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Optimum technoeconomic energy autonomous photovoltaic solution for remote consumers throughout Greece

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Abstract

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

Keywords: Autonomous photovoltaic system; Optimum system sizing; Remote consumers

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1. Introduction

Photovoltaic systems (PVSs) significantly contribute to environmental protection and potentially reduce the dependence of Europe on oil imports. However, their main disadvantage remains the relatively high cost compared with their annual yield. On the other hand, the PVS laboratory efficiency recently approached its theoretical upper limit, while the cost of PVS electricity production has remarkably decreased and is still shrinking (Fig. 1) at a rate faster than that of any other energy production technology [1]. This considerable cost reduction turns PVSs into a viable electrification solution, especially for remote stand alone applications and high solar intensity areas [2,3].

In Greece, and especially in the Aegean and Ionian Archipelago areas, several isolated consumers (such as private farms, tiny villages, shelters, lighthouses, telecommunication stations etc.) have no access to an electrical grid [4]. So far, in an attempt to cover their urgent electrification needs, they consider small oil fired electrical generators to be their only alternative. Besides, most Greek territories possess, due to the geographical position of Greece, an abundant and reliable solar supply all year round, Fig. 2.

Hence, to face the urgent electrification problem of remote consumers spread throughout Greece, the present study is devoted to investigating the possibility of creating an integrated photovoltaic station based on a small photovoltaic generator and an energy (battery) storage device, along with the corresponding electronic equipment. Mainly this analysis focuses on estimating the optimum dimensions of a stand alone PVS under the restriction of minimum installation cost for several representative Greek areas, Fig. 2.

2. Proposed configuration-system sizing

In an attempt to facilitate the electricity demand problem of remote consumers, while taking advantage of the excellent solar potential of Greece, the following autonomous PVS is proposed, see also Fig. 3. In particular, the stand alone PVS comprises an array of PV modules connected to

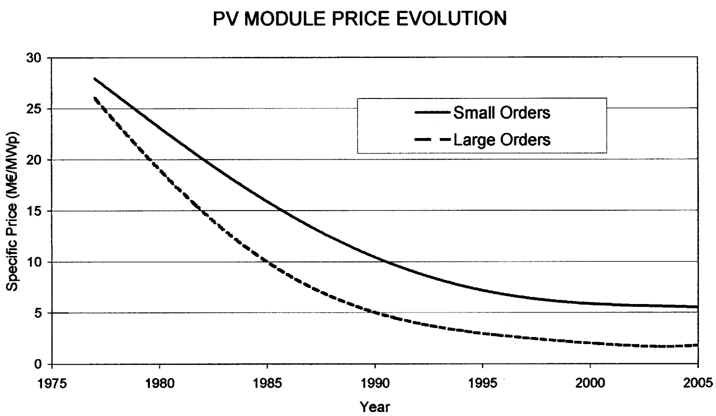

Fig. 1. Photovoltaic modules price evolution (estimation after 2002).

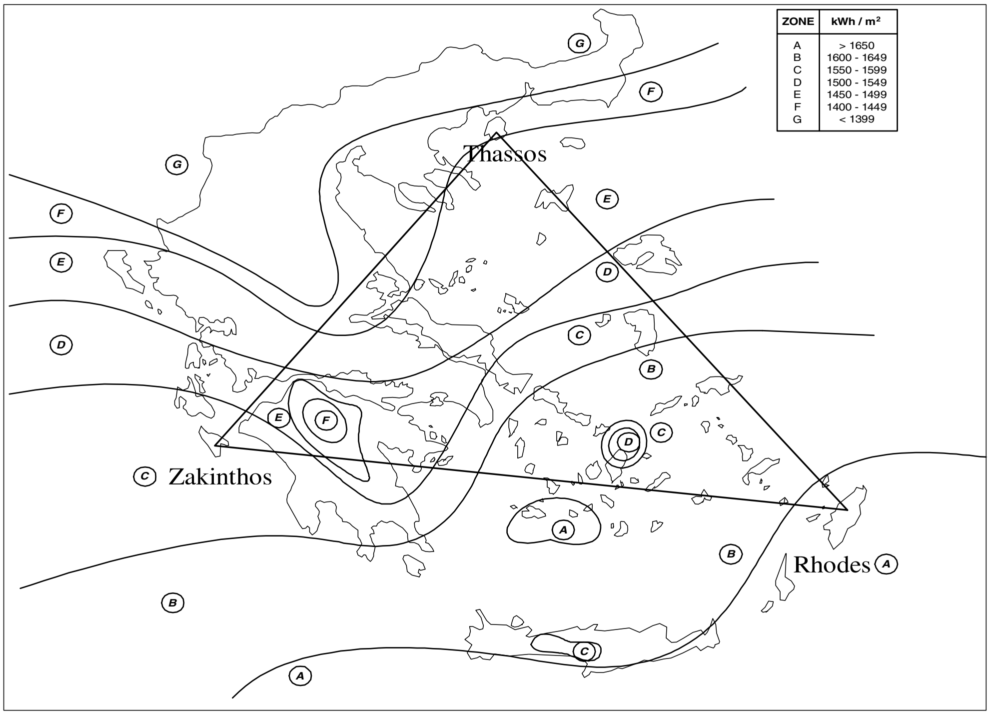

Fig. 2. Solar potential of Greece [22].

a battery via a battery charge controller or to a DC/AC inverter. Keep in mind that the battery charge controller switches the PV array off when the battery is fully charged and switches (rejects) the load off before the battery gets completely discharged, e.g. DOD $\geqslant$ DOD_L. The usage of a maximum power point tracker (MPPT) is not suggested for small scale applications [5]. The energy storage system (a lead-acid battery is found to be the most appropriate solution, given the present technological status [6]) should be adequate to store the energy production during sunlight hours for use at night or bad weather conditions. Finally, since most applications are based on alternating current [7], a DC/AC inverter is also required.

Recapitulating, the proposed PVS is based [8] on:

(i) A photovoltaic system of "z" panels ("N_0" maximum power of every panel), properly connected (z_1 in parallel and z_2 in series) to feed the charge controller to attain the voltage required. The peak power of the photovoltaic array "N_{PV}" is given as:

$$N_{PV} = z \cdot N_0 \quad (1)$$

and

$$z = z_1 \cdot z_2 \quad (2)$$

(ii) A DC/AC charge controller [9] of "N_c" rated power, charge rate "R_{ch}" and charging voltage "U_{CC}"

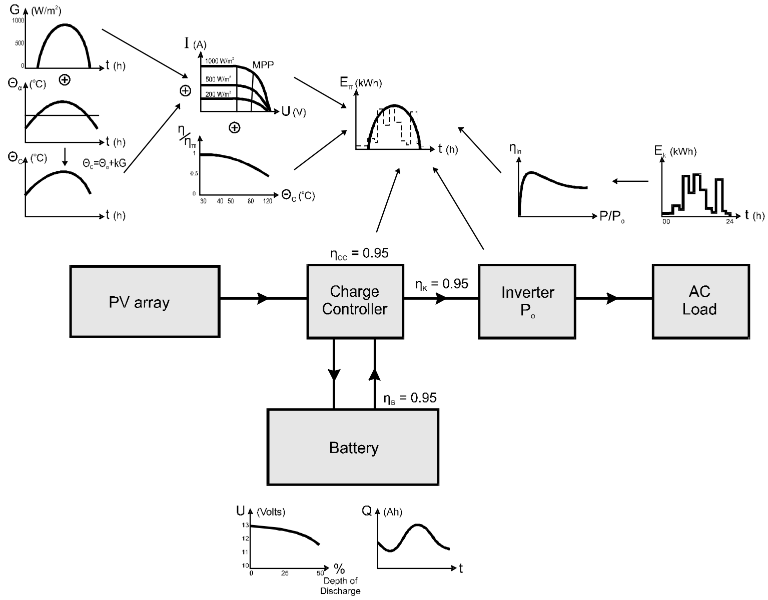

Fig. 3. Proposed autonomous PVS configuration for remote consumers.

(iii) A lead-acid battery storage system [10] with total capacity of "$Q_{\max}$", operation voltage "U_b" and maximum depth of discharge "DOD_L", thus:

$$Q_{\min} = (1 - DOD_L) \cdot Q_{\max} \tag{3}$$

(iv) A DC/AC inverter [11] of maximum power "N_p" able to meet the consumption peak load demand, increased by an appropriate safety factor (e.g. 1.3).

(v) The non-active part of the installation, including supporting structures, power conditioning devices and wiring.

Accordingly, during the long lasting service period of the installation (20–30 years is assumed to be a realistic value), the following operational modes may appear:

(a) The power demand "N_D" is less than the power output of the PV array at the outlet of the inverter, i.e.:

$$\Delta N = \eta_{INV} \cdot N_{PV} - N_D \succ 0 \tag{4}$$

In this case, the energy surplus "ΔN" is stored via the battery charge controller. If the battery is full ($Q = Q_{\max}$), the residual energy "E_{res}" is forwarded to low priority loads.

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

(c) There is no solar energy production (e.g. zero solar radiation, system not available etc.), i.e. $N_{PV} = 0$. In this occasion, all the energy demand is fulfilled by the battery-charge controller-DC/AC inverter subsystem, provided that $Q > Q_{\min}$. In cases (b) and (c), when the battery capacity is near the bottom limit, an electricity demand management plan should be applied, otherwise the load would have to be rejected.

Summarizing, the main parameters, defining the size and subsequently the first installation cost of a similar system, include the photovoltaic module number "z" and peak power "N_0", the batteries maximum capacity "Q_{max}", selected to guarantee the system energy autonomy for the desired time period along with the rest of the electronic equipment (inverter, charge controller), and the peak load capacity "N_p".

3. Proposed analytical solution

As already mentioned, the main objective of this analysis is to estimate the appropriate dimensions of a stand alone PVS for remote consumers sited all around Greece. The main inputs of the problem are:

- Detailed solar radiation "G" measurements for a given time period (e.g. one year) usually on a horizontal plane
- Ambient temperature "θ" data for the entire period analysed
- Operational characteristics (current, voltage) of the photovoltaic modules selected, i.e. $I = I(U, G)$ and "N_0"
- Operational characteristics of all the other electronic devices of the installation, i.e. inverter efficiency, battery cell ($Q - U$; θ) curve etc.
- The electricity consumption profile, based on information provided by the Hellenic National Statistical Agency [12], on an hourly basis (see Fig. 4), being also dependent [13–15] on the year period analysed (winter, summer, other).

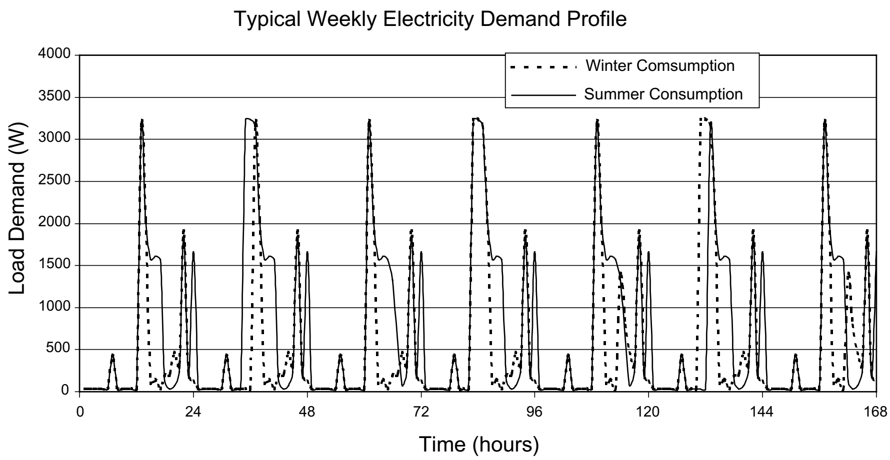

Fig. 4. Typical electricity demand profile of the remote consumer analyzed.

Using the above described information, one should define the numerical values of the photovoltaic panels number "z" and the battery maximum size "Q_{max}". For this purpose a computational algorithm "PHOTOV-III" has been used, in order to perform the necessary parametric analysis on an hourly energy production-demand base.

Thus, for each pair of "z" and "Q_{max}", the "PHOTOV-III" algorithm (Fig. 5) is executed for a specific time period (e.g. one month, six months, one year etc.) and for an hour long time step, while emphasis is laid on obtaining zero load rejection operation. If this is not achievable, the battery size is increased, and the calculation is repeated until the no load rejection condition is fulfilled, i.e.:

$$Q^* = \mathbf{min}\{Q_{max}\} \tag{5}$$

Then, the number of photovoltaic panels is increased, and the calculation is performed from the very beginning. After integration of the analysis, a $(z - Q^*)$ curve is predicted under the no load rejection restriction. To get a clear cut picture, keep in mind that for every pair of $(z - Q^*)$, the stand alone photovoltaic system is energy autonomous for the period investigated. Finally, the optimum pair may be selected from the $(z - Q^*)$ no load rejection curve if an optimisation criterion is set.

4. Optimum solution estimation on the basis of minimum first installation cost

Integrating the present analysis, it is interesting to introduce the estimation of the first installation cost function, which is used in order to calculate the optimum configuration selected. More specifically, the initial cost "IC_0" of a photovoltaic stand alone system can be approximated as:

$$\mathrm{IC}_0 = C_{PV} + C_{bat} + C_{elec} + f \cdot C_{PV} \tag{6}$$

where "C_{PV}" is the photovoltaic modules ex-works cost. For small size systems this cost varies [16,17] between 5000€/kWp and 7000€/kWp. Similarly "C_{bat}" is the battery bank buy cost expressed [17,18] as:

$$C_{bat} = c_b \cdot Q_{max} \tag{7}$$

where "c_b" slightly depends on battery capacity. Thus, for the local market, from a market survey concerning lead-acid batteries, the following semi-empirical relation may be used:

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

Additionally, the cost of the major electronic devices is a function of the peak load demand (e.g. inverter) and the photovoltaic modules rated power (e.g. charge controller). Thus, since the maximum electricity demand of the remote consumer under investigation is prescribed, one may use the following simplified relation, which is valid for the local market:

$$C_{elec} = a + b \cdot (z \cdot N_0) \ (z \cdot N_0 \geqslant 1 \text{ kW}) \tag{9}$$

with $a = 1000$€ and $b = 250$€/kW.

Finally, the balance of system (BOS) cost is expressed via the first installation cost coefficient "f" (excluding the cost of electronic equipment). According to available information [5,8]

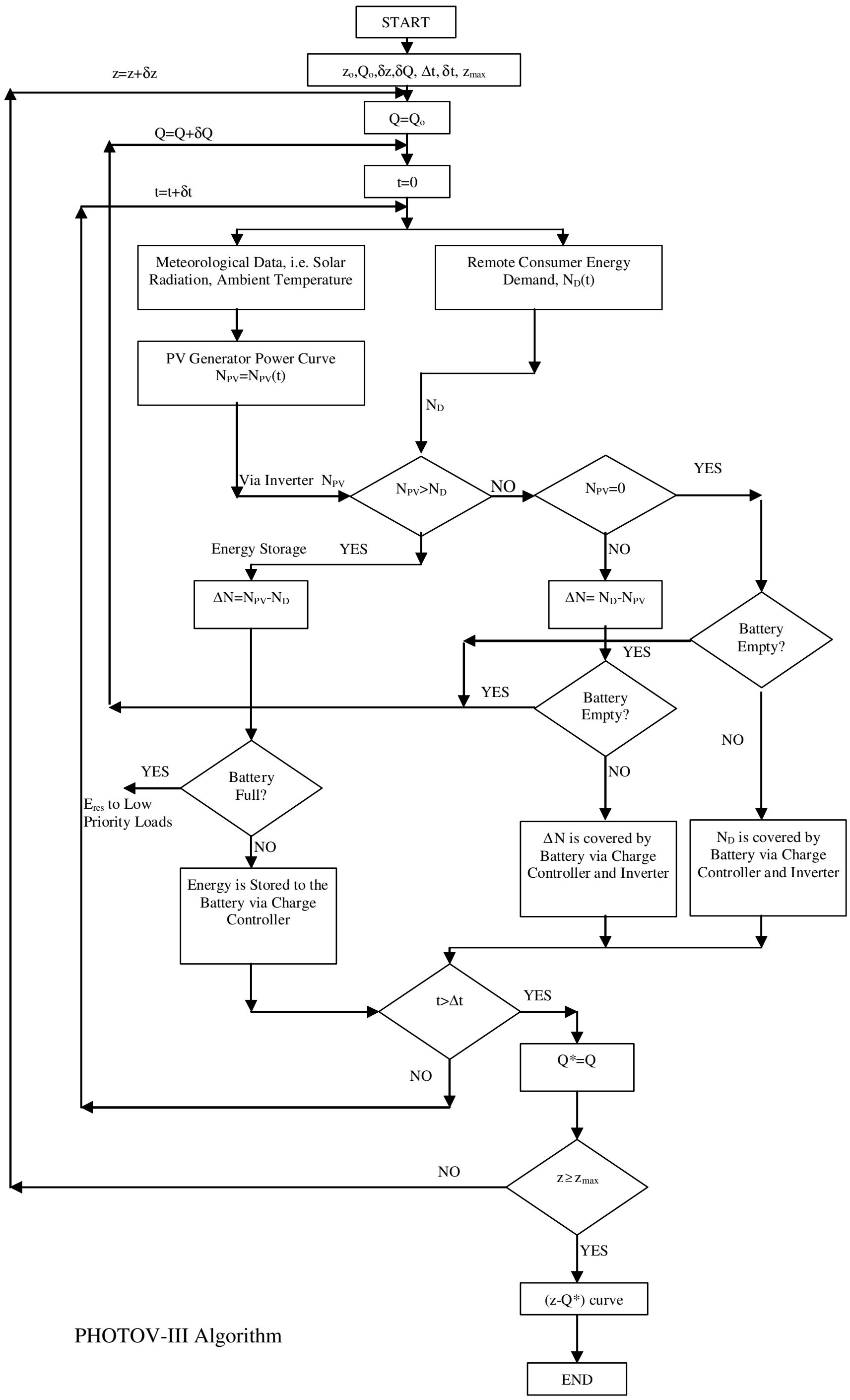

Fig. 5. PHOTOV-III algorithm.

regarding remote photovoltaic installations, $f = 5$–15%. Recapitulating and substituting Eqs. (7)–(9) into Eq. (6), one gets:

$$\mathrm{IC}_0 = \zeta \cdot z \cdot \mathbf{Pr} \cdot N_0 \cdot (1 + f) + c_b \cdot Q_{max} + a + b \cdot z \cdot N_0 \quad (10)$$

where "ζ" is a function of "z" (i.e. $\zeta = \zeta(z)$), expressing the scale economies for increased number of photovoltaic panels utilized, see also Fig. 1. Subsequently, "P_r" is the specific buy cost of a photovoltaic panel (generally $P_r = P_r(N_0)$) expressed in €/kW$_p$.

Consequently, according to Eq. (10), the initial installation cost is a function of "z" and "Q_{max}" if "N_0" is defined. Thus, one may write:

$$\mathrm{IC}_0 = \mathrm{IC}_0(z, Q_{max}) \quad (11)$$

By drawing the corresponding initial cost constant-price curves, it is possible to estimate the optimum (minimum initial cost) solution, which guarantees energy autonomy of the remote consumer for the time period examined. In fact, since the optimum solution is strongly dependent on the slope of the initial cost (IC_0 = constant) curves, a more detailed investigation is required, considering the present status and future potentiality of the international market [1,19].

On top of that, it is important to note that the Greek state and European Union strongly subsidize small PVSs, the subsidization percentage varying between 40% and 70%. For comparison purposes, it is interesting to note that the grid connection cost [16,19] exceeds 10 000€/km, in regions with a local electrical network.

5. Application results

Rhodes is a medium size sunny island (98 500 habitants, area of 1398 km^2) in the SE Aegean Sea, located approximately 600 km from Athens. The island is a very famous tourist resort, possessing extremely attractive coast and abundant sunlight. Several small islands are scattered near Rhodes, which is the capital of the Dodecanese complex. In those islands, a remarkable number of isolated families reside, having no access to a reliable electrical grid. Hence, they cover their needs using small oil fired Diesel generators [20].

For all the above mentioned reasons, the Rhodes area is one of the most promising Greek territories in which to build and operate autonomous photovoltaic systems with significant social, environmental and financial benefits. Fig. 6 presents the measured [21] monthly averaged solar energy values (kWh/m^2 mo) for the specific year analysed, in comparison with the long term (1970–1982) monthly averaged experimental values [22]. Obviously, the year investigated may be characterized as having typical solar potential, presenting a monthly average distribution similar to the long term data. Accordingly, in Fig. 7, the measured solar radiation (on an hourly basis) on a horizontal plane is demonstrated for the worst winter (December) and summer (June) solar potential weeks. Parallel measurements of ambient temperature are also utilized. According to the data provided, the proposed installation may possibly face two or three continuous days lacking noteworthy solar radiation.

Using the available experimental data for Rhodes island and applying the "PHOTOV-III" numerical algorithm, the calculation results concerning autonomous photovoltaic panel and battery capacity combinations are summarized in Fig. 8 for several panel tilt angles (β). More

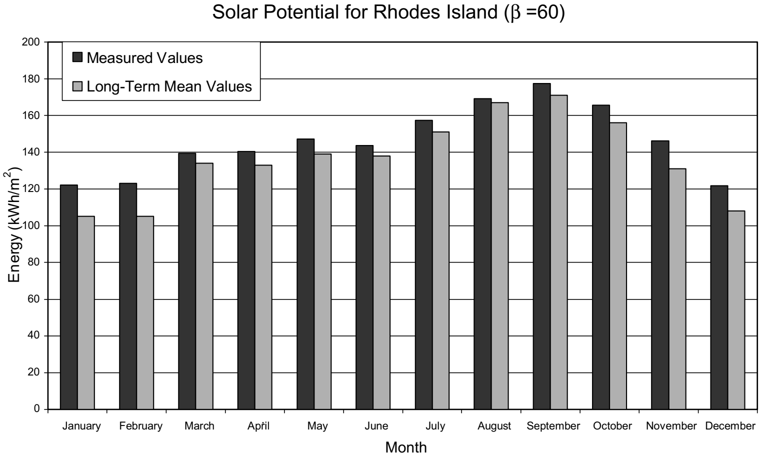

Fig. 6. Measured solar energy potential for Rhodes island.

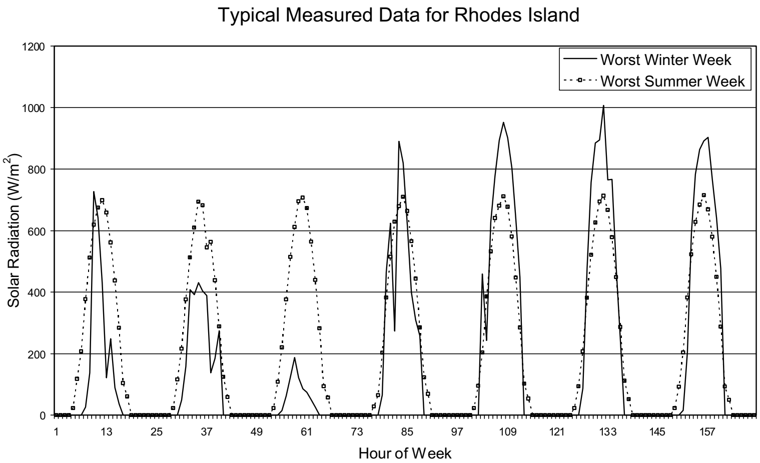

Fig. 7. Measured data on hourly basis for Rhodes island.

specifically, in Fig. 8, one presents all the energy autonomy ($Q_{\max} - z$) pairs of a PVS for panel tilt angles varying from zero to ninety degrees ($0° \leqslant \beta \leqslant 90°$). For almost all constant "β" energy autonomy curves, two distinct parts can be defined. In the first part, the battery capacity is significantly reduced as the photovoltaic number is slightly increased. This rapid change is more evident for "β" angles greater than 50°. In the second part, the battery capacity remains almost constant, not depending on the photovoltaic panels number, achieving an asymptotic value of $Q_{\max} = 1000$ Ah, for all "β" values examined.

On the other hand, the influence of the "β" angle on the PVS configuration is significant. More specifically, there is a considerable "z" diminution as "β" increases from 0° to 30°, while the "z" number is significantly increased as "β" takes values from 60° to 90°, under the restriction of

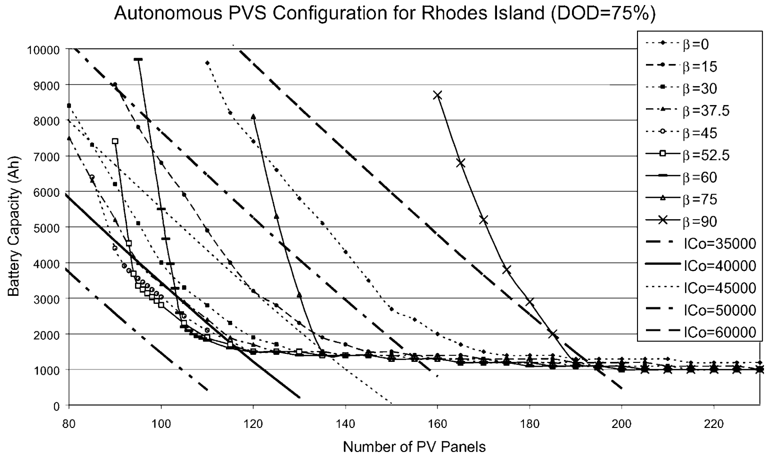

Fig. 8. Optimum autonomous PVS configuration for Rhodes island.

constant battery capacity. Finally, for "β" values in the region of 35°–60°, there are several rational ($Q_{max} - z$) combinations that guarantee zero load rejection for the time period analysed.

This last comment is more obvious if the constant initial cost curves (without any subsidization) are taken into consideration. In this context, one has the ability to select the minimum initial cost solution that guarantees the system energy autonomy for the year examined. Hence, the optimum configuration may be achieved using either ninety five photovoltaic panels ($z = 95$, $N_0 = 51$ W) at a panel tilt angle of 52.5° and battery capacity of 3350 Ah (DOD = 75%, 24 V) or one hundred five panels ($z = 105$, $N_0 = 51$ W) at a panel tilt angle of 60° and battery capacity of 2190 Ah. Keep in mind that the "IC_0 = constant" curves are based on current local market information, valid during 2002. Concluding, the minimum initial cost autonomous PVS configuration at the Rhodes region turns out to be the second configuration (Fig. 9), with a minimum capital to be invested equal to 19 000€, since there is a 50% state subsidization option for small photovoltaic systems (under 20 kW) in the current frame of the National Competitiveness Programme.

Another interesting information resulting from the application of the "PHOTOV-III" numerical code is the annual energy surplus "E_{res}" of the stand alone system, Fig. 10. As expected, the energy surplus is a linear function of the photovoltaic panels' number, while for "z" greater than 90 the energy surplus represents a significant part of the PVS energy consumption (i.e. approximately 5 MW h per year). At this point, it is important to mention that the minimum initial cost solution (i.e. $\beta = 60°$, $z = 105$, $Q_{max} = 2190$ Ah) represents a low energy surplus case.

Subsequently, analysing the energy surplus profile for the optimum system configuration on a monthly basis, Fig. 11, one may easily observe that there is a considerable solar energy over production during the hot months (summer), a fact that may encourage the optional usage of the energy surplus by a small desalination plant [23] in order to cover the increased clean water demand during summer.

The second case to be analysed concerns Zakinthos (39 000 habitants, area of 434 km^2), an island located at the South Ionian Sea next to NW Peloponessos. Zakinthos island also possesses a very high solar potential, Fig. 2, while the local wind speeds are limited. Hence the exploitation of photovoltaic energy is a most promising electrification solution for remote consumers.

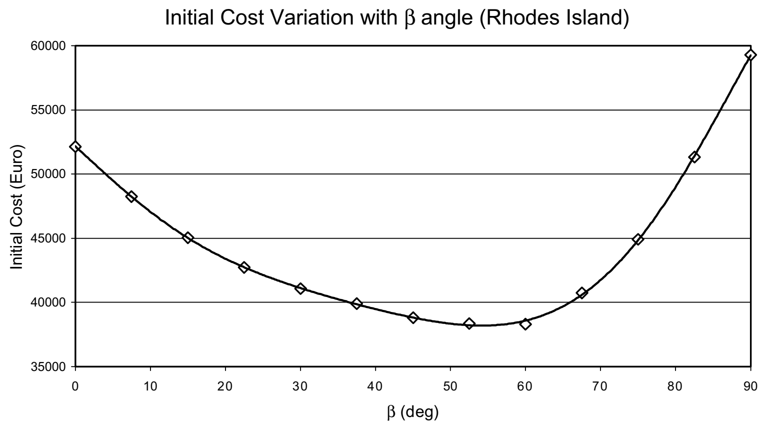

Fig. 9. Influence of panel tilt angle on first installation cost of an autonomous PVS.

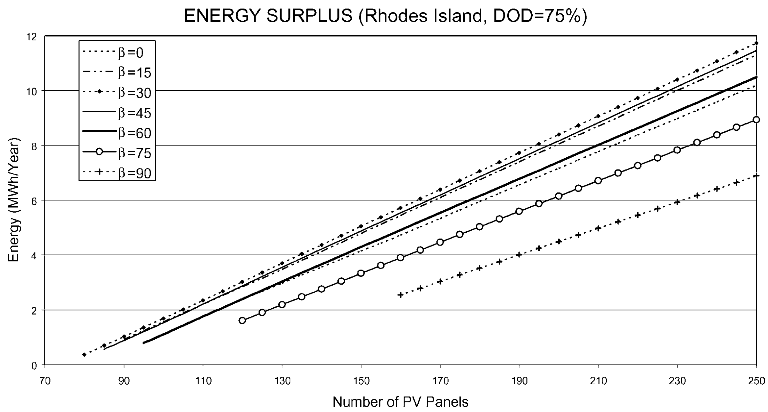

Fig. 10. Energy surplus of an autonomous PVS in Rhodes island.

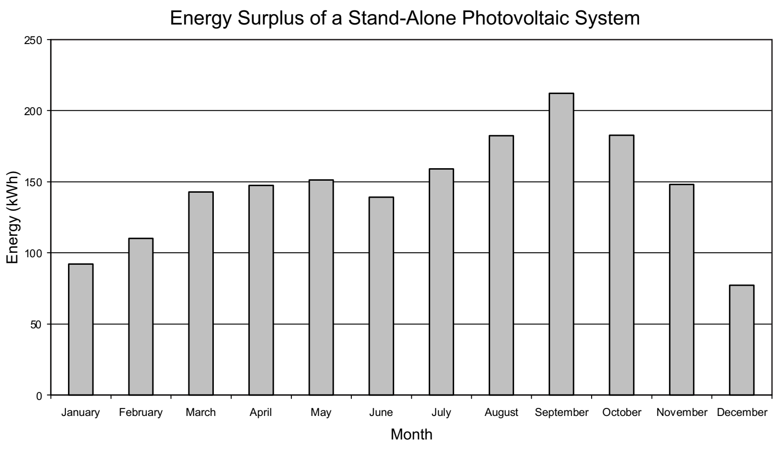

Fig. 11. Energy surplus profile for the optimum autonomous PVS configuration, Rhodes island.

Generally speaking, the solution obtained for Zakinthos island, Fig. 12, concerning the optimal PVS configuration for various panel tilt angles is quite similar to the Rhodes island solution, considering that they are almost 1000 km apart. Thus, as in the previous case, for constant battery bank capacity, there is a considerable "z" reduction when "β" increases from 0° to 30°, while the opposite change is encountered when "β" exceeds 60°. Another interesting conclusion drawn from Fig. 12 is the asymptotic behaviour of the battery capacity needed (1450 Ah) to guarantee energy autonomy of the system, being almost independent of the photovoltaic power used.

The minimum initial cost solution can be estimated using the "IC_0 = constant" curves, see also Eq. (10). Hence, the minimum initial cost configuration is based on 120 photovoltaic panels of 51 W each (i.e. $N_{PV} = 6120$ W), a 24 Volt battery of 5000 Ah (90 kWh, DOD = 75%), while the corresponding first installation cost is approximately 49400 Euro, being normally half subsidized by the Greek State.

Evidently, by using an increased number of photovoltaic panels, there is a remarkable energy excess, which is a linear function of the photovoltaic panel number "z", Fig. 13. As expected, the energy surplus for high "β" values is less than the corresponding surplus for medium and low "β" values (i.e. $\beta \leqslant 45$), while the optimum PVS configuration for a panel tilt angle equal to 60° achieves quite limited energy surplus values, Fig. 13.

The last case investigated is Thassos, a small North Greece island (13500 habitants, area of 395 km^2), located in the north Aegean Sea, near Kavala city. In this area, the solar radiation is below those of Rhodes or Zakinthos, however being greater than 1400 kWh/(m^2 and year). Using the "PHOTOV-III" numerical code to define the size of an energy autonomy PVS in this North Greece area, the calculation results are summarized in Fig. 14, along with the constant initial cost curves. For this last case, the ($Q_{max} - z$) curves are similar to the ones of Figs. 8 and 12, although the slope of the constant "β" curves is less abrupt than those of the Rhodes and Zakithnos island cases. On top of that, the size of the proposed PVS configuration is almost double (i.e. 185 photovoltaic panels of 51 W and 5300 Ah of nominal battery capacity), leading to a first

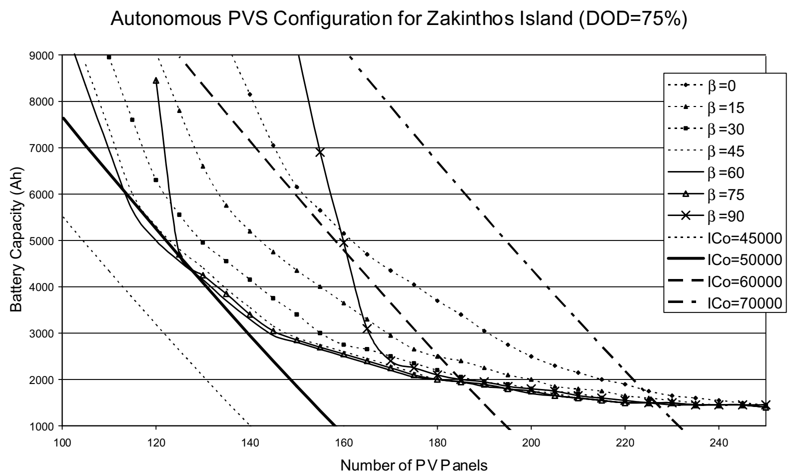

Fig. 12. Optimum autonomus PVS configuration for Zakinthos island.

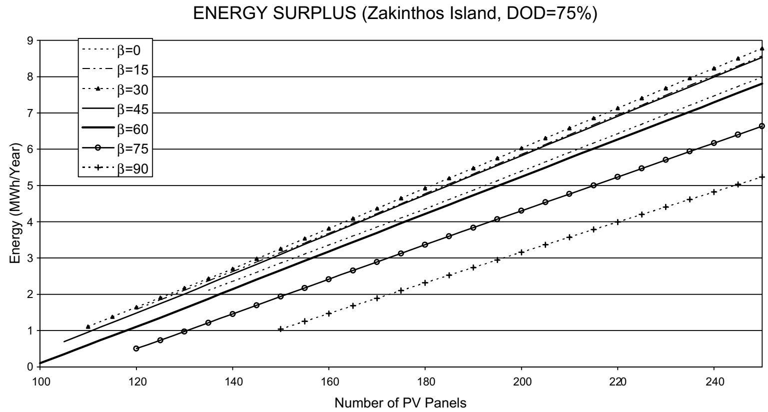

Fig. 13. Energy surplus of an autonomous PVS in Zakinthos island.

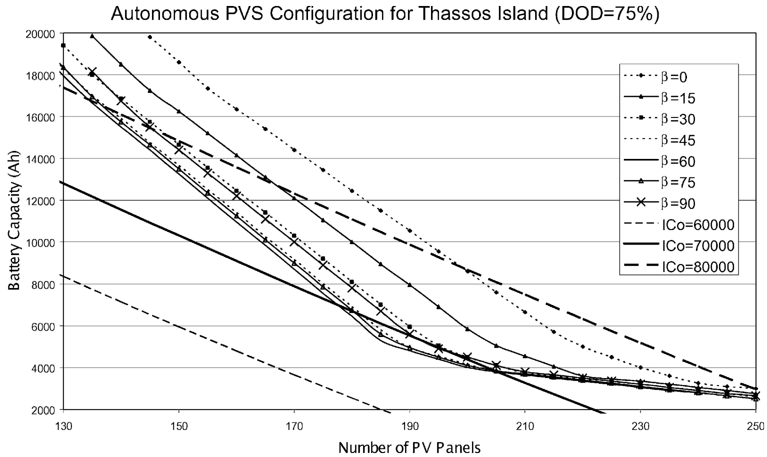

Fig. 14. Optimum autonomous PVS configuration for Thassos island.

installation cost close to 68 000€, without any external subsidization. Finally, as in the previous two cases examined, the optimum panel tilt angle for a PVS in Thassos island is also 60°.

Another interesting output of the proposed analysis is the annual energy surplus distribution given in Fig. 15 for all the system combinations analysed. As derived from Figs. 10, 13 and 15, the energy surplus in the Thassos area presents a distribution similar to those of the Rhodes and Zakinthos cases, however being lower than those of the other regions for the same "z" number. On the other hand, the optimum configuration solution leads to higher energy surplus values due to the increased photovoltaic panel number used.

Recapitulating, Table 1 presents the calculation results concerning the main characteristics of an autonomous photovoltaic system situated in three representative island territories of Greece, Fig. 2. For comparison purposes, Fig. 16 portrays the initial cost variation for all three regions analysed, and for the same time period, as a function of the panel tilt angle. According to the

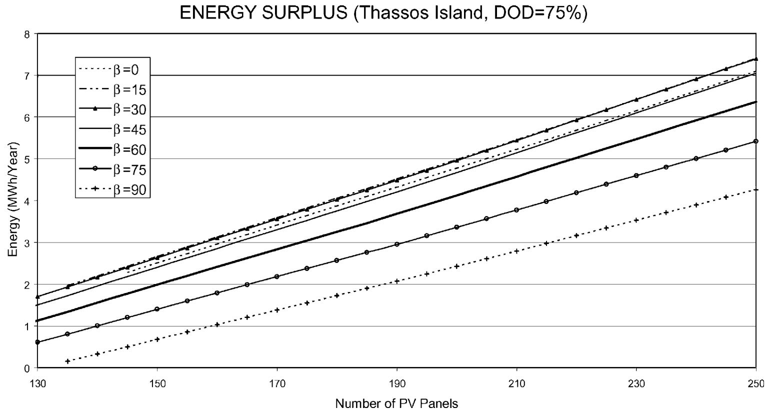

Fig. 15. Energy surplus of an autonomous PVS in Thassos island.

Table 1
Photovoltaic stand alone system characteristics for representative Greek islands

Location	(z) PV panel number	Q_{max} (Ah)	IC_0 (€)
Rhodes island	105	2190	38 300
Zakinthos island	120	5000	49 400
Thassos island	185	5300	68 100

information presented, the optimum tilt angle is around 60° for all the cases analysed, while the dimensions and the initial cost of an autonomous photovoltaic system are strongly dependent on the exact location, or more accurately, the solar potential of the installation. Thus, it is quite amazing to remark that between the south and north Aegean Sea one needs more than double battery bank capacity and almost 80% greater photovoltaic power to meet the electricity requirements of the same consumer. However, the first installation cost is not prohibitive, even for

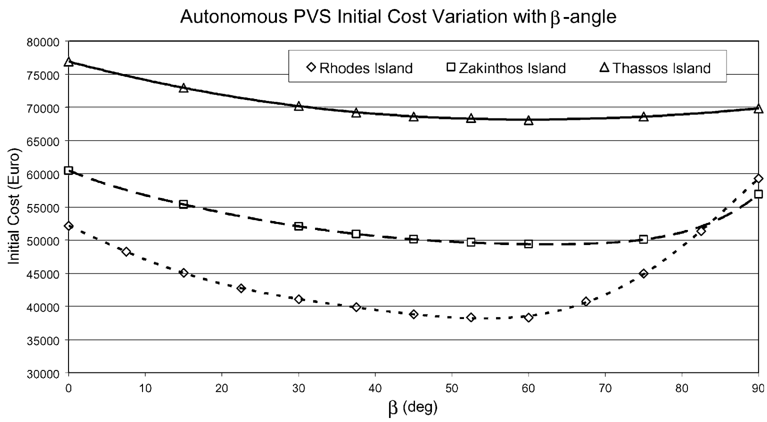

Fig. 16. Initial cost variation with panel tilt angle for typical Greek island PVSs.

the worst case, considering the significant financial support provided by the Greek State (≈50%) and the required amount of almost 10 000–12 000€/km of electrical grid extension.

6. Conclusions

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

Among the most interesting findings of the present research is the energy autonomous curve ($Q_{\max} - z$) shape and the impact of panel tilt angle on it. Accordingly, one may underline the remarkable autonomous PVS size difference between South and North Greece locations, leading to a more than 75% higher initial cost in the North than in South Greece. However, in all cases analysed, the capital to be invested, considering the 50% State subsidization, varies between 19 000 and 39 000€, being equivalent to 1.5–3 km of electrical grid extension, if obtainable.

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

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