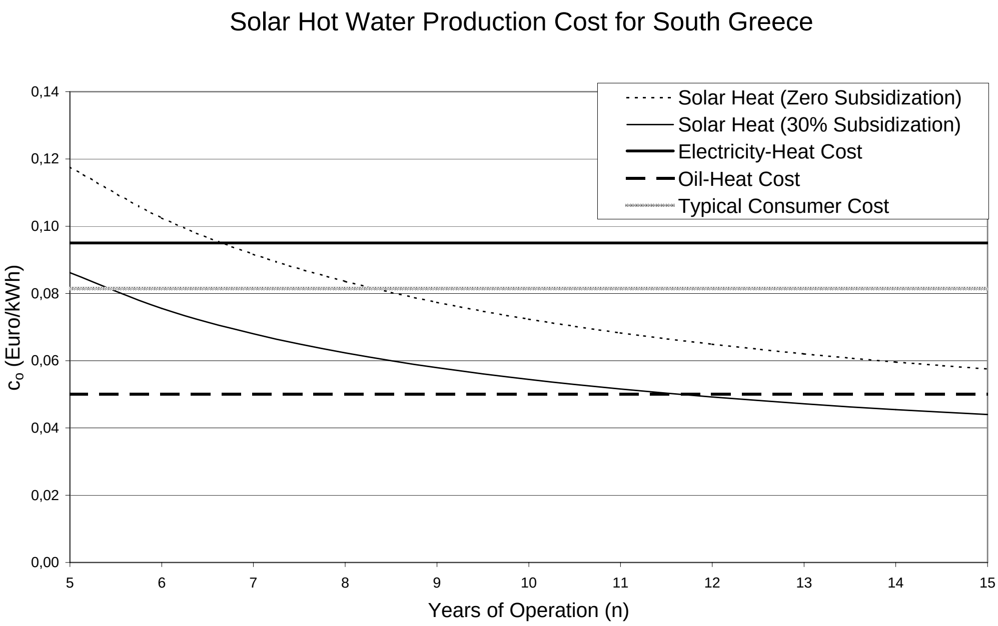

Figure 10: Solar hot water production cost variation with DSWHSs years of operation in South Greece

20% lower than the corresponding ones of 1990. On top of this, there is only a small number of consumers that cover their hot water needs using a central boiler, especially during the hot months of the year. For this purpose, the real consumer hot water production cost is estimated and included in Figs 8 to 10. Thus, it is considered that the representative consumer covers 30% of his needs (mainly during winter months when central heating boilers are operating in Greece) using oil, and the rest 70% utilizing an electric heater. For this consumer the expected payback period varies from 5 ½ to 6 ½ years (for installations located in South and North Greece respectively) in cases with 30% subsidization, and from 8 to 10 years in cases with zero subsidization, see Table II. Similarly, the corresponding BCR_{15} values are bounded between 0.5 and 0.8 for an application without State subsidization and between 1.35 and 1.81 in case of maximum (30%) subsidization.

Table II: Synopsis of Cost-Benefit Analysis Results for Representative Greek Regional Territories

Installation Region	Zero Subsidization (γ=0%)		Maximum Subsidization (γ=30%)	
	Pay Back	**BCR_{15}**	**Pay Back**	**BCR_{15}**
Central Greece	8.2	0.79	5.6	1.78
North Greece	9.9	0.50	6.4	1.36
South Greece	8.0	0.81	5.5	1.81

Finally, one should discuss the possibility of imposing subsidization for DSWHSs throughout Europe. Most central and north European countries use various financing procedures to stimulate their solar thermal markets[15][24]. For example, recently[26] the German government has announced a 35% grant increase in an attempt to support the purchase of solar thermal systems, with the aim of doubling Germany's solar thermal installations by 2006. In this context, grants for solar panels for hot water and space heating are increased from 92 Euro to 125 Euro for each square meter of collector surface installed. This effort is funded through revenues from the so-called Eco-tax. Unfortunately, in Greece all financial incentives in favour of DSWHSs are eliminated, under a new national energy policy shift towards a wider public acceptance and utilization of the imported natural gas.

Let's make it clear; the authors strongly believe and support the idea that these "so called solar systems grants" are only a small portion of the avoided social and environmental cost, whenever clean solar energy substitutes for the heavily environmental polluting and grossly imported, and under depletion fossil fuels[2][10][27][28]. In fact, there is a common agreement among researchers that the above-mentioned avoided cost, for a ten-year operating solar system, amounts to 50% of the present purchase value of a DSWHS, minimal. Hence, the abolition by the Greek State of any financial grants regarding the DSWHSs installations is a clearly unfair and partial action, strongly in favour of the imported natural gas the use of which jeopardizes the future of the domestic solar thermal market, as well as the future survival possibilities of the corresponding local manufacturers.

4. Sensitivity Analysis

The calculated results concerning the estimated solar hot water production cost of a DSWHS installed in central Greece (almost the 2/3 of the existing installed solar systems are located there) are shown in the following sections presented in terms of the main parameters entering the problem.

4.1 System Utilization Factor

As it is clearly stated in section 3.2, the annual energy gain of a DSWHS depends not only on the available solar potential locally but also on the degree of the system's utilization. For this purpose one may define the annual utilization factor "UF" of any DSWHS according to the following equation:

$$UF = \frac{E_o}{H_T \cdot A_C} = \frac{\varepsilon_o}{H_T} = \sum_{i=1}^{i=365} \min\left\{ \overline{\eta}_i \cdot \frac{H_i}{H_T}, \frac{Q_i}{\cdot H_T \cdot A_c} \right\} \tag{24}$$

where "H_T" is the total available annual solar radiation per square meter collector's surface received locally. The "UF" describes the portion of this available solar energy that is finally used by the consumer, taking into account the DSWHS efficiency and the daily/seasonal hot water consumption pattern.

So, using the definition of "UF", equation (15) finally reads:

$$c_o^{(n)} = f_1 \cdot [(1-\gamma) + m \cdot f_2] \cdot \frac{Pr \cdot (1+f)}{UF \cdot H_T} \tag{25}$$

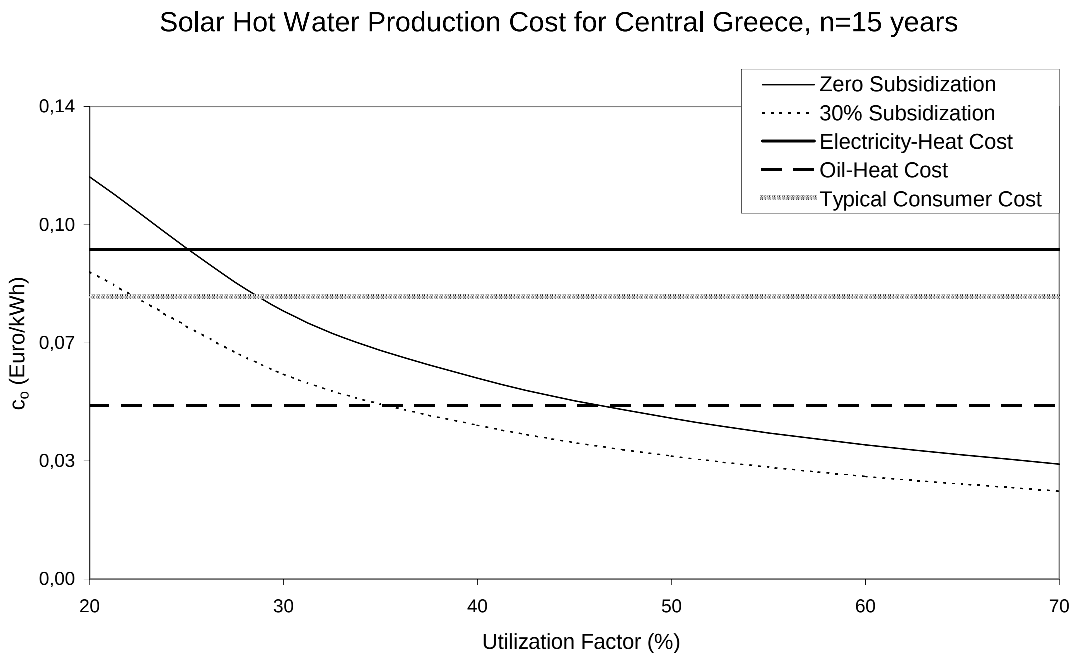

Figure 11: Solar hot water production cost vs. the Utilization Factor of DSWHSs

equation (25) presents explicitly all main parameters affecting the system's solar hot water production cost, i.e. the location "H_T", the utilization factor "UF", the turnkey price "Pr.(1+f)", the length of the service period "n", the annual M&O cost "m", the investment subsidization percentage "γ" and the local market economic parameters "f_1 and "f_2", or more specifically, the market capital cost "i", the non solar heat production cost annual escalation rate "e" and the system's M&O cost inflation rate "g_m".

According to the results shown in figure (11) the impact of the utilization factor on the viability of a DSWHS is dominant, especially for low "UF" values. For example, when considering a DSWHS operating for 15 years in central Greece (H_T=1730kWh/(m^2.year)), the annual "UF" should exceed the 26% mark in order to be more cost efficient than electricity, and 46% in order to be able to compete with oil. This last value is quite high (annual reduced heat gain equal to 800kWh/m^2), approaching the upper limits of equation (24). Even in cases of a 30% subsidization value, the corresponding "UF" value of a DSWHS that replaces oil-heat is almost 36%. However, the results are not very disappointing for the typical Greek owner of a DSWHS operating without major problems for 15 years, since the corresponding "UF" values are 30% and 23% for installations without and with maximum subsidization, respectively.

4.2 System Dimensions

Using the information presented in section 3.1, one may support that the sizing of a DSWHS is another important factor affecting its financial competitiveness. Thus, according to figure (4) there is an optimum solar collector area value that minimizes the system's specific cost. On top of this, the system cost and its efficiency are also influenced by the size of the hot water storage tank in conjunction with the collector surface and the consumer's hot water demand.

After a detailed analysis of the operation of a DSHWS, located in central Greece for ten years without any initial installation cost subsidization, one gets the results shown in figure (12), as a function of the system's collector surface area size. According to these results, the optimum system collector surface area varies between 3.5m^2 and 4.5m^2, on the basis of the current market data. As it comes out, this means that the best-cost efficiency installation should serve six (6) to eight (8) persons, a quite higher value than the average number of members constituting a typical Greek family. The heat cost difference between a system appropriate for 6-8 persons and a system designed to serve a typical four

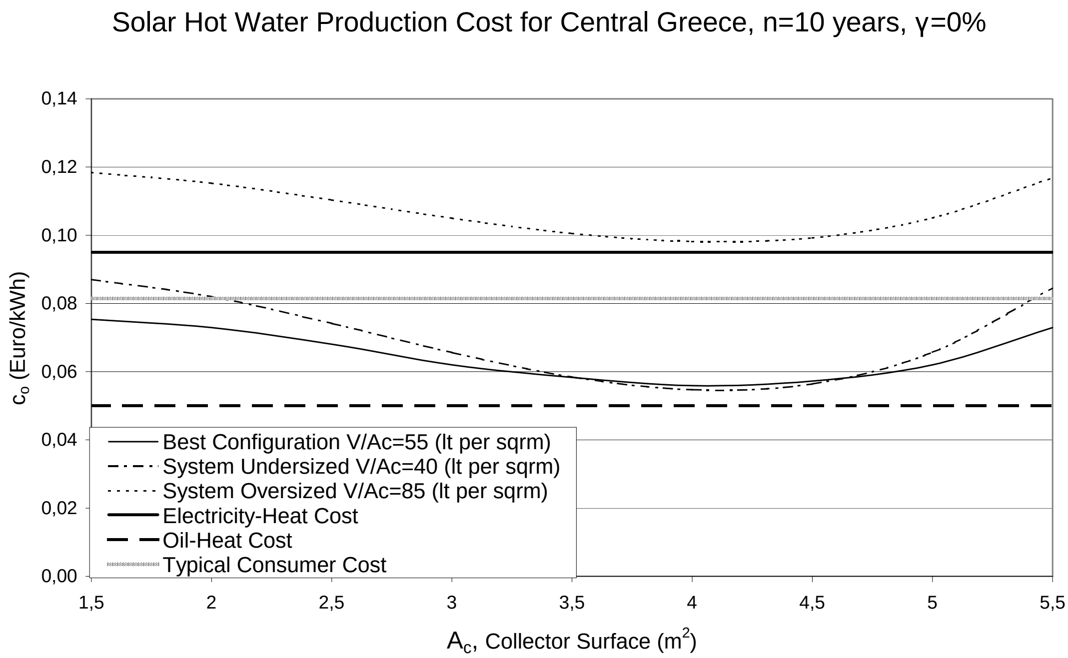

Figure 12: Impact of DSWHSs sizing on the solar hot water production cost

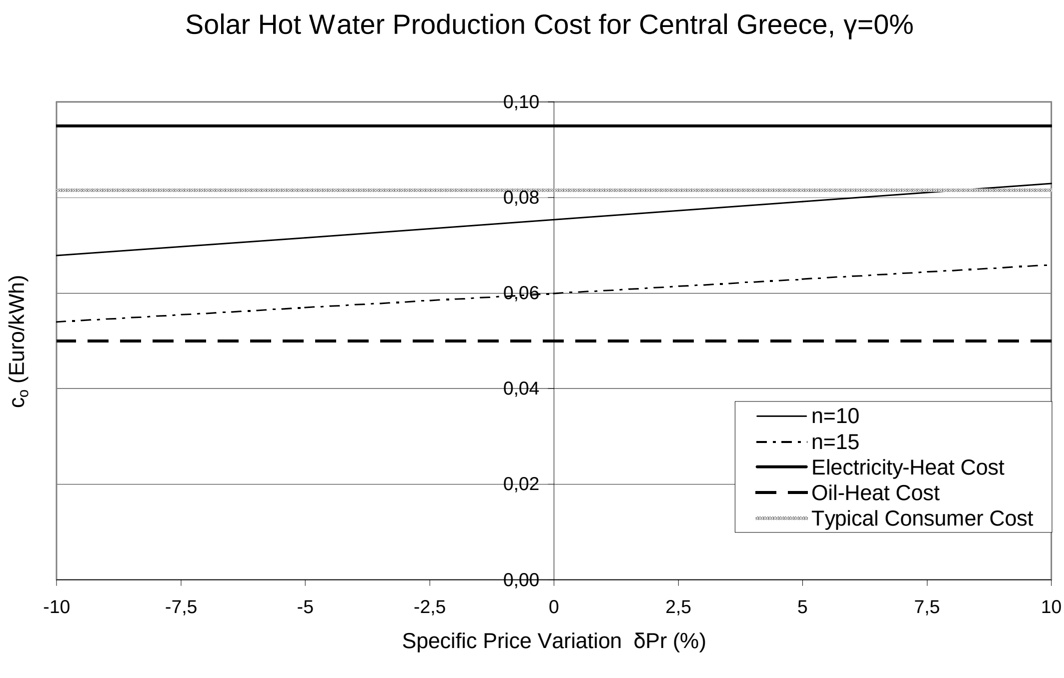

Figure 13: Impact of DSWHSs specific price on the solar hot water production cost

member family is almost 0.015€/kWh, representing a full 25% increase of solar hot-water production cost.

The expected heat cost is significantly increasing in case that the hot water tank capacity is oversized, hence for the extreme case situation presented in figure (12), the DSWHS operational cost exceeds the corresponding electricity cost value. On the other hand, if the hot water storage tank is undersized (i.e. less than 55lt per m^2 of collector surface), the system purchase cost is fairly reduced. However, the utilization factor of the system is also remarkably decreased, leading to solar heat production cost values relatively higher than the ones with the best configuration, especially for small and large systems. In this case one should also mention that since an undersized system cannot fulfil the consumer needs, additional fossil fuel consumption is needed.

4.3 System Reduced Price Variation

The initial turnkey cost of a DSWHS includes the ex-works price of the equipment needed and the corresponding installation cost. The application of new technological achievements and the economies of scale decrease the prices of most energy production systems in the international market. However, one cannot disregard the market's inflation rate that in many situation augments the production cost. In figure (13) one may examine the impact of a rational specific price variation (-10% up to +10%) on the hot water production cost of a typical DSWHS, operating without problems, for ten (10) or fifteen (15) years, in central Greece, excluding any state subsidization.

As it is expected, any specific price reduction diminishes solar heat cost, while the corresponding variation is almost linear. Besides, the specific price impact is stronger for the 10 years of operation than for the case of 15 years. It is also important to note that even when decreasing by 10% the DSWHS purchase price, the systems cannot compete with the oil-heat production cost without any social-environmental consideration to be taken into account. Additionally, only if the turnkey price of a DSWHS increase exceeds the 8% the system is not financially viable for a typical consumer, and for 10 years service period.

4.4 System Annual M&O Cost Impact

The application of modern design and improved construction techniques leads to more efficient and reliable installations[25]. The direct result of this evolution is a remarkable decrease of the M&O cost. On the other hand one should also take into account the relatively increasing labour cost, especially after the establishment of the new European currency, replacing old drachmas.

In figure (14) one can notice the almost linear variation of solar heat cost in relation with the variation of the annual M&O cost coefficient value. Even at zero M&O coefficient cost solar water heating cannot compete -at the present- the oil-heat production cost. Additionally, if the annual M&O cost coefficient surpasses the 4% mark then the system under investigation is no more financially attractive for a typical Greek consumer, in case of 10 years service period. Looking further, the break-even value approaches the 8% mark for a system operating for 15 years without major problems. For such a high

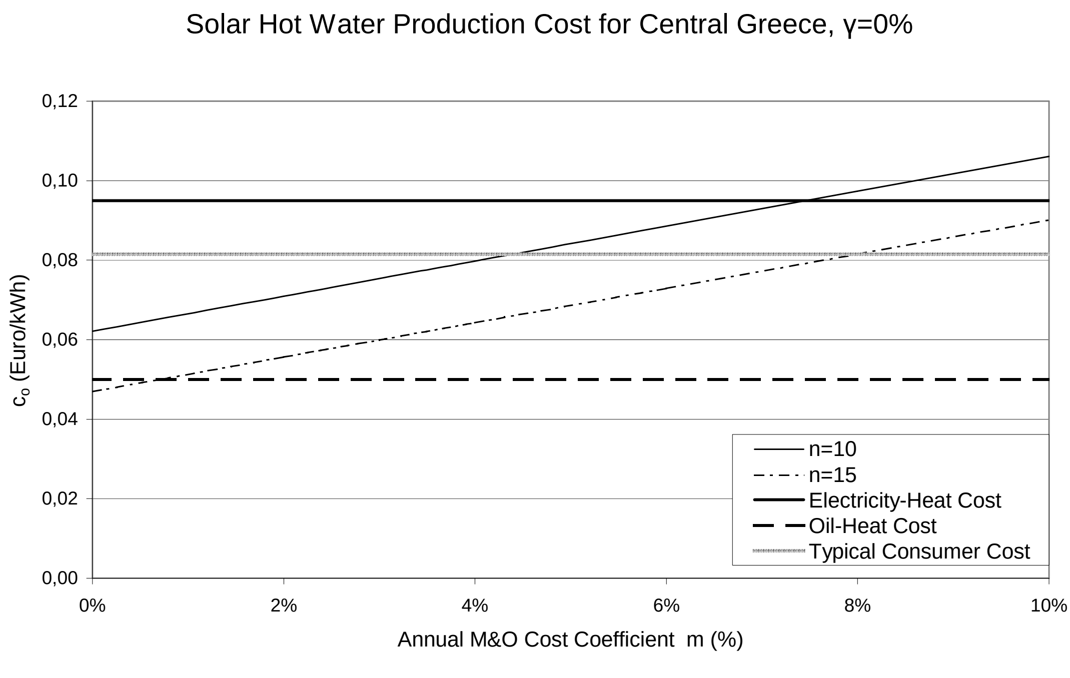

Figure 14: Impact of DSWHSs M&O cost on the solar hot water production cost

M&O cost value, even electrical water heaters appear to be more cost efficient than solar systems.

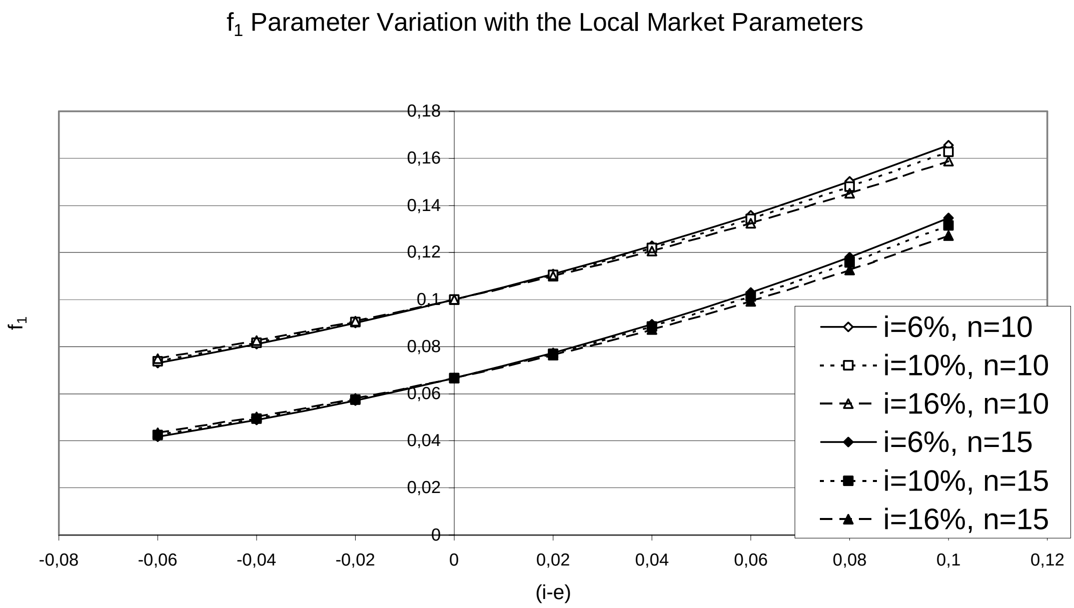

Figure 15: Variation of solar hot water production cost parameters with capital cost and heat price annual escalation rate

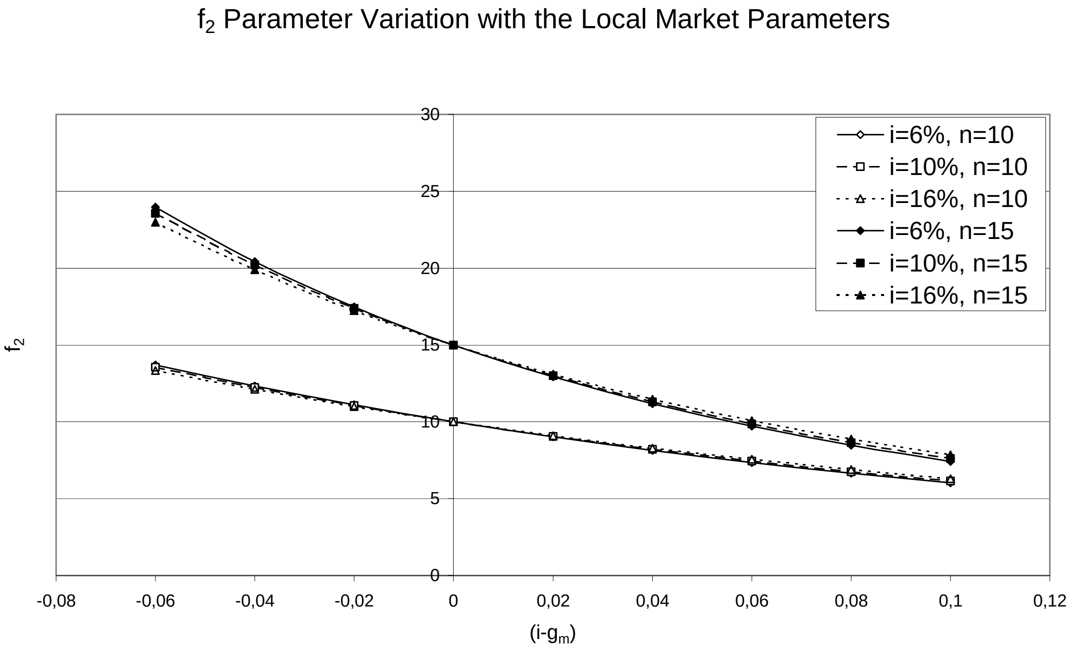

Figure 16: Variation of solar hot water production cost parameters with capital cost and M&O cost annual inflation rate

4.5 Local Market Financial Situation

It is commonly agreed that the economic situation of a local market strongly affects any investment. According to the model developed, the capital cost, the heat purchase price annual escalation rate and the M&O cost annual inflation rate are the parameters directly involved in the cost benefit evaluation of a DSWHS. Taking a closer look at equations (11) and (12) describing the "f_1" and "f_2" terms which appear in equation (25), one may state that "f_1" is a function of the capital cost "i" and the difference between capital cost and heat annual escalation rate "i-e", while "f_2" depends on the capital cost "i" and on the difference between the capital cost and the M&O cost inflation rate, in excess of the operational time of the installation "n".

From figures (15) and (16) one may conclude that the capital cost index "i" does not significantly affect "f_1" and "f_2", for any reasonable choice of the "i" value ("i" usually stays in the range 6%≤i≤16%). On the other hand, there is a strong variation of "f_1" with (i-e) and "f_2" with (i-g_m), while "f_1" and "f_2" vary almost inversely, see also equations (11) and (12). In this context, one may examine the dependence of solar water heat cost variation on (i-e) and on (i-g_m) only, disregarding the minor direct impact of the capital cost. figure (17) shows that the capital cost of the heat escalation rate difference affects almost linearly the heat production cost, while quite lower is the impact of (i-g_m). Taking into consideration that the (i-e) value, in Greece, during the last decade, remains higher than 6%, one could easily understand the competitiveness deficit that a DSWHS has for a typical consumer in the local market. On the contrary, in case that the solar water heating annual escalation rate exceeds the local market capital cost (e.g. after a major oil crisis), then solar systems should even compete the oil-heating production cost.

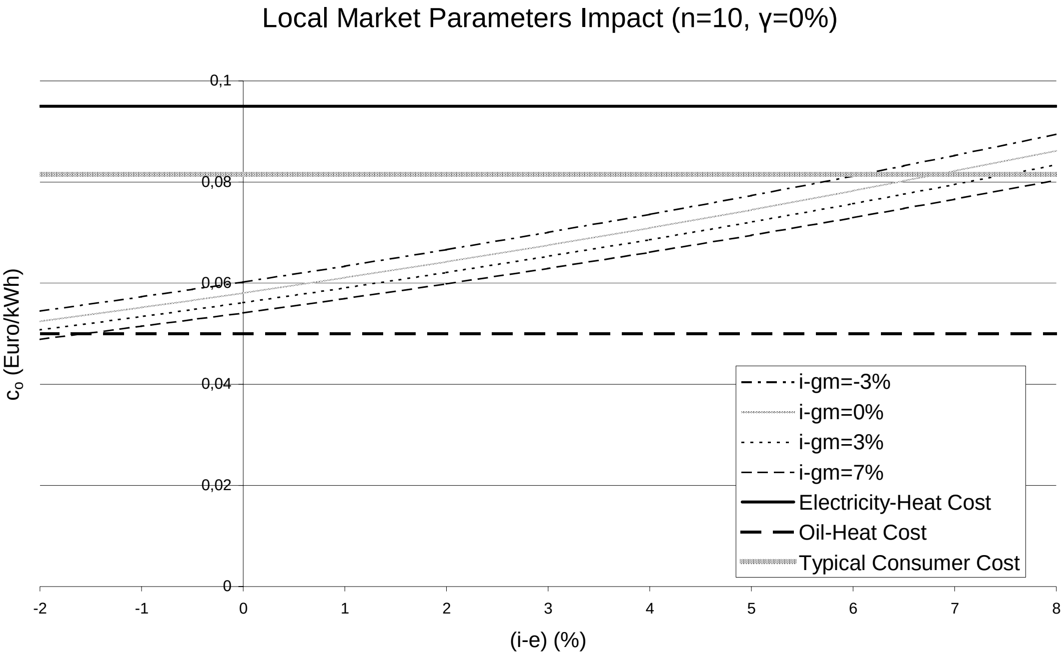

Figure 17: Impact of local market parameters on the solar hot water production cost

As far as the M&O cost annual inflation rate is concerned, one could easily see that the solar heat cost decreases as the inflation rate remains low, in comparison with the capital cost index. However, a "g_m" increase of the order of 10% slightly affects the solar heat cost, i.e. by almost 0.005€/kWh.

Recapitulating, according to the proposed cost-benefit model, the parameters that significantly affect the economic viability of DSWHSs, in Greece or elsewhere, are the utilization factor (clearly positive), the appropriate system sizing, the system specific cost variation (linearly), the installation service period (positively) and the heat cost production escalation rate (in relation to market capital cost). Rather less important one could characterize the impact of the annual M&O cost, the direct impact of local market capital cost and the annual M&O cost inflation rate (in relation to market capital cost). In any case, DSWHS cannot compete with oil or natural gas heat production, while they are clearly more cost effective than electric heaters, despite the fictitiously far down kept value of low voltage electricity in Greece.

5. Conclusions and Proposals

The present work investigates the sluggish solar collector market situation currently in Greece, despite the abundantly available solar radiation and the severe environmental and macroeconomic benefits imposed in the local society by the penetration of these solar systems in the domestic energy balance. For this purpose, an integrated cost-benefit method is presented, analysing the economic viability and attractiveness of contemporary DSWHSs. The developed model requires analytical presentation of the major problem parameters considered; including the system reduced initial installation cost, the corresponding utilization factor and the existing subsidization opportunities.

Accordingly, solar hot water production cost is estimated for each potential solar zone in Greece, as a function of the DSWHSs service period. The numerical values achieved are successively compared with the available alternative ones based on electricity or oil and natural gas. Finally, a quite extensive sensitivity analysis is carried out, in order to demonstrate the impact of the main techno-economic parameters on the fiscal behaviour (solar heat cost production for ten and fifteen-years operation) of contemporary DSWHSs in order to explain the sceptical and reluctant attitude of local consumers towards domestic solar energy applications.

According to the results obtained, it is almost obvious than under the current situation solar heat cannot compete with oil and natural gas heat production, in pure financial terms. It is only after the remarkable social and environmental benefits of solar energy replacing fossil fuel fired systems are introduced in the market competition (e.g. as an initial installation cost subsidization), the DSWHSs may become more cost efficient than the corresponding oil or natural gas ones. On the other hand, DSWHSs are definitely more financially attractive than electric heaters, even with zero subsidization, under the precondition of ten years service period and a 25% annual utilization factor, at least. It is also worthwhile mentioning that the DSWHSs profitability is very sensitive to changes of the utilization factor, the system proper sizing, the heat cost escalation rate and the initial installation cost; thought, it is slightly less sensitive to changes of the M&O cost. The direct impact of the capital cost index and the annual inflation rate on solar heat production cost seems to be limited.

As a final comment, the authors cannot be optimistic about the penetration of new DSWHSs in the local market under the current techno-economic situation, especially in view of the introduction of natural gas in the urban tertiary sector. Only in case that a rational incorporation of the external cost (the benefits resulting when fossil fuels systems are replaced by solar energy ones) in the DSWHSs purchase there is a strong possibility of local solar thermal market recovery. In addition, a prosperous market segment is the Greek islands, taking into consideration their excessive electricity production cost and the seasonal hot water demand due to summer tourism. One also should not disregard the substantial cost advantage of DSWHSs in comparison with electric heaters as well as the remarkably improved quality of contemporary systems that guarantee long operational period and minimal maintenance and operational cost.

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APPLICATION OF A GAS-TURBINE EXHAUSTED GASES TO BRACKISH WATER DESALINATION. A TECHNO-ECONOMIC EVALUATION

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Abstract

During the last twenty years, the electricity generation system of Crete Island has been actually based on the operation of several gas turbines, presenting an annual utilization factor higher than 50%. Despite the undeniable advantages of modern gas turbines, one cannot disregard the huge quantities of hot exhausted gases produced, containing almost two thirds of the chemical energy of fuel consumed. On the other hand, the island faces serious water resources insufficiency problems, especially during hot periods of the year. In this context, the island electricity generation utility (Public Power Corporation-PPC) is planning to allocate the so far unexploited exhausted gases of a recently installed gas turbine (LM-6000) at the Linoperamata-Heraklion power station to the neighboring municipality of Gaziou. The main idea elaborated in the present study is the techno-economic evaluation of a new desalination plant, utilizing a thermal desalination process and taking advantage of the heat content of the above-mentioned gas turbine. According to the results obtained, it is almost certain that the proposed desalination plant is able to produce an amount of clean water adequate to cover the local habitants' needs at a moderate cost, not only saving almost 15,000 tones of imported oil per year but also alleviating the local environment from several flue gases.

Keywords: Desalination; Cogeneration; Gas Turbine; Production Cost

1. Introduction

During the last twenty years, the electricity generation system of Crete island has been actually based on the operation of several gas turbines, representing more than 65% of the installed electrical power of the local network[1]. Generally speaking, gas turbines are normally used to cover peak load demand[2]. This is not the case for Crete island, where the utilization factor of the existing gas turbines exceeds 50% per annum[3], mainly due to increased electrical load demand, inability of the base thermal power units (steam turbines) to face even the basic load demand of the system along with significant delay[4] in erecting new thermal power stations.

On the other hand, Crete island faces a serious water insufficiency problem, -as the majority of the Aegean Sea islands- especially during the hot periods of the year[5]. In fact, Cretan water reserves are quite remarkable but the amplifying irrigation needs gradually consume the island's water reserves. As a direct result of this situation, the clean water reserves start diminishing[6], hence the water purchase cost is constantly increasing, currently approaching or even exceeding the value of 1€/m^3.

In this context, the island electricity generation utility (PPC) is planning to allocate the exhaust gases of a recently installed gas turbine (LM-6000) in the Linoperamata-Heraklion power station to the neighboring municipality of Gaziou. Up till now the totality of the outlet produced go directly to the atmosphere without taking advantage of their thermal energy. The main idea elaborated in the present study is the techno-economic evaluation of a new desalination plant, using a thermal desalination process, based on the heat of outgases resulting by the LM-6000 gas turbine. On top of this, the intention of PPC to allot exhausted gases heat is also considered, as compensation to the local habitants for the environmental impacts[7][8] resulting from the operation of the Linoperamata thermal power station.

For this purpose, the present work investigates the techno-economic viability[9][10] of a similar application in the local socio-economic environment. More specifically, the main dimensions of the proposed solution are initially determined on the basis of appropriate mass and energy balance calculations[11][12]. Accordingly, all available information concerning the first installation and the maintenance and operation cost of the complete desalination plant are also taken into account[13]. This study is integrated via a complete cost-benefit analysis, in order not only to estimate the marginal clean water production cost but also divide this cost in each main cost component. In this way, the monetary value of the heat energy -granted by PPC to the local habitants- may also be calculated on an annual basis.

2. Present Situation

The LM-6000 gas turbine -rated electrical power of $43.3MW_e$- has been installed[3] in the Linoperamata of Heraklion power station since 2002, in an attempt to facilitate the considerably increased electrical load of the island during the last years. According to official data[14], the net outlet power of the unit is $42.77MW_e$, while the mass flow rate of the hot outgases (456°C) is 123.7kg/sec. Using the above presented information, the existing heat rejected -compared with the atmospheric 20°C- may be estimated equal to $57.4MW_{th}$. Assuming that the outlet temperature to the environment ends up to 150°C, a remarkable part -approximately $39.7MW_{th}$- of the rejected heat can be employed. Bear in mind that -lacking any heat recovery mechanism- this significant heat amount has been hitherto lost.

At the same time, the water consumption of the adjoining municipality of Gaziou exceeds the 2,600,000m^3 per year, definitely presenting upward trends. More specifically, evaluating the most recent available data[13], it is obvious that over 1,800,000m^3 of potable water are annually consumed by the local habitants, while another 850,000m^3 are respectively engrossed for agricultural purposes. After a thorough analysis concerning the market price of clean water in the area, it is rational that the mean price of the potable water is 0.53€/m^3.

3. Proposed Solution

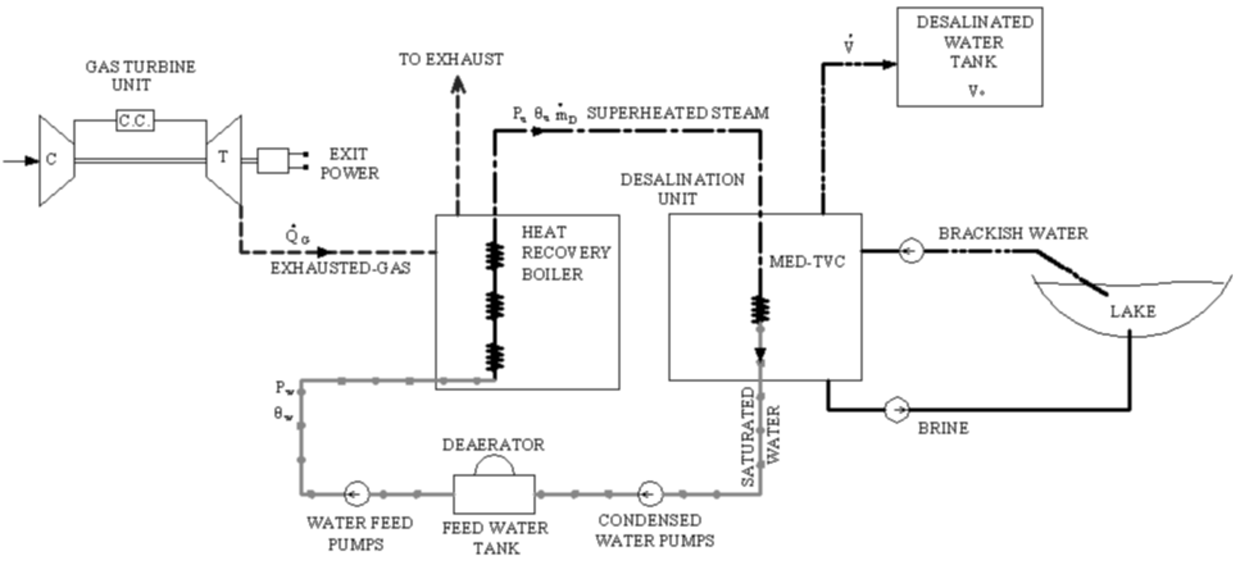

Figure 1: Schematic presentation of the proposed cogeneration-desalination plant

For the accomplishment of the proposed investment, the following parts are required, see also figure (1):

a. A heat recovery boiler for the production of superheated steam (pressure of 7bar and temperature of 180°C) from input water of 90°C and 10bar. The input heat results from the mass flow rate of 123.7kg/sec of the LM-6000 gas turbine exhausted gases, while the expected efficiency of the boiler ranges between 70% and 90%.
b. A new thermal desalination plant based on a multi-effect (three to five effects are considered) distillation procedure, accompanied by thermal vapor compression (MED-TVC) for increased performance ratio[11][12][15]. The rated capacity of the installation is $460m^3/h$ of potable water, using brackish water from the bordering lake of Almiros. The corresponding gained output ratio (GOR) value is approximately 8.1 (kg of distillate/kg of steam used), while the steam leaves the desalination unit in a saturated condition. Finally, the specific energy consumption of the installation "q" is approximately equal to $65kWh_{th}$ per cubic meter of potable water produced[12][15][16].
c. A condensed water collection system, which leads the saturated steam to the existing feed water tank. Accordingly, after the thermal deaerator of the water, the feed water pumps lead the working fluid to the boiler at a pressure of 10bar.
d. The brackish water system. This system includes the suction apparatus for unprocessed water, the pretreatment equipment, the transportation pipelines and the corresponding pumps. Accordingly, the processed byproduct should return to the Almiros Lake, via a parallel network and the appropriate saline-water (brine) pumps.
e. The network of clean water transportation and the corresponding water reservoir. In the present situation, the storage volume of the proposed water reservoir is set equal to $6,000m^3$, due to existing land usage constraints[13].

4. Definition of the System Main Dimensions

Once all main components of the proposed desalination-cogeneration system have been introduced, their main dimensions should accordingly be defined by using an integrated energy balance analysis[2][11][12][17][18][19].

4.1 Heat Recovery Boiler Analysis

In consideration of the data[13][14] concerning the LM-6000 gas turbine exhausted gases (mass flow rate "m_G" 123.7kg/sec and temperature "θ_{in}" of 456°C), the corresponding "Q_{GIN}" input heat is given as:

$$Q_{G_{in}} = m_G \cdot C_p \cdot (\theta_{in} - \theta_a) \tag{1}$$

This input heat is mainly absorbed by the water-steam circuit "Q_o", while a small part "Q_l" of it turns to system loss (≈1.3%). Finally, a considerable part of the input heat is included in the exhausted gases (θ_{ex}≈150°C) going to the atmosphere. More specifically, according to the energy conservation equation concerning the heat recovery boiler, one may write:

$$Q_o = Q_{G_{in}} - Q_{G_{ex}} - Q_l = m_G \cdot C_p \cdot (\theta_{in} - \theta_a) - m_G \cdot C_p \cdot (\theta_{ex} - \theta_a) - Q_l \tag{2}$$

where "θ_a" is the ambient temperature and "C_p" is the constant pressure specific heat, being mainly a function of the gases' temperature, i.e. $C_p=C_p(\theta)$.

Applying numerical values on equations (1) and (2), the resulting effective heat (absorbed by the water-steam mass flow rate) is approximately $39.3MW_{th}$. This energy is used to transform the input water (enthalpy h_w=420kJ/kg) to superheated steam (enthalpy h_u=2799kJ/kg). Hence the resulting steam mass flow rate "m_o" is given as:

$$m_o = \frac{Q_o}{h_u - h_w} \tag{3}$$

According to equation (3), the expected steam production approximately equals to 16.4kg/sec or 59tn/h. Finally, a remarkable part "a" of steam produced is consumed by the installation in order to cover the energy demand of several subsystems, thus only the remainder "m" of steam is forwarded to the desalination process, i.e.:

$$m = (1 - a) \cdot m_o \tag{4}$$

4.2 Energy Analysis of Desalination Unit

Using equations (1) to (4), the produced superheated steam mass flow rate entering the desalination unit, for potable water production via a MED-TVC desalination procedure, may be calculated. The output temperature "θ_o" of the resulting condensate is approximately 100°C. Hence, the useful energy "Q^*" given to the brackish water is estimated as:

$$Q^* = m \cdot (h_u - h_o - \delta h) \tag{5}$$

where "δh" is the enthalpy drop during the steam transportation from the boiler to the desalination unit and "h_o" the condensate enthalpy. Subsequently, the energy "Q_{des}" absorbed by the desalination procedure is estimated via the heat transfer efficiency of the unit "η_{des}", ranging between 85% and 95%. Thus, the corresponding "Q_{des}" value can be expressed as:

$$Q_{des} = \eta_{des} \cdot Q^* \tag{6}$$

Using the available information by the corresponding literature[11][12][15], the specific heat absorbed per cubic meter of produced clean water "q" varies between 50 and 70kWh/m^3. Subsequently, the potable water volume rate "V" can be predicted as:

$$V = \frac{Q_{des}}{q} \tag{7}$$

Finally, using the energy conservation equation throughout the desalination unit one may estimate the desalination unit outlet temperature of the potable water, see for example Darwish and El-Dessouky[11].

4.3 Additional Energy Consumptions

During the complete desalination procedure, there are several additional energy consumption devices using either superheated steam from the outlet of the heat recovery boiler or electrical energy from the LM-6000 gas turbine[13]. Since the present analysis is also interested in the feasibility of the complete installation, the additional energy consumption amounts are as well taken into consideration, i.e.:

- ✓ Boiler feed water pumps (pressure increase 10bar, mass flow rate 60tn/h)
- ✓ Brackish water transportation pumps (pressure increase 2bar-3bar, volume flow rate 2000m^3/h)
- ✓ Potable water transportation pumps (pressure increase 1.5bar-2bar, volume flow rate 500 m^3/h)
- ✓ Brine transportation pumps (pressure increase ≈2bar, volume flow rate 1500 m^3/h)
- ✓ Saturated water transportation pumps (pressure increase 0.5bar, mass flow rate 60tn/h)
- ✓ Other auxiliary devices, estimated electrical energy consumption 0.2kWh$_e$/m^3 per cubic meter of potable water produced.

Summarizing, the electrical energy consumption "ε" of the proposed installation can be roughly estimated to be between 1.0 and 1.5kWh$_e$/m^3. This value is in accordance with the established values[11][12][15][16] for similar desalination systems, according to which "ε" should vary between 0.8 and

$1.5kWh_e/m^3$. For increased security, the maximum value of "ε" is adopted in the cost-benefit analysis of the next section.

5. Cost-Benefit Analysis

5.1 Initial Cost

The numerical value of the proposed desalination plant investment cost is a combination of the initial cost and the corresponding maintenance and operation (M&O) cost[10]. More specifically, the initial cost "IC_o" includes the market price of all the equipment used for the clean water production, along with the corresponding installation cost. Besides, the cost for manufacturing the clean water storage reservoir is also included. After an extensive market survey[12][13][14][20][21][22], the corresponding buy cost values for the proposed desalination plant are included in Table I.

Table I: First installation cost analysis

	First Installation Cost Main Components	Value
1	Heat recovery boiler (*steam mass flow rate 60t/h, pressure 10bar, outlet temperature 150°C, maximum gas inlet temperature 480°C*)	850,000€
2	Water pumps, steam-water pipelines (*max pressure 12bar*)	270,000€
3	Modifications of the gas-turbine (LM-6000) outlet part	100,000€
4	Boiler and water pumps transportation and installation cost	180,000€
5	Desalination unit (MED-TVC), *rated potable water production 460m³/h*	900,000€
6	Transportation network of brackish water	400,000€
7	Transportation network of desalinated water and water storage reservoir	500,000€
8	Commissioning and educational cost	100,000
	Total Cost	**3,300,000€**

Recapitulating, the turnkey cost of the proposed installation is found equal to 3,300,000€, while this value may normally vary between 2,700,000€ and 3,900,000€.

5.2 Investment Cost

As it is well accepted, the future (after –n years of operation) value of the investment cost is a combination of the initial investment cost "IC_n" and the maintenance and operation cost. The future value of the initial investment cost can be expressed as:

$$IC_n = (1-\gamma)\cdot IC_o \cdot (1+i)^n \quad (8)$$

where "γ" is the subsidy percentage by the Greek State and "i" is the corresponding capital cost in the local market. According to the existing Greek Development Law (2601/98), clean water production investments based on cogeneration are subsidized by a 30%, i.e. γ=0.3.

Subsequently, the maintenance and operation (M&O) cost can be split into the fixed maintenance cost "FC_n" and the variable one "VC_n". For simplicity reasons, the variable M&O cost is not explicitly analyzed here. Furthermore, during the first years of operation, the corresponding term is usually incorporated in the fixed M&O cost.

In this context, the annual fixed M&O cost of the desalinated water production plant can be expressed as a fraction "m" of the corresponding initial capital invested (assuming also an annual increase of the cost equal to "g^m") plus the annual energy consumption cost. This value depends on the electricity consumption cost as well as on the necessary heat purchase value. The electricity term results as the product of the annual electrical energy consumption "$\varepsilon\cdot V_t$" with the corresponding electricity purchase value "c_e". Subsequently, the heat consumed purchase cost is the product of the specific heat consumed, the annual water production volume and the heat price value. Using the above information one may write that:

$$C_n = \left\{(1-\gamma)\cdot IC_o + m\cdot IC_o \sum_{j=1}^{n}\left[\frac{1+g^m}{1+i}\right]^j + \varepsilon\cdot c_e\cdot V_t\cdot \sum_{j=1}^{n}\left[\frac{1+e}{1+i}\right]^j + q\cdot c_q\cdot V_t\cdot \sum_{j=1}^{n}\left[\frac{1+e_q}{1+i}\right]^j\right\}\cdot (1+i)^n \tag{9}$$

where "V_t" is the annual clean water production volume (m^3), "ε" is the specific electricity consumption (kWh/m^3) of the desalination plant and "e" the mean annual electricity price escalation rate. Similarly, "q" is the specific heat consumption per cubic meter of clean water production, "c_q" is the input heat reduced cost and "e_q" is the corresponding heat cost annual escalation rate.

5.3 Investment Revenue

Subsequently, the total savings (in current values) over an n-year period, due to the clean water production, are given as:

$$R_n = c_w\cdot V_t\cdot (1+i)^n\cdot \sum_{j=1}^{n}\left[\frac{1+w}{1+i}\right]^j \tag{10}$$

where "c_w" is the current price of clean water produced by the desalination plant and "w" is the mean annual escalation rate of water price. As it is obvious, the desalinated water price should be definitely lower than the corresponding market price of potable water for every case examined, in order the proposed investment to be economically viable.

5.4 Break-Even Equation

By comparing the total expenses and the corresponding total savings of the investment for a specific service period of the installation ($n=n^*$), lower than the normal lifetime of the desalination plant, one gets:

$$C_n - R_n = 0 \tag{11}$$

or equivalently:

$$IC_o\cdot\left[(1-\gamma)+m\cdot f_g\right] + V_t\cdot(\varepsilon\cdot c_e\cdot f_e + q\cdot c_q\cdot f_q) - c_w\cdot V_t\cdot f_w = 0 \tag{12}$$

where the auxiliary functions "f_x" are defined as:

$$f_x = \sum_{j=1}^{n}\left[\frac{1+x}{1+i}\right]^j = \frac{1+x}{1+i}\cdot\left(1+\frac{1+x}{1+i}+...+\left[\frac{1+x}{1+i}\right]^{n-1}\right) \tag{13}$$

with $x=g^m$; $x=e$; $x=e_q$ and $x=w$.

It is important, at this point, to mention that equation (12) can be solved in order to estimate the marginal desalinated water production cost, if the service period of the installation and the capital cost of the market are defined.

5.5 Clean Water Production Cost

For the estimation of the marginal production cost per cubic meter of desalinated water, on the basis of the proposed desalination plant, one may solve equation (12), thus:

$$c_w = \frac{IC_o}{f_w \cdot V_t} - \frac{\gamma \cdot IC_o}{f_w \cdot V_t} + \frac{m \cdot IC_o}{V_t} \cdot \frac{f_g}{f_w} + \varepsilon \cdot c_e \cdot \frac{f_e}{f_w} + q \cdot c_q \cdot \frac{f_q}{f_w} \quad (14)$$

According to equation (14), the current value of desalinated water produced by the proposed desalination configuration, operating for an unobstructed n-year period, mainly depends on:

i. The initial capital invested (first term of the Right Hand Side (RHS) of equation (14))
ii. The State subsidization percentage (second term of the RHS of equation (14))
iii. The annual M&O cost parameter (third term of the RHS of equation (14))
iv. The specific cost of the electrical energy consumed (fourth term of the RHS of equation (14))
v. The reduced cost of the heat input of the installation (fifth term of the RHS of equation (14))

Bear in mind that all terms mentioned are properly modified in order to regard the time variation of the issue's economic parameters (e.g. capital cost, inflation ratio, electricity and heat buy cost, etc.).

6. Desalinated Water Production Cost Results

Applying the above-presented analysis on the proposed desalination plant "DP" configuration, the time-variation of the corresponding clean water production cost may be estimated. For this purpose, the parameters of equation (14) take values of Table II. All values selected are based either on extensive market surveys[13] or on local market records[10].

Table II: Central values of the main parameters of the cost-benefit analysis

Parameter	Numerical Value	Units	Parameter	Numerical Value	Units
IC_o	3,300,000	€	c_e	0.041	€/kWh
γ	30	(%)	e	2	%
m	2.8	(%)	q	60	kWh_{th}/m^3
g^m	4	(%)	w	2	(%)
ε	1.5	kWh_e/m^3	V_t	2,500,000	m^3
i	8	(%)			

Hence, according to the results of figure (2), the expected clean water production cost is definitely below 0.37€/m^3, even after five years of the proposed desalination plant's operation. More specifically, the maximum water production cost after five years of operation approximates 0.32€/m^3, while for 15-years of operation it is below 0.2€/m^3 -an aspect underlining the desalination plant's considerable cost reduction with operational time.

Accordingly, for the short-term operation of the proposed DP, the first installation cost represents more than two thirds of the corresponding production cost. On the other hand, there is a significant reduction of the initial cost contribution in figure (2) as the service period of the installation increases. In this case, the required electricity purchase cost becomes quite remarkable; while a fair increase is also encountered for the M&O cost contribution in the installation marginal production cost.

Finally, all the above-presented calculation results comprise a 30% State subsidization on the first installation cost of the DP, as well as a zero purchase cost for the heat absorbed by the installation. Although these assumptions were principally made during the present analysis, for comparison purposes figure (3) demonstrates the marginal production cost increase of desalinated water in the theoretical case that either no first installation cost subsidization is considered (i.e. γ=0%) or a rational price (e.g. c_q=0.002€/kWh_{th}) is attributed to the input heat amount. As it comes out from figure (3), the viability of the proposed investment is strongly questioned even at a minimum input heat charge, since

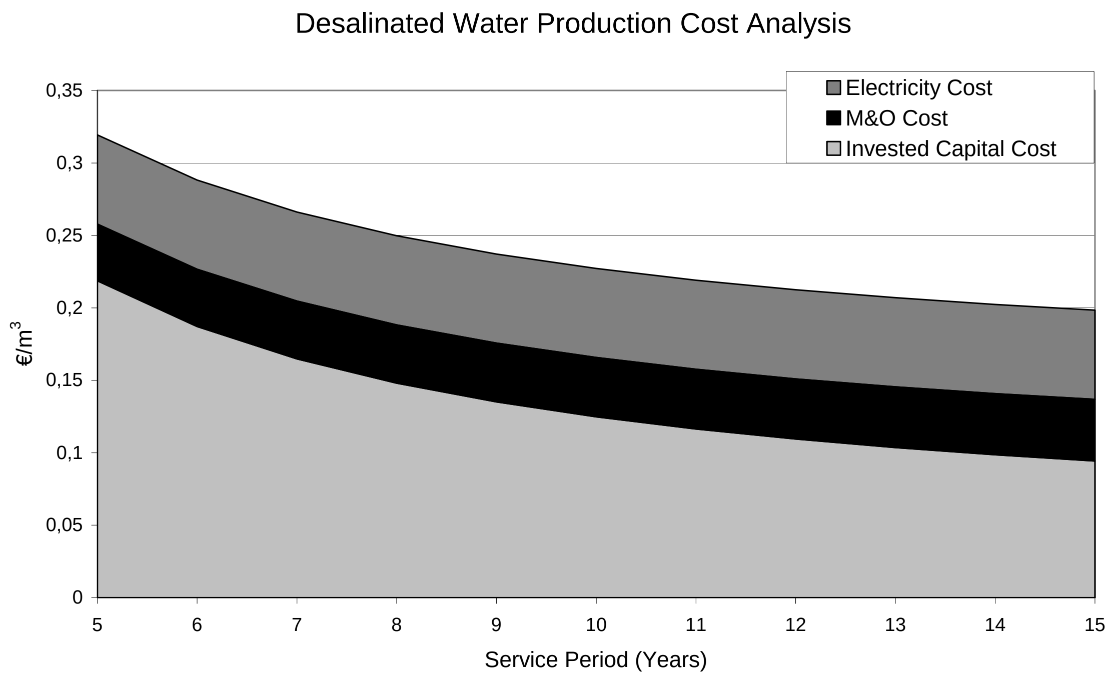

Figure 2: Desalinated water marginal production cost analysis in the course of time

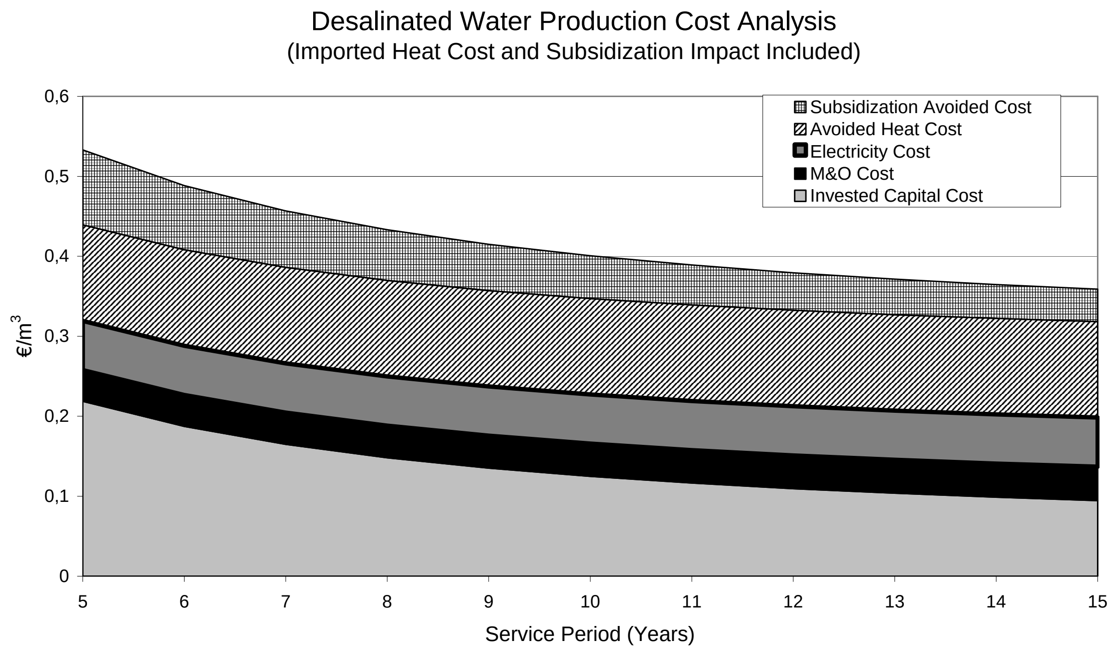

Figure 3: The impact of imported heat cost and State subsidization on desalinated water marginal production cost

the clean water production cost is respectively increased by 0.12€/m^3, for the entire operational life of the investment. Hence, the corresponding monetary value of annual heat energy -granted by PPC to the local habitants- exceeds the 350,000€/year in constant values. Similarly, in case of zero State subsidization of the investment, the corresponding marginal production cost of the installation increases up to 0.095€/m^3 for the 5-years operation and 0.04€/m^3 for the 15-years operation of the desalination plant. Hence, the maximum production cost in this theoretical worst scenario varies between 0.53€/m^3 and 0.36€/m^3 respectively.

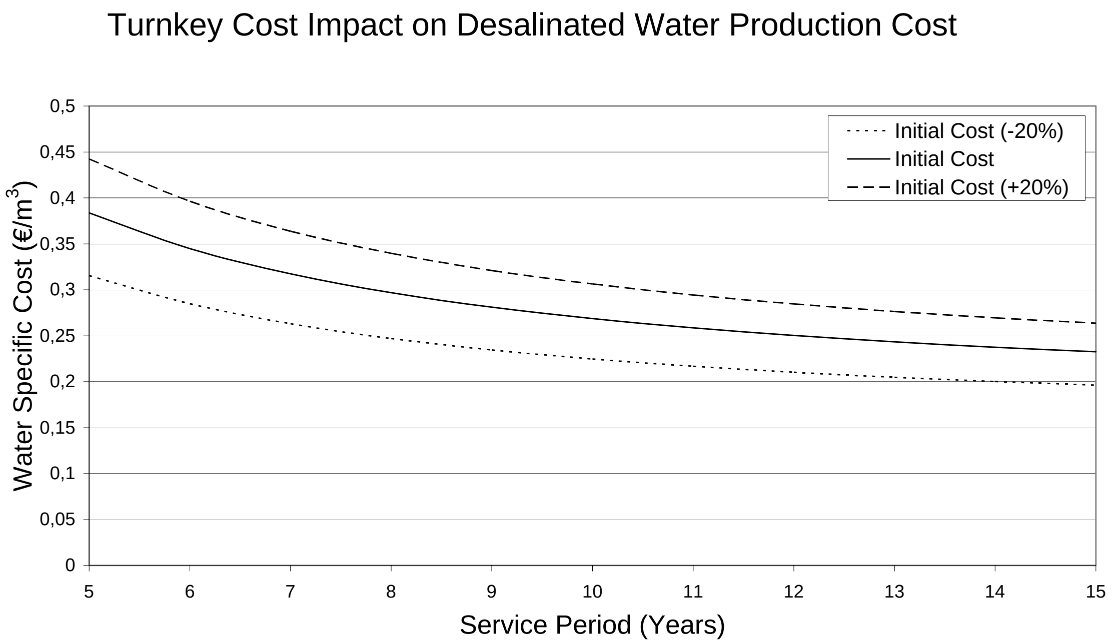

Figure 4: Turnkey cost impact on desalinated water marginal production cost

The calculation results concerning the estimated desalinated water production cost of the proposed installation are presented in the following, as a function of the main parameters of the problem.

6.1 Turnkey Cost of the Investment

As already mentioned, the turnkey cost of the investment includes the ex-works price of the equipment required and the corresponding installation and commissioning cost. According to figure (4) a remarkable cost modification is encountered in case that the first installation cost varies ±20% around the proposed numerical value. More precisely, the corresponding marginal production cost variation is 0.11€/m^3 for the 5-years operation and 0.07€/m^3 for the 15-years operation of the proposed installation.

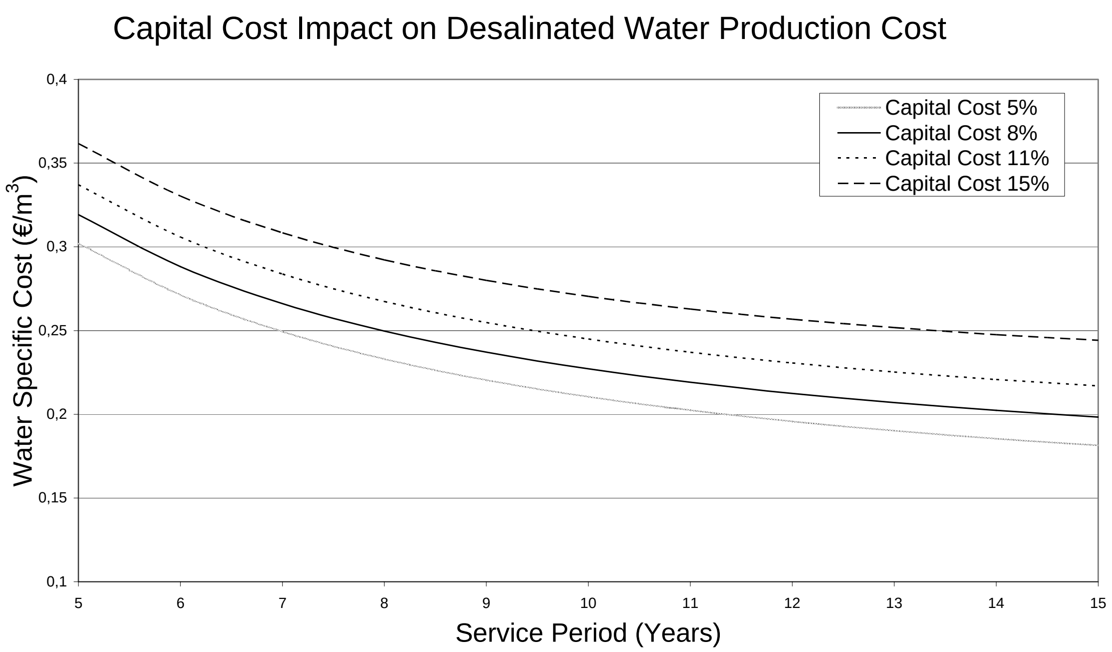

Figure 5: Capital cost impact on desalinated water marginal production cost

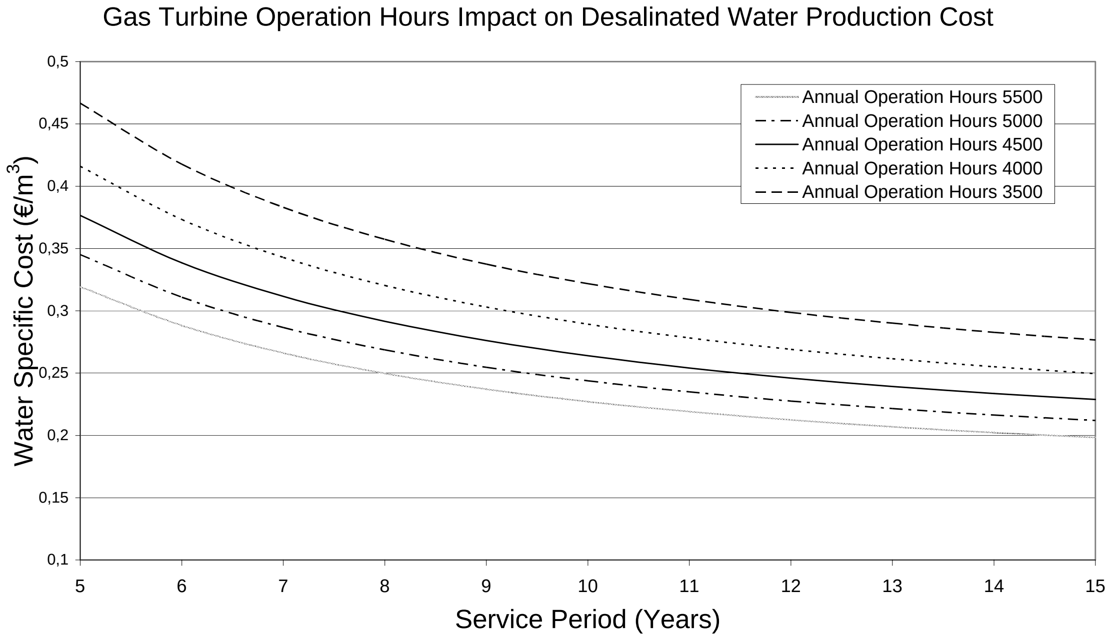

Figure 6: Gas turbine operation hours impact on desalinated water marginal production cost

6.2 Capital Cost

It is widely accepted that the capital cost depends on the financial status of local market and particularly on the existing investment opportunities, the timing of repayment, the risk of investment and the inflation rate of economy, in order to obtain positive inflation-free capital return. In the present investigation the capital cost values analyzed range between 5% and 15%, values quite realistic for the E.U. market. According to figure (5), the water production cost increases in proportion to the capital cost, i.e. approximately 0.006€/m^3 by 1% increase of the capital cost. As a result, the 5-years production cost varies between 0.3€/m^3 and 0.37€/m^3, while the corresponding value for the 15-years operation is between 0.18€/m^3 and 0.25€/m^3.

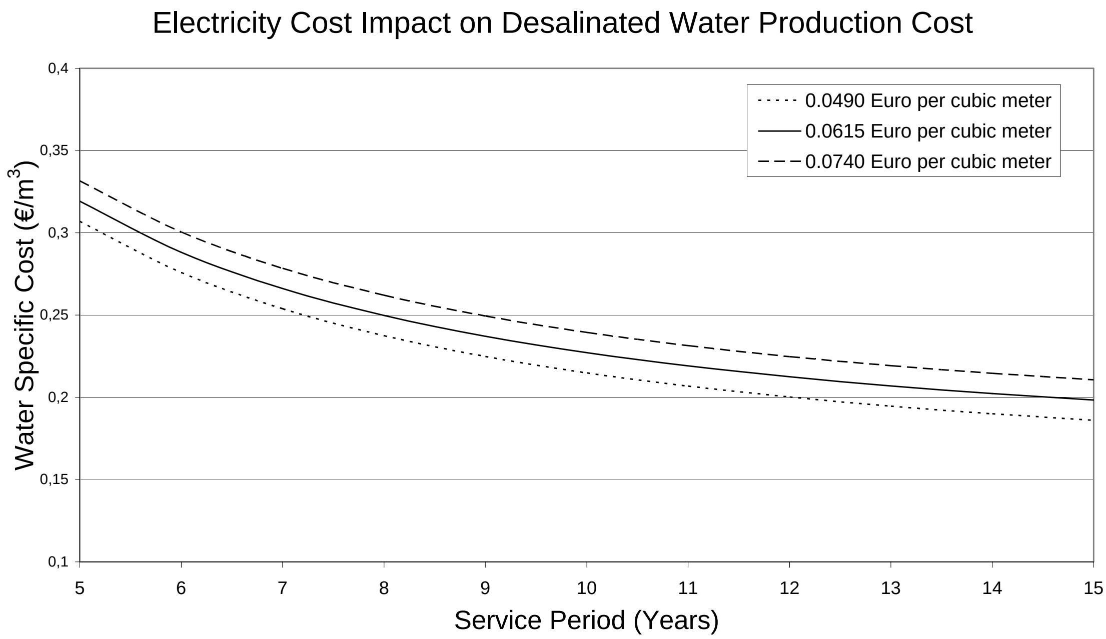

Figure 7: Imported electricity cost impact on desalinated water marginal production cost

6.3 Hours of Operation of the LM-6000 Gas Turbine

Generally speaking, the vast majority of the existing gas turbines operate to cover peak load demand. This is not the case for Cretan electricity generation system. As a result, the majority of the island's gas turbines practically approximate 5500 hours of full operation per annum[1][3]. Considering that the exhaust gases of the LM-6000 gas turbine is the main energy input of the examined installation, figure (6) analyzes how the annual utilization factor of the LM-6000 engine affects the desalinated water production cost. According to the results obtained, the clean water production cost increases (for a short-term operation) by almost 0.035€/m^3 for every 500 fewer operational hours, per year of electricity generation unit. In case of long-term operation (e.g. 15-years) the corresponding marginal production cost increases by 0.02€/m^3.

6.4 Input Electricity Purchase Cost

The proposed desalination plant is mainly based on input heat, in order to accomplish its basic operation activities. However, an adequate electricity amount is also required to support the auxiliary subsystems of the installation. figure (7) demonstrates the impact of an electricity purchase cost variation equal to ±0.0125€/m^3 (in comparison with 0.0615€/m^3 -the central value of Table II) on the corresponding time-evolution of the clean water production cost. Using the information presented, it is apparent that any electricity purchase cost increase/decrease leads to an equivalent desalinated water production cost increase/decrease almost independently of the operational years of installation.

Recapitulating, the turnkey cost of installation, the local market capital cost, the hours of annual operation of the corresponding power station (gas turbine) and the required input electricity buy-cost are the main parameters that significantly affect the marginal production cost of the proposed desalination plant, in excess of the operational years of the unit. In this context, any decrease of the turnkey cost of installation, the market capital cost, the electricity purchase cost or any increase of the utilization factor of the system leads to a corresponding production cost decrease, Table III. In most cases investigated, the clean water marginal production cost changes more intensely for a short-term operation of installation than for a long-term one, see also equation (14).

Table III: Impact of main parameters on the desalinated water production cost

Cost-Benefit Parameter	5-years Service Period	15-years Service Period
Capital Cost Variation from 5% to 15%	Production Cost Increase from 0.30€/m^3 to 0.37€/m^3	Production Cost Increase from 0.18€/m^3 to 0.25€/m^3
Turnkey Cost Variation ±20%	Production Cost Variation 0.11€/m^3	Production Cost Variation 0.07€/m^3
Operation Hours of Gas Turbine	0.035€/m^3 Production Cost Increase for every 500 fewer operational hours per year	0.020€/m^3 Production Cost Increase for every 500 fewer operational hours per year
Input Electricity Purchase Cost Variation ±0.0123€/m^3	Production Cost Variation ±0.0123€/m^3	Production Cost Variation ±0.0123€/m^3
Subsidization Percentage Variation from 0% to 30%	Production Cost Increase 0.095€/m^3	Production Cost Increase 0.042€/m^3
Input Heat Charge 0.002€/kWh$_{th}$	Production Cost Increase 0.12€/m^3	Production Cost Increase 0.12€/m^3

7. Conclusions and Proposals

The present study implements the idea of fulfilling a small island community's requirement for clean water by using the high temperature of an already operating gas turbine exhausted gases on a cogeneration basis. For this purpose, the proposed desalination plant basic dimensions are estimated using available official data along with an integrated mass flow and energy conservation analysis. The annual production capacity of the desalination plant analyzed surpasses the 2,500,000m^3 of potable water, hence covering the annual water consumption of the municipality involved.

Accordingly, an integrated cost-benefit analysis is carried out in order to examine the financial viability of a similar venture. The resulting marginal production cost value is less than 0.37€/m^3, being equal to the corresponding average current price of the available clean water in the area. In order to improve reliability of the proposed solution, an extensive sensitivity analysis is carried out, regarding desalinated water production cost under predefined variations of the basic parameters of the problem. The entirety of the results obtained support realization of such an investment.

The main issue to be ensured in the course of time is the local electricity utility engagement to allocate the gas turbine exhausted gases to this specific desalination plant of the adjoining municipality of Gaziou, at no cost. If this last precondition is fulfilled, it is almost certain that the proposed desalination plant is able to produce an amount of clean water adequate to cover the local habitants' needs at a moderate price, not only saving almost 15,000 tones of imported oil per year but also alleviating the local environment from significant quantities of air pollutants.

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PART FOUR

ENVIRONMENT

- Air Pollution
- Environmental Impacts
- Sustainability

TEMPORAL EVOLUTION OF THE SULPHUR OXIDES EMISSIONS FROM THE GREEK ELECTRICITY GENERATION SECTOR

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Abstract

The Greek electricity production sector is based -as far back as the early 60's- on the usage of local lignite and imported heavy-oil. Hence the electricity production process is assumed responsible for a significant contribution to air pollution, including 80% of the national sulphur dioxide emissions. In this context, an extensive and thorough analysis is carried out concerning the SO_2 effluents coming from the electricity generation sector during the 1995-2002 period. For this purpose, the available long-term official measurements are taken into consideration and analysed in depth. According to this analysis, the SO_2 emissions factor ratio between Southern Greece and Northern Greece lignite fired stations is in the order of 25:1. Additionally, one may definitely state that there is a considerable surcharge of sulphur oxides released by the Greek electricity production system, which although showing a fairly decreasing tendency, it is still above the 8.5gr/kWh consumed. Finally, the positive contribution of the natural gas, gradually replacing other fuels, and the operation of a new desulphurisation unit in S. Greece are clearly counterbalanced by the significant and constant annual electricity consumption amplification of the last decade.

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

1. Introduction

Any continuous technological development is closely associated with increased energy consumption. One of the most user-friendly energy resources used by contemporary societies is electricity. For this reason, there is a considerable, per capita, electricity consumption amplification for most developed countries, approaching 3.5%, annually[1]. However, till now, electricity generation is worldwide based mainly on thermal power stations (TPS), utilizing either fossil fuels, or nuclear reactor fuels. As a direct result of this choice, several environmental dangerous by-products are released, like extremely dangerous fissionable materials, huge quantities of thermal waste and substantial amounts of air pollutants[2][3][4].

Greece, since 1950, has based its electricity production system on locally mined lignite and imported heavy-oil[5]. So far, there are no nuclear power units, while the existing numerous hydropower stations remain most of the time idle, showing a utilization factor of less than 15% during the last 15 years. In fact, lignite and heavy oil fired stations produced during 2002 almost 80% of the national electricity production, figure (1), while the contribution of renewable energy sources (mainly wind) and large hydropower units rated less than 10%. It should be noted that during the last decade there is no solid fuel imports for electricity production, while only a small portion from the almost 100,000,000 barrels of crude oil imported annually is 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) are 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.

Kaldellis J.K., Voutsinas M., Paliatsos A.G., Koronakis P.S., 2004, *"Temporal Evolution of the Sulphur Oxides Emissions from the Greek Electricity Generation Sector", Environmental Technology J.**,** vol.25, pp.1371-1384.*

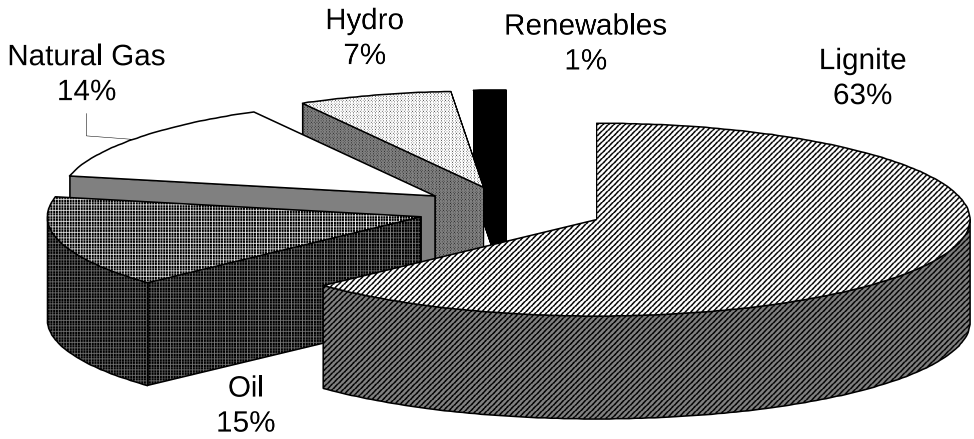

Figure 1: Greek national electricity production fuel sources for the year 2002

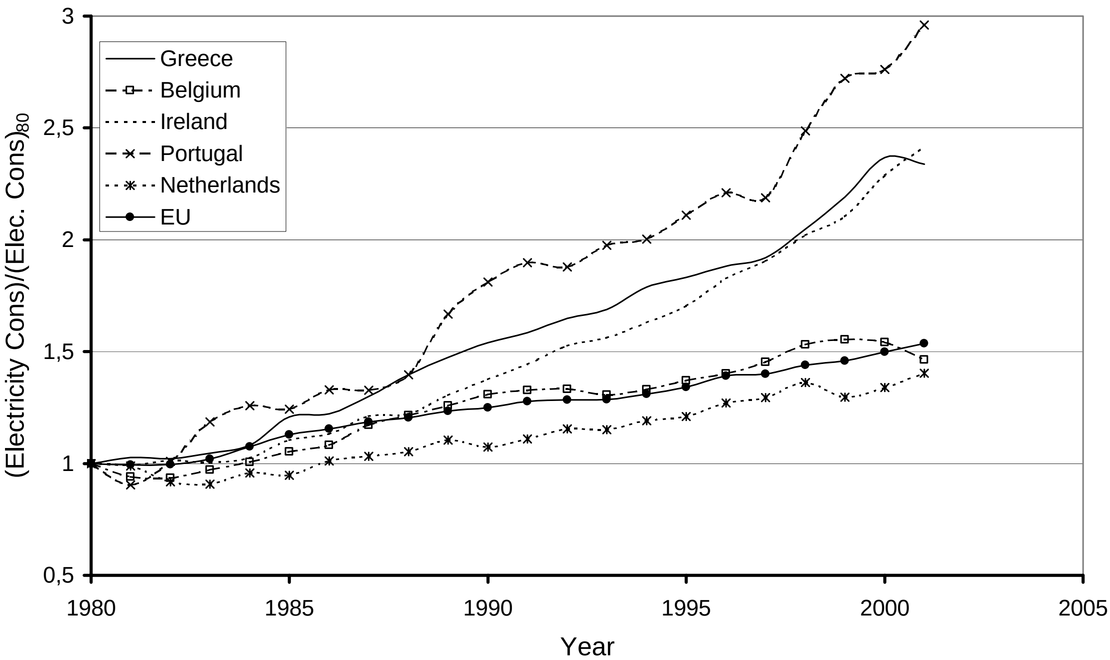

Figure 2: Electricity, per cap, consumption variation ratio for Greece and other E.U. countries, relatively to 1980 values

In order to obtain a clear-cut picture of the national electricity consumption escalation rate one may compare the time series of yearly electricity consumption, per capita, of Greece with the corresponding consumptions observed in several other E.U. country members, figure (2). As it becomes obvious from the data shown[1][6] the annual electricity consumption growth in Greece is approximately 6%, while the expected value for the next decade is estimated between 4.0% and 4.5%[7]. One should also note that the specific electricity consumption (kWh/cap) annual escalation rate is quite higher than the corresponding value per capita GDP, for the same time period, figure (3).

In as much, Greek electricity production sector is assumed responsible, according to several official reports[8][9][10], for the release of more than 50% of CO_2, for almost 80% of SO_2 and for approximately

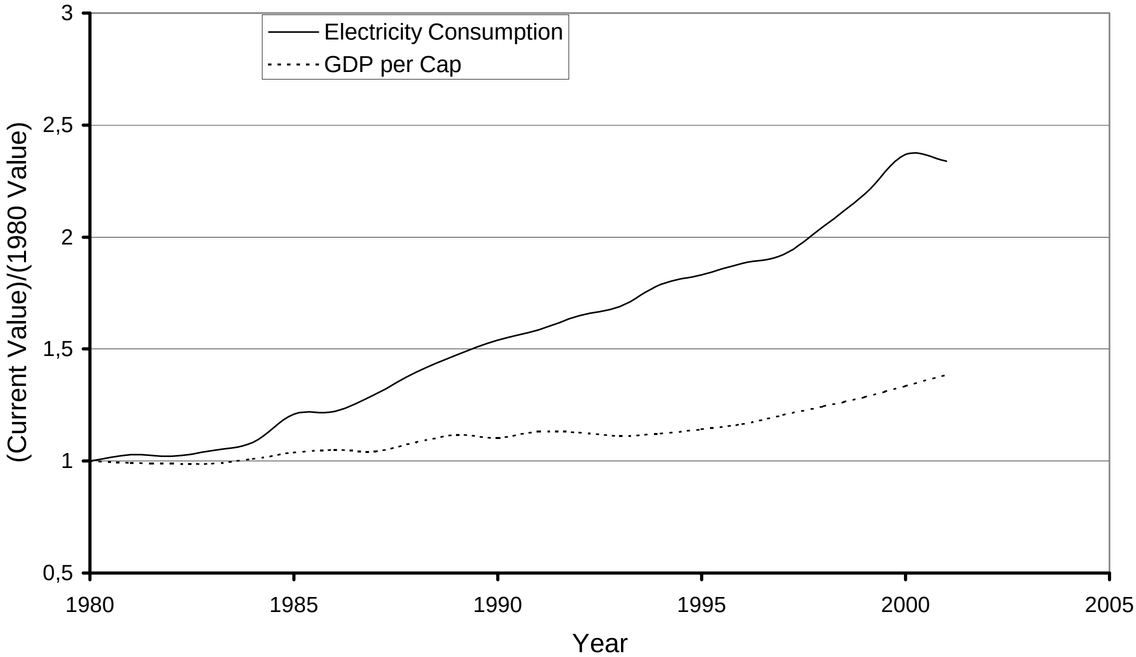

Figure 3: Comparison between electricity consumption and GDP, per cap, for Greece

25% of NO_x national emissions. Taking into consideration that Greece -a country member of E.U.- has accepted specific obligations for the reduction of the emissions of greenhouse gases and the protection of its local citizens from dangerous toxic effects of the various harmful gases and particles release[11], like sulphur dioxide, nitrogen oxides etc, it is very important for national purposes to evaluate the time series concentrations of all these flue gases emitted by the power stations of the corresponding national electricity production sector.

In addition to above mentioned air pollutants, several other flue gases like carbon monoxide, volatile organic compounds and solid particles are characterized as equally dangerous air pollutants. However, the contribution of electricity production sector to carbon monoxide and volatile organic compounds is limited[12][13], while only recently a systematic recording of solid materials emissions by local TPS has started[14]. Taking into consideration the dominant role of electricity generation on the national sulphur oxides emissions, the present work is focused on investigating in detail the corresponding sulphur dioxide emissions for the 1995-2002 period[15][16]. Local data collected is first compared with relative information regarding other regions of the world found in the literature and then used accordingly to make a simple forecast of the expected air pollutants emissions for the near future.

2. Greek National Electricity Production System

Officially[5][7] according to the Greek Regulatory Energy Authority (RAE) and till recently (2001) the State controlled Public Power Corporation (PPC), the Greek Electricity Production System (EPS) is divided in two branches. The first one contains the interconnected mainland electricity production network based on eleven large-scale power stations, where local lignite, imported heavy oil and natural gas are used. In this main branch belong also 15 large hydropower stations along with several other small hydropower units built throughout the mainland[17]. The second branch includes 35 medium-small autonomous -diesel and heavy oil fired- power stations spread out all over the Aegean Archipelago[18]. In this latter group one should include the medium sized -heavy oil fired- power stations of Crete and Rhodes islands. In the present study special attention is paid to the mainland electricity production sector, since this branch is by far the major air pollutants source[19].

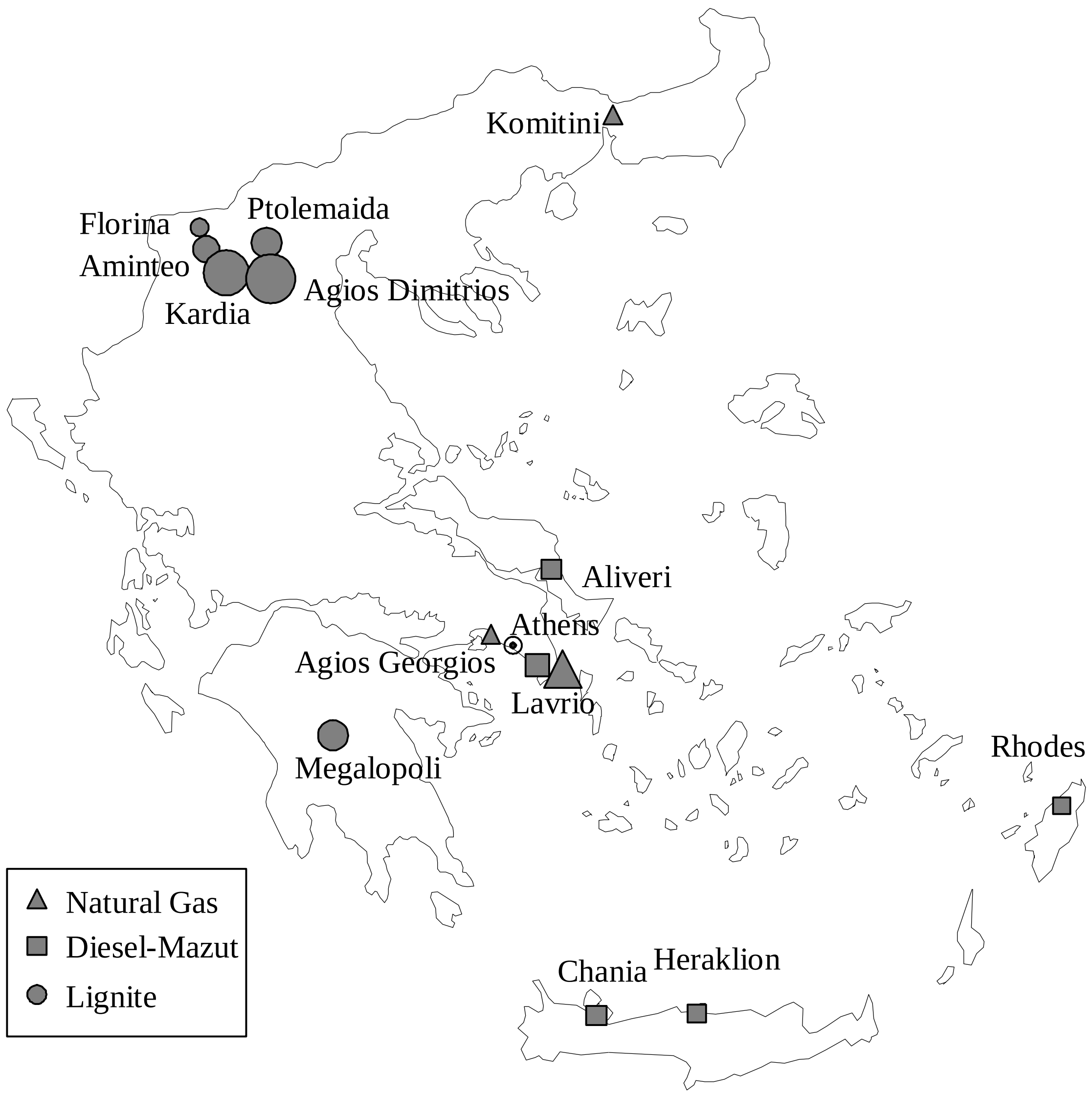

Figure 4: Greek mainland major thermal power stations, 2002

All Greek mainland thermal power stations are presented in Table I, where one may find for every TPS the rated power along with the number of units, the fuel used, the location and the operation start up time. According to RAE the national electricity production centre is located in West Macedonia, figure (4, where the two biggest TPS (Agios Dimitrios and Kardia) operate using the local lignite ore reserves. In S. Greece, operates the lignite fired station of Megalopolis (Peloponesse), while in central Greece operates one heavy-oil fired station in Aliveri of Euboea, as well as two natural gas fired TPS in Attica major region where Athens is located, figure (4). A new gas fired station in Komotini (Thrace) and a lignite fired one in Florina (NW Macedonia) have recently joined the national EPS. Thus, at the beginning of 2003, one may list the regional power capacity of the thermal power stations of Greek mainland EPS according to the type of fuel used as follows, see Table I:

a. 4380MW in N. Greece using lignite local ore
b. 850MW in S. Greece using lignite local ore
c. 1104MW using Natural Gas
d. 830MW using heavy-oil (mazut)

Table I: Greek Mainland Thermal Power Stations Basic Characteristics

Power Station	**Power Unit**	**Start Up**	**Rated Power MW**	**Load Factor (2002)**	**Fuel Used**	**Location**
Liptol	I	1959	10	53.6%	Lignite	W. Macedonia
	II	1965	33	53.6%		
Ptolemaida	I	1959	125	70.0%	Lignite	W. Macedonia
	II	1962	125	71.5%		
	III	1965	300	49.9%		
	IV	1973	300	67.9%		
Kardia	I	1975	300	76.2%	Lignite	W. Macedonia
	II	1975	300	63.3%		
	III	1980	300	84.6%		
	IV	1981	300	89.9%		
Agios Dimitrios	I	1984	300	84.8%	Lignite	W. Macedonia
	II	1984	300	45.8%		
	III	1985	310	78.9%		
	IV	1986	310	78.7%		
	V	1997	366.5	79.7%		
Aminteo	I	1987	300	77.4%	Lignite	NW. Macedonia
	II	1987	300	80.6%		
Megalopolis-A	I	1970	125	64.9%	Lignite	Peloponessos
	II	1970	125	69.5%		
	III	1975	300	65.7%		
Megalopolis-B	IV	1991	300	76.4%	Lignite	Peloponessos
Aliveri	I	1953	40	-	Mazut	Euboea
	II	1953	40	-		
	III	1968	150	53.7%		
	IV	1969	150	55.2%		
Lavrio	I	1972	150	50.5%	Mazut	Attica
	II	1973	300	51.2%		
	IV	1996	174	72%	Diesel/ Natural Gas	
	New	2002*	570	-		
Agios Georgios	VIII	1997	160	45.4%	Natural Gas	Athens
	IX	1998	200	52.2%		
Florina	I	2002*	330	-	Lignite	NW. Macedonia
Komotini	I	2002*	492	-	Natural Gas	Thrace

(*) *The station has been operating, during 2002, under initial testing rates*

Moreover to that, one should add a total power capacity of 400MW of mazut fired medium and small size power stations and another 750MW total of small diesel fired internal combustion engines located in the numerous Greek islands of Aegean Archipelago.

In an attempt to understand better the contribution of each fuel used in the Greek electricity production sector, one may observe in figure (5) the time-series of national electricity generation for the 1980-2002 period, according to the type of fuel used. There are three main conclusions drawn after a thorough investigation of figure (5). First, one cannot disregard the significant increase of electricity production (and consumption) during the last twenty years, mounting from 20000GWh to almost 50000GWh. Second, the contribution of renewable energy sources is insignificant for the entire period examined, including the large hydro power stations of the mainland. Finally, a noticeable natural gas contribution is encountered during the last three years, which however cannot be remarkably amplified due to the natural gas grid carrying capacity limits.

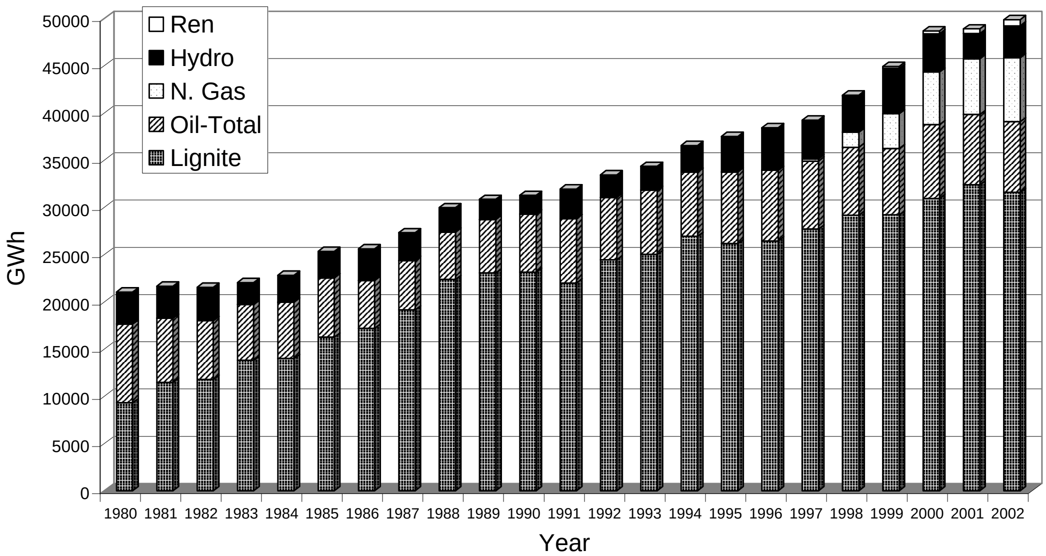

Figure 5: Time-series of national electricity generation and fuel sources responsible

3. Time Evolution of Electricity Related Sulphur Oxides Annual Emissions

As it is well known[2][10][15][20], the utilization of fossil fuels is closely related to the emissions of several flue gases. In the present study -focused on the electricity generation sector only- there is an investigation of the time-series of sulphur oxides "SO_x" emissions from local power stations. More precisely, the SO_2 and SO_3 are produced when the sulphur present in the solid and liquid fossil fuels is burned out exhibiting a bright flame and a 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 flue gases. The SO_2 -being one of the most common anthropogenic air pollutants in urban areas- is one of the ingredients of the smog appearing in many cities[21]. 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[22][23].

Using well established data[8][10][16], energy sector is found responsible for more than 95% of the total SO_2 emissions, while the rest SO_2 derives its origin from industrial processes, like sulphuric acid production, cement and aluminium plants. In Greece, the majority of SO_2 is produced by the thermal power plants of PPC, mainly those using low quality lignite and heavy oil. According to official data[24] the sulphur content of 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 the corresponding ones of the previous decade, mainly due to the quality deterioration of the available lignite in the fields. Similarly, the sulphur content of heavy oil (mazut) used by the oil fired local power stations is between 2.8% and 3.6%.

In this context, Greek EPS is found responsible for annual emissions of more than 350ktn of sulphur dioxide for the last ten years, at least. It is noteworthy to mention that electricity generation plants (large combustion plants) play a decisive role in the E.U. efforts to combat acidification, eutrophication and ground-level ozone. In this context, the 2001/81/EC Directive designates Greece's annual SO_2 emissions ceiling equal to 523kton, by year 2010. In addition, the Large Combustion Plant Directive (2001/80/EC) is not violated at the moment, since the actual national limit is 320kton per year for all "existing" (operating before 1987) power plants. In addition, one cannot disregard the remarkable time variation of SO_2 annual emissions shown in figure (6). More specifically, according to figure (2), year by year, there is a considerable electricity demand increase, leading to additional fossil fuel consumption. On the other hand, the natural gas arrival and its remarkable diffusion to the

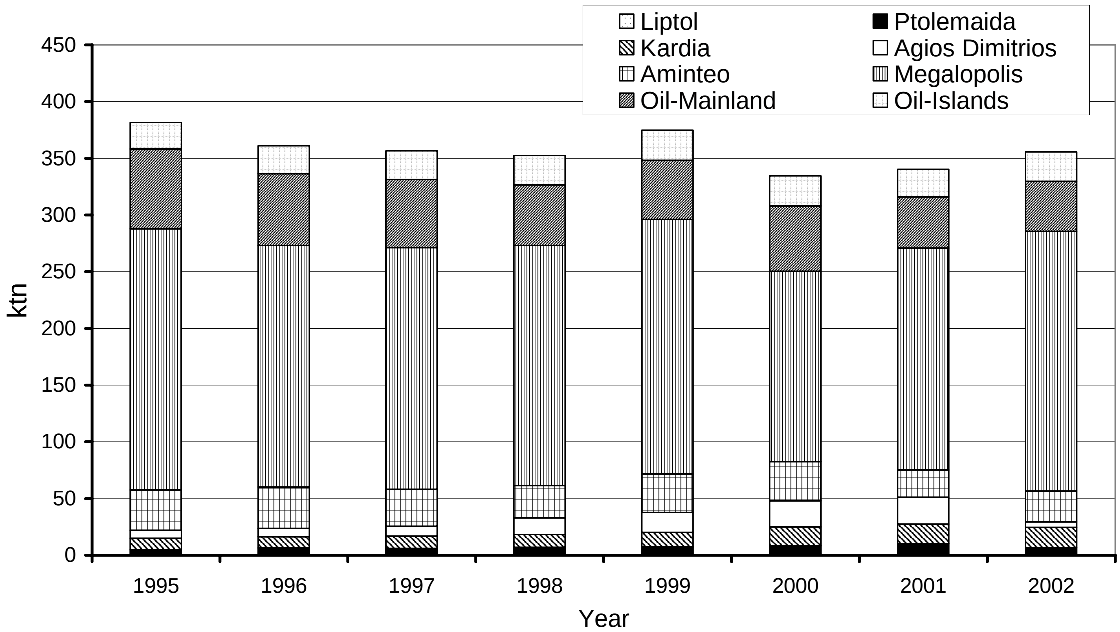

Figure 6: Sulfur dioxide (SO_2) annual emissions attributed to Greek electricity generation power stations

national electricity generation (≈14% for 2002), along with the commencement of operation of the new desulphurisation system at Megalopolis B unit of 300MW, has led to a substantial confinement of the corresponding SO_2 emissions.

Taking a closer look at the available information (measurements by PPC[24]) one should stress the fact that the 850MW of S. Greece lignite fired TPS produce more than 50% of the sector's annual emissions, despite the operation of the desulphurisation system in Megalopolis B power unit. Similarly, the oil-fired TPS (in mainland and the islands) contribute substantially (20% to 25%) to the sector's annual SO_2 emissions during the last decade. One should keep in mind that the entirety of N. Greece lignite fired TPS produce only the remaining 25% of annual SO_2 emissions, while Aminteo TPS is responsible for more than one half of this portion. Finally, it should be pointed out that the two biggest national TPS (i.e. Agios Dimitrios 1600MW and Kardia 1200MW) are found responsible for less than the 10% of the SO_2 annual release. Nevertheless, during the last three years, a considerable SO_2 emissions increase has been encountered from the operation of these two big TPS.

Summarizing, one may clearly state that the Greek electricity production sector keeps up producing huge quantities of sulphur dioxide, while it is clear that there is a lot to be done towards a systematic effort to decelerate the corresponding escalation rate. The former contradicts undersigned international and European Union efforts to stabilize air pollutants emissions at the 1990 levels.

4. Prediction of Electricity Generation SO_2 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, in course of time, concerning the SO_2 emissions. In order to get a clear picture of the electricity related SO_2 air pollution burden on every consumer, an attempt is made to express the SO_2 emissions in relation to the amount of electrical energy reaching the consumers, i.e. electricity delivered to the consumption, including the total efficiency of the corresponding TPS and the line transmission losses from the TPS to the main consumption centres (1%-5%). Thus, the coefficients given are expressed in kg (or gr) of SO_2 released per kWh consumed. For this purpose one may use the measurements concerning the annual flue gas

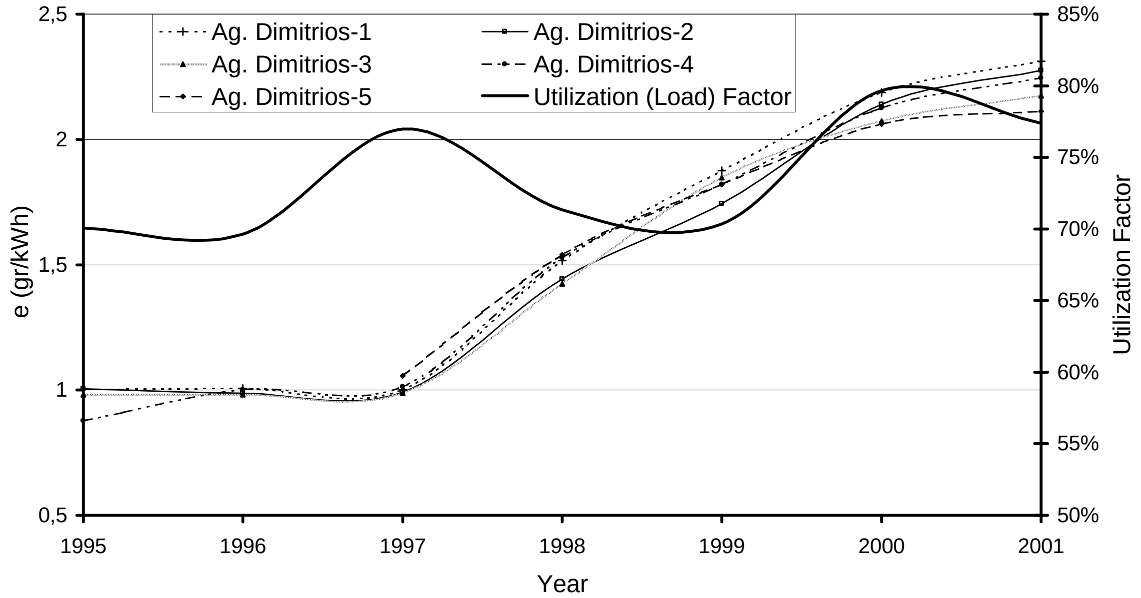

Figure 7: Time series of Agios Dimitrios (1600MW) power station SO_2 emissions factors

emissions of every thermal power unit of Greek EPS along with the corresponding net electricity generation, modified in order to take into consideration energy line transmission losses.

Thus, one may define the SO_2 emissions factor "e_j" of the "j" TPS as:

$$e_j = \frac{(m_{SO_2})_j}{E_j} \tag{1}$$

where "$(m_{SO2})_j$" is the annual mass emissions of SO_2 and "E_j" is the annual energy yield of the "j-th" TPS, including line transmission losses.

Calculation results (on annual basis) shown on figure (7) concerning the Agios Dimitrios 1600MW TPS indicate a continuous increase of the corresponding emissions factors encountered after 1997. More precisely, the SO_2 reduced emissions factors raise from approximately 1gr/kWh in 1997 to almost 2.3gr/kWh in 2001. It is also interesting to note that all five units, including the latest one built in 1997, show the same tendency, mainly due to the lignite consumed same characteristics. More specifically, during 1997 and 1998 the lignite ore used is characterized by an increase of sulphur content as well as a decrease in the lower specific calorific value of the fuel burned. This remarkable SO_2 emissions increase becomes even more important due to the fact that Agios Dimitrios is the biggest Greek power station, presenting a utilization factor higher than 70%.

Subsequently, from data presented in figure (8) one may examine the SO_2.time-series emissions factors of Kardia 1200MW TPS. As in the previous case, significant emissions factors amplification is encountered after 1998 (mainly attributed to an increase of sulphur content as well as to a degradation in the lower specific calorific value of the fuel consumed), pushing the corresponding values near 2.3g/kWh by 2002. One should bear in mind that all four Kardia units are covering base load (utilization factor over 70%), while their thermal efficiency is almost constant during the period examined.

Accordingly, the four units of Ptolemaida 620MW TPS are investigated, figure (9). Using the calculation results obtained, one may observe a remarkable time variation of SO_2 emissions factor for

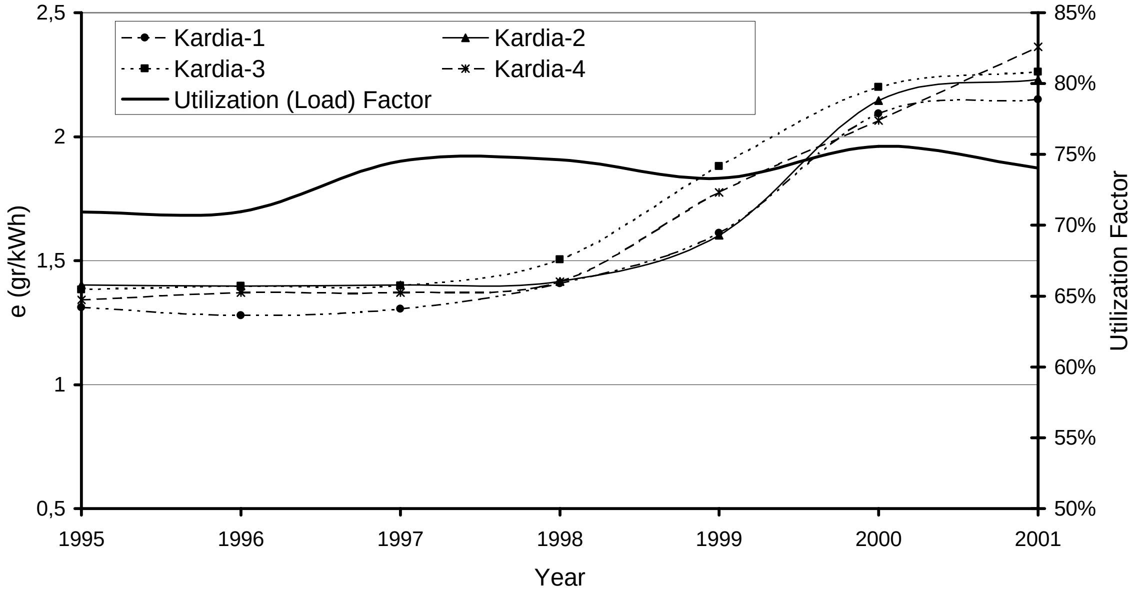

Figure 8: Time series of Kardia (1200MW) power station SO_2 emissions factors

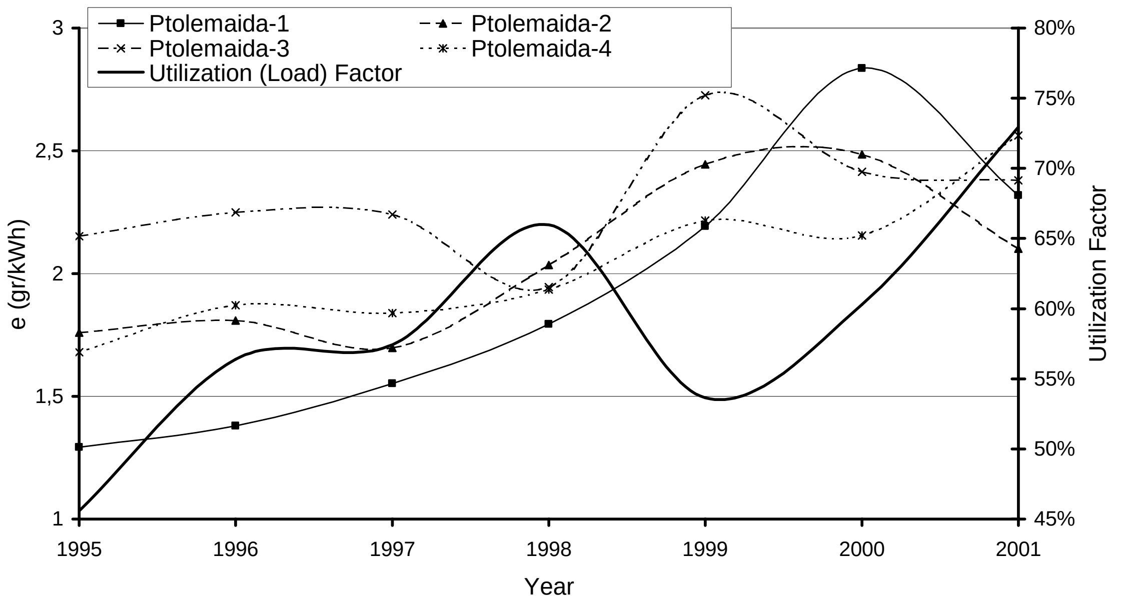

Figure 9: Time series of Ptolemaida (620MW) power station SO_2 emissions factors

all four power units along with a generally increasing trend. As a result, all the Ptolemaida units' emissions factors exceed the 2.1gr/kWh mark during the last three years shown. When comparing the time evolution of SO_2 emissions factors for the power units of Ptolemaida TPS, one should remember the quite different size and age of these stations, see also Table I. In addition, according to information provided by PPC, renovation activities had taken place during 1999-2001 in these units (realized at different time periods), 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 N. 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

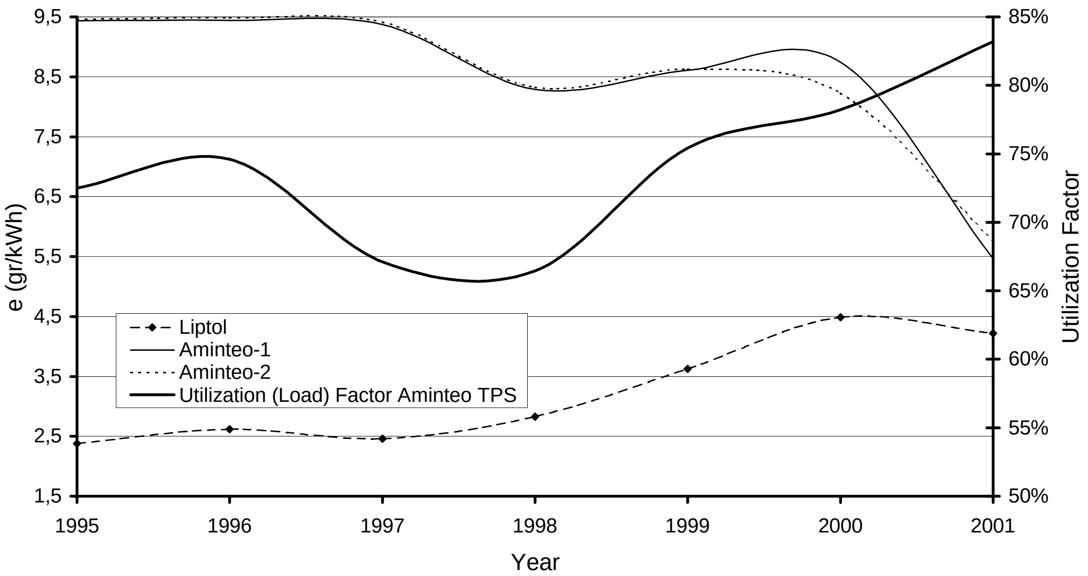

Figure 10: Time series of Aminteo (600MW) and Liptol (45MW) power stations SO_2 emissions factors

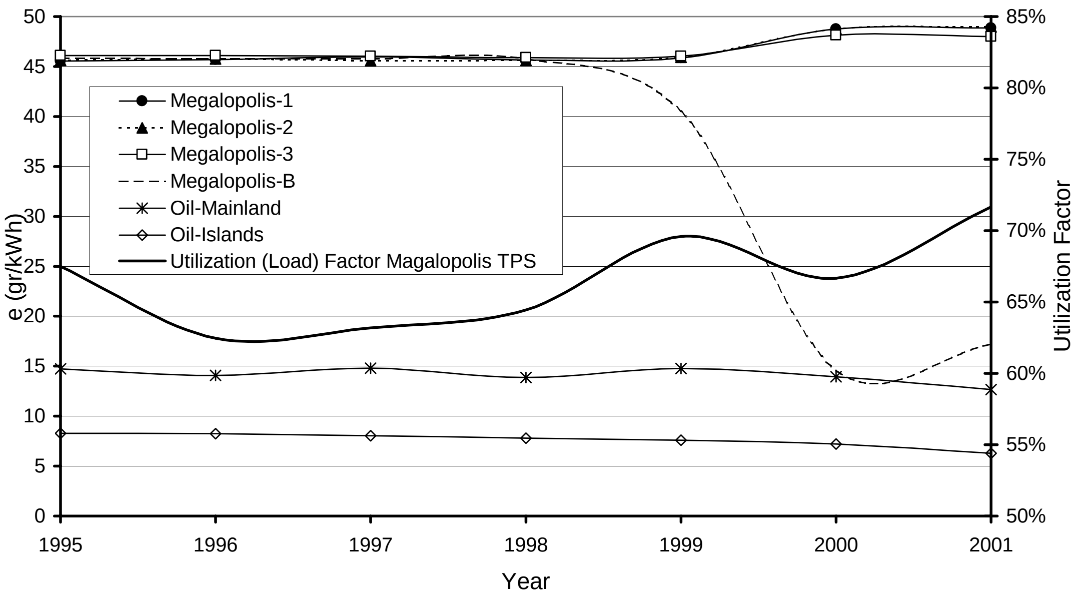

Figure 11: Time series of Southern Greece's lignite and oil-fired (mainland and islands) power stations SO_2 emissions factors

Greek TPS, operating since the fifties. The Liptol corresponding SO_2 emissions factor time series exhibits an almost similar tendency as all the other TPS already analysed, figure (10). On the other hand, the Aminteo TPS emissions factor, being by far the highest in N. Greece (9.5gr/kWh), presents a remarkable diminution after 1998. Thus, by 2001 the SO_2 emissions factor value is just over 5gr/kWh, quite a positive evolution on the environmental impact of the local electricity generation sector.

Finally, the S. Greece's lignite and the oil fired (located in the mainland and the islands) TPS SO_2 emissions factor time series distributions are given in figure (11). More specifically, the oil fired TPS show an almost constant with time distribution, while the three Megalopolis-A units (550MW) present

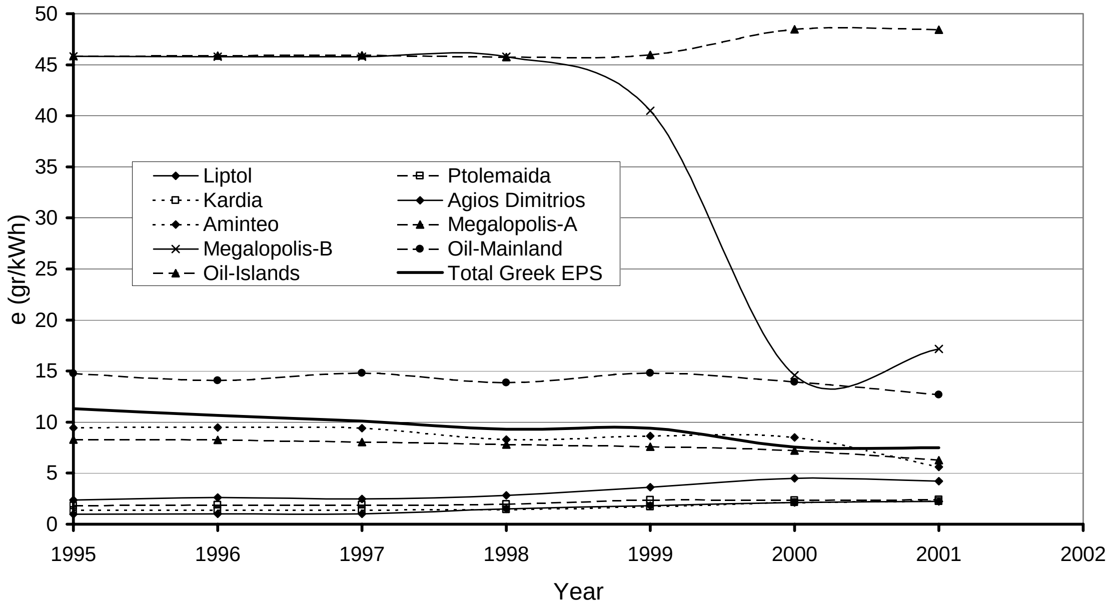

Figure 12: Time series of Greek electricity generation power stations sulfur dioxide emissions factors

increasingly high SO_2 emissions factor values, approaching the 50gr/kWh. On the other hand, the beginning of operation in 1999 of the new desulphurisation unit in Megalopolis-B (300MW) power station has led to a drastic SO_2 reduced emissions down to the level of 15gr/kWh by 2001.

Summarizing, in figure (12) one may examine the time series of the SO_2 emissions factors of all Greek major TPS (see also Table I). As it is obvious from the results obtained, the SO_2 emissions factors of the Greek TPS demonstrate an almost constant upward trend for the entire period analysed, see for example figures (7) and (8) concerning the Agios Dimitrios and Kardia biggest Greek TPS. However, this is not the case for the Megalopolis-B TPS where the new desulphurisation unit has commenced operation in 1999. More specifically, the following remarks are valid:

- The values of South Greece SO_2 emissions factors are at-least one order of magnitude higher than the rest Greek TPS ones, taking into consideration the higher sulphur content and the lower specific calorific value of the lignite used, as well as the absence of any abatement technologies.
- The operation of the desulphurisation unit at Megalopolis-B station affects the country average value, leading to an almost 1.5gr/kWh decrease of the corresponding SO_2 emissions. However, even after the operation of the desulphurisation unit, the Megalopolis-B emissions factor value is clearly higher than the corresponding N. Greece lignite fired TPS ones.
- The mainland heavy-oil SO_2 emissions factor is quite high, being almost twice the corresponding national mean value, since the sulphur content of the fuel used is approximately 3% in an attempt of PPC to limit the fuel purchase cost.
- Among the N. Greece lignite fired TPS, Aminteo power station presents a considerable higher emissions factor value (8.5gr/kWh) than all other N. Greece TPS, being gradually reduced during the last three years. This may be explained by taking into account the fact that the fuel used in Aminteo TPS possesses the lowest specific calorific value in N. Greece (approximately 5000Kcal/kgr), while the availability of the existing abatement technologies reaches the international standards only after 2000.
- One should mention the substantially lower (compared to the national average value) emissions factor value of the two major Greek TPS (i.e. Ag. Dimitrios and Kardia) for the whole period analysed, although both stations show a slight but continuous increase during the last four years, mainly due to the quality deterioration of the available lignite in the corresponding fields. Bear in mind that these two largest power stations of the country are equipped with a Flue Gas Desulphurisation (FGD) system, presenting a moderate environmental efficiency.

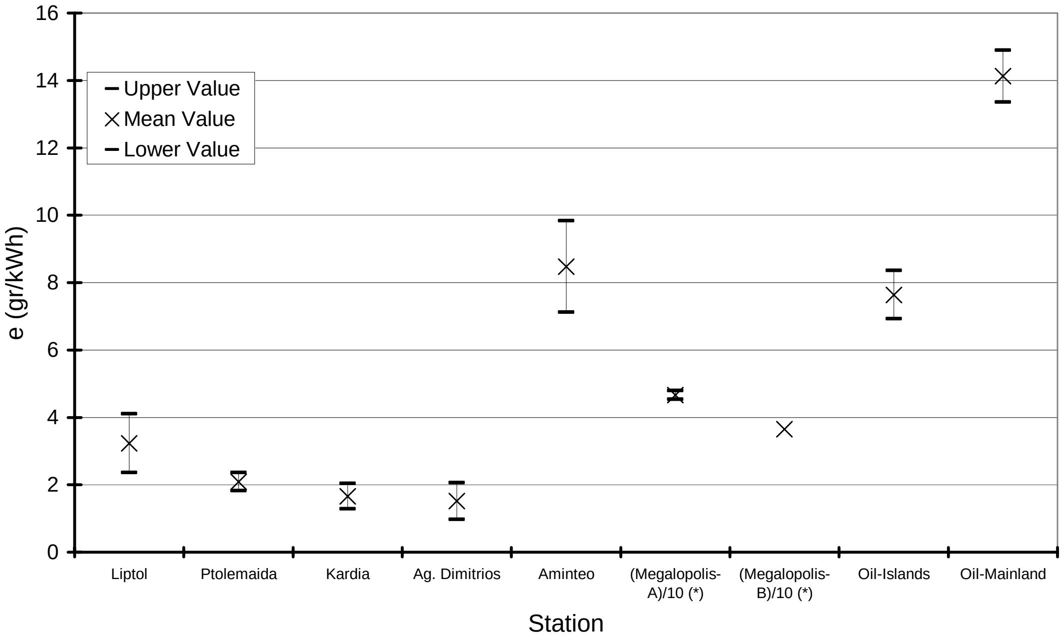

Figure 13: The mean spread of SO_2 emissions factor values for the Greek Thermal Power Stations considered, years 1995-2002 ((*) Attention: *Megalopolis TPS data is divided by ten*)

As a general outcome of the above analysis, one may clearly state that there is a considerable environmental surcharge of sulphur oxides released by the Greek EPS, which although at a decreasing rate, it is still over the 8.5gr per kWh consumed.

5. Discussion of the Results

According to the data presented, there is a significant diversified spread of the specific SO_2 emissions factor values among the major TPS of Greece. More precisely, the emissions factor ratio between S. Greece and N. Greece lignite fired plants is in the order of 25:1, while even in the same geographical area there are remarkable differences, figure (13). Also in figure (13), one may observe the last decade average value of the SO_2 emissions factor of each one of the major lignite fired Greek TPS, along with the corresponding standard deviation. The differences encountered may be attributed to the fuel main characteristics, like lower heating (calorific) value, fuel sulphur content and sulphur retention in ash. On top of that, one should also take into consideration the reduction of efficiency and the availability of secondary measures. If such actions are adopted the corresponding environmental impact could be retarded. Finally, the thermal efficiency of the TPS under examination and a reliable value concerning the electricity transmission (from the TPS to the consumption) losses are also necessary for further analysis.

In this context one may use the following general equation, for a first estimation of SO_2 emissions in course of time "t", i.e.:

$$^{(SO_2)}e_j(t) = 2 \cdot \gamma_{s_j} \cdot (1-\alpha_{s_j}) \cdot \frac{1}{\eta_{e_j} \cdot (1-\zeta) \cdot H_u} \cdot (1-\eta_{sec_j} \cdot \beta_j) \qquad (2)$$

where "$(\gamma_s)_j$" is the sulphur content in fuel, "$(\alpha_s)_j$" is the sulphur retention in ash, "H_u" is the lower specific calorific value of fuel, while "$(\eta_{sec})_j$" is the efficiency and "β_j" is the availability of the existing anti-pollution measures for the j-th TPS. Lastly, "$(\eta_e)_j$" is the TPS thermal efficiency and "ζ" is the corresponding electricity transmission losses decimal factor. 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 are adopted[18][24]. More specifically, the lower specific calorific value of S. Greece's lignite varies between 3900Kcal/kgr and 4700Kcal/kgr, while the corresponding values of N. Greece are 5000Kcal/kgr and 6200Kcal/kgr, respectively. Similarly, the sulphur content of lignite used has already been described in section 2, while the sulphur retention in ash ranges between 32% and 40%. In as much, 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[2][10] according to the type of each TPS.

Results coming from equation (2) are fairly in agreement with the corresponding experimental values, Table II. Since, the exact sulphur content of the fuel used is not known the maximum and minimum values are used; hence the corresponding minimum and maximum values of SO_2 emissions factors are employed. As a general conclusion, one may state that for N. Greece TPS abatement strategies or technologies do exist. However, their efficiency and their availability is lower than the established values. This is not the case for Megalopolis-A and oil-fired TPS, since the emissions factors realized prove the absence of any anti-pollution measures. Finally, Megalopolis-B TPS latest emissions factor value, although only 1/3 of the last decade's average value, it is quite higher than the expected one, taking into consideration that a new desulphurisation unit operates there since 1999. Most discrepancies can be explained either by questioning the real sulphur content of the fuel used, or by investigating the lower specific calorific value of the lignite mined locally.

Table II: SO_2 Emissions Factors for Greek Thermal Power Stations (1995-2002) in kg/MWh

Thermal Power Station	**Min-no measures(*)**	**Max-no measures**	**Min-with measures**	**Max-with measures**	**Mean Value(+)**	**2001 Values(+)**
Liptol	11.2	16.1	1.2	1.7	3.2	4.2
Ptolemaida	11.4	16.4	1.2	1.8	2.1	2.4
Kardia	8.9	16.5	1.0	1.8	1.7	2.2
Agios Dimitrios	9.5	17.7	1.0	1.9	1.5	2.2
Aminteo	13.7	22.9	1.5	2.5	8.5	5.6
Megalopolis-A	41.1	53.7	4.5	5.9	46.6	48.4
Megalopolis-B	46.6	60.9	5.1	6.7	36.5	17.2
Oil-Mainland	16.7	19.1	1.8	2.1	14.1	12.7

(*) According equation (2) and the chemical characteristics of the fuel used
(+) According to assessed experimental data, provided by PPC[24]

The specific emissions factor values obtained from the previous experimental analysis of the local TPS data are compared with corresponding values presented by the authors in a previous study[15] and by E.U. report in 1999[25], Table III. More precisely, one can see the wide spread of the values given for representative E.U. countries, concerning the SO_2 emissions factor values from the electricity generation sector. In this context, only the carbon containing fuels used in the UK power industry were marked to produce (during the previous decade, e.g. 1994) higher SO_2 per kWh than the Greek power sector. Recent information indicates that in 2001 the corresponding specific SO_2 emissions factor in the UK has dropped to 2.7kg/MWh, due to the electricity generation switch from coal to gas and the application of FGD technology on two large power stations of the country. On the other hand, Netherlands electricity generation surcharge is minimal, taking into account the limited utilization of coal in the country's electricity generation plants.

Table 3. Specific emissions (kg/MWh) from fossil-fuelled TPS (1994-1998)

Air Pollutant	**Netherlands[25]**	**UK[25]**	**UK(2001)**	**Denmark[25]**	**Greece[15]**
SO_2	0.38	14.0-16.4	2.7	2.9	6.4

Similar results are presented for the Spanish electricity production sector[23], where a sulphur tax impact on the electricity-generating sector was imposed. In addition, the same order of magnitude of sulphur oxide emissions are mentioned[20] for several lignite-fired TPS operating in Austria, Romania and former Yugoslavia, strongly depending on the chemical composition and other characteristics of the fuel used. Similar data is also validated for Polish electricity production sector[26], during a study analysing the technologies and costs of SO_2 emissions reduction. Finally, the results obtained here are also validated by the data provided[22] during a detailed analysis of regional effects of SO_2 emissions for many parts around the world, including Europe, North America and China.

According to the data presented concerning the national electricity production sector one may definitely state that during the last decade there is a considerable demand amplification, while most experts forecast[6][7][9] 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 N. Greece lignite and imported natural gas, the expected flue gases emissions factors values should keep up with the 2000-2002 values, since the corresponding fuel-mix should remain constant. In addition, one should take into consideration 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%) is going to 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[27][28], the expected annual SO_2 emissions of Greek electricity generation sector should exceed the 450ktn by 2010. For the time being, the per cap annual SO_2 release from the Greek electricity generation sector is almost 33.5kg/cap, a value that is definitely higher than the corresponding E.U. mean one (12.4kg/cap).

6. Conclusions

The electricity generation sector sulphur oxides emissions for the last decade are estimated using detailed official data concerning the major local thermal power stations. According to the results obtained, a fair reduction by 15% of the national emissions factor of SO_2 is encountered, mainly due to the recent natural gas penetration and the operation of a desulphurisation unit in S. Greece Megalopolis-B power unit. However, the impact of this modest SO_2 emissions factor reduction could be counterbalanced by the continuous electricity consumption amplification registered the last ten years.

More specifically, the Megalopolis-A TPS (representing only 5%) of the country’s power capacity produces almost 67% of the electricity sector SO_2 emissions. Additionally, there is an undesirable SO_2 emissions factors increase for the N. Greece operating power stations during the last four years, which could jeopardize the positive impact of the natural gas utilization in the local electricity generation sector. Finally, since more than 90% of the national electricity production is based on carbon containing fuels, a systematic sulphur dioxide release diminution effort should be made in order for the local electricity generation sector to comply with the Large Combustion Plants Directive (2001/80/EC).

Recapitulating, after a detailed evaluation of the Greek electricity sector SO_2 emissions data concerning last decade, the conclusions drawn should be carefully addressed. For the entire period analysed there is a significant SO_2 emissions increase resulting from the continuous energy consumption amplification. An adverse action is needed if the State chooses to cover any further electricity demand using low quality lignite, imported heavy oil and natural gas. Otherwise the situation will continue to deteriorate during the next few years, whilst the Greek electricity generation sector is bound to release considerable amounts of sulphur dioxide.

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THE IMPACT OF GREEK ELECTRICITY GENERATION SECTOR ON THE NATIONAL AIR POLLUTION PROBLEM

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Abstract

Since the early sixties, the Greek electricity production sector has been based on local lignite and heavy-oil, being gradually replaced by imported natural gas only quite recently. Therefore, the electricity generation process -beyond the economic and macroeconomic cost- is assumed responsible for significant air pollution. In this context, an extensive and thorough analysis is carried out concerning the quantities of air pollutants that have resulted from the electricity sector during the 1995÷2002 period. For this purpose, all obtainable data are initially considered and analysed, followed by an integrated numerical model developed from basic-principles, in order to estimate the air pollutants created from electricity generation. The results presented are based on official data, analysing the SO_2, NO_x and CO_2 produced on the basis of the fuel utilized. Among the most interesting results of the present survey emerges the continuous increase of air pollutants with time, mainly attributed to the electricity demand amplification and the state policy of using N. Greece lignite and imported natural gas in the mainland and diesel-oil in the Aegean Sea territories. This strategy practically leads to remarkable air pollution rise during the next decade, a fact that is also validated by the application of the developed analytical model.

Keywords: Air Pollution; Electricity Generation; Thermal Power Stations; Energy Policy; Analytical Model; Emission Factors; Energy Coefficient

1. Introduction

Since the early sixties, the Greek electricity production sector has been based on local lignite and heavy-oil. After the recent natural gas introduction in the local market, a gradual replacement of

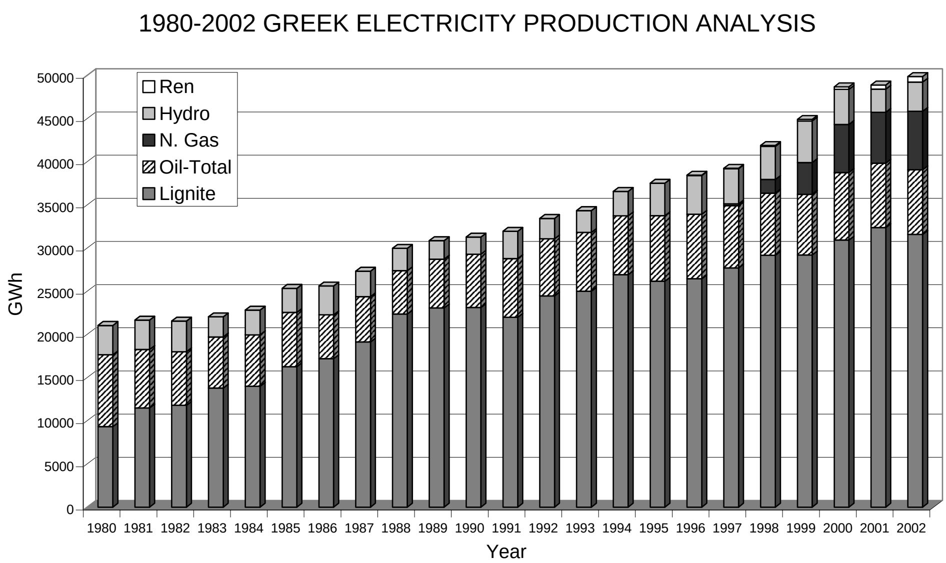

Figure 1: Time-evolution of electricity production profile in Greece

***Kaldellis J.K., Spyropoulos G., Chalvatzis K., 2004**, "The Impact of Greek Electricity Generation Sector on the National Air Pollution Problem", Fresenius Environmental Bulletin, vol.13(7), pp.647-656.*

lignite and heavy-oil (mazut) by imported natural gas[1] takes place. Besides, several internal combustion engines and gas turbines -using mainly diesel-oil[2] - operate in autonomous thermal power stations located in most islands. On the other hand, the considerable number of the existed hydro power stations presents a very low utilization factor in comparison with the thermal power stations, due to water reserves deficit and the applied electrical load management plant[3]. Finally, only recently,

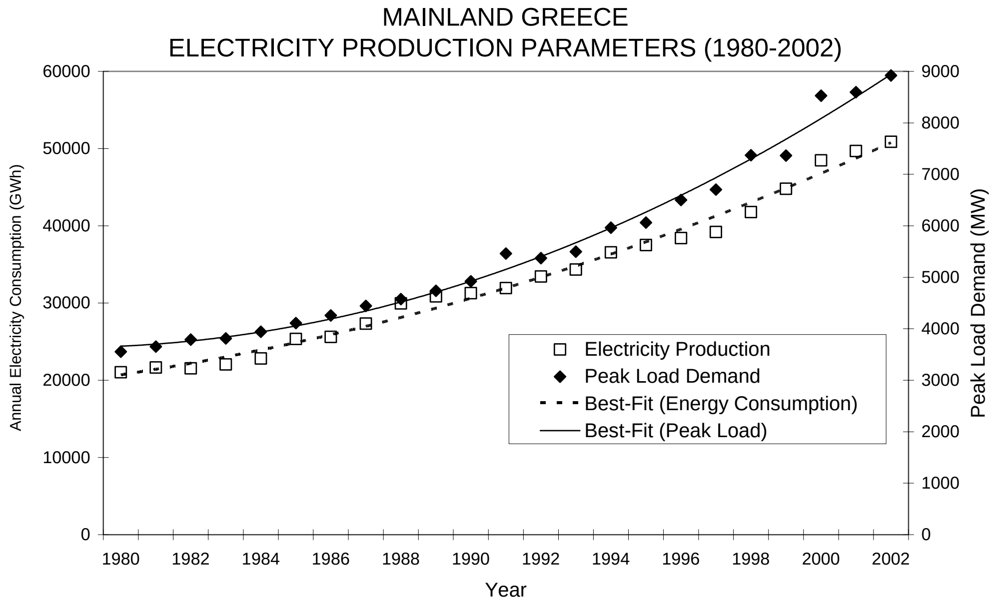

Figure 2: Greek mainland electricity demand parameters time-evolution

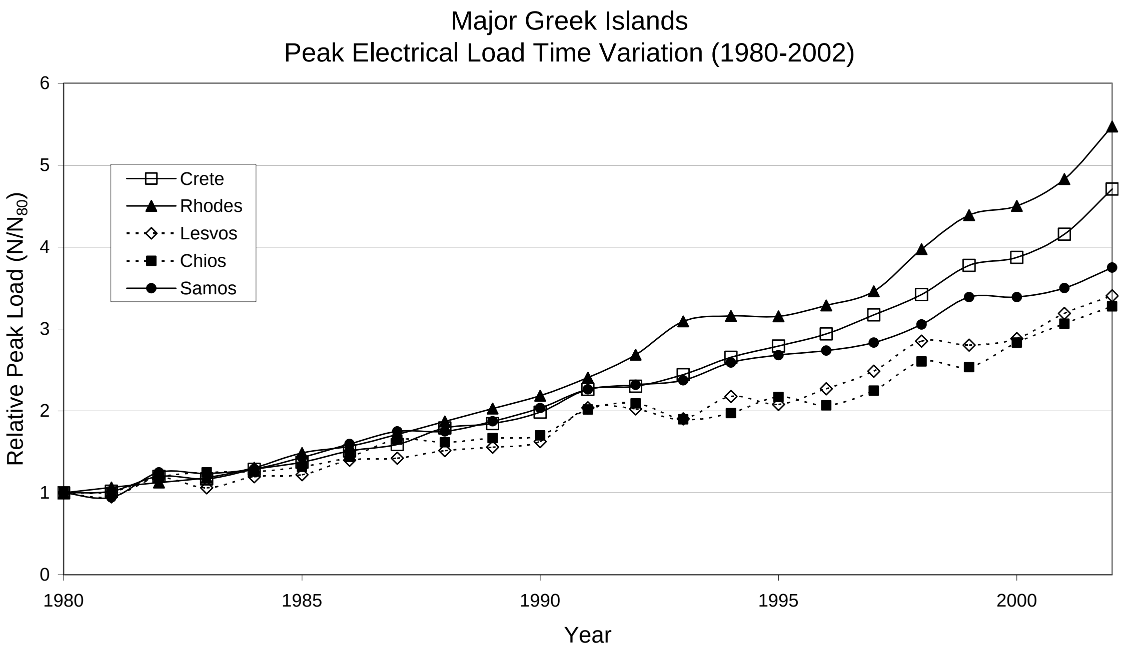

Figure 3: Peak load evolution for the major Greek Islands

a modest number of wind parks started their operation, mainly on Euboea (mainland grid) and Crete island[4]. However, as it is obvious from (figure (1)), lignite and oil contribute with more than 85% to the local electricity production.

Energy consumption and demand have significantly increased in Greece during the last decades, approaching the 32000ktoe in 2002[5][6]. In this context, the electricity consumption increase[7] has approximated 4% per annum (see figure (1)), while the maximum (peak) load increase of the mainland electrical grid is much more abrupt (6%), (see figure (2)). The problem seems to be particularly critical for the various Aegean Sea islands, including Crete, Rhodes, Lesvos and Chios. More specifically, the maximum load demand escalation in these islands has exceeded 250% during the last twenty years (figure (3)). The situation is even worse in the medium-small autonomous island power systems, where the corresponding escalation rate exceeds 400%. Therefore, the establishment of new electricity production plants is an extremely urgent requirement[8], in order to protect the national and autonomous electrical grids from several troubles, like voltage and frequency instabilities or even total black-outs.

As already mentioned, the Greek electricity production is almost exclusively based on fossil fuel, being assumed responsible for important air pollution, beyond the economic and macroeconomic cost. According to previous studies[9][10], more than 50% of the country's CO_2 production is attributed to the electricity sector. In addition, electrical production contribution to SO_2, NO_x and TSP is crucial, representing in most cases a considerable part of countrywide emissions[11]. Bear in mind that a systematic recording of solid materials created by local thermal power stations (TPS) commenced only recently.

In this context, an extensive and thorough analysis is carried out concerning the air pollutants quantities resulting from the electricity generation sector, during the 1995÷2002 period. For this purpose, the available historical data are initially considered and analysed. Accordingly, an integrated numerical model is developed from the basic-principles, in order to estimate the expected air pollutants produced from electricity generation. Finally, official data and calculation results are compared with corresponding data from other well-established organizations. The present study is integrated with a short discussion concerning the air pollution impact during the next few years.

2. Brief Presentation of Greek Electricity Generation System

Using the official data[6][12] from Greek Regulatory Authority of Energy (RAE) and Greek Public Power Corporation (PPC), the local electricity generation system (at the beginning of 2003) is divided in two branches. The first part contains the mainland electricity production network based on thermal power stations (TPS) with rated capacity of 7200MW, along with 3400MW of renewable energy production stations, mainly large and small hydropower installations (3100MW).

The second part includes 35 medium-small autonomous thermal power stations (APS) of 547MW and 18MW resulting from renewable energy sources exploitation, spread throughout the Aegean Sea. In this group, there should also be embraced two medium-sized thermal power stations on Crete Island (approx. 580MW) and almost 70MW of renewables, along with 208MW of thermal power units operating in Rhodes island, Table I.

More precisely, the Greek thermal power stations can also be categorized according to the fuel used, as follows; see Table I:

a. 4280MW using N. Greece lignite
b. 850MW using S. Greek lignite
c. 1134MW using Natural Gas
d. 830MW using heavy-oil (mazut) in mainland
e. 1340MW using diesel-oil and mazut in Greek islands

On top of that, the electricity production of each group along with the corresponding capacity factor and efficiency may be estimated by using the most recent official data; Table I.

According to Table I, the efficiency of most TPS is exceeding 31%, their effectiveness being in direct proportion to their age. It is also important to mention that the capacity factor of most lignite fired stations of N. Greece exceeds 73%, while the corresponding value of the TPS based on natural gas is only 60%.

Table I: Greek electricity generation system thermal power stations (in operation end 2002)

Power Station	*Start Up*	*Rated Power (MW)*	*Fuel Used*	*Capacity Factor*	*Efficiency*	*Location*
Liptol	1959	43	Lignite	64%	25%	W. Macedonia
Ptolemaida	1959	850	Lignite	73%	31%	W. Macedonia
Kardia	1975	1200	Lignite	74%	33%	W. Macedonia
Agios Dimitrios	1984	1586.5	Lignite	78%	33.5%	W. Macedonia
Aminteo	1987	600	Lignite	83%	34.4%	W. Macedonia
Megalopolis-A	1970	550	Lignite	70%	29.5%	Peloponessos
Megalopolis-B	1991	300	Lignite	77%	31.8%	Peloponessos
Aliveri	1953	380	Mazut	60%	36.5%	Euboea
Lavrio	1972	450	Mazut	47%	35.1%	Attica
Lavrio (New)	1996	774	Natural Gas	60%	35.8%	Attica
Agios Georgios	1997	360	Natural Gas	61%	35.4%	Athens
Linoperamata	1965	253	Mazut-Diesel	66%	31%	Crete
Chania	1969	330	Diesel	51%	30%	Crete
Rhodes	1967	208	Diesel	55%	29%	Rhodes
APS	1967	547	Diesel-Mazut	42%	27%	Aegean Archipelago

Using the latest official data[12] of (figure (4)), 26.3TWh of electricity have been produced during 2002 by using N. Greece lignite, 5.0TWh from the group (b) by using S. Greece lignite, 6.8TWh by using Natural Gas, 4.5TWh by using mazut and 3TWh by diesel fired engines. The above-described analysis is extremely important, being the base for the estimation of air pollution in consequence of electricity generation.

3. Electricity Related Air Pollutants Production

As it is widely accepted, consumption of fossil fuels is closely related to the production of several flue

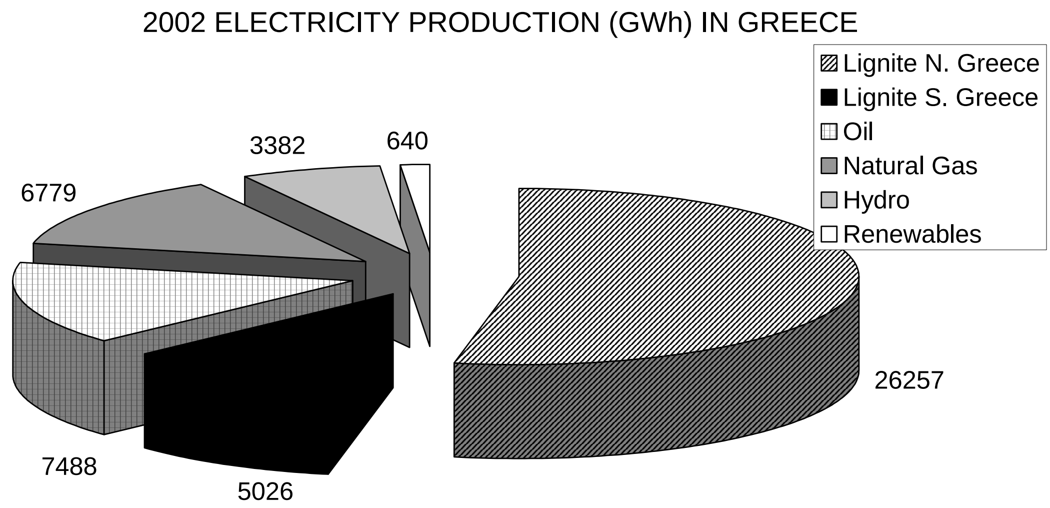

Figure 4: Analysis of electricity production in Greece (GWh), 2002

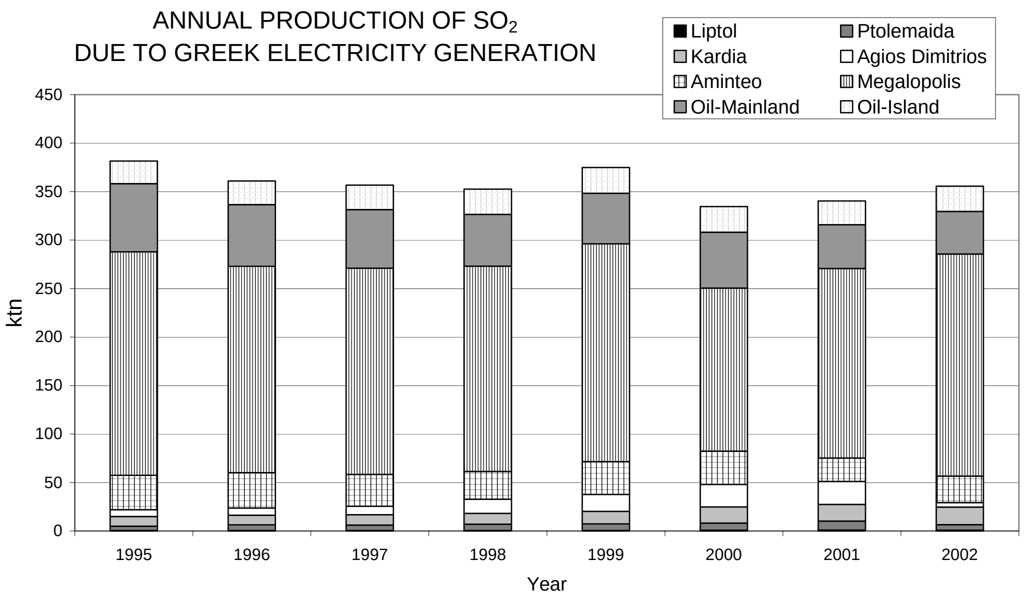

Figure 5: SO_2 annual production from Greek electricity generation sector

gases. As this present survey is mainly focused on the electricity generation sector, a thorough examination of time-evolution of the sulphur "SO_x" and the nitrogen "NO_x" oxides production is required. The "CO_2" production is also demonstrated, as this flue gas is assumed responsible for the greenhouse effect.

The SO_2 and SO_3 (named SO_x) are created 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 in urban areas- is one of the ingredients of the smog appearing in big cities[13][14]. The SO_2 is colourless with a very characteristic smell. In combination with humidity it is finally transformed to sulphuric acid, one of the most corrosive acids being primary responsible of the acid rain. Figure (5) indicates time-evolution of the SO_2 production as a result of electricity generation. As it is obvious from the data presented, there has been a considerable variation in the sulphur oxides production during the last decade, mainly attributable to the increased electricity

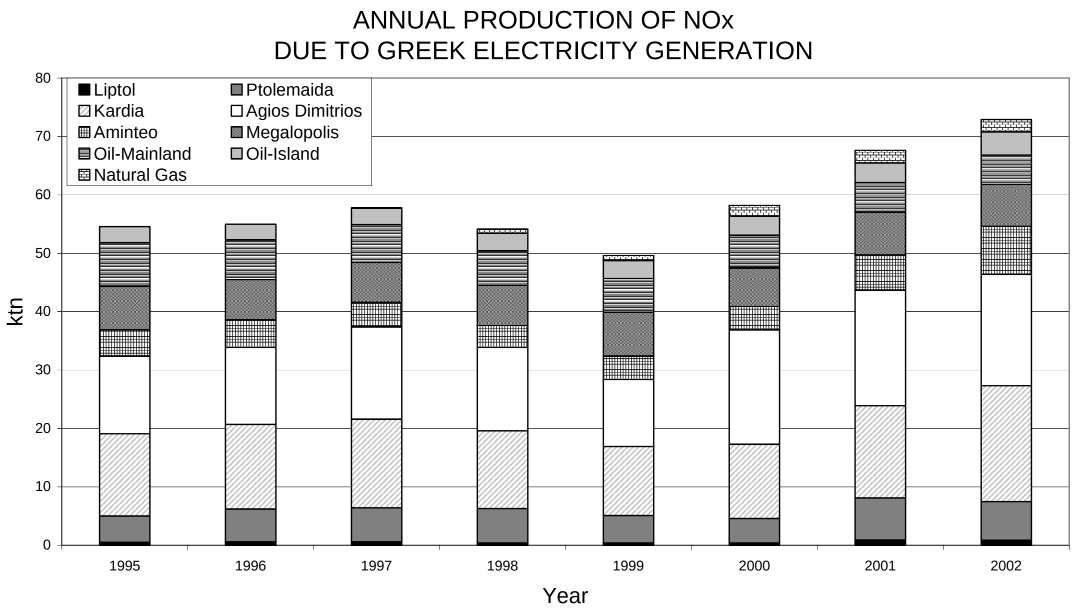

Figure 6: NO_x annual production from Greek electricity generation sector

consumption and the operation of new desulphurisation units at S. Greece power stations. In addition, one should underline the dominant contribution of S. Greece (Megalopolis TPS) lignite consumption to the national SO_2 production, although the corresponding electricity generation represents only 10% of the total annual demand (figure (4)).

Similarly, NO_x (NO, NO_2) result by the reaction between nitrogen and oxygen in very high temperatures like inside car combustion chambers, power stations, industries and central heating systems. Keep in mind that this chemical reaction gives a 95% NO and only a 5% NO_2. It is interesting to note that the NO is a colourless 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[15][16]. The NO_2 has a brown-red colour and a very characteristic annoying smell. It is one of the prime gases appearing in smog, being also assumed responsible for the acid rain. Figure (6) demonstrates that the NO_x production is also gradually increasing, despite the introduction of natural gas in the local market. Keep in mind that the NO_x increase rate is more abrupt than the SO_2 one, while the natural gas consumption will not drastically settle this problem in actual fact.

Finally, the carbon dioxide (CO_2) is produced upon complete burning of carbon; it may therefore be a measure for the quantity of fossil fuels used in a country[17][18]. Although no- toxic, when CO_2 is found in a non-ventilated area in large quantities, it may cause asphyxia. On the other hand, the carbon dioxide is the main culprit for the greenhouse effect, which may change the climate of our planet. In this context, it is important to mention that electricity generation is found responsible for almost 55% of the CO_2 production[11][19] countrywide. On top of that, according to (figure (7)), there is no CO_2 increase-rate deceleration[9][20], as the local electricity generation system is almost exclusively based on fossil fuels utilization.

Recapitulating, the Greek electricity production sector keeps on producing huge quantities of flue gases, while no attempt is made at decelerating the corresponding escalation rate. This result is in contradiction of the international and European Union efforts to stabilize air pollutants emission at the 1990 levels. It also underlines the present incompetence of the 1st National Program to actively contribute to the climatologic protection of our planet.

4. Electricity Related Emission Factors

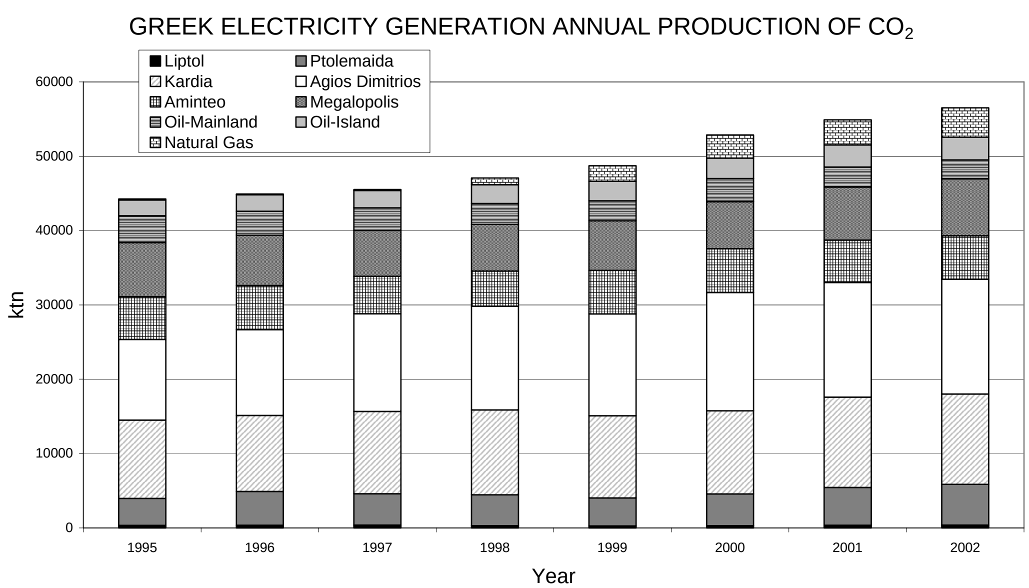

Figure 7: CO_2 annual production from Greek electricity generation sector

Using previous work by the authors[21], the total annual quantity "$^{(k)}P(t)$" of air pollutant "k" produced by Greek electricity generation related activities is given as:

$$^{(k)}P(t) = E(t) \cdot \sum_i {}^{(k)}e_i(t) \cdot \varepsilon_i(t) \quad (1)$$

where "i" describes the specific fuel used (e.g. S. Greece-lignite, N. Greece-lignite, Diesel-oil, "Mazut", Natural gas, renewables, etc.) and "ε_i" is the fuel consumption array for the electricity generation sector, i.e.:

$$\varepsilon_i(t) = \frac{E_i(t)}{E(t)} \quad (2)$$

Keep in mind that "E(t)" is the annual primary energy consumption (usually in toe) of the electricity production sector. As it is obvious, the following relation is valid:

$$\sum_i \varepsilon_i(t) = 1.0 \quad (3)$$

Besides, comparing the primary energy consumption and the electricity demand "E_d" by local society, one may write:

$$E_d(t) = E(t) \cdot \sum_i \eta_i(t) \cdot \varepsilon_i(t) \pm E_{bal} \quad (4)$$

where "η_i" is the efficiency (including line transmission losses from the TPS to the main consumption centers) of all thermal power stations using the fuel "i" and "E_{bal}" is the electricity balance (imports, exports) of the country.

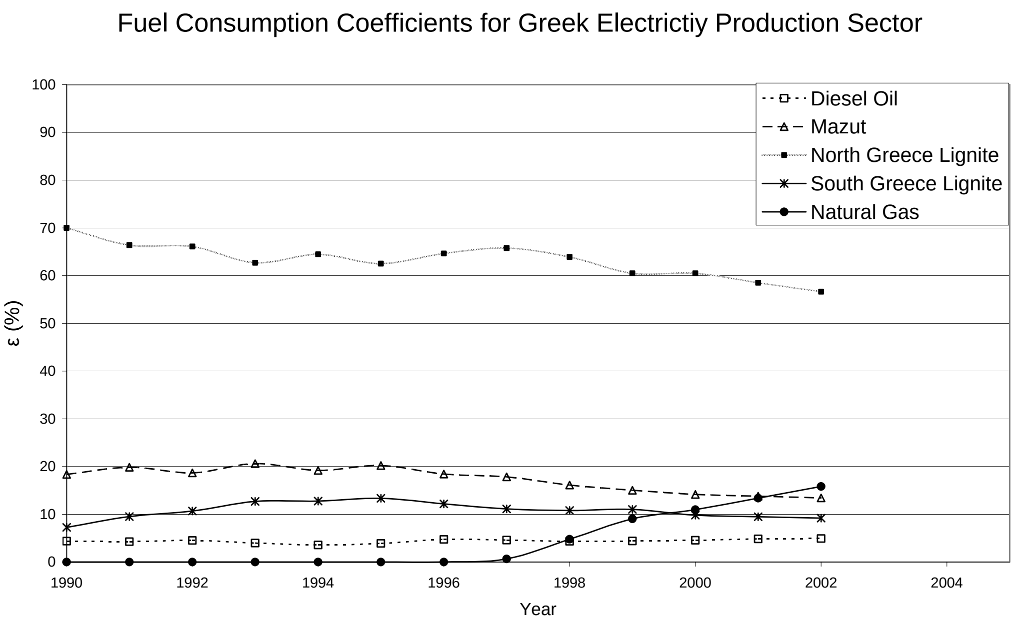

Figure 8: Fuel contribution on the national electricity generation

Subsequently, "$^{(k)}e_i$" is the time depending emission factors array for every air pollutant "k", created due to the consumption of fuel "i" in the electricity production sector, during the time-period "t", i.e.:

$$ {}^{(k)}e_i(t) = \frac{{}^{(k)}P_i(t)}{E_i(t)} \quad (5) $$

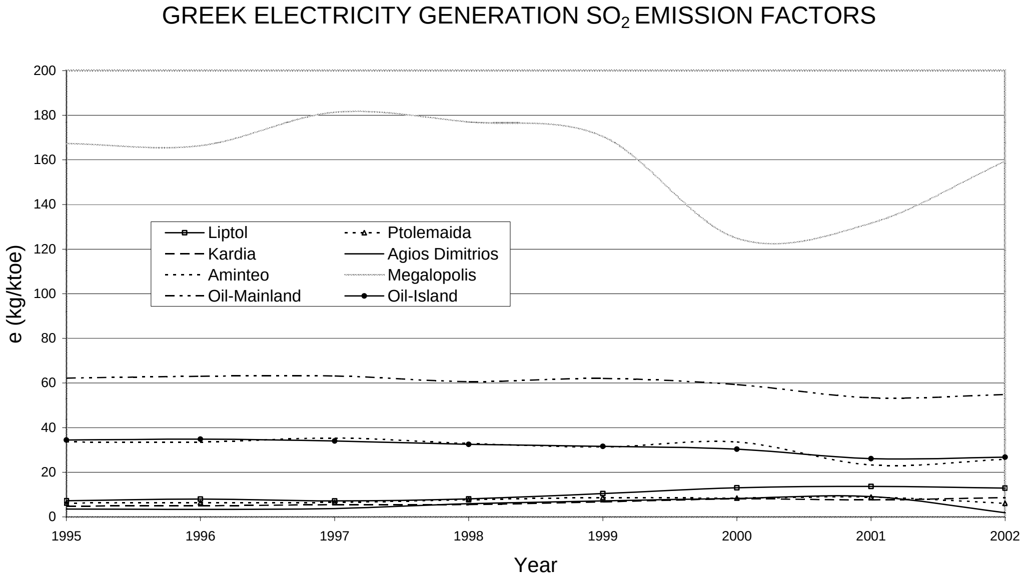

Figure 9: Greek electricity generation SO_2 emission factors time evolution

The main factors influencing the air pollutants production of electricity generation and included in the proposed analysis are the following:

- ✓ Evolution of energy consumption ($E_d(t)$)
- ✓ Fuel-mix and internal reorganization including fuel substitution ($\varepsilon_i(t)$)
- ✓ Energy efficiency status and improvements ($\eta_i(t)$)
- ✓ Existence and efficiency of pollution control measures ($e_i(t)$)

Using the definitions of equations (1) to (5) and the official data by local electricity production sector, it is possible to estimate the time evolution of the corresponding emission factors of the sector for the SO_2, NO_x and CO_2 flue gases.

Before the analysis of the emission factors time-distribution, it is interesting to investigate the fuel contribution coefficients "ε_i " for the national electricity generation (figure (8)). According to official data, there has been a remarkable substitution for the N. Greece lignite (from 70% to 57%) by imported natural gas during the last years. A parallel heavy-oil substitution is also encountered by natural gas, while the contribution of S. Greece lignite and diesel oil operation (mainly due to the island Autonomous Power Stations) remains almost unaffected.

Accordingly, (figure (9)) evaluates the main fuels used emission factors distribution, concerning SO_2. As a general idea, between 1999 and 2001, a considerable "${}^{SO2}e$" decrease (≈25%) for S. Greece lignite has taken place, mainly due to the operation of the new desulphurisation unit at Megalopolis B (300MW) TPS. Unfortunately, in 2002 the corresponding emission factor attains the value of 160gr/toe. On the other hand, the N. Greece lignite emission factors distributions remain almost unaffected, being far beneath the corresponding heavy-oil one. Generally speaking a slight decrease of the emission factors values appears in most cases, apart from the Liptol one. In this context, the main value of the N. Greece lignite fired stations is approximately 8gr/toe of lignite consumed, being almost 20% below the corresponding 1999 value. This turns to be extremely important, as the authors expect N. Greece lignite and imported natural gas to cover over 80% of the national electricity demand during the next decade. Finally, diesel-oil emission factor distribution remains almost constant, getting slightly influenced by the quality of diesel oil used[22].

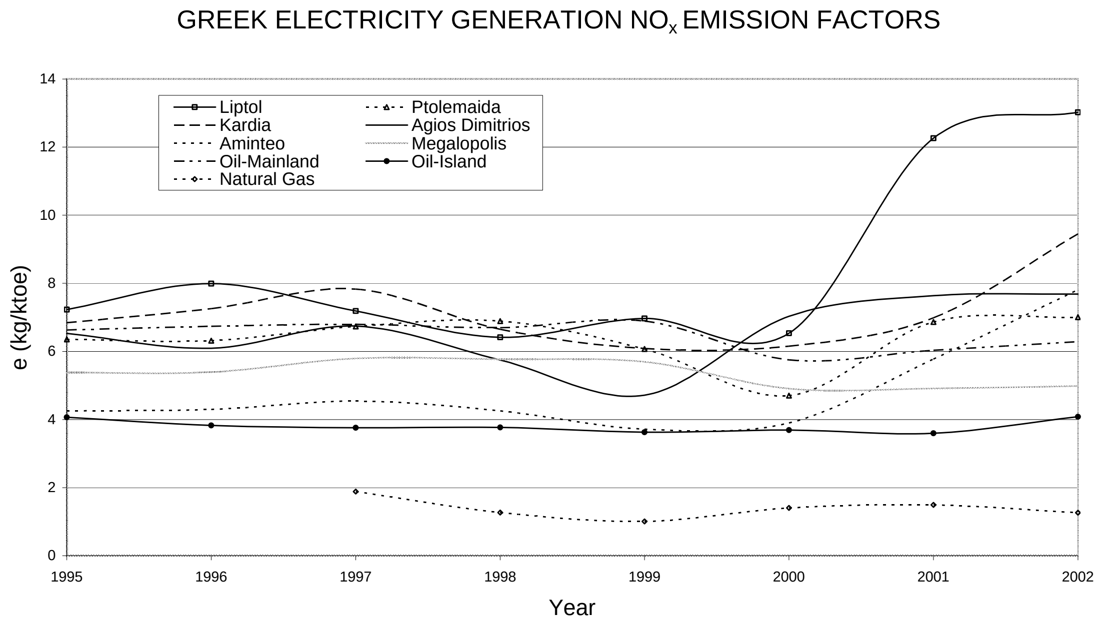

Figure 10: Greek electricity generation NO_x emission factors time evolution

Subsequently, one has the possibility to examine the corresponding "NO_x" emission factors distribution for the primary fuels used in our country (figure (10)). As it is obvious from the presented data, the time variation of "NO_x" emission factors is not very strong (excluding the Liptol 200MWh/year case), while the N. Greece lignite and oil-fired (mazut or diesel) TPS present the highest values. In this context, the natural gas contribution to the "NO_x" production cannot be ignored, while S. Greece lignite and mazut based stations show a slight decrease of the corresponding "e" values. This is not the case for N. Greece lignite. More specifically, the average emission factor value for the major N. Greece TPS is almost 8gr/toe for 2002 compared with approximately 6gr/toe produced in 1995.

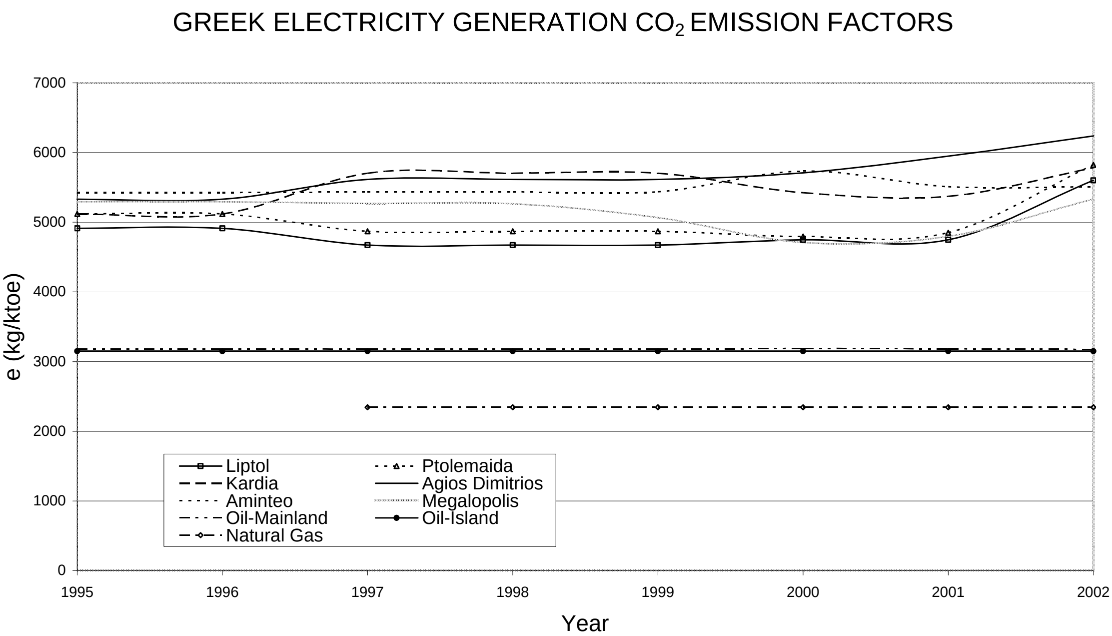

Figure 11: Greek electricity generation CO_2 emission factors time evolution

Finally, figure (11) demonstrates the time-distribution of the estimated "CO_2" production emission factors, based[11][22][23] on the primary characteristics of the fuels used (weight content-mass fraction, specific calorific value etc.). In this case, no-significant time variations are expected, while the data given are compared with similar results from other research groups[9][24]. As a general statement, the remarkable CO_2 production volume, from the local electricity generation, presents a slightly increasing tendency. It is also noteworthy that the mean CO_2 production from the lignite-fired stations is almost 5600gr/toe, a value exceeding the one suggested[23] by IPCC (approx. 4200gr/toe), mainly due to the low quality of local lignite consumed.

5. Expected Air Pollutants Production for the Near Future

According to the results presented for the national electricity production sector, a considerable energy demand amplification has taken place during the last years, e.g. from 36,000GWh in 1995 to 50,000GWh in 2002. In this context, most experts anticipate[5][8][20] a continuously increasing electricity demand, while -up to 2010- the corresponding annual increase rate is expected to vary between 3.0% and 4.0%.

This significant energy demand increase should be covered using N. Greece lignite and imported natural gas. However, considering that supplementary natural gas imports -lacking infrastructure strengthening- are unworkable, the major electricity demand increase (2.0%-2.5%) is going to be

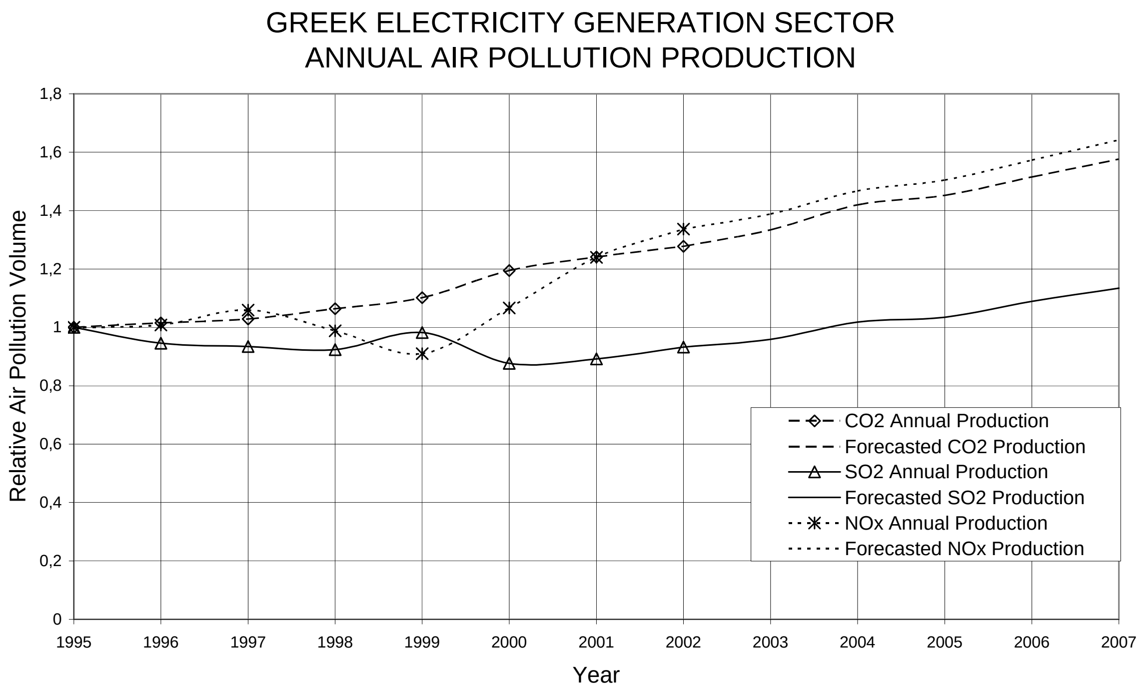

Figure 12: Air pollution production from the Greek electricity generation sector

covered by further exploitation of domestic N. Greece lignite. On the other hand, diesel-oil appears to be the only solution for the electricity consumption of all Greek islands, Crete and Rhodes included[25]. The only possibility to exploit the excellent wind potential of the Aegean Archipelago, by using large-scale applications, is the establishment of reversible wind-hydro power stations[26], in order to encounter the time-depending local electricity demand with the stochastic wind-energy production.

At the same time, one may expect a slight improvement on the existing TPS efficiency (0.2%-0.5%), mainly due to renovation activities and natural gas usage replacing solid fuels. Finally, no remarkable amelioration of the various air pollutants emission factors is anticipated, since the former State controlled PPC lacks substantial antipollution measures, in view of its privatisation policy. In this context, most "e" values should actually remain at the 2000-2002 levels.

Applying the above-described assumptions and using equations (1) to (5), the expected SO_2, NO_x and CO_2 production volume up to 2007 may be accurately estimated; (figure (12)). The results obtained are presented in a non-dimensional form, using 1995 values as the reference year. During 2004, further air pollutants are built-in, considering the increased electricity consumption resulting from the 2004 Olympic Games activities. As it is obvious, a significant electricity-related augmentation is expected in air pollutants, during the next five years, in comparison with 2002, which for CO_2 approaches the 21%, while slightly lower values are attributed for SO_2 and NO_x (19.5% and 20.5%) respectively.

This negative evolution strongly questions the efficiency of the 1st National Program for Greenhouse Gases Prevention, and underlines the necessity of extensive energy saving and renewable resources utilization during the application of the 2nd National Program. In the opposite case, our country has no chance to meet the European target for Greenhouse gasses emission limitation, deteriorating at the same time the Greek citizens living quality due to the increased concentration of dangerous air pollutants, like SO_2 and NO_x.

6. Conclusions and Proposals

An integrated and time-extensively analysis is presented, concerning the national air pollutants emissions resulting from the Greek electricity generation sector. The results hereby presented are founded on official data, analysing the SO_2, NO_x and CO_2 production on the basis of the fuel utilized. Among the most interesting results of the present survey emerges the continuous increase of air pollutants with time, mainly attributed to the electricity demand amplification and the unjustified state policy of using N. Greece lignite and imported natural gas in the mainland and diesel-oil in the Aegean Sea territories.

This strategy practically leads to remarkable air pollution rise during the next decade, a fact that is also validated by the application of the developed analytical model. On the other hand, only by introducing efficient energy saving measures in the industrial and tertiary sector it is possible to decelerate the annual electricity consumption escalation rate. Besides, a significant air pollution decrease may be accomplished in cooperation with a considerable wind and hydropower penetration, both in mainland and the Greek islands. On top of this, solar energy, biomass and geothermal can satisfactorily facilitate both electricity and thermal needs of local consumers.

Recapitulating, the results obtained may clarify the existing air pollution situation and assist Greek society in taking vital decisions regarding local electricity production sector for the next few years, seriously considering the significant air pollution impact on everyday life. Hence, the predicted electricity resulting emission factors provide important information-scientifically documented- in order to display the air pollution impact during the forthcoming energy choices.

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INCORPORATION OF SUSTAINABILITY CONSIDERATIONS INTO THE INDUSTRIAL OPERATIONAL PLANNING SYSTEMS

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Abstract

The core objective of the production planning systems, i.e. the most efficient utilization of various resources, is also the underlying concept of the production-integrated environmental protection. In this context, the main goals of the present work are to investigate the potential of integrating the environmental factor in the industrial production management functions, to identify the interactions between the environment-related and the production planning parameters, and to recommend the accommodation of the environmental constraints and the corresponding optimization criteria in the well established production planning systems.

Keywords: Production Planning and Scheduling; Production Integrated Pollution Prevention; Mathematical Programming

1. Introduction

In recent years the environmental issues related to the industry have been growing in both quantity and complexity. Environmental performance is no longer classified as the use of add-on technologies to comply with environmental laws. There is a consensus that pollution prevention or waste minimisation is the most effective strategy for reducing environmental impacts of the industrial processes. Production-integrated environmental protection is implemented through various measures of different complexity and need for capital investment, including:

- Technological changes for the avoidance and the minimization of emissions, such as the use of new low waste technology.
- Changes in the technical specifications of the products and/or changes in the production processes and use of less hazardous substances.
- Recovery and recycling of materials and substances
- Development and implementation of environmental management systems.
- Appropriate production management plans, since not only the technology itself, but also the way it is operated is very important

Sometimes the first step for major environmental investments is to change the current production practices. Major environmental issues in the production sector include the reduction of resource consumption, cutting emissions of solvents, nitrogen oxides and sulphur oxides, and waste minimisation in general. Many of these measures are used in industry extensively as efficiency improvement and good management practices rather than for environmental protection purposes and can often be applied with little or no cost in all the areas of a plant, including production, maintenance operations, and raw material and product storage. For the successful application of various soft production integrated environmental protection measures, it is important either to develop new decision support systems that take into account the correct relationships and interconnections between the traditional factors of production and the newly recognized environmental factor, or to extend the already existing, well established, tested and operating decision support systems to that effect.

Kondili E., Kaldellis J.K., 2004, *"Incorporation of Sustainability Considerations into the Industrial Operational Planning Systems", ESCAPE 14 International Conference, Lisbon, Portugal.*

2. The Integration of Environmental Aspects in the Production Planning Systems

The efficient utilization of resources has never been so much emphasized, as it is today. Along this direction, significant progress has been achieved in the development and implementation of commercially available production management systems of varying complexity and functionality that support and improve the quality of decision-making in a wide spectrum of strategic and operational aspects and aim to obtain significant benefit in the form of increased productivity and resource utilisation.

Planning and scheduling are complex processes, where decisions are taken at different stages within the supply chain and at different levels in the management hierarchy (Planning, Scheduling and Operations). Today, production planning is often usually carried out with the use of more or less sophisticated tools, that can take into account a serious number of parameters.

In fact, the core objective of the production planning systems, i.e. the most efficient utilization of various resources, is also the underlying concept of the production-integrated environmental protection. Therefore, it is promising to seek the opportunities for incorporating environmental considerations in the well established, familiar and already operating industrial production planning systems. Thus, the decision support methods of the production planning systems regarding logistics, allocation of resources and the manufacturing of goods can be extended, in order to take into account the environmental parameters of the plant in an integrated and not separate manner. Under this principle, environmental oriented planning of production systems can be realised[1]. The main question is how the main problems considered in the supply chain management systems, i.e. inventory management, product mix planning, scheduling and production control could be extended, in order to include environmental aspects. The matching of some conventional production planning with the corresponding environmental issues is indicated in Table I[2].

At the same time, the interest that has lately been shown in the production-integrated environmental issues is reflected in various applications that have appeared in the literature, applying optimisation and Operations Research approaches[3] within the manufacturing stage related to the integration of production design – planning with environmental issues.

For example, Wua et al[4] carried out a detailed study that demonstrates how the multi-criteria decision-making approach could be applied, to figure out the optimal production planning program in an uncertain environment. Cooper et al[5] surveyed the current state of literature in management science / operations research approaches to air pollution management. In their work, attention is turned to mathematical programming models, from simple linear models to quite sophisticated stochastic models that have appeared in the literature dealing with these topics. Zhou et al[6] have proposed a goal programming model to address the multiobjective function problem for the supply chain optimisation with sustainability considerations.

Table I: Matching of production planning functions with environmental issues

Production Management Function	Corresponding Environmental Consideration
Strategic planning	High level decision making for pollution prevention and waste minimisation
Raw materials procurement	Recycling and reuse capability.
Inventory management	Eco-balancing for commodities sourcing
Demand management	Environmental objectives in determining orders
Product mix planning	Product mix respecting environmental standards
Scheduling	Use environmental oriented production rules

3. Mathematical Programming Methods for the Production Planning

Scheduling and planning are inherently optimization problems, the solution of which suggests the user how exactly to operate the facility. In general, the formal definition of the scheduling problem is as follows:

Given:
- A time horizon, a set of product orders, recipes for the required products, details on the availability of equipment, storage, raw materials, utilities or any other constraint

Determine:
- The allocation of operations in the units and the available resources, the timing of operations for each unit and the flow of material throughout the plant

So as to optimise one (or more) criteria, that express an appropriate performance measure of the production system, such as:
- Minimize the total delay, or the total operational cost, or the total changeover cost, or the total energy, water, raw materials consumption, or maximise the total profit.

The production planning and scheduling are clearly optimization problems. Recent years have seen the emergence of general methodologies for their solution, based on a mathematical programming approach and providing considerable flexibility with regard to process structure and resource utilization[7].

The modelling of the production planning and scheduling as optimisation problems and their solution through mathematical programming methods offer the capability to handle a variety of different problems, such as short term scheduling, campaign planning and scheduling and plant design, in a consistent manner. Hence, this approach is the catalyst for the integration of the environmental factor in the production planning systems, since it facilitates the accommodation of any operational constraints expressing environmental considerations, as well as the inclusion of any optimisation criterion expressing environmental issues.

4. Environmental Production Planning Model Development

4.1 Optimisation Criteria

One of the most commonly used optimisation criteria for production planning and scheduling determination is the total cost minimization. However, in many cases, the utilities cost or the changeover cost may be hidden behind other, more significant in quantitative terms costs, thus underestimating the environmental dimension of the problem. In an environmentally oriented production planning system, these cost terms must be taken into account explicitly and isolated from the other terms.

In the case of utilities cost minimization, the operating costs depended on specific units to tasks assignment should be determined in detail. For example, the use of the most harmful equipment from an environmental point of view could be assigned a very high / prohibitive operating cost allocation, thus minimizing the chance of this specific assignment. Definitely, advanced cost analysis in relation to production planning is essential for handing reliably these issues. Today there is a growing awareness of the environmntal costs, such as pollution charges and resource conservation fees that have to be taken into account in the production planning scheme.

Other optimisation criteria that can be considered in environment-oriented production planning systems are:
- Optimisation of the wastewater treatment plant operation, to avoid disturbances.

- Minimisation of (a specific type) of waste, or of the total inventory cost, the total production cost – including explicitly all production-related environmental costs, or of the overall production time.
- Maximisation of the utilisation efficiency of the production equipment

In addition, for the short-term scheduling problem, environmental oriented production rules could probably express the allocation of units to processes according to minimal set-up emissions by the priority use of production units with greater efficiencies and less consumption and emission factors, or by avoiding unforced waiting times and any high emission set-up measures, or by harmonising capacity utilisation.

4.2 Constraint Set

The constraint set usually involved in the production planning systems include mass balances throughout the system, batch size restrictions due to the size and type of the available equipment, equipment size, type and availability, also including pollution processing equipment and wastewater treatment plants and constraints in the quantities, timing and availability of the various other resources required, such as manpower, energy, water, raw materials, steam, and intermediate storage.

Certainly, to implement this approach a detailed analysis of the material and energy flow through the system is required, including mass balances for each substance and emphasizing the parameters that affect the environmental behavior of the system, such as the flowrate and timing of the liquid effluent discharges, the concentration of CO, CO_2, Nitrogen Oxides, CFCs and halons, the emissions of Volatile Organic Compounds arising from solvents use, the consumption of resources and utilities, such as water, energy, steam, raw and auxiliary materials, the type and quantities of solvents and, in wastewater streams, parameters such as BOD, COD, SS, oils, N, P, metals, cyanides and chlorides. Moreover, process related restrictions within the overall production chain must be considered explicitly, e.g. standards for emission to air, water and soil, sequence dependend changeover costs, time dependent smog emissions, maximum waiting times between production units, energy and material supply limits over time. It should be noted that, alternative optimisation criteria may be used, depending on the needs and the objectives that the plant needs to satisfy, for the same constraint set.

4.3 Special Cases

Beyond these general statements, there are specific cases where production planning and scheduling issues have serious environmental dimensions and, therefore, the appropriate approach of the planning problem with explicit consideration of this environmental dimension will play a crucial role in the improvement of the environmental behavior of the production system. Some of the waste generated in the industry is a consequence of process inefficiency, as is the case with product changeover waste. Often the generation of this waste is processing-sequence dependent and there is a strong dependence of the setup and cleanup times and costs on the product sequence in equipment items. This is a problem that can be faced with the appropriate scheduling. Accordingly, effluents generated in setup and cleanup tasks are a source of waste that can significantly be reduced with a proper schedule. In this case, the optimization criterion for the production scheduling should refer to the minimization of the number of changeovers or changeover costs.

Another case is the one that the resource consumption is either product sequence dependent, i.e. depends on the sequence of different products in the same equipment or storage facility, or allocation dependent, and i.e. varies with the specific assignment of products or processing tasks to production units. In these problems, production planning cannot reduce the specific resource requirement of an individual processing step carried out in a particular piece of equipment. However, the overall resource consumption can significantly be reduced by organizing the production, so that the most efficient equipment is used for each processing step and the most utility intensive processing task sequences are avoided[8]. Certainly this has to be satisfied against the need for timely satisfaction of customer orders and all other system constraints.

5. Implementation Issues and Success Factors

A structured approach is necessary to identify, evaluate and implement the integration of production planning to environmental issues. The basic steps to be followed are:

- Analysis of the existing production planning system functions. It should be noted that the production planning system of the company may not necessarily be an advanced and sophisticated computer aided system, but a set of rules and decisions made by the production planning department, supported by any type of system.
- Identification of the parameters, constraints and optimisation criteria involved in the existing production planning systems
- Quantitative definition of all the environmental aspects, i.e. identification of all sources of wastes, investigation of the factors that influence the volume and the composition of the wastes and, in general, the company's environmental behaviour.
- Detailed cost parameters estimation, with special attention to those associated to the environmental performance of the production plant (e.g . emission charges)
- Matching between the environmental and production planning parameters and accommodation of all the environmental parameters in the production planning constraints and optimisation criteria.
- Formulation of the mathematical programming model, including all system constraints an the appropriate optimisation criterion.

The environmental oriented production planning systems will mainly succeed in companies with well-established production practices and good availability of information on the details of the process streams. On the other hand, the effectiveness of these systems requires continuous monitoring, evaluation of the results achieved and exploitation of the evaluation results for the improvement of the system.

6. Concluding Remarks

The proposed methodology is used to systematically identify and evaluate the environmental improvement opportunities through the integration of the environmental factor in the production planning systems. The application of such systems can show the effects of various operational and structural constraints on the environmental behaviour of the plant. In addition, the proposed approach will contribute significantly in the identification of the relationships between the environmental and the production planning parameters of the system. The improvements brought about through simple low or no cost changes in procedures will also provide significant financial savings, since they will result in a more efficient use of raw materials, energy, water and resources in general. The significant contribution of the proposed approach is also that the environmental factor is accommodated in the whole company's operation, in accordance with the modern production-integrated pollution prevention principles.

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TRANSBOUNDARY AIR POLLUTION IN GREECE ECONOMIC AND POLITICAL ASPECTS

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Abstract

During the last twenty-five years the Greek economy has been presenting a considerable development rate unfortunately accompanied by significant rise in the level of air pollution. In an attempt to evaluate the contribution of local economy activities on the increased air pollutants production encountered, one cannot disregard the responsibility of the transboundary transport of remarkable quantities of flue gases. On top of this, the geographical position of the country -located in the SE of Europe in the middle of several rapidly developing countries- constitutes the appropriate framework for important transboundary air pollution (TAP) exchange. Moreover, national and international concern about TAP led to the establishment of several research activities, like the European Monitoring and Evaluation Programme (EMEP). At first emphasis was set on sulphur dioxide, but subsequently the significant contribution from nitrogen species was recognized. The present work is based on long-term data concerning the TAP balance between Greece and its neighbors in the course of time. In this context, the contribution of imported and exported air pollutants quantities on the country's air pollution balance is examined in detail. Special attention is also focused on investigating the economic, political and social aspects of this rather complex situation.

Keywords: Transboundary Air Pollution; Economic Aspects; Political Aspects; EMEP; Sulphur Dioxide; Nitrogen Oxides

1. Introduction

Europe has experienced during the last decades the threatening consequences of the transboundary transfer of dangerous air pollutants. Up to that time problems caused by the rising production of acidifying and eutrophying gaseous pollutants have been realized but their effects were thought to be only local around the area into which they were produced. In contradiction to that belief numerous lakes and hectares of forests in Scandinavia were found to be exposed in very high acidity, which had not been produced in the nearby area. Acid compounds that had been emitted in central Europe degradated the forestal and aquatic ecosystems of the Scandinavian Peninsula[1].

The recognition of the problem of transboundary transfer of certain air pollutants throughout the European continent led in 1979 to the initiation of "The Convention of Long-Range Transboundary Air Pollution" (CLRTAP)[2], which had set a clear framework not only for the environmental and health consequences but also for the internationally cooperative approach needed for their abatement. The Convention was signed by the European Community, while 34 governments established the European Monitoring and Evaluating Programme (EMEP) for the promotion of scientific research and intensive monitoring of the TAP effect, funded by the Organization for Economic Cooperation and Development (OECD).

By 1985 the first protocol had been issued and signed. Its agreements emphasized on the reduction of the sulphuric air pollutants produced in the signatory countries. More precisely the parties were expected to reduce their sulphur dioxide (SO_2) emissions by 30% relatively to their emission levels of 1980, in a period of 8 years, i.e. until 1993. That protocol was the main reason for major investments - especially among the European counties- which promoted the massive installation of desulphurization

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units in the large-scale industrial plants. Furthermore, natural gas, which had been utilized mainly in the tertiary sector, turned to be the new environmentally friendly option for all the energy consuming sectors, containing only traces of sulphur.

The increase of road transport as well as the lack of any abatement measures resulted in the steady growth of the nitrogen oxides production. The United Nations Economic Commission for Europe (UNECE) implemented the 1st Nitrogen Protocol in year 1988, asking the signatory parties to keep their nitrogen oxide emissions below the 1987 levels until the year 1994.

Although the "first generation" protocols contributed a lot to the emissions control, the monitoring procedures were still reporting high acidity in several ecosystems. This fact set the need for a different approach, as scientific research should answer the question of how much acidity were the ecosystems able to receive maintaining also their balance[3][4]. Data from all the participating countries were collected in order to sort out solutions for minimizing the environmental damage with the lowest economical cost. The second sulphur protocol was drawn under this perspective. Taking into account the transboundary transport of air pollution, as well as the ecosystems limits, each country was examined individually and asked to lower its emissions at an adequate level. The latest evolution of the legal and policy framework for the abatement of acidification and eutrophication was set in the EU by the emission ceiling directives (e.g. Directive 2001/80/EC).

2. Air Pollution Transfer Through the Greek Borders

The EMEP network, utilizing the national air pollutants emissions, the local meteorological phenomena as well as the local land surface of each region, results in data about the transboundary transfer of air pollution among the countries that participate in the monitoring and evaluating program[5][6].

Greece, although being a EU member has no land borders with any other EU country. Only the north Greek borders with Bulgaria, Former Yugoslavian Republic of Macedonia (FYROM) and Albania are land borders. The availability of information about the FYROM is very low and therefore the authors used the former Yugoslavia data for their study. As one may see on figure (1), to the west and east directions Greece has the Ionian and Aegean Seas as natural borders to Italy and Turkey correspondingly.

Figure 1: South Balkan region map

Although it is known that transboundary air pollution transfer occurs not only with direct border countries but also with more distant regions, like the northern Balkan Peninsula and the central Europe the contribution of the latter is practically eliminated due the large distance. Therefore the authors have taken into account only the data for the countries mentioned above to estimate not only the air pollutant quantities that Greece receives but also the ones that Greece exports through its borders.

3. Transfer of Oxidized Sulphur Air Pollutants

Oxidized sulphur is one of the pollutants emitted mainly by the coal and heavy-oil fired combustion sources. Therefore the basic polluters are the large-scale electricity generation stations as well as some forms of transport like overseas and heavy-duty road transport[7][8]. In figure (2) one may notice the time evolution of the oxidized sulphur air pollutants, which Greece receives from its neighboring countries.

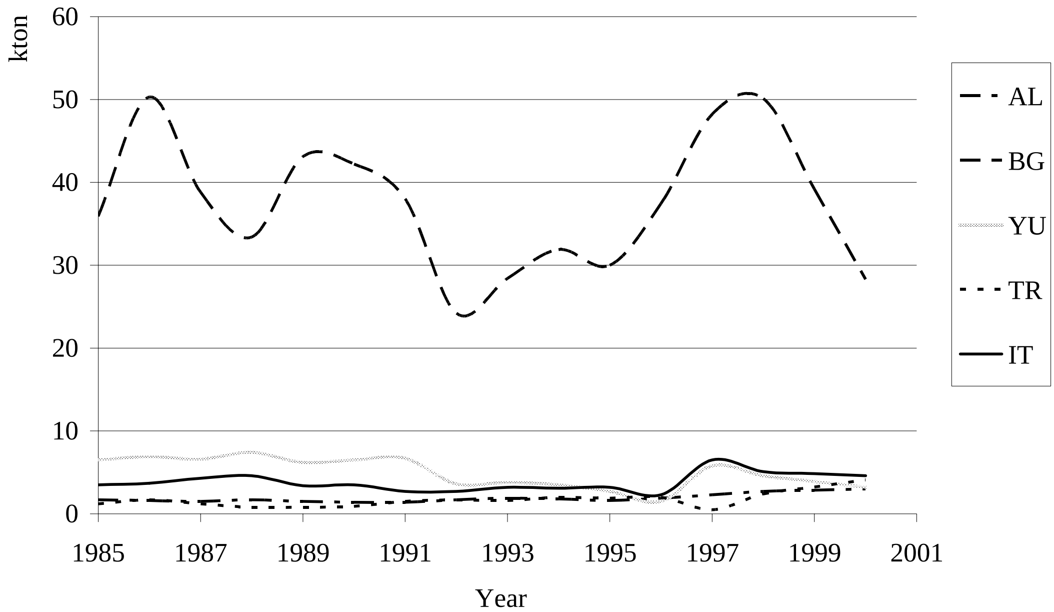

Figure 2: Evolution of Greek SO_2 imports

Bulgaria, being the main exporter of sulphur dioxide to Greece, amounts for the year 2000 the 60% of the total emissions imported in Greece from abroad. It is important to note that the time evolution began in 1985 with 36 thousand tones, while just after the 1990 it shows a declining trend due to the fall of the socialistic regime and the collapse of the local economy. This declining period lasted for only two years, thus in 1993 the emissions exportation started to rise again. Thus, in 1997 the corresponding emission values become significantly higher in comparison with the 1985 levels[9]. Finally, the start-up of the new nuclear power stations in substitution of some of the countries oldest coal fired power stations resulted in the noteworthy reduce of the local SO_2 production and therefore its exportation was cut down by 43%.

Albania although being a rather insignificant sulphur dioxide exporter to Greece follows a time evolution similar to the one of Bulgaria, due to their same political regime history. Therefore the stabilized SO_2 quantities transported to Greece in the 1985-1990 period are rising only after the liberalization of the local market and are finally doubled by 2000 in comparison with the 1985 base year level.

Former Yugoslavia faced several political and economical crises in the examined period, which reduced its local emissions, as it is reflected in the air pollutant quantities that Greece received, figure (2). In this context the political changes that took place in the 90's almost cut down in half the emissions exported in Greece, while in 1995-1996 the civil war had about the same effect. The last crisis at the Montenegro region in the 1999-2000 period resulted in a sharp decline after the 1997-1998 rising trend period.

Turkish contribution to the Greek sulphur dioxide imports is found to be quite low in contradiction to the countries national emissions[10]. However one should not disregard that in the examined period the imports of sulphur dioxide in Greece from Turkey have been increased by 241%.

Italy is the only neighboring to the Greece country, which is an industrialized EU member. Despite this fact the air pollution exchange between the two countries is found to be rather low. This may be explained by the existence of the Ionian Sea between the tow countries, as well as by the fact that Greece neighbors mostly to the least developed south Italian region, as one may notice in figure (1). Moreover, Italy, in compliance to the relevant EU directives, has done a great effort to control its air pollutant emissions and therefore their transboundary transfer is rather low and has not changed significantly during the 16-year examined period[11].

As the overall situation of the air pollution imports to Greece has been analyzed above, it is now useful to examine the corresponding sulphur dioxide exports to the neighboring countries. One may notice in figure (3) that the exports of SO_2 from Greece are following a continuing increasing trend. This trend may be found rather acute, as in the case of Italy, where sulphur dioxide exported quantity has been doubled in the examined period or having a lower rate like in the case of Albania. It is noteworthy to mention that during the 1985-2000 Greece has invested a lot in the direction of eliminating the sulphur dioxide production. This has been achieved mainly by the installation of audit and control equipment in the large scale emitters of the electricity generation and industrial sectors, in addition to the penetration of natural gas in the local energy market[12].

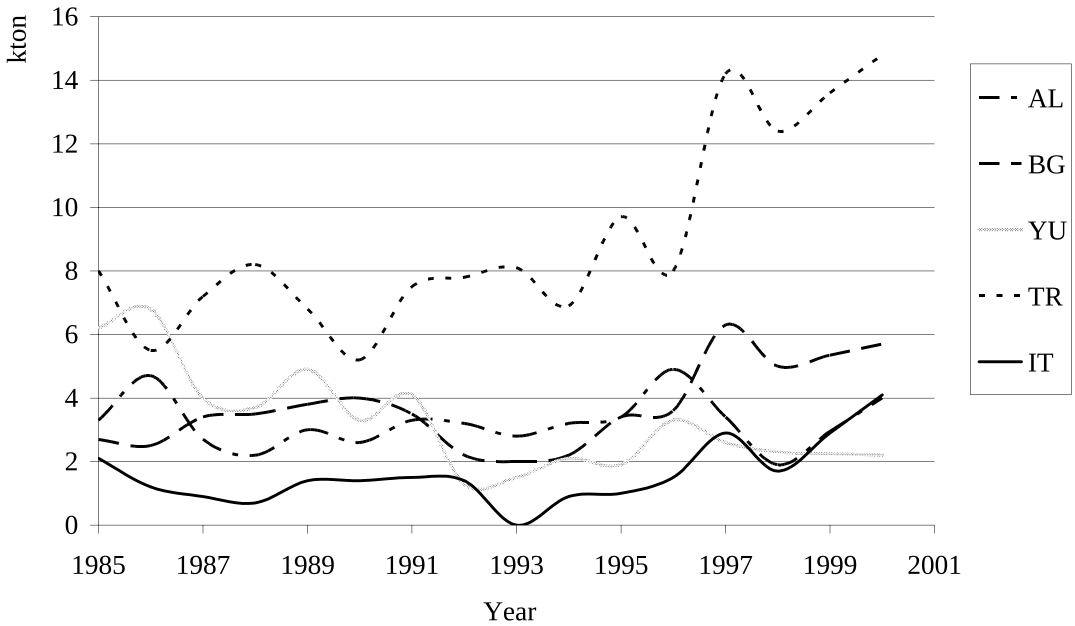

Figure 3: Evolution of Greek SO_2 exports

In contradiction to the other neighboring countries, Yugoslavia is the only one to present significant reduction in the sulphur oxide emissions that were received from Greece, since in 2000 Yugoslavia received only the one third of the quantity that had received in the 1985 base year.

According to the available information Turkey is a minor exporter of SO_2 to Greece, while in figure (3) one may notice that at the same time it is the major receiver of the Greek sulphur dioxide exports. Taking under consideration that Turkey produces a significant amount of sulphur dioxide it is obvious that the local meteorological phenomena tend to transfer the air pollutants from the west to the east.

Local meteorological phenomena as well as the local topography are the main reasons for which Bulgaria is found to be the major exporter to the South Balkan Peninsula but only a minor importer.

For the rest of the examined countries the received quantities do not differ significantly from the ones emitted. Thus during the 1985-2000 period only minor changes have been occurred and therefore the final balance cannot be found inclined to the one or the other side.

4. Transfer of Oxidized Nitrogen Air Pollutants

Oxidized nitrogen air pollutants are mostly produced by the transport sector from the internal combustion engines. Therefore the emitting sources are mainly non-stationary and found spread through out the urban areas as well as in the national road networks[13]. In figure (4) one may notice the time evolution of the oxidized nitrogen air pollutants that Greece receives from its neighboring countries.

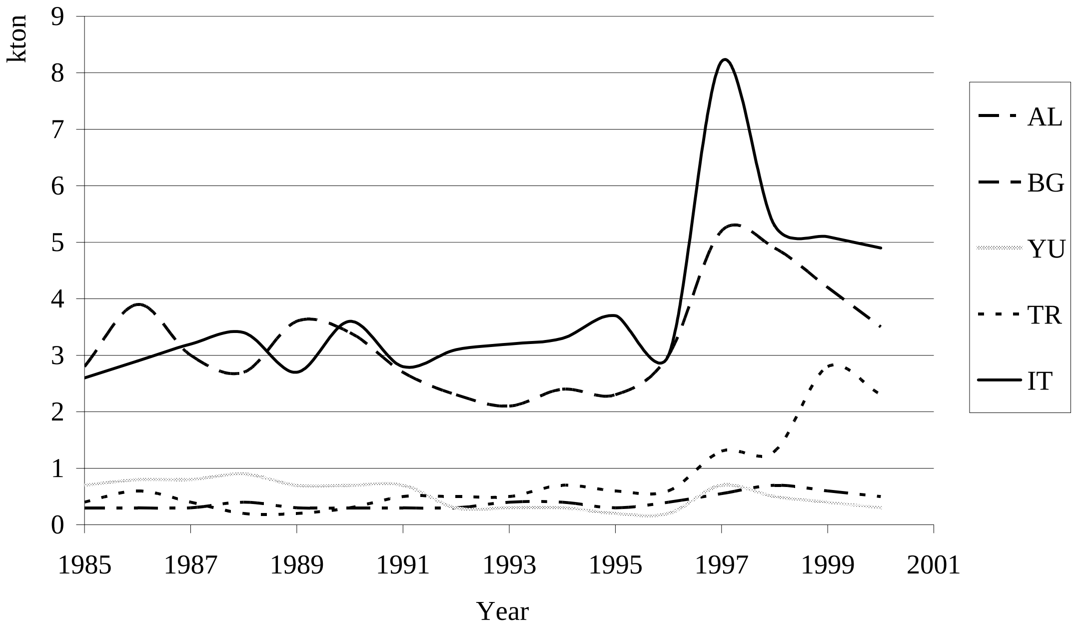

Figure 4: Evolution of Greek NO_X imports

Italy is the most important nitrogen oxides exporter to Greece, representing the 41% of the total emissions received for the year 2000. During the 16-year examined period the total annual quantity of oxidized nitrogen air pollutants transferred from Italy to Greece has been almost doubled resulting in 4.9 thousand tones for 2000. In this context one may assume that the growth of the transport sector activity practically overwhelms the efforts made from Italy to control its emissions in compliance to the relevant directives (Directive 2001/80/EC of the European Parliament).

Bulgaria is the second most important exporter of nitrogen oxides to Greece, amounting 29% of the total emissions received for the year 2000. Despite the fact that Italy and Bulgaria begun in 1985 from the same level, the political crisis that the latter came into in the early 1990's slowed down its

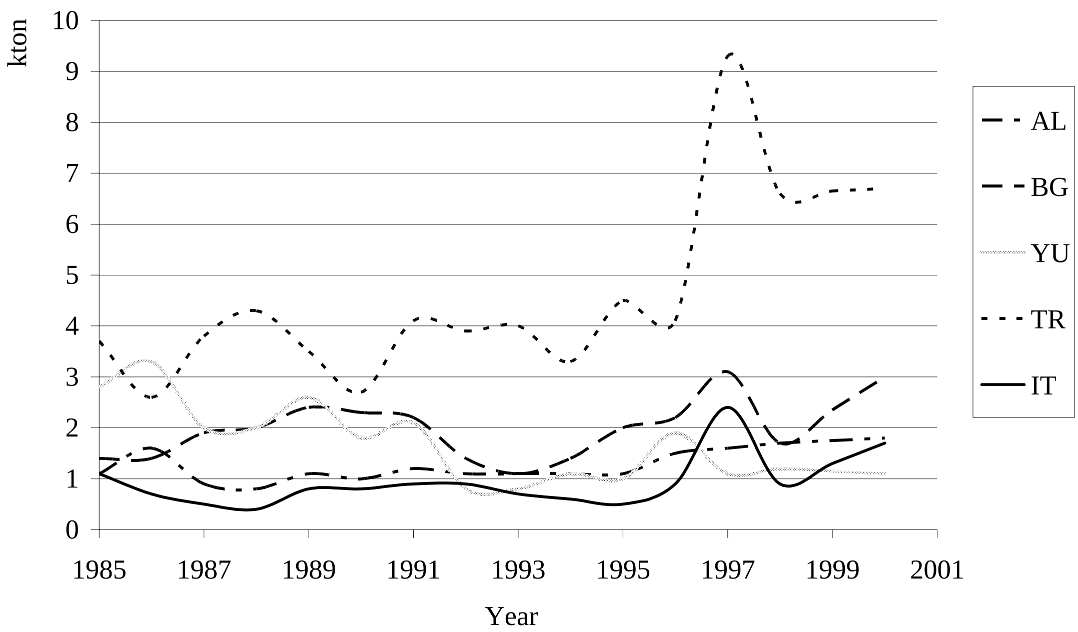

Figure 5: Evolution of Greek NO_X exports

development rate and therefore its emission levels. As a result the quantity exported during 2000 is higher than the 1985 only by 25%.

Turkey is the country presenting the most rapid growth in its nitrogen oxides transboundary transfer to Greece. The 2000 quantity is found to be higher than the one of 1985 by a factor of almost six. This fact reflects the growth of the Turkish economy, which has led during the last two decades to an important increase of the private transportation sector. The lack of any pollution control measures as well as the continues growth of the local economy are the main reasons for which Turkey is expected to play a major role in the exportation of nitrogen oxides to Greece.

Albanian exportation of oxidized nitrogen is ranging over the examined period between 0.3 and 0.7 thousand tones, presenting a rather stabilized attitude. Yugoslavia is the only region, which exports are following a declining trend after the several political and civil crises that the country experienced.

As in the oxidized sulphur air pollutants case, Turkey is also the major receiver of Greece oxidized nitrogen exportation. More precisely for the year 2000 Greece exports to Turkey 6.7 thousand tones nitrogen oxides representing the 42% of the total quantity exported during the same year.

Bulgaria presents the higher annual relative increase in its oxidized nitrogen air pollutants imports. Taking into consideration that all the neighboring to Greece countries are facing a major growth of the quantities that import from Greece, one may realize that the Greek nitrogen oxides production is gradually increasing, despite the country's efforts to comply with EU Emission Ceiling Directives.

Albania and Italy NO_x imports from Greece started in 1985 from the same level. Accordingly, despite the fact that their time evolution has been quite different they came to (2000) similar results. In fact the 1.1 thousands tones of NO_x pollutant quantities received in 1985 became after 16 years equal to 1.7 and 1.8 thousand tones respectively. Finally, Yugoslavia, in contradiction to the other neighboring to Greece countries, is the only one that presents a declining evolution of the nitrogen oxides quantities received.

5. Discussion of the Results

The analytical results already presented underline the fact that Greece received in 2000 from its neighboring countries larger (by 13.3 thousand tones) quantities of sulphur dioxide emissions than those exported to them. Bulgaria is the major exporter of sulphur dioxides to Greece, while Turkey is the major importer. Regarding the nitrogen oxides case the situation is rather different, as our country is benefited from the transboundary transfer of those pollutants. More precisely, in 2000 Greece exported 3.8 thousand tones of oxidized nitrogen more than the quantity that Greece imported by its neighboring countries in the same year.

Bear in mind that sulphate and nitrate aerosols from air pollutants emissions are found responsible for various damages in human health as well as serious degradation in several different ecosystems. For this reason further studies of their transboundary transfer should be held out in order to contribute in the national and international environmental management and planning. In addition to the serious health and environmental consequences, the corresponding financial cost of the TAP exchange is also interesting to be investigated. The monetary evaluation of damages to fisheries, crops, forests, ancient monuments and human health will permit the further implementation of the EU "The polluter pays" principle in the environmental and international economics.

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THE CONTRIBUTION OF THE GREEK ELECTRICITY GENERATION SECTOR ON THE GLOBAL CLIMATE CHANGE

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Abstract

Electricity generation in Greece is based mainly on the utilisation of local lignite as well as imported heavy oil and natural gas. As a result the contribution of the electricity sector to the national air pollutants emissions is of major importance. In the present paper, the authors, using recent official data, are specifying the dependence degree of electricity production to carbon dioxide emissions in Greece, while proposing methods of eliminating this dependence through the adoption of environmentally friendly choices.

Keywords: Carbon Dioxide; Climate Change; Electricity; Air Pollution

1. Introduction

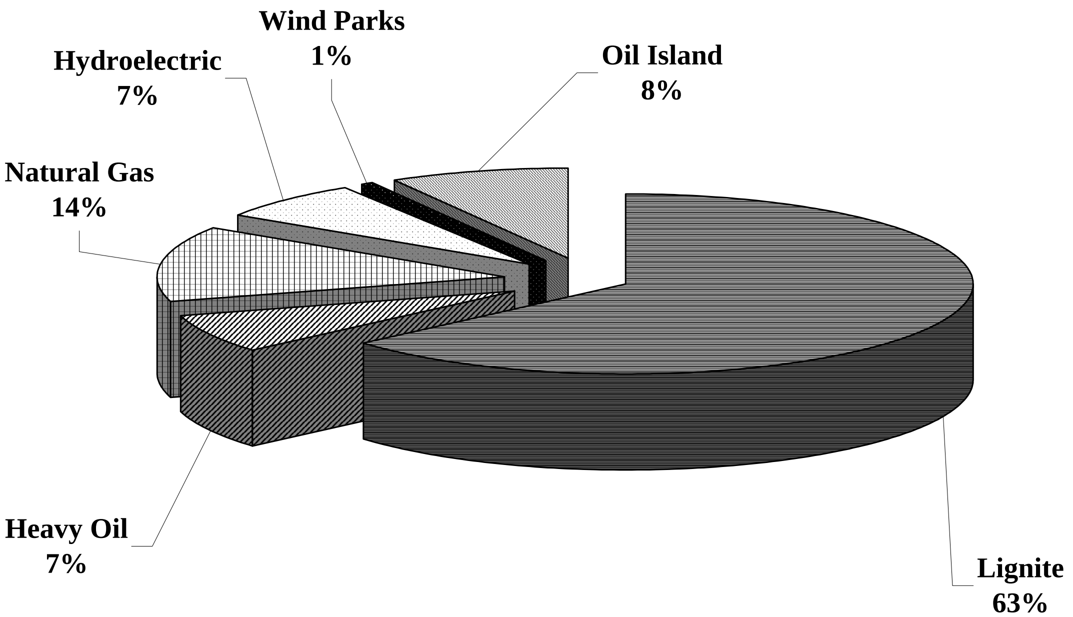

Figure 1: Analysis of electricity production in Greece, 2002

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[1]. Only recently a remarkable natural gas penetration in the Greek energy market tends to change the fuel mix of the electricity sector. On the other hand the hydroelectric power stations although amounting a rather high installed capacity, their contribution is relatively low basically due to water reserves deficit and applied electrical load management plan[2]. Finally, despite the high wind potential of the country, the contribution of the wind parks to the Greek electricity production is still limited[3].

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As one may notice in figure (1), where the net electricity production for the year 2002 is presented, the usage of lignite and heavy oil is of major importance representing more than 75% of the total production. The natural gas stations already provide 14%, while hydroelectric and wind power stations contribution does not exceed 8%.

2. Presentation of Greek Electricity Generation System

Using official data[4][5] from Greek Regulatory Authority of Energy (RAE) and Greek Public Power Corporation (PPC), the local electricity generation system (at the beginning of 2003) is divided in two branches. The first part contains the mainland electricity production network based on thermal power stations (TPS) with rated capacity of 7200MW, along with 3400MW of renewable energy production stations, mainly large and small hydropower installations (3100MW).

The second part includes 35 medium-small autonomous thermal power stations (APS) of 547MW and 18MW resulting from renewable energy sources exploitation, spread throughout the Aegean Sea[6]. In this group, there should also be embraced two medium-sized thermal power stations on Crete Island (approx. 580MW) and almost 70MW of renewables, along with 208MW of thermal power units operating in Rhodes island, Table 1.

In this context, the Greek thermal power stations can also be categorized according to the fuel used, as follows; see Table I:

a. 4280MW using N. Greece lignite
b. 850MW using S. Greek lignite
c. 1134MW using Natural Gas
d. 830MW using heavy-oil (mazut) in mainland
e. 1340MW using diesel-oil and mazut in Greek islands

Table I: Greek electricity generation system thermal power stations (in operation end 2002)

Power Station	**Start Up**	**Rated Power MW**	**Fuel Used**	**Location**
Liptol	1959	43	Lignite	W. Macedonia
Ptolemaida	1959	850	Lignite	W. Macedonia
Kardia	1975	1200	Lignite	W. Macedonia
Agios Dimitrios	1984	1586.5	Lignite	W. Macedonia
Aminteo	1987	600	Lignite	W. Macedonia
Megalopolis-A	1970	550	Lignite	Peloponessos
Megalopolis-B	1991	300	Lignite	Peloponessos
Aliveri	1953	380	Mazut	Euboea
Lavrio	1972	450	Mazut	Attica
Lavrio (New)	1996	774	Natural Gas	Attica
Agios Georgios	1997	360	Natural Gas	Athens
Linoperamata	1965	253	Mazut-Diesel	Crete
Chania	1969	330	Diesel	Crete
Rhodes	1967	208	Diesel	Rhodes
APS	1967	547	Diesel-Mazut	Aegean Archipelago

It is interesting to mention that Greek lignite deposits present significant differences between their natural characteristics. This is the main reason explaining why the lignite-fired power stations are usually divided into two categories. More precisely the north Greece lignite possesses higher calorific value (up to 50%) than south Greece one, while ash and moisture are found in N. Greece deposits on lower levels. Finally, the sulphur content of south Greece lignite is up to ten times higher than the corresponding one of the north Greece lignite.

Accordingly, the heavy oil-fired stations examined (Table I) are located in Euboea, Attica and Crete Island. In all cases the fuel used meets specific standards thus the results obtained from those stations are considered together.

Finally the recent gas-fired power stations in Attica are old heavy-oil fired stations that have been modified in order to use natural gas. Furthermore, a combined cycle technology power station started its operation utilizing natural gas, in northeast Greece (Thrace) at the end of 2002.

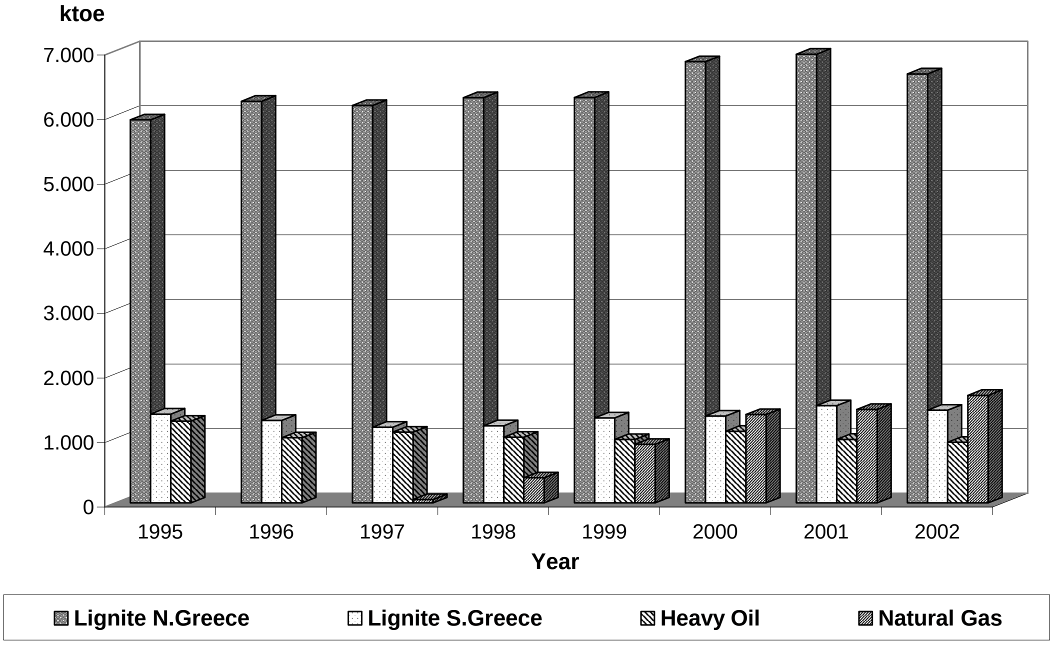

Figure 2: Fuel mix evolution in local electricity production

In figure (2) the evolution of the Greek fossil fuel mix in the electricity generation sector (EGS) for the time period 1995-2002 is presented. One may notice the key role of N. Greece lignite, something that is also obvious from the rather high installed capacity in the north Greek regions. Heavy oil-fired stations are used mostly to cover peak loads due to their high operational cost. As a result their contribution to the national electricity production does not exceed the one of the S. Greece power stations, despite the much lower installed capacity of the latter.

3. Analysis of Electricity Generation Carbon Dioxide Production

Electricity production in Greece is assumed responsible for the emission of various air pollutants, some of which are related to local environmental deterioration[7][8], while others are accused for the worldwide climate change[9][10]. Carbon dioxide emissions belong in the second category, although Greek contribution to the planet total emissions does not exceed 0.6%[11][12]. Despite this fact it is essential, within the European environmental policy framework, to examine in detail the effectiveness of the 1st National Program for Greenhouse Gases Prevention[13].

Carbon dioxide (CO_2) is produced upon complete combustion of carbon. Although not toxic, when found, in a non-ventilated area, may cause asphyxia. On the other hand, the carbon dioxide is the main culprit for the greenhouse effect, which may change the climate of our planet. In this context, it is important to mention that electricity generation is responsible for almost 55% of the CO_2 production[9][10] countrywide. Figure (3) presents the evolution of carbon dioxide emissions due to the electricity generation[14] in Greece for the time period 1995–2002, where the overall increment of total emissions is more than 20%.

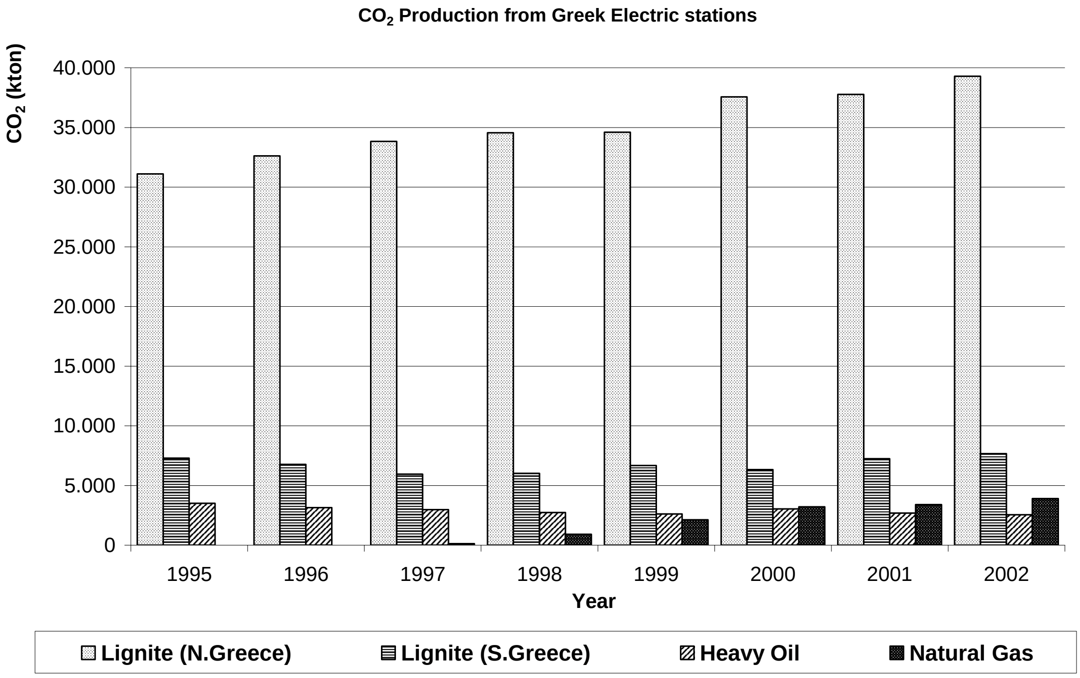

Figure 3: CO_2 production from Greek power stations

Keep in mind that during 1997-98 the heavy oil-fired station of Agios Georgios (Attica) was modified to use natural gas; consequently a substantial amount of heavy oil used in the electricity generation sector was partially replaced. The carbon dioxide emission factor of natural gas is lower than the corresponding factor of heavy oil or lignite[15][16]. Therefore, this fact explains why carbon dioxide emissions from natural gas fired stations are quite low relatively to their significant contribution to the overall national electricity production.

North Greece lignite presents a very high contribution in the national emissions of carbon dioxide due to its dominant role in the electricity sector. The above result is moreover amplified by the relatively high carbon dioxide emission factor of N. Greece lignite, while the continuous exploitation of the local reserves affects the fuel quality, which keeps falling in the last years.

All Greek lignite-fired power stations are utilising the fuel reserves, which exist in their local area. Differences in the natural characteristics of each reserve result in a variety of carbon dioxide emission factors between these stations[15].

Figure (4) presents the time average emission factors of each lignite-fired station along with the corresponding standard deviation for the last decade. South Greece power stations are located in the Megalopolis major area, while the already presented power stations are sited in north Greece. As one may observe North Greece lignite average emission factor is higher than the one of South Greece.

Figure (4) shows that the power stations with the highest carbon dioxide emission factor are those of Ag. Dimitrios and Kardia, with mean values 5617 kg(CO_2)/toe and 5480 kg(CO_2)/toe respectively. Bearing in mind that these two power stations are the most active in the Greek electricity network, one may easily conclude that their contribution to the national "CO_2" production is quite significant.

The station with the lowest carbon dioxide emission factor value is the one of Liptol with a value of 4867 kg(CO_2)/toe, while the station of Megalopolis -the only one of South Greece- comes next. The standard deviation of the fossil fuel-fired power stations is approximately 300 kg(CO_2)/toe, excluding the value for Ptolemaida TPS (415 kg(CO_2)/toe). This variation is mainly attributed to the fuel quality variation as well as to the corresponding utilisation procedure.

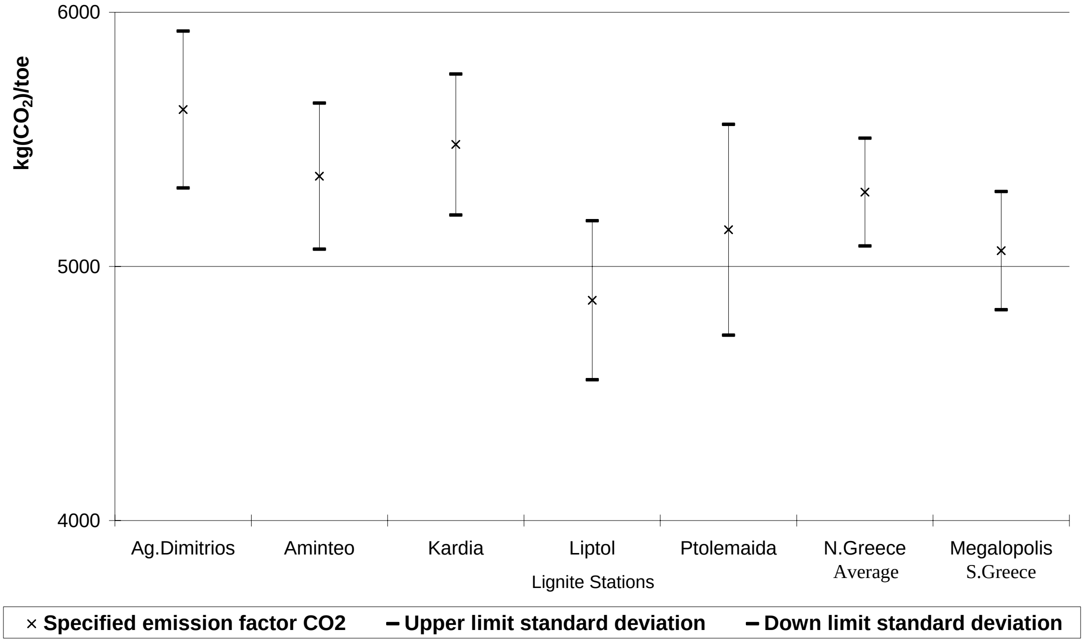

Figure 4: Specific CO_2 emission factors for Greek lignite fired power stations

4. Forecasting the Carbon Dioxide Production from Greek EGS

As a rather fast developing country, Greece, presents a quite high growth rate in electricity consumption, which in the last years exceeds 3% annually[4][11]. This is unfortunately accompanied by an increase in the corresponding air pollutants emission.

Taking into consideration the already calculated emission factors and the official data[17] about the forthcoming power stations to be installed, an analytical estimation for the carbon dioxide emissions until the year 2007 is presented. The energy scenario examined is based on the installation of more than 5000 MW of electricity generation stations, according to the Greek Regulatory Authority of Energy (RAE). The new fossil fuel-fired power stations scheduled for the next years consist of 330 MW utilising North Greece lignite, 895 MW using the combined cycle natural gas technology and 3010 MW based on compatible natural gas technology stations. One should notice that apart from the lignite station, the rest are the first private thermal power stations of the Greek electricity network. As shown in figure (5) the above scenario leads the energy related air pollutants to a major amplification, since during the time period examined the carbon dioxide emissions are expected to rise by almost 30%.

According to the data presented in figure (5), the Greek electricity generation sector keeps on producing huge quantities of carbon dioxide, while no attempt is made at decelerating the corresponding escalation rate[9][18]. This result is in contradiction with the international and European Union efforts to stabilize greenhouse emission gases at the 1990 levels[19]. It also underlines the encountered incompetence of the 1st National Program to actively contribute to the climatologic protection of our planet.

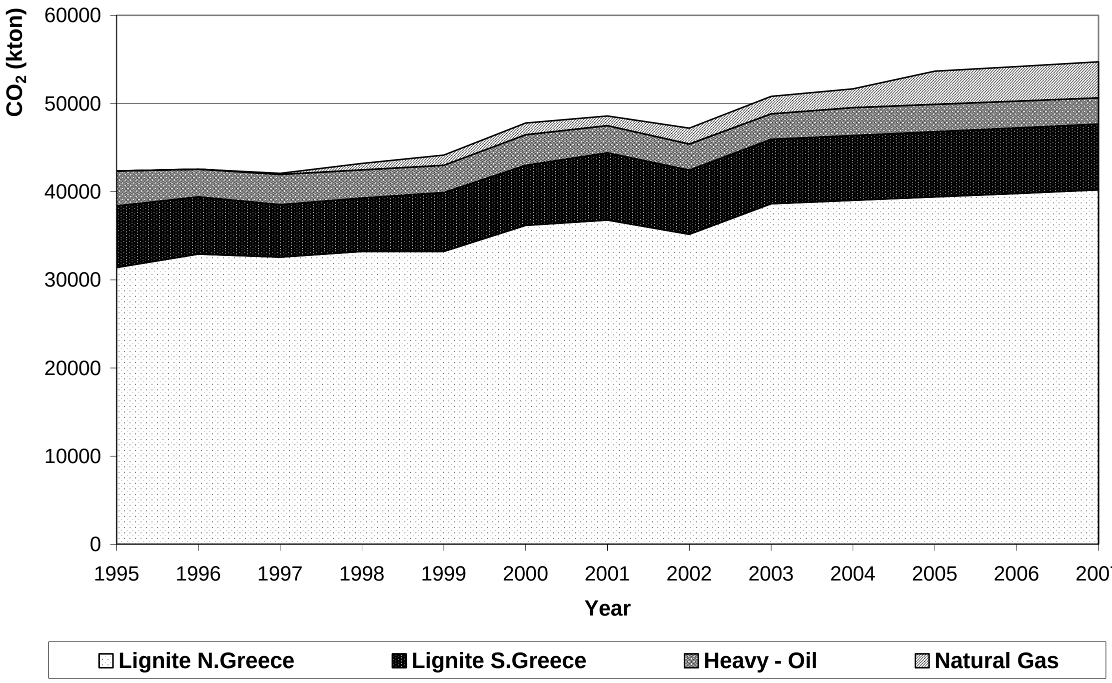

Figure 5: Estimation of Greek EGS carbon dioxide emissions for the near future

5. Conclusion

Electricity generation sector is the major source of carbon dioxide emissions in Greece. This reality is not subjected to any change in the next years due to the increasing electricity demand and the national energy plan, which is based on fossil fuels. This fact results to the conclusion that the carbon dioxide emissions from the electricity sector will keep on increasing in the coming years. This augmentation questions our country's solvency in abiding by the agreements made under the Kyoto protocol framework for the control of the greenhouse gases emission.

Unfortunately, the lack of any secondary measures, for reducing the carbon dioxide content in the flue gases after burning fossil fuels, underlines the need for cleaner energy generation along with an effective plan for optimising the energy efficiency in Greece.

The first alternative may be satisfied by promoting the usage of renewable energy sources. More specifically our country possesses excellent wind and solar potential. Even if large-scale electricity production stations from solar power are not economically feasible, the same cannot be supported for wind power applications. Furthermore, the existent hydro power stations would be possibly contribute more to the national electricity production if their operation was based on a different load management plan.

Thus, only by introducing efficient energy saving measures -in the industrial and tertiary sector- in order to decelerate the annual electricity consumption escalation rate, and by replacing the heavy polluting existing TPS by renewable energy based plants a significant air pollution decrease may be accomplished. In the opposite case the Greek electricity generation sector should continue to surcharge the environment with several air pollutants, significantly contributing on the forthcoming climate change of our planet.

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ESTIMATING THE ENERGY RELATED NITROGEN OXIDES PRODUCTION IN GREECE, FOR THE NEXT DECADE

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Abstract

Energy has a dominant role in almost all human activities. Unfortunately, the energy production process is found responsible for severe air pollution, beyond the monetary and macroeconomic cost. According to several official studies, Greek economy is almost exclusively based on fossil fuel, i.e. locally extracted low-quality lignite and imported crude oil. Recently a remarkable imported natural gas penetration is realized in the local energy market. Considering, therefore, the air pollutants production per economic sector and fuel used, the proposed work presents an integrated numerical model, able to estimate the nitrogen oxides quantities resulting from the various energy resources utilized. Thus, by using the proposed model, one may estimate on a medium-term time horizon the evolution of energy related nitrogen oxides production, according to selected typical scenarios. Finally, the analytically developed frame provides all necessary information -scientifically documented- in order to display the nitrogen oxides impact during the forthcoming energy choices.

Keywords: Energy; Nitrogen Oxides; Air Pollution; Fossil Fuels

1. Introduction

The impact of energy in everyday life quality is -out of question- dominant. Electricity being by far the user-friendliest form of energy tends to substitute other forms in many different aspects of consumption. In this context, one may notice the use of electricity for air conditioning in the tertiary sector instead of diesel oil, as well as the partial substitution of conventional cars with electricity-powered means of transport. Finally, the industrial sector experiences massive replacement of old steam-powered oil-fired equipment with modern electric machines[1].

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 to be very dangerous for the public health. Oxidized nitrogen pollutants except being connected to the worldwide climate change[2] they also contribute to local environmental degradation.

Nitrogen oxides production in Greece as well as in the vast majority of developed countries is driven by the transport sector. Despite the massive renewal of the private vehicles that took place in the early 90's the sector's contribution is growing in an increasing trend[3][4]. Focusing on the reasons of this trend we should notice the steady enlargement of the amount of vehicles used in Greece as well as the inadequate control of their proper operation, leading to their catalytic converters gradual degradation[5].

In figure (1) one may observe the sector analysis of the NO_x production in Greece, for the year 2000. It is interesting to mention that transport holds the 60% of the total emission, while electricity and industry are producing 22% and 15% respectively of the national volume[6].

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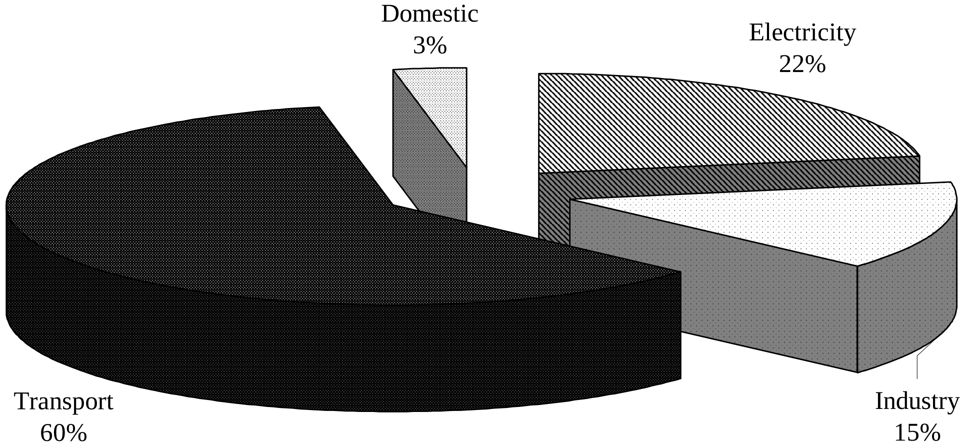

Figure 1: Sector NO_x emissions in Greece, 2000

Although the electricity sector cannot be considered as the main emitter of nitrogen oxides in Greece, it is still the sector where audit and control can be applied in a more efficient way due to the small number of emitting sources. Taking into consideration the opportunities offered by the electricity generation to bound the national nitrogen oxides emissions, the present work is focused on investigating in detail the corresponding emissions for the last decade.

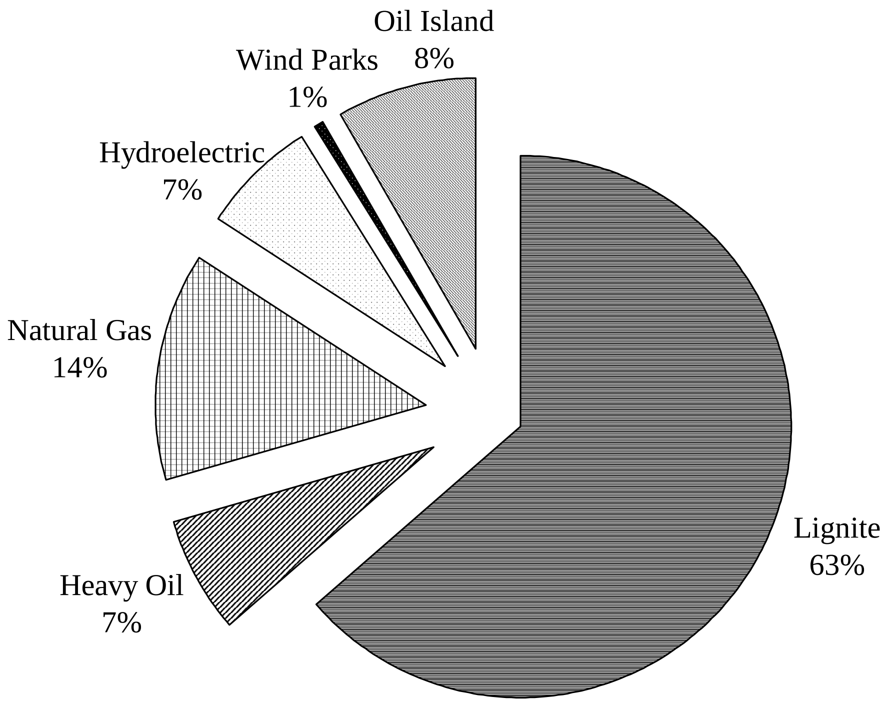

Figure 2: Analysis of electricity generation in Greece, 2002

2. Greek Electricity Sector Analysis

Greek power stations are mostly utilizing fossil fuels for their operation, as it is obvious from figure (2). More precisely, the mainland electricity power network is based -from its foundation in the early '60s- on local lignite, while only recently a significant natural gas penetration is encountered[7].

According to the Greek Regulatory Energy Authority (RAE) the Greek Electricity Production System (EPS) is divided in two branches. The first one contains the interconnected mainland electricity production network based on eleven large-scale power stations, where local lignite, imported heavy oil and natural gas are used. In this main branch belong also 15 large hydropower stations along with several other small hydropower units built throughout the mainland. The second branch includes 35 medium-small autonomous -diesel and heavy oil fired- power stations spread out all over the Aegean Archipelago. In this latter group one should include the medium size -heavy oil fired- power stations of Crete and Rhodes islands.

In this context, the national electricity production centre is located in West Macedonia, where the two biggest thermal power stations "TPS" (Agios Dimitrios and Kardia) operate using the local lignite ore reserves. In S. Greece, operates the lignite fired station of Megalopolis (Peloponesse), while in central Greece operates one heavy-oil fired station in Aliveri of Euboea, as well as two natural gas fired TPS in Attica major region where Athens is located. A new gas fired station in Komotini (Thrace) and a lignite fired one in Florina (NW Macedonia) have recently joined the national EPS. Moreover to that, one should add a total power capacity of 400MW of mazut fired medium and small size power stations and another 750MW total of small diesel fired internal combustion engines located in the numerous Greek islands of Aegean Archipelago.

Thus, at the beginning of 2003, one may list the regional power capacity of the thermal power stations of Greek mainland EPS according to the type of fuel used as follows:

a. 4380MW in N. Greece using lignite local ore
b. 850MW in S. Greece using lignite local ore
c. 1104MW using Natural Gas
d. 830MW using heavy-oil (mazut)
e. 1340MW using diesel-oil and mazut in Greek islands

As one may notice in the above list the lignite-fired power stations are presented into a regional separation due to the important differences found in the quality and physical characteristics of the local fuel reserves. In detail the north Greece lignite presents a significantly higher calorific value (50% higher in average than the corresponding reserves of south Greece), while moisture and ash contents are found to be in lower levels. The sulphur content of the south Greece reserves are higher than in north Greece by a factor up to ten, with obvious effect to the sulphur dioxide emissions. On the other hand, nitrogen oxides "NO_x" formation is based mostly on the burning procedure and the atmospheric nitrogen; hence the fuel content in nitrogen has only a fair role to the corresponding air pollutant emissions.

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 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. Keep in mind that this chemical reaction gives a 95% NO and only a 5% NO_2. It is 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[4]. 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

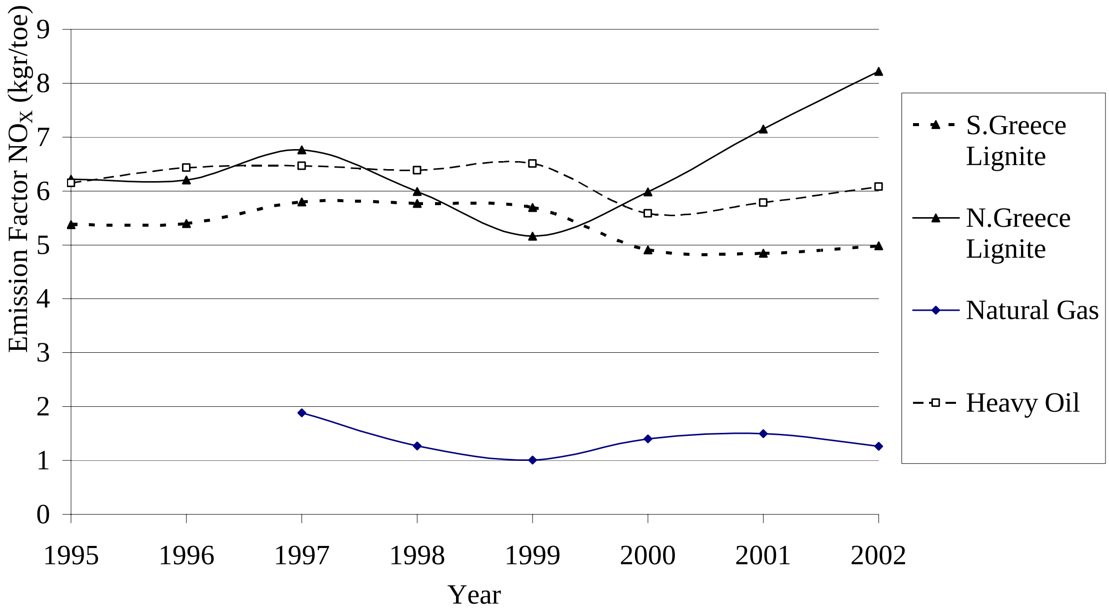

Figure 3: NO_x emission factor values for Greek power stations

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.

3. Estimation of Nitrogen Oxides Production

Considering the mass of air pollutants production and fuel used one may define the NO_X. emission factor "e_j" of the "j" TPS as:

$$e_j = \frac{m_{NO_X}}{E_j} \tag{1}$$

where "m_{NOX}" is the annual NO_X mass production and "E_j" is the energy content of the fuel used at the "j" TPS[8].

For the calculation of the results presented in figure (3), official data have been used[9]. Lignite fired stations are divided in the South and North Greek regions, while natural gas and heavy oil stations are presented without any separation. One may observe the study increase of the N. Greece lignite NO_X emission factor, after 1999. More precisely, the NO_X emission factors rose from approximately 5.2 kgr NO_X/toe in 1999 to almost 8.2 kgr NO_X/toe in 2002. On the contrary, south Greece lignite fired stations present a much more stable distribution during the examined period, i.e. values equal to 5.5 kgr NO_X/toe.

The corresponding heavy oil NO_X emission factor shows an almost similar tendency, while its actual value is slightly higher than 6.3 kgr NO_X/toe. Finally, the natural gas-fired stations present a significantly lower NO_X emission factor, with a very narrow variation in the examined time period. The deNO_X systems used in those stations result in a NO_X emission factor almost four times lower than the national mean value. According to the data presented above and previous studies[10] by the authors, the weighted NO_x emission factors for each fuel consumed may be utilised in case that the total emitted NO_x quantity is required.

Summarizing in figure (4) one may observe the total NO_X production for the examined period. The lignite-fired stations are presented separately due their significant contribution in the NO_X production.

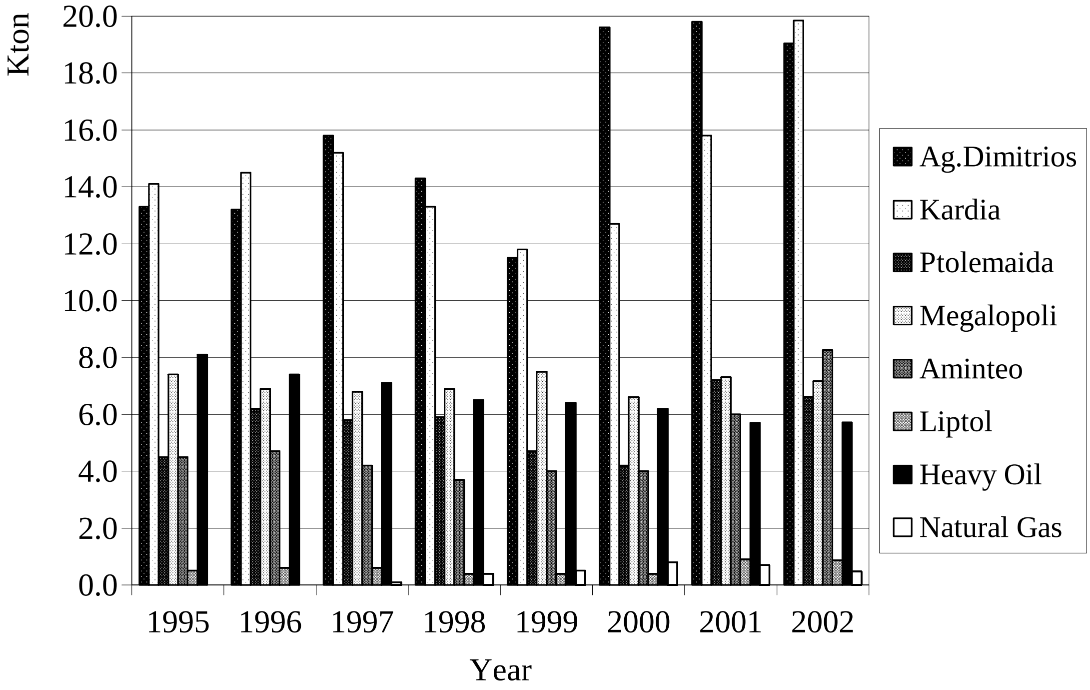

Figure 4: NO_x production from Greek thermal power stations

The official data of NO_x emissions[9] concerning natural gas are based mainly on the Ag. Georgios power station, installed capacity of 360 MW. Comparing the natural gas and oil-fired TPS one may notice that the former are operating in a more environmentally friendly way.

4. Nitrogen Oxides Production in the Forthcoming Energy Scenarios

According to data presented concerning the national electricity production sector one may definitely state that during the last years there is a considerable demand amplification, while most experts forecast[11][12][13][14] a continuous electricity demand increase with a mean annual rate of 4% up to 2010.

Furthermore, official data presenting the future electricity network in Greece emphasize on the extension of the lignite fired stations by 330MW, while the natural gas and combined power stations should increase their installed capacity by 3010MW and 895MW respectively[3].

Thus by using the available data for the expected investments in the energy sector we can estimate the corresponding -per fuel- consumption evolution. In this context, the natural gas penetration keeps on its high rate, resulting in total consumption increase by 55% in comparison with the current value, while the corresponding rate for heavy oil usage is found negative by 58%. Subsequently, lignite consumption is almost stable since the forecasted increase is slightly over 2%, while the hydropower stations are expected to increase their installed capacity by 778 MW up to the reference year of 2010.

The above-described scenario takes also into account a significant increase in the utilization factor of the existing lignite fired stations, in order to cover the amplified electricity demand. In figure (5) the NO_X emission factors, estimated in the previous section, are utilized for the calculation of the corresponding annual production distribution for the 1995-2010 period.

Thus, in figure (5) one may observe that despite the forecasted energy production growth by almost 4% per annum, the corresponding NO_X production slightly exceeds a 4.5% total increment for the period 2004 to 2010, under the condition that all the expected investments in the electricity generation sector should be realized. According to the results obtained, one should underline the vital importance of the natural gas, being the electricity generation fuel with the lowest emission factor, in the NOx emission reduction effort. However, the utilization degree of the existing natural gas network is already near its limits. In this context infrastructure improvements are necessary for a significant further exploitation of natural gas in Greece.

As it is well known the basic natural gas supplier of our country is Russia, using the transportation network through Bulgaria. Energy security reasons ordered for another supplier, this time from the Caspian Sea reserves, with a connecting pipe via Turkey. Besides, as the Greek and Italian natural gas networks are planned to be interconnected this means that not only Greece but also Europe will be benefited from this connection. Bear in mind that energy security matters were raised from the foundation of the Greek natural gas network; thus apart from the Russian natural gas our country imports liquefied natural gas from Algeria. The evaporation capacity of the "Revithousa" station is scheduled to be increased from capacity of 270 m^3/h to $1000m^3/h$. Moreover, a new compression station will be installed in north Greece[15] in the near future.

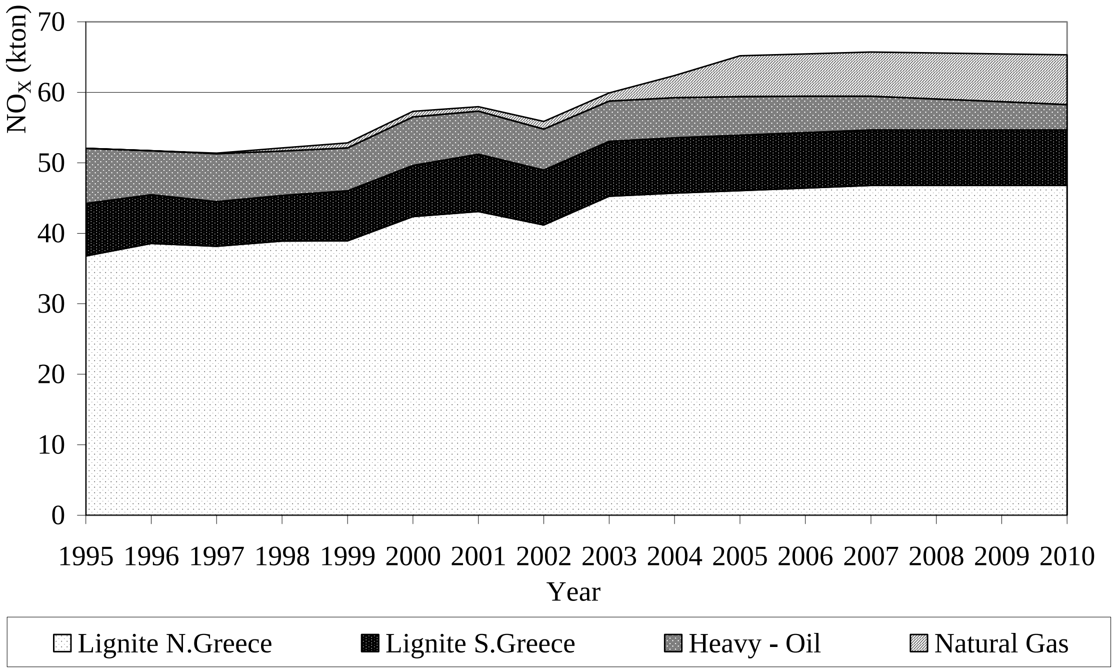

Figure 5: Estimation of electricity driven nitrogen oxides production up to 2010

5. Discussion of the Results

The share of the N. Greece lignite fired stations in the production of nitrogen oxides is of significant importance, since they correspond almost to the two thirds of the Greek electricity production. It should be mentioned that only the newly lignite-fired station of "Florina" in the north Greece is equipped with $deNO_X$ technology. The recently installed and the future scheduled natural gas fired stations are also using technology for low NO_X emissions. The authors believe that strict auditing and control measures should be adopted in all the others thermal power stations.

Hence, our country's compliance to the Directive 2001/80/EC of the European Parliament should be definitely based on improvements of the existing lignite-fired station. Taking into consideration their vital contribution in the Greek electricity generation sector and their importance on supporting the domestic economy one should stress their innovation with the corresponding abatement technologies in the next five years. Besides, new technology should improve their energy efficiency with obvious effects on their financial and environmental performance. The energy sector can also improve its environmental performance with the further exploitation of the renewable energy sources. These relatively new electricity generation techniques, except from being by far the most environmentally friendly option can also significantly contribute in a medium-term planning targeting the energy independency of our country. If these systematic efforts are not made during the next few years, the Greek national electricity production sector is going to 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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