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Present situation and future prospects of electricity generation in Aegean Archipelago islands

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Abstract

The Aegean Archipelago is a remote Hellenic area, including several hundreds of scattered islands of various sizes. In these islands more than 600,000 people are living mainly in small remote communities. The main economical activities of the islanders are apart from tourism, seafaring, fishery, agriculture and stock farming. One of the major problems of the area is the insufficient infrastructure, strongly related with the absence of an integrated and cost-effective electrification plan. In this context, the present work is concentrated on analyzing the present situation and demonstrating the future prospects of electricity generation in the Aegean Archipelago islands. For this purpose, one should first investigate the time evolution of the corresponding electricity generation parameters (i.e. annual electricity consumption, peak power demand, capacity factor, specific fuel consumption) for the last 30 years. Subsequently, the corresponding diesel and heavy-oil consumption along with the electricity production cost for every specific autonomous power station of the area are investigated. Special attention is paid in order to estimate the contribution of renewable energy sources (RES) in the energy balance of each island. Finally, an attempt is made to describe in brief the most realistic electricity production solutions available, including the operation of hybrid RES-based power plants in collaboration with appropriate energy storage facilities. Additionally, the idea of connecting the islands of the area with the mainland and interconnecting them is also taken into consideration.

Keywords: Peak load; Autonomous power station; Wind energy

1. Introduction

The Aegean Archipelago is a remote Hellenic area, including several hundreds of scattered islands of various sizes, see Fig. 1. For administrative purposes these islands are divided in two large groups, i.e. the islands belong either to the North or to the South Aegean region. In fact, the former area includes the prefectures of Lesvos, Chios and Samos, while the latter contains the prefectures of Cyclades and Dodecanese. On top of these islands, in the Aegean Sea one may find the Sporades complex, located in the NW of the Aegean Archipelago and belonging to the Magnesia prefecture (Thessaly-mainland), excluding the Skiros island, which is part of the Euboea prefecture. In addition to the islands already mentioned, one should mention the islands of Samothrace and Thassos, both situated in the north Aegean Sea and belonging to the Evros and Kavala prefectures, respectively. Finally, in SE of Peloponnesus there exist the small islands of Kithira and Antikithira. In the present analysis, the island of Crete, being the biggest Greek island, is excluded, since it is the subject of several independent studies by the authors and by other researchers (Kaldellis et al., 2004a).

According to official data (G.S.N.S.S.G., 2006), the permanent population of the area presents a rather divided picture. Thus, as shown in Fig. 2, permanent population increase has been noticed in the case of the South Aegean region during the last 15 years, while in the case of the northern islands the permanent habitants' number remains relatively stable with a slightly declining trend. The main economic activities of the islanders, presenting a strong variation among different islands, are apart from tourism, seafaring, fishery, agriculture and stock farming. On the other hand, industry has not yet been developed.

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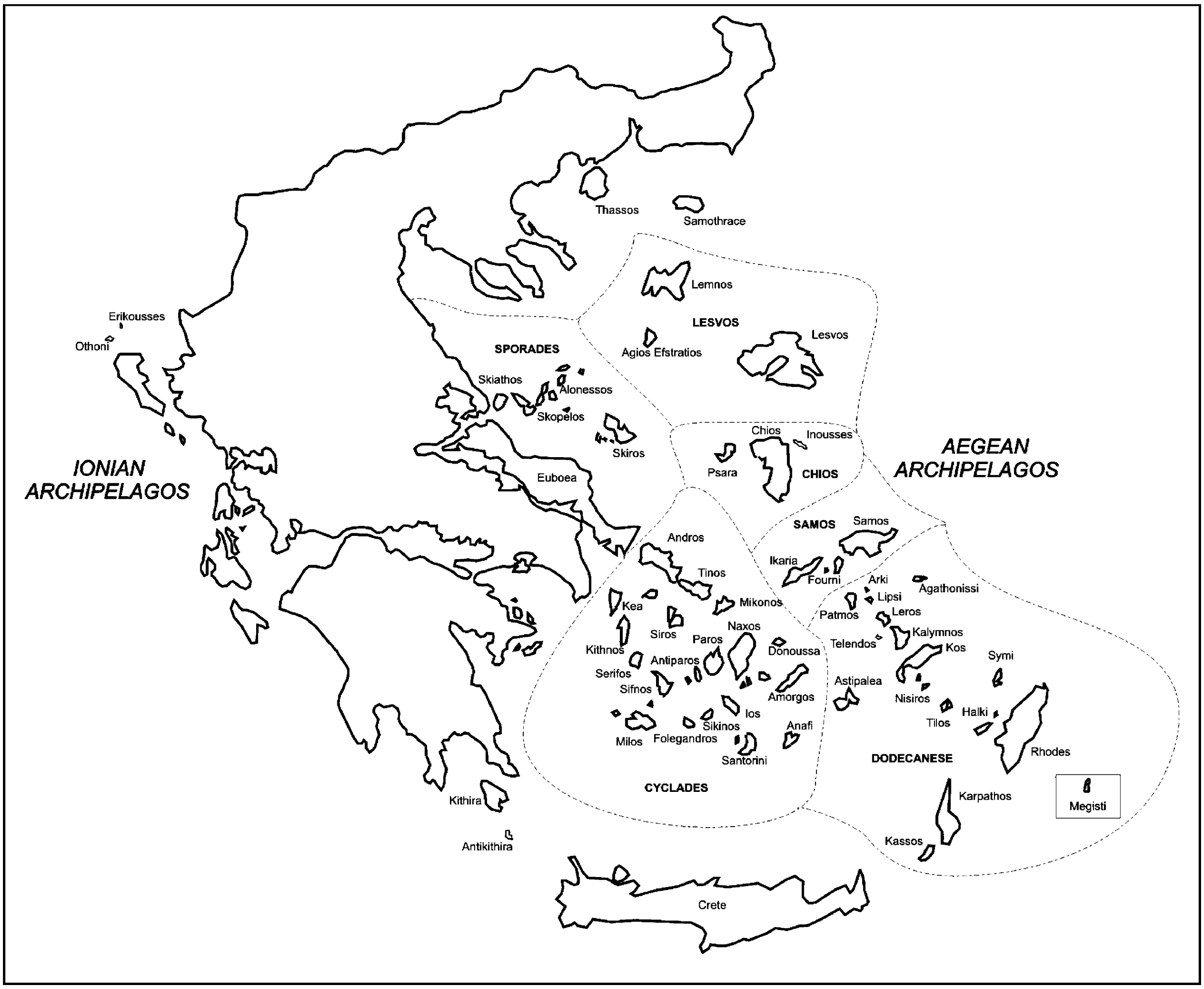

Fig. 1. Aegean Archipelago complex of islands.

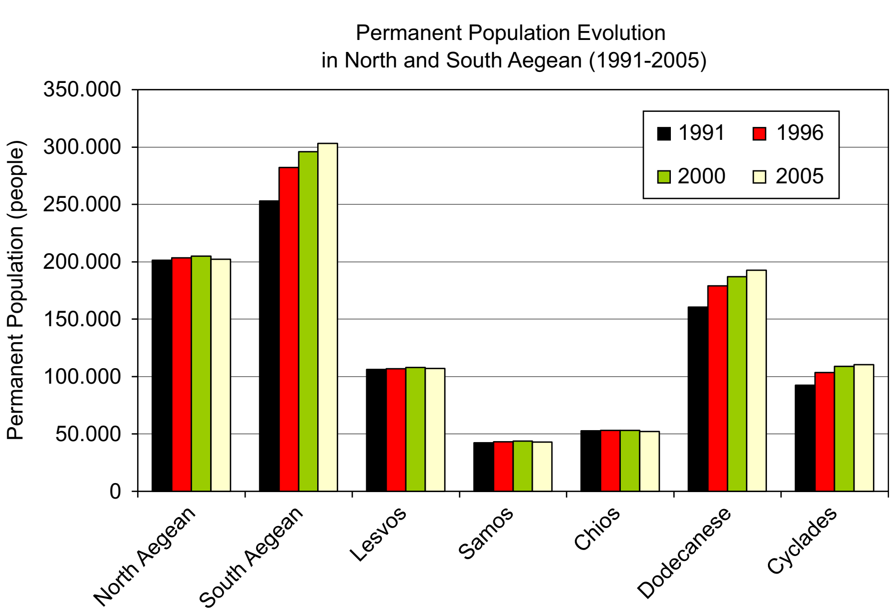

Fig. 2. Permanent population evolution in the Aegean Archipelago region.

Recapitulating, in Table 1 one may find some additional information concerning the Aegean Archipelago islands, i.e. area, permanent population, annual tourists' arrivals, major islands and biggest cities. One should also not disregard that most islands of S. Aegean face serious water shortage problems (Kaldellis et al., 2004b). According to the existing data the biggest islands of the area are the islands of Lesvos, Chios, Rhodes, Samos, Lemnos, Naxos, Siros, Mikonos, Santorini, Paros, Karpathos, Kos, Kalimnos, Ikaria, Skiros and Skiathos. The biggest cities of the area are Mitilene, which is the administrative centre of the North Aegean region, Rhodes which is the biggest city of the Archipelago, Siros being the administrative centre of the South Aegean region, and Chios.

2. The existing electricity generation system of the islands

The electricity demand in the Aegean Archipelago islands has up to now been covered (PPC, 2005) by the existing (32) autonomous power stations (APS), based on internal combustion engines and gas turbines, which belong to the former Greek Public Power Corporation (PPC). In specific cases, like in those of Thassos, Samothrace and Sporades (excluding Skiros), the islands are connected to the nearest available mainland electrical network. The existing APS total installed capacity is approximately equal to 800 MW, while the corresponding electricity generation during 2005 is almost 2200 GWh (RAE, 2006).

The rated power of the existing thermal power units varies from 100 kW in the case of very small islands up to 36 MW for the gas turbine operating since 1987 in Rhodes island. In Fig. 3, we demonstrate the number of "in operation" thermal power units (internal combustion engines and gas turbines) divided according to their rated power. Using the available information, approximately 220 thermal power units operate in the Aegean Archipelago, most of them being in operation for almost 20 years. The result of this situation is that several units present serious problems, being out of service for remarkable time periods, while their real output is almost 15% less than their rated power, especially during summer.

To facilitate the in depth analysis of the electricity generation problems in the Aegean Archipelago APS, one may divide the existing power stations in five subgroups, on the basis of their rated power, see also Table 2. More precisely, the first group includes the existing big APS, with rated power higher than 50 MW, like the ones of Rhodes, Lesvos, Kos–Kalimnos, etc. The last group includes very small islands, with rated power less than 1 MW. In this

Table 1
Basic data concerning the Aegean Archipelago region

Prefecture	Population (2005 estimations)	Area (km^2)	Annual tourists arrivals (2004)	Major islands	Big cities
Lesvos	107,050	2154	135,023	Lesvos, Lemnos	Mitilene, Mirina
Chios	52,337	904	46,360	Chios	Chios
Samos	43,015	778	114,445	Samos, Ikaria	Samos
Cyclades	110,400	2572	325,917	Paros, Siros, Mikonos, Andros, Naxos	Hermoupolis, Naxos, Tinos, Paros, Andros, Milos
Dodecanese	192,714	2663	1,556,250	Rhodes, Kos, Kalimnos, Karpathos	Rhodes, Kos, Kalimnos

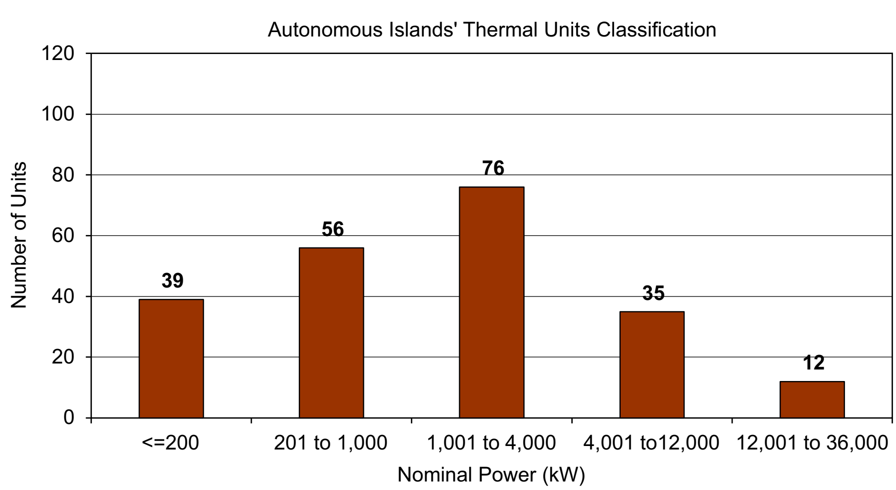

Fig. 3. Existing thermal units in Aegean Archipelago on the basis of their rated power.

category, one may find the tiny islands of Agios Efstratios, Donoussa, Megisti, etc.

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

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

Table 2
Aegean islands classification in terms of APS installed capacity

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

3. Electricity generation time evolution

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

3.1. Electricity generation

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

More specifically, according to Fig. 8, describing the electricity generation time evolution for the N. Aegean

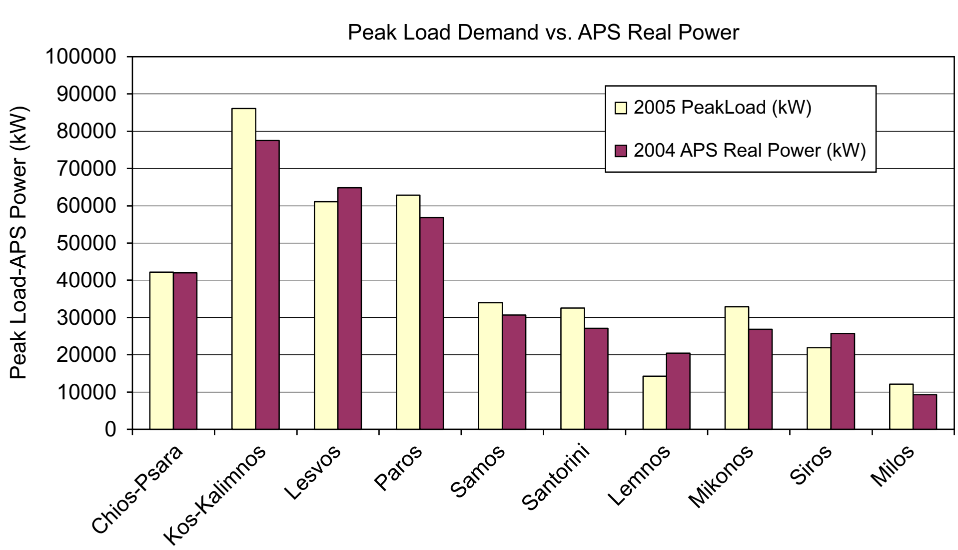

Fig. 4. Peak power demand vs. "in operation" power in Aegean Archipelago islands.

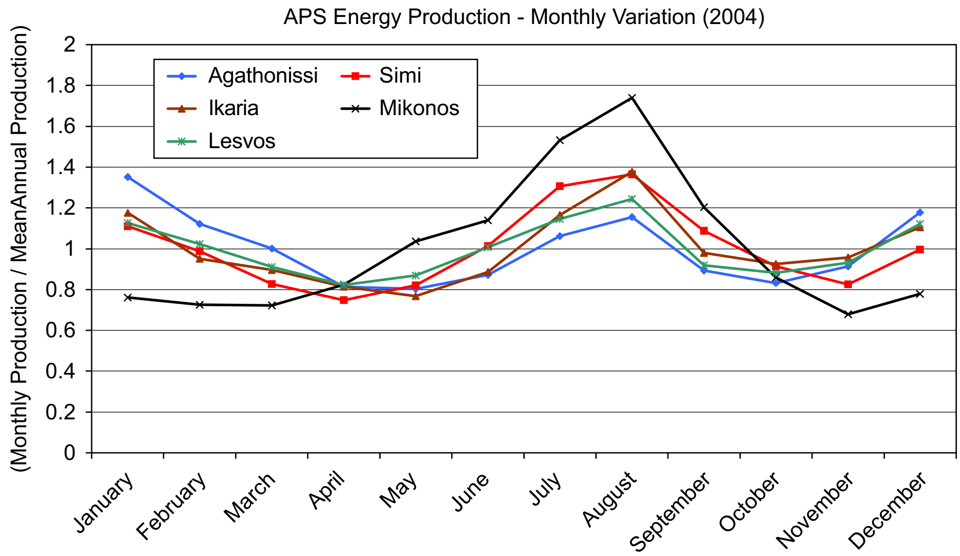

Fig. 5. Annual electricity consumption variation in Aegean Archipelago islands.

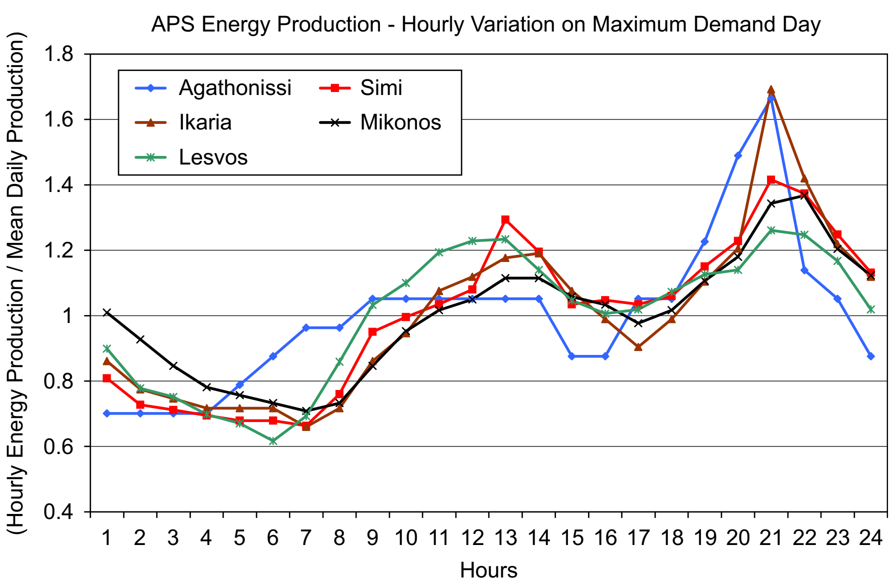

Fig. 6. Daily electricity consumption variation in Aegean Archipelago islands.

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

Accordingly, the electricity generation increase for the islands of S. Aegean is much more intense, especially during the last 10 years. This increase is almost exponential for the islands of Santorini (annual increase $\varepsilon \approx 13.6\%$) and Mikonos (annual increase $\varepsilon \approx 10.6\%$), mainly due to their explosive touristic activity, Fig. 9. In this context, the electricity generation of Kos–Kalimnos APS presents the highest value (exceeding the one of Lesvos island), i.e. approaching the 300 GWh/yr. Similarly, the APS of Paros exceeds the 180 GWh during 2005, while both APS of Siros and Santorini approach the value of 100 GWh annually.

Subsequently, the electricity generation of the small-size APS of S. Aegean show the same behavior as the ones of

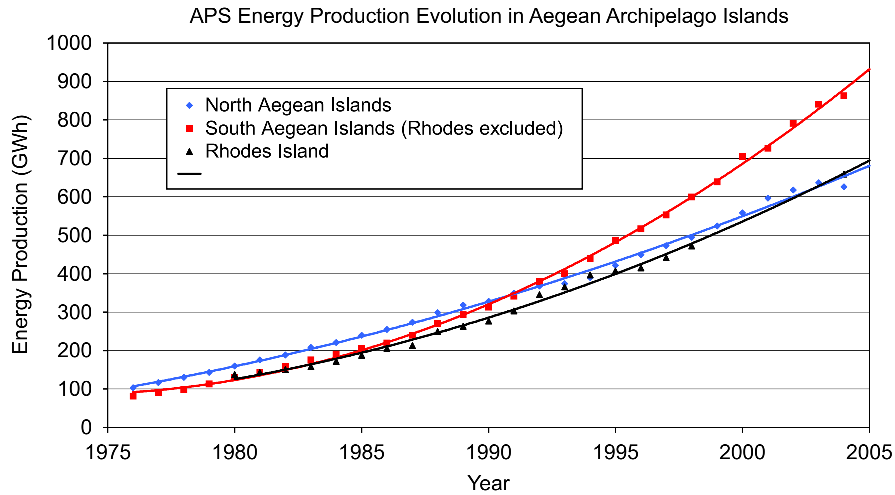

Fig. 7. Electricity generation in Aegean Archipelago area.

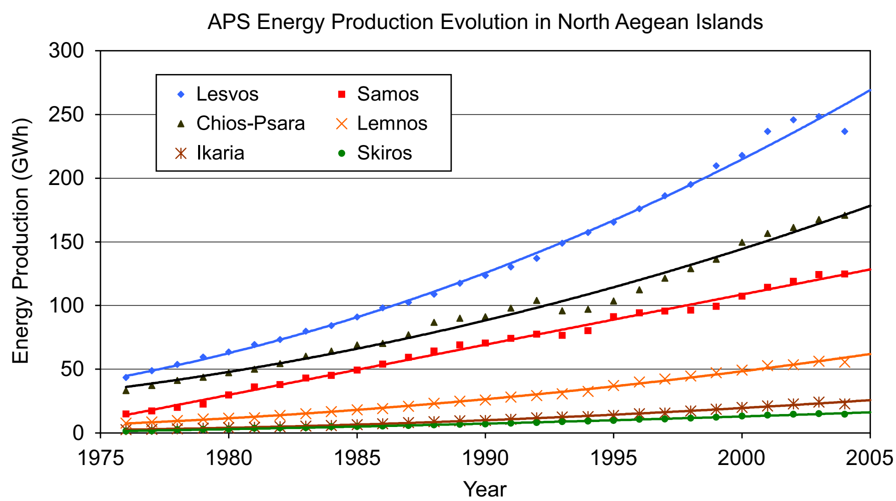

Fig. 8. Electricity generation in North Aegean islands.

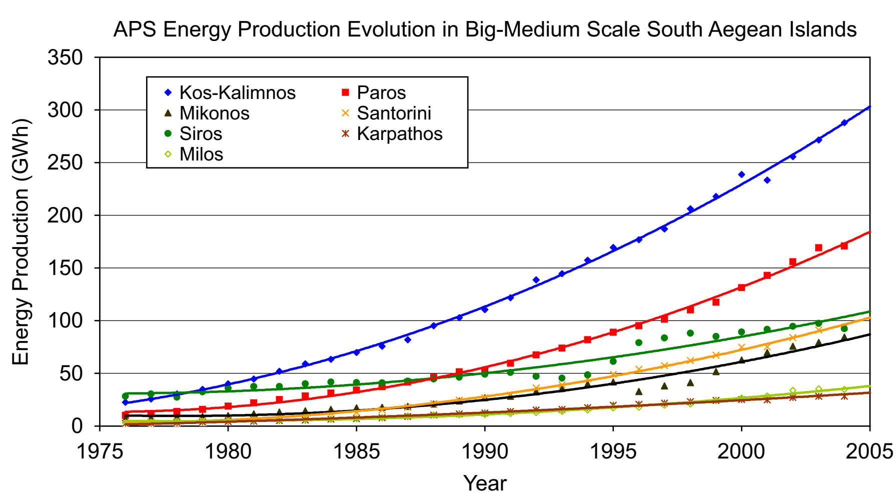

Fig. 9. Electricity generation in South Aegean big-medium size islands.

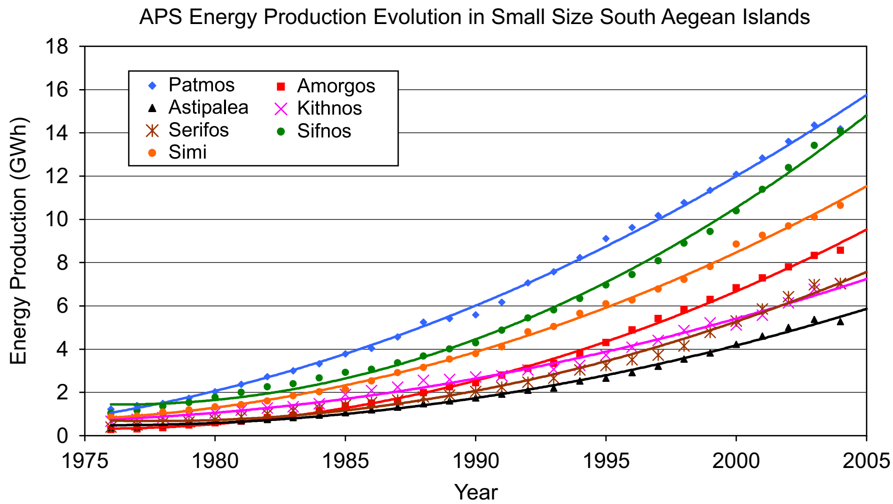

Fig. 10. Electricity generation in South Aegean small-medium size islands.

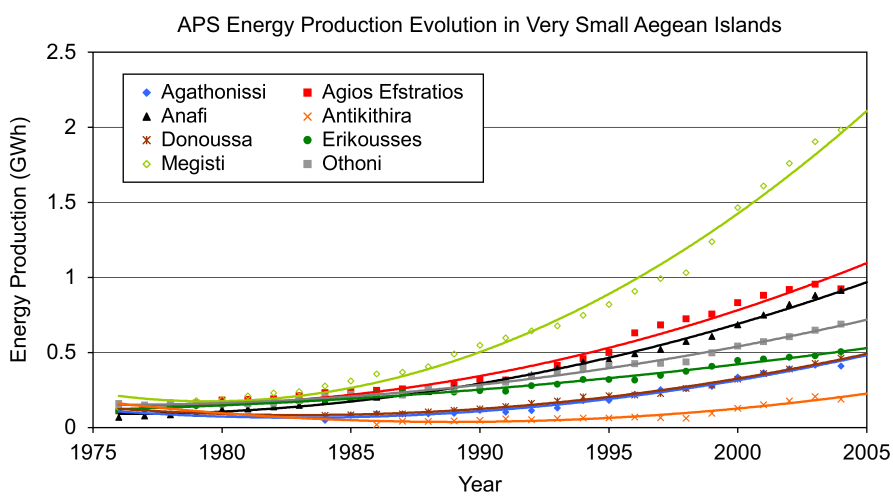

Fig. 11. Electricity generation in Greek tiny islands.

the first group, see Fig. 10. In fact, most islands of the area present an over-linear electricity consumption increase, while the electricity consumption in 2005 is more than 10 times the corresponding value of 1975, leading to an average annual increase rate "ε" of almost 10% (see Appendix A, Eq. (A.1)). Summarizing, in 2005 the electricity generation of the APS of the S. Aegean Archipelago (excluding Rhodes) is 950 GWh/yr, hence the entire electricity consumption of the S. Aegean area (including Rhodes) is almost three times the corresponding value of N. Aegean.

The proposed analysis shows an increased interest for the very small islands of the Aegean Archipelago (Kaldellis et al., 2001b), taking into consideration of their poor infrastructure and the dominant importance of the electricity production in everyday life. In Fig. 11, one may find the time evolution of their electricity generation. In all cases examined, including the two tiny islands of north Ionian Sea (i.e. Erikousses and Othoni islands), there is a remarkable electricity generation increase. The corresponding maximum annual electricity consumption does not exceed the 1 GWh, excluding the Megisti island electricity generation, which slightly exceeds 2 GWh.

3.2. Peak power demand

According to the available official information (PPC, 2005; Kavadias and Kaldellis, 2002), the peak power demand and annual energy production behavior of most Aegean Archipelago islands present the same time variation (i.e. parabolic and in some cases exponential increase), resulting in long-term average annual increase rates $\bar{v}$ of the order of 10% (see Appendix A, Eq. (A.2)). More specifically, the time evolution of the South Aegean islands is more intense than the one of the N. Aegean area, Figs. 12 and 13. For example, if one compares the peak load

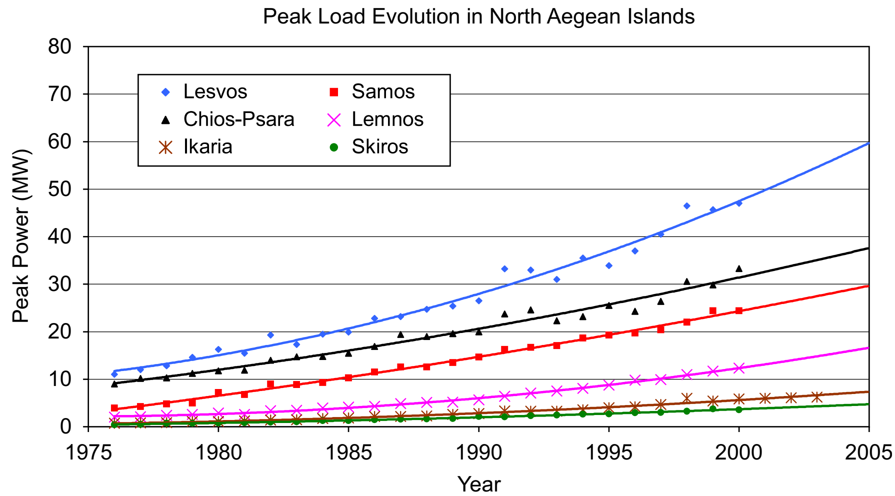

Fig. 12. Peak load demand in North Aegean islands.

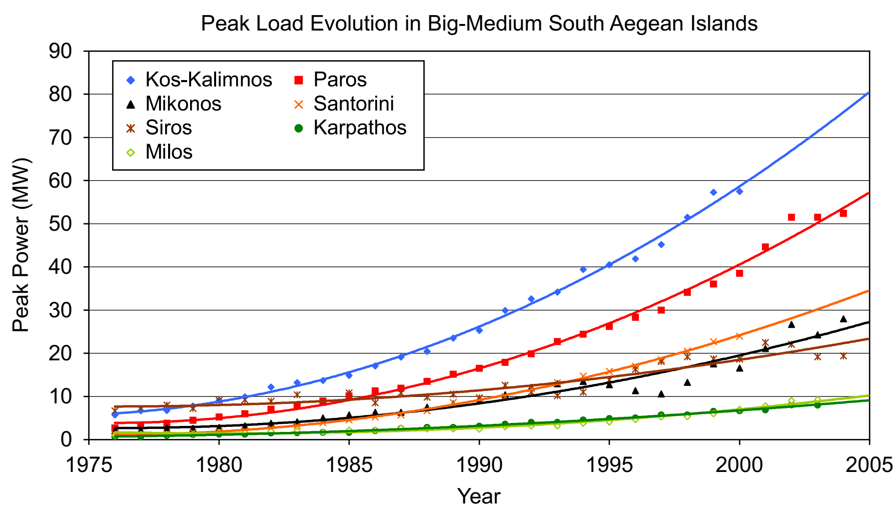

Fig. 13. Peak load demand in South Aegean islands.

demand time evolution between the Lesvos and the Kos–Kalimnos APS, one should notice that although during 1975 the Lesvos peak power demand was two times the one of Kos–Kalimnos, after 1992 the latter surpassed the maximum load demand of Lesvos island. Therefore, during 2005 the peak load demand of Lesvos island is almost 20% less than the one of Kos–Kalimnos.

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

As already mentioned, in the majority of the islands examined the APS real capacity alone is either insufficient or hardly covering the expected electricity demand increase. The islands of Mikonos, Santorini, Milos, Kithnos and Serifos face the biggest problem. On the other hand, only some of the very small islands like Agathonisi, Agios Efstratios, Anafi and Antikithira are sufficiently supplied. A common strategy, recently adopted once again, dictates the impermanent installation of support units (e.g. gas turbines) in order to serve for the

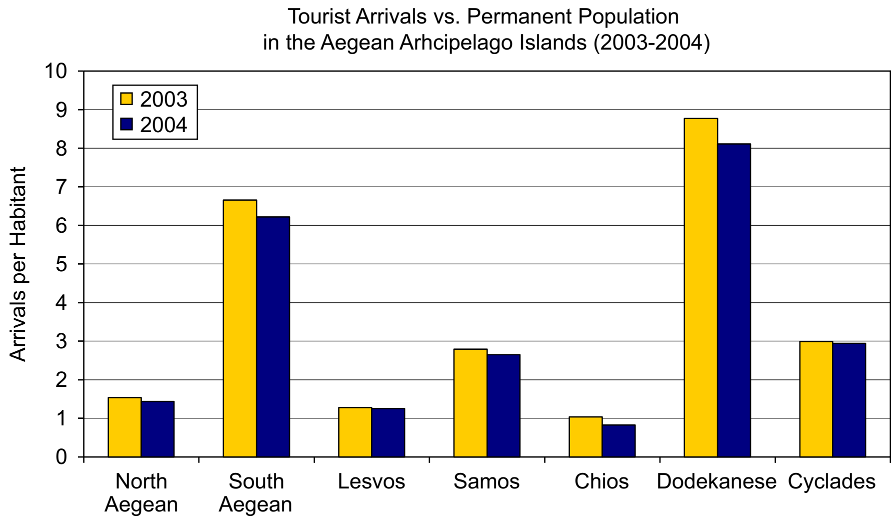

Fig. 14. Tourist arrival vs. permanent population in the Aegean Archipelago regions.

Table 3
Additional thermal power to be installed in 2006

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

islands' needs during the summer season. In this context, in May 2006, the Greek Ministry of Development approved the licensing of installing additional thermal electricity generation units of 85.7 MW, so as to ensure the electricity demand satisfaction during the 2006 summer in 13 of the non-interconnected islands of the Aegean Archipelago, see also Table 3 (RAE, 2006). However, by facing the urgent problems of the islands only on annual basis, one cannot apply a long-term energy strategy for the development of the area.

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

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

3.3. *Utilization degree of existing thermal power units*

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

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

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

The most rational explanations for this behavior are the following:

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

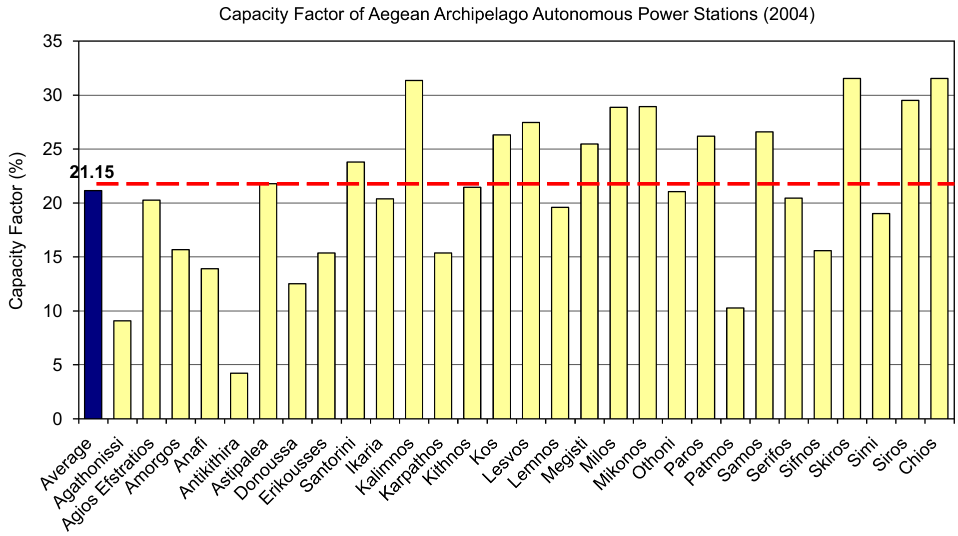

Fig. 15. Utilization degree of existing thermal power units in Aegean Archipelago APS.

years, the technical availability of the aged engines to consider proves to be quite low.

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

3.4. RES contribution

The Aegean Archipelago is an area with excellent wind potential and abundant solar energy (Kaldellis et al., 2002b), while in some islands one may find remarkable geothermal reserves and considerable biomass feedstock. Unfortunately, the only RES exploitation activity "E_{RES}" is based on wind energy applications, hence in several islands one may find small- or medium-sized wind parks, with the maximum installed wind power being less than 10 MW. At this point it is important to note that the first wind parks have been installed in Aegean Archipelago islands since 1980s (Kaldellis et al., 2003), while during 1990–1993 the installed by the Greek PPC wind power approached 30 MW. Since then, one cannot mention any serious wind park creation activity by PPC, while the only activity encountered is due to private wind parks erection, mainly in the islands of Lesvos, Kos and Chios (Kaldellis et al., 2006a).

In fact, the major wind energy exploitation activity is encountered in Lesvos island, where during 2004 almost 28.7 GWh of wind-based electricity "E_{RES}" has been produced (see Appendix A, Eq. (A.3)), as well as in Chios (18.2 GWh/yr) in Kos (18.3 GWh/yr) and in Samos (17 GWh/yr) islands. The result of this moderate activity is the production of almost 110 GWh of wind electricity, which represents only the $r = 5\%$ of the corresponding annual electricity consumption of the area (see Appendix A, Eq. (A.4)). Using the most recent available official data, one may find in Fig. 16 that the maximum wind energy penetration is encountered in the islands of Karpathos ($r = 13.5\%$) and Lesvos ($r = 11.5\%$), while in certain islands, like the islands of Agios Efstratios and Rhodes the corresponding contribution is almost zero. The main reason reported by the experts for such a low wind energy penetration is the restrictions set to the wind energy contribution in order to maintain the local grids' stability due to the stochastic wind speed behavior and the strongly variable electricity consumption (Kaldellis et al., 2006b).

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

4. Fuel consumption and electricity production cost

According to the available official information all the APS operating in the Aegean Archipelago area utilize diesel oil and heavy oil (mazut). More specifically, the annual diesel oil consumption of all the APS of the area, including Rhodes, approaches 100,000 t of diesel and almost 400,000 t of Mazut. In Fig. 18, one may find the time evolution of the annual fuel consumption of the biggest APS of the Aegean Sea, i.e. Kos–Kalimnos, Lesvos, Paros, Samos and Chios. It is important to note that in all

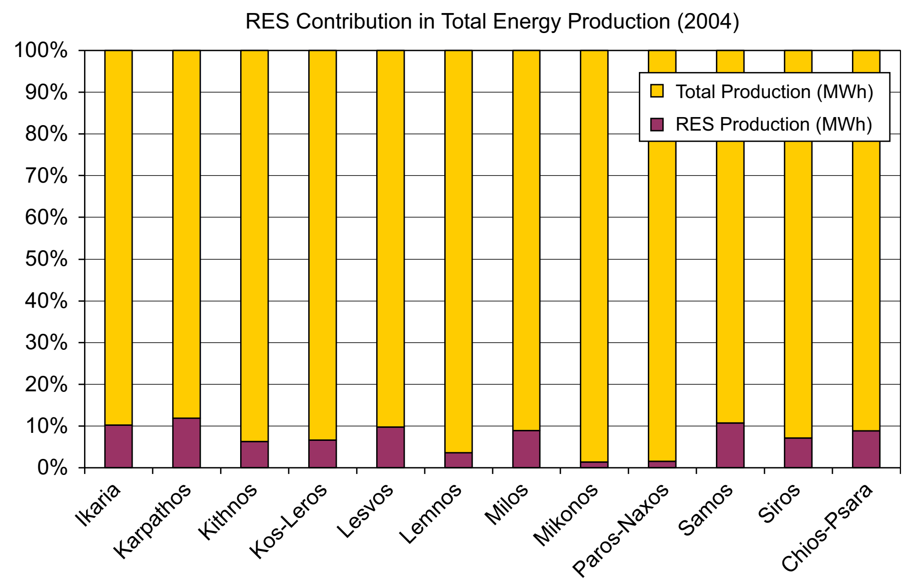

Fig. 16. RES contribution in the total energy consumption of selected Aegean Archipelago islands during 2004.

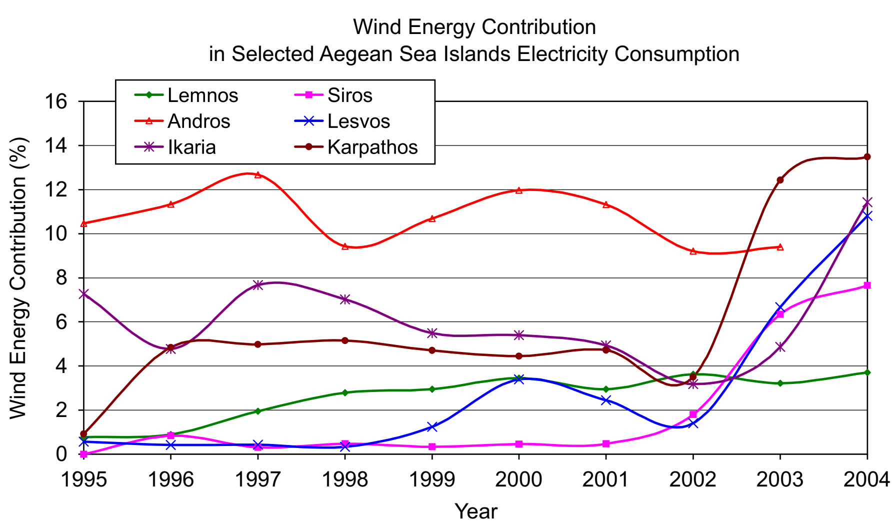

Fig. 17. Time evolution of wind energy contribution in the total energy consumption of selected Aegean Archipelago islands.

cases examined, a significant fuel consumption increase, being in complete accordance with the corresponding electricity generation amplification during the same period, may be observed; see also Figs. 7–11.

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

$$\mathrm{SFC} = \frac{M_f}{E_y}, \tag{2}$$

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

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

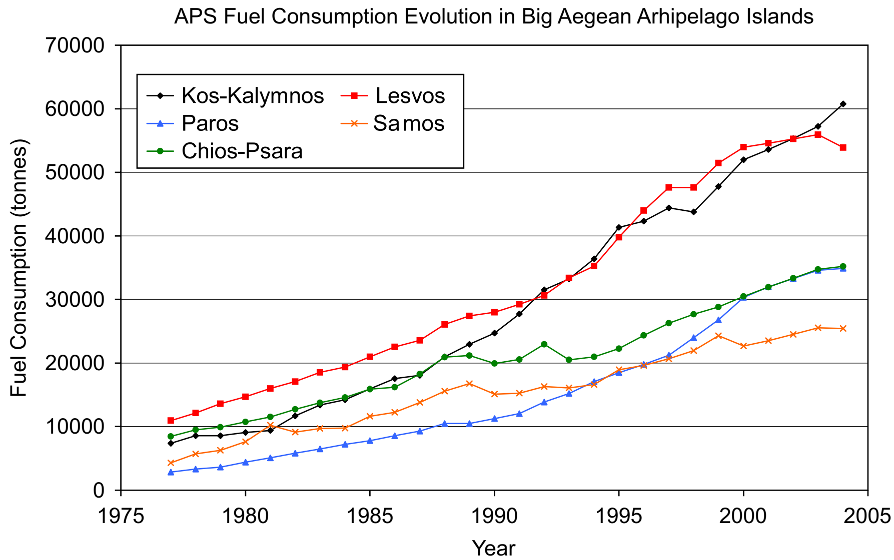

Fig. 18. Time evolution of fuel consumption of selected Aegean Archipelago islands.

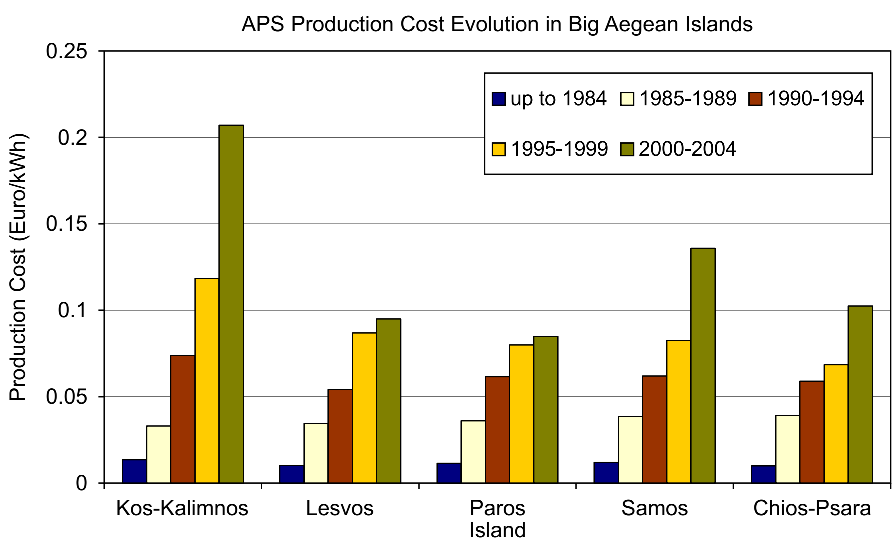

Fig. 19. Time evolution of electricity production cost of selected Aegean Archipelago islands.

Another additional aspect concerning the electricity generation of the area is the considerable APS production cost increase in the course of time (in historical values). In several cases, one may observe current electricity production values that are almost 10 times the corresponding values of 20 years ago.

Comparing now the above-mentioned values with the corresponding electricity price "$p(t)$" time series in the local market (Kaldellis, 2002), one may note significant financial loss "$\delta c(t)$" (see Appendix A, Eq. (A.6)), for the vast majority of the existing APS, see for example Fig. 20. During the last 20 years, only the Chios island APS has been financially viable, this not being the case for all the other big APS. On top of this, it is worthwhile to mention that the APS production cost in most cases examined is much higher than the price offered by the local network administrator (PPC) to the wind-based electricity production (Kaldellis et al., 2004a), being currently around 80 €/MWh. The result of this analysis underlines that the operation of the Aegean Archipelago APS leads to severe financial loss (see Appendix A, Eq. (A.7)), for the Greek PPC, which is equal to approximately $R(t) \approx 200{,}000{,}000$ €/yr.

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

According to the new directive (2003/54/EC) dispositions, the non-interconnected islands defined as "isolated

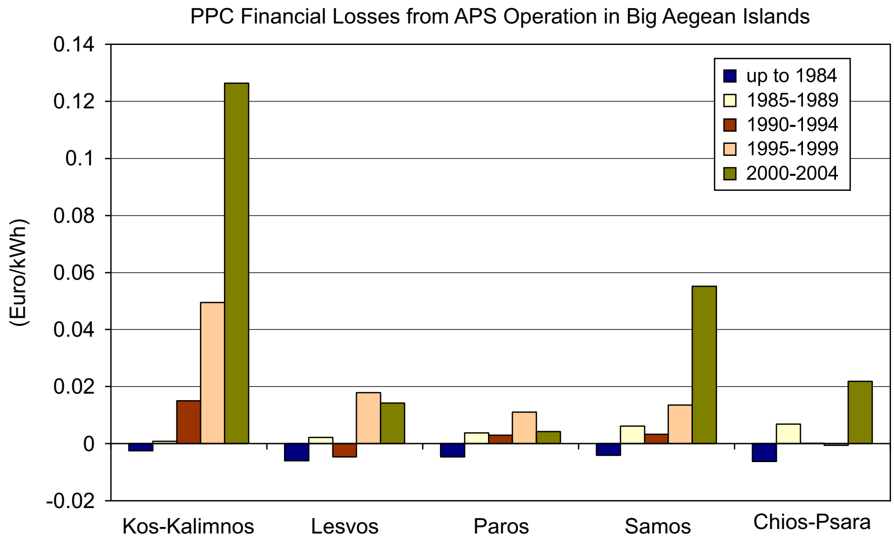

Fig. 20. Time evolution of electricity production financial loss/gain due to the operation of the APS in selected Aegean Archipelago islands.

micro grids'' (total electricity consumption less than 500 GWh during 1996) can be excluded by the proposed adjustment concerning the electrical market liberalization. Besides, emphasis should be laid to ensure the islands' safe supply.

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

According to the official version of the law concerning RES (3468/06) and in regard to the non-interconnected islands, the absorption priority ensured in the national grid and concerning the energy production of independent producers and the energy surplus by own producers is not guaranteed in the case of non-interconnected islands. In case that the RES-based electricity generation absorption leads to the local grid's instability, the administrator is not obliged to adhere to the previous commitment, not safeguarding the prospect for higher RES penetration levels (Kaldellis et al., 2004a).

5. Presentation of the available electrification solutions

The Aegean Archipelago area possesses (Gaglia et al., 2000) important RES potential (Fig. 21). Infact, in the entire area long-term wind speed measurements (PPC, 1986) indicate annual wind speed values higher than 6 m/s, while in some islands annual mean wind speed values up to 10 m/s have been recorded. On top of this, the calm spell periods are rather limited (Kaldellis and Kavadias, 2006), hence one may use wind energy to cover the electricity needs of the habitants throughout the entire year.

On the other hand, the solar potential of the area is quite high, since in all cases exceeds the 1500(kWh/m^2)/yr offering remarkable opportunities to meet either the thermal (Kaldellis et al., 2005a) or the electrical needs (Kaldellis et al., 2004c) of the local societies. More specifically, in the S. Aegean area the available solar potential is even higher, i.e. annual value higher than 1650(kWh/m^2)/yr, especially during summer, hence contributing to face the corresponding excessive (due to tourism) energy requirement of this period of the year.

Additionally, in several islands of the Aegean Archipelago one may find remarkable geothermal fields (Kondili and Kaldellis, 2005). In fact the most well known (since 1970) geothermal reservoirs are located in the islands of Milos and Nissiros (geothermal fluid temperature 300 °C). These two high enthalpy geothermal fields may be used in order to create two power stations of 100–150 and 50 MW_e, respectively. Significant geothermal fields have also been located in Lesvos island, where the first 10 MW_e power station is under schedule (RAE, 2006).

Finally, in various islands the existing biomass is used to cover thermal needs. The necessary raw material comes either from forest residuals or agricultural activities (Balaras et al., 1999). According to preliminary estimations one may produce annually almost 2000 GWh of thermal energy. Unfortunately, the periodic biomass availability and the low energy density of the raw material (Kaldellis and Sakkas, 2001) discourage any potential investment in the energy production area at the moment.

Despite the significant energy potential of the islands, the daily and seasonal variation of the local consumption in combination with the stochastic behavior of the wind speed

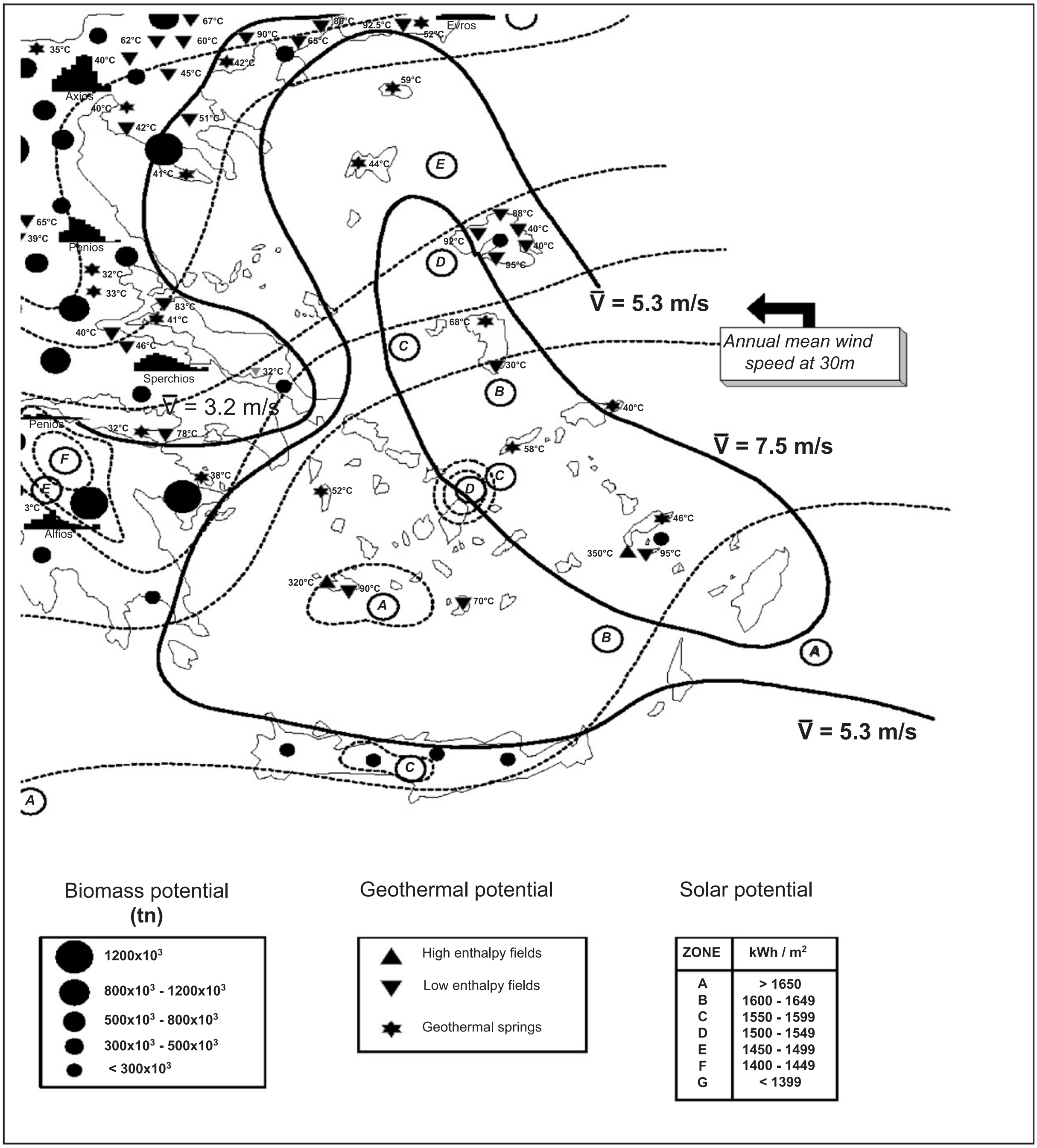

Fig. 21. RES potential in the Aegean Archipelago region.

poses serious constraints on the wind energy contribution in the local electricity generation (Kaldellis et al., 2006b). More precisely, the local network operator permits the penetration of wind power up to 30% of the instantaneous electricity maximum demand, in order to guarantee the local grid's stability in case that the available wind speed suddenly zeros. The result of these factors is a quite limited wind energy contribution to the local electricity consumption, see also Fig. 16.

The main obstacles for the exploitation of the available geothermal potential are the total absence of the necessary legal frame (up to law 3175/03) and the relatively small size of the existing electrical grids that cannot absorb the high geothermal potential of the area, e.g. Milos and Nissiros islands. Taking into account that all these islands are not interconnected, it is obvious that only small-scale applications may be operated. However, these applications would not only partially exploit the existing potential but would not benefice from any scale economies either. Finally, the unsuccessful operation of the pilot geothermal power plant of 2 MW in Milos island in 1987, which has been abandoned due to environmental impact claims by local habitants (Marouli et al., 2001), jeopardize any similar activity during the next 20 years.

Finally, the scattering of the islands and the seasonal availability of biomass raw material discourage the systematic exploitation of the available biomass potential of the area. In fact, the existing biomass is used on individual basis, although the idea of cogeneration applications to cover thermal and electrical loads is under evaluation in several big or medium sized islands (Kaldellis et al., 2002a).

To face these problems, the authors have since the previous decade proposed several electricity generation solutions with remarkable positive side effects (Kaldellis et al., 2001a, 2006c). These solutions are based on the exploitation of the available RES potential in collaboration with appropriate energy storage facilities. Similar hybrid configurations are the most cost-effective solutions to meet the electrification requirements of the Aegean Archipelago with significant environmental and social benefits.

More specifically, for the small and very small islands or for regions with relatively low wind potential one may create photovoltaic-based power stations along with energy storage (e.g. batteries) facilities (Kaldellis, 2004b) in order to replace the existing thermal power stations, operating at very high cost (higher than 200 €/MWh). It is important to mention that according to the recently voted law for RES (3468/06) there is a significant price compensation for PV-based electricity generation, which approaches the 450 €/MWh.

Subsequently, for big and medium sized areas with high-wind potential one may adopt the wind–hydro solution, based on the collaboration of wind parks and reversible hydro power stations operating as water pumping and energy production facilities (Kaldellis and Kavadias, 2001). In this case, the wind parks face the corresponding load demand, while any energy surplus is stored via the water pumping system at a high-level reservoir. In case of energy deficit, the water reserves are utilized via the hydro turbines of the installation to cover the excess power demand. In a more integrated concept (Kaldellis et al., 2005b) one may use the RES-based energy production to enhance the water reserves of the local communities.

Finally, for the islands where remarkable geothermal potential exists one may develop an integrated energy production facility to meet electrical and thermal energy requirements of the local community. This solution would be much more financially attractive if the nearby to the geothermal field islands were interconnected. In fact the possibility of interconnecting the Aegean Archipelago islands with the mainland electrical network in order to create an integrated electricity transportation network presents serious advantages and disadvantages (RAE, 2005), the detailed presentation of them being out of the scope of the present paper.

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

Recapitulating, according to the conclusions of a recent report (RAE, 2005) published by RAE-PPC-HTSO, the interconnection of the north-eastern Cyclades islands is essential. The proposed solution suggests the interconnection of Siros to the Lavrio power station (possibly via Kithnos and Kea). Next, the current plan suggests the internal interconnection for the islands of Siros, Mikonos, Paros–Naxos, Andros and Tinos, therefore exploiting the already existing interconnection via Euboea as well. Finally, the plan supports that Milos should also be included in the previous group, in order for its geothermal field to be widely exploited.

6. Conclusions and proposals

The Aegean Archipelago includes a large number of islands of various size scattered between the Greek mainland and the East coast of Asia Minor, where more than 600,000 people are living mainly in small remote communities. All these islands cover their electrification needs using outmoded APS based on thermal power units. In order to propose a realistic, environmental friendly and financially attractive solution, one first investigates the time evolution of the corresponding electricity generation parameters for the last 30 years.

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

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

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

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Appendix A

Annual electricity consumption increase "ε_i" for the year "i"

$$\varepsilon_i = \frac{1}{E_i}\frac{\mathrm{d}E}{\mathrm{d}t}\bigg|_i = \frac{1}{E_i}\cdot\frac{E_{i+1}-E_{i-1}}{2}, \tag{A.1}$$

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

Peak-load long-term (n-years period) average annual increase "$\bar{v}$"

$$\bar{v} = \left(\frac{N_n}{N_o}\right)^{1/n} - 1, \tag{A.2}$$

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

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

$$E_{\mathrm{RES}} = \int_{\mathrm{o}}^{T} N_{\mathrm{RES}}(t)\,\mathrm{d}t = \sum_{i=1}^{8760} N_{\mathrm{RES}_i}, \tag{A.3}$$

where "$N_{\mathrm{RES}}(t)$" is the corresponding renewable electricity generation and "N_{RES_i}" is the mean power output of the RES-based power stations during the hour "i" of the year.

Annual RES contribution "r" in the local electricity production balance

$$r = \frac{E_{\mathrm{RES}}}{E_{\mathrm{tot}}} = \frac{E_{\mathrm{RES}}}{E_{\mathrm{APS}}+E_{\mathrm{RES}}} = 1 - \frac{E_{\mathrm{APS}}}{E_{\mathrm{APS}}+E_{\mathrm{RES}}}, \tag{A.4}$$

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

Electricity generation specific cost "c_{el}"

$$c_{\mathrm{el}} = \frac{C_{\mathrm{tot}}}{E_{\mathrm{tot}}\sum_{j=1}^{j=n}((1+e)/(1+i))^j}, \tag{A.5}$$

where "C_{tot}" is the total cost of the local electrical network, including (Kaldellis and Kavadias, 2006) the first installation cost, the fixed and variable maintenance and operational cost of the equipment used, the imported diesel-oil cost as well as the labor and general administrative cost in present values. In Eq. (A.5) "e" is the electricity price annual escalation rate (e.g. $e = 3\%$) and "i" is the corresponding capital cost of the local market.

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

$$\delta c(t) = c_{\mathrm{el}}(t) - p(t), \tag{A.6}$$

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

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

$$R(t) = -\sum_{j=1}^{32} \delta c_j(t) E_j(t), \tag{A.7}$$

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

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