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REVIEWS - LETTERS - REPORTS

A GENERAL AND SYSTEMATIC PROCEDURE FOR THE TECHNICAL/ECONOMIC/SOCIO–ENVIRONMENTAL ASSESSMENT OF RESIDENTIAL STAND ALONE AUTONOMOUS PV SYSTEMS: APPLICATION TO A SMALL–SCALE RSAAPS INSTALLED IN THE CITY OF XANTHI/THRACE, GREECE

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The present paper describes a general and systematic procedure (for the purpose of optimum sizing; technical, economic and socio-environmental assessment; and simulation of the system operation) suitable for a complete study (in the planning stage or after system installation) of any residential stand alone (non grid-connected), autonomous (completely independent of other power sources) PV system (RSAAPS). A case study of a real small-scale RSAAPS operating in the city of Xanthi/Greece is assessed thoroughly and the suitability of the proposed procedure is realized and validated.

K e y w o r d s: RSAAPS, optimum sizing, technical analysis, economic/socio-environmental analysis, operation simulation, practical verification

1 INTRODUCTION

The photovoltaics (PVs) are promising, safe, expandable, maintenance-free, silent and reliable decentralized/ distributed sources of energy which may contribute, in a serious manner, in meeting the constant growth of the world electricity demand (especially in summer months) and to the need for renewable, and environmental friendly electric power. PV systems may be used as autonomous stand alone [1] or grid-connected systems [2], or in combination with other energy sources to form hybrid power systems [3]. For practical applications the type of system to be chosen depends on the actual needs to be met, the location and the budget.

The simplest form of a PV system is the SAAPS. This system is used mainly for remote power applications including water pumping, telecommunications, signaling/lighting and battery charging purposes or it may power remote residences (RSAAPS) where an electric grid is not available or economically justified. The RSAAPS is very attractive and usually includes a PV generator (with its support structure), and BOS (with energy storage system (battery), charge controller (and/or MPP Tracker), stand alone inverter, cables, switches, fuses and protection diodes) as shown in Fig. 1.

A necessary general and systematic procedure for the thorough study of a RSAAPS is presented in depth and it is applied through a case study to a real RSAAPS (including an extended monitoring system making possible the measurement and storage of several key parameters) operating in the Thrace Region of Greece (city of Xanthi). In every step of the proposed procedure the needed/obtained magnitudes are indicated and the relevant literature is referred. This procedure incorporates accurate and practical mathematical models and it is applicable to any such system/project for the purpose of achieving a proper design (including a complete technical/economic/socio-environmental assessment) and conducting through simulations a thorough investigation of system operation.

2 THEORETICAL ANALYSIS AND PRACTICAL VERIFICATION OF THE PROPOSED PROCEDURE

A simplified representation of the proposed general and systematic procedure for performing a thorough analysis of a RSAAPS is shown in Fig. 2. This procedure is implemented through a developed special computer program (via M-File, Simulink and Graphical User Interface of Matlab software) and is applied to a real small-scale RSAAPS (see Fig. 1) operating on the rooftop (12 m *agl*) of the Electrical Engineering Laboratory building in the city of Xanthi /Thrace region of Greece.

2.1 Description of the systematic procedure for solar potential evaluation of a selected site with respect to a RSAAPS installation

The solar resource is free, renewable, distributed and non-pollutant, but it suffers from its intermittent nature and thus can not be predicted and programmed deterministically. For a RSAAPS to be a reliable and economically viable choice it is mandatory, before its design/installation, to select the most suitable site among a number of candidates and statistically assess its solar

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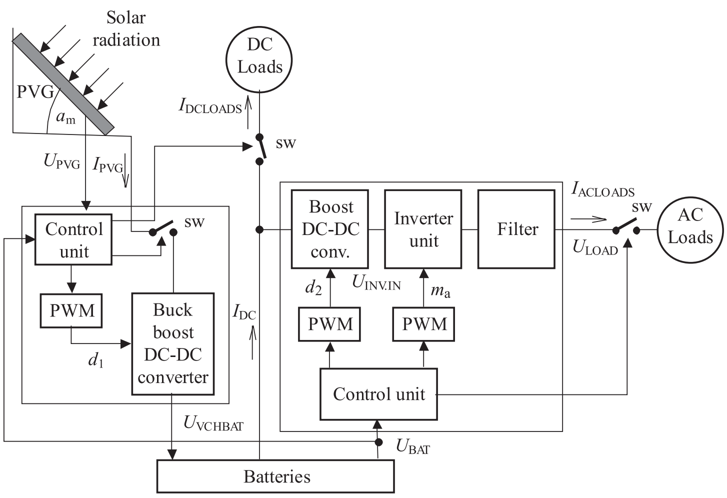

Fig. 1. A simplified typical schematic representation of RSAAPS

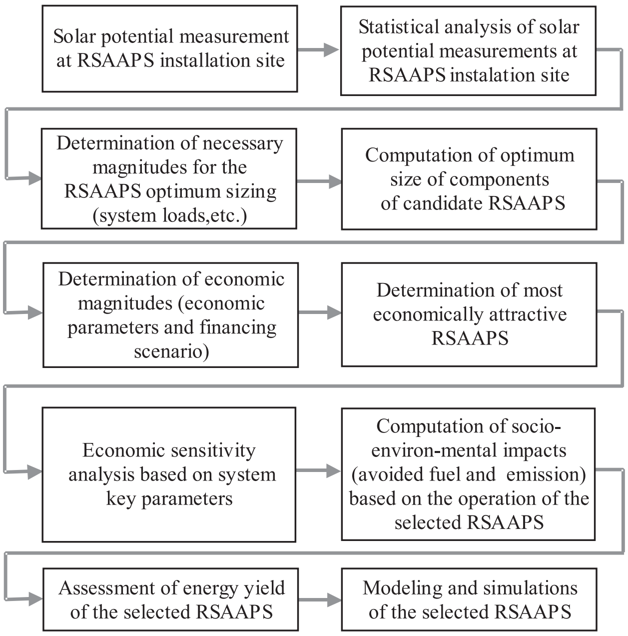

Fig. 2. A simplified representation of the proposed general and systematic procedure for performing a thorough analysis of a RSAAPS

potential. This requires relevant long term measurements from a typical meteorological station.

For this analysis the needed magnitudes are the latitude of the RSAAPS installation site (for the city of Xanthi this is 41.1414°), and the mean hourly values of total solar radiation $R_{\mathrm{MHTHP}}\,(\mathrm{W/m^2})$ impinging on a horizontal plane on the surface of the earth (for the sunny hours of the day of each month, taken from the associated long term measurements). In the case study of this work the R_{MHTHP} values were measured/recorded using a BABOOC-ABC meteorological station (which is installed at the School of Engineering Campus of DUTH in the city of Xanthi at a height of 14 m *agl*) for the years 2001–2006 (see Table 1).

In order for the solar potential evaluation procedure to be complete (with respect to the selected site), the following relevant magnitudes should also be computed [4–7]:

- The mean per day monthly values of the incident total solar radiation $R_{\mathrm{MDMTHP}}\,(\mathrm{W/m^2})$ on the PV panels at 0° angle position (*eg* for the selected site see Fig. 3).
- The annual solar deviation $\delta\,(^\circ)$ and sunset hour angle $\omega\,(^\circ)$ (*eg* for the selected site see Fig. 4).
- The mean monthly values of extra-terrestrial radiation $R_{\mathrm{MMETHP}}\,(\mathrm{kWh/day\,m^2})$ impinging on a horizontal plane being on the boundaries of the atmosphere (*eg* for the selected site see Fig. 5).
- The mean per day monthly values of the diffuse radiation $R_{\mathrm{MDMDHP}}\,(\mathrm{W/m^2})$ impinging on the PV panels at 0° angle position (*eg* for the selected site see Fig. 6).
- The mean monthly clearness index (MMCI) (*eg* for the selected site see Fig. 7).
- The mean monthly values of the ratio MMRDT, being the mean monthly diffuse divided by the mean monthly total solar radiation on the PV panels at 0° angle position (*eg* for the selected site see Fig. 8).
- The monthly optimum slope $a_m\,(^\circ)$ of a south faced PV array (which is usually determined with the linear search method), and the associated values of the mean per day monthly total solar radiation R_{MDMTSP} $(\mathrm{W/m^2})$ impinging on a plane with slope a_m, the value of which must be adjusted once every month to the optimal monthly inclination angle (*eg* for the selected site see Table 2).
- The aggregation of mean monthly per day total solar radiation $R_{\mathrm{AMMDTSP}}\,(\mathrm{W/m^2})$ impinging on a tilted PV panels position ($a \neq 0^\circ$) for a whole year (*eg* for the selected site see Fig. 9).
- The mean monthly per day total solar energy $E_{\mathrm{MMDTBFS}}\,(\mathrm{Wh/m^2})$ impinging on the PV generator with the best fixed tilt angle (*eg* for the selected site it is 35°, see Fig. 10).

Table 1. Mean hourly values of total solar radiation R_{MHTHP} (W/m^2) impinging on the horizontal position (0 °) of the PV panels (for the sunny hours of the day of each month) *wrt* a selected site at Xanthi/Greece for the years 2001-2006 at a height of 14 m *agl*

Sony hours	9.00	10.00	11.00	12.00	13.00	14.00	15.00	16.00	17.00	18.00
	R_{MHTHP} (W/m^2)									
January	-	43.2	81.3	125.5	133.9	140.9	144.7	110.3	16.1	-
February	25.1	80.1	150.5	180.2	250.2	265.1	225.3	180.1	18.4	-
March	72.4	103.4	216.7	276.0	321.2	321.1	239.6	178.5	18.2	-
April	120.0	150.1	300.2	350.2	415.2	380.1	320.1	270.0	180.7	18.6
May	195.3	200.6	227.1	346.7	533.1	523.9	441.3	329.5	240.7	19.7
June	206.4	270.0	330.5	490.3	485.1	432.9	370.7	293.4	214.2	150.0
July	230.1	246.5	290.3	407.8	581.6	570.2	529.9	443.5	311.5	211.0
August	180.1	261.9	398.3	463.8	619.9	543.6	472.1	415.3	262.2	171.5
September	121.1	130.1	318.9	416.7	436.0	445.6	344.2	256.6	20.2	-
October	52.6	146.2	213.0	274.3	291.0	291.6	245.7	154.4	17.5	-
November	35.6	91.7	148.3	213.0	226.6	217.0	163.2	119.5	16.3	-
December	15.7	60.5	103.6	129.0	162.5	155.5	116.5	16.2	-	-

- means that the corresponding values are lower than 15 W/m^2

Table 2. Monthly optimum slope a_m (°) and associated mean per day monthly total solar radiation R_{MDMTSP} (W/m^2) of the PV array facing south

Month	1	2	3	4	5	6	7	8	9	10	11	12
a_m (°)	67	59	45	26	9	0	4	20	38	55	66	70
R_{MDMTSP} (W/m^2)	144	241	254	288	339	324	382	393	359	290	255	178

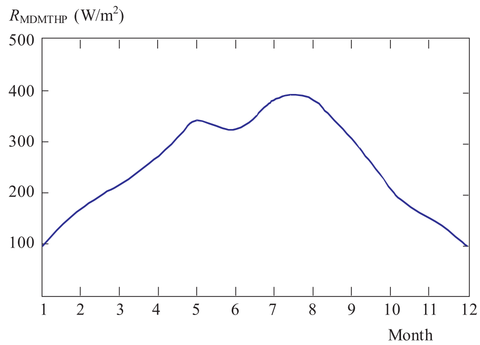

Fig. 3. Mean per day monthly values of total solar radiation R_{MDMTHP} (W/m^2) impinging on the PV panels at 0 °angle position

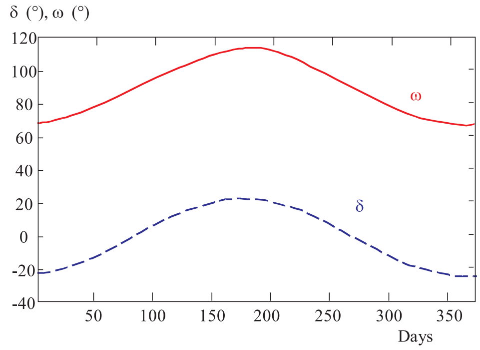

Fig. 4. Annual solar deviation δ (°) and sunset hour angle ω (°)

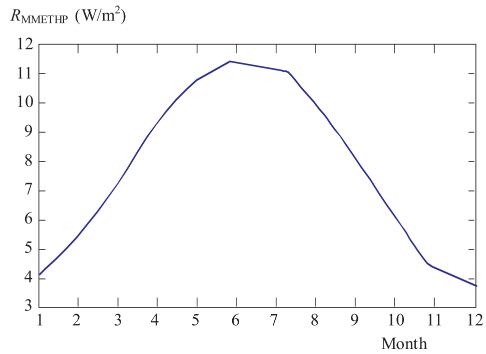

Fig. 5. Mean monthly values of extra-terrestrial radiation R_{MMETHP} (Kwh/day m^2) impinging on a horizontal plane being in the boundaries of the atmosphere

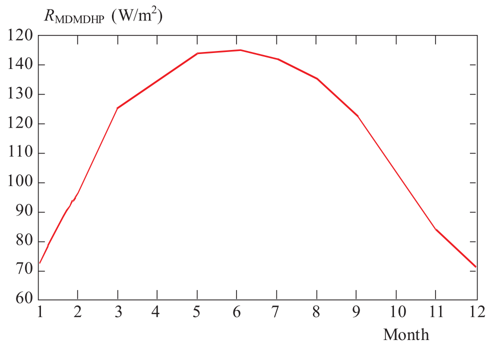

Fig. 6. Mean per day monthly values of the diffuse radiation R_{MDMDHP} (W/m^2) impinging on the PV panels at 0 °angle position

2.2 Description of the systematic procedure for optimum sizing of a RSAAPS

Unlike the grid-connected and hybrid PV systems, in RSAAPS the photovoltaic generator must provide the total power load demand. The major problem in RSAAPS is the determination of the optimum relationship between the PV array and the storage battery, so that the required amount of energy to be supplied with specific reliability. Therefore, before the installation of a RSAAPS, it is re-

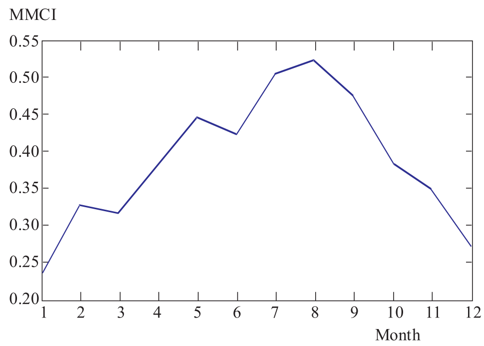

Fig. 7. Mean monthly clearness index MMCI

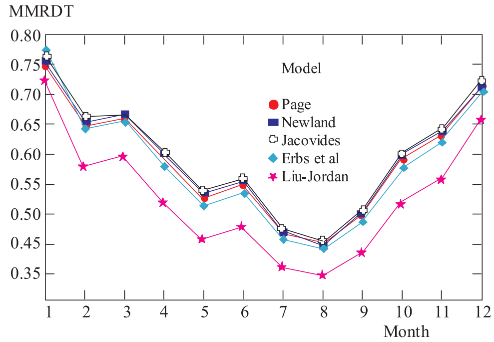

Fig. 8. Mean monthly values of the ratio MMRDT, being the mean monthly diffuse divided by the mean monthly total solar radiation on the PV panels at 0 °angle position

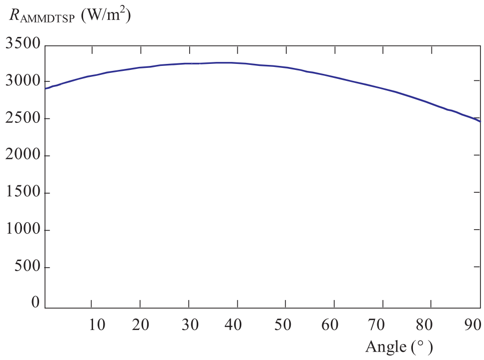

Fig. 9. Annual values of total solar radiation R_{AMMDTSP} ($\mathrm{W/m^2}$) impinging on a tilted PV panel position ($a \neq 0$) based on aggregate mean monthly per day values

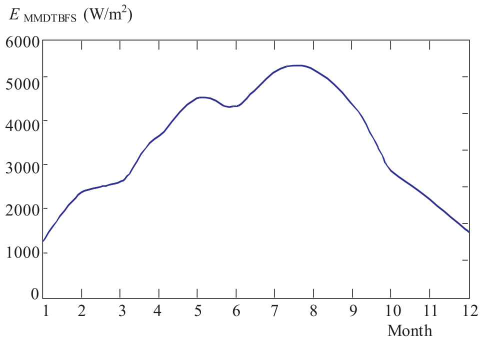

Fig. 10. Mean monthly per day values of total solar energy E_{MMDTBFS} ($\mathrm{Wh/m^2}$) impinging on the installed PV generator with a fixed tilt angle of 35 °

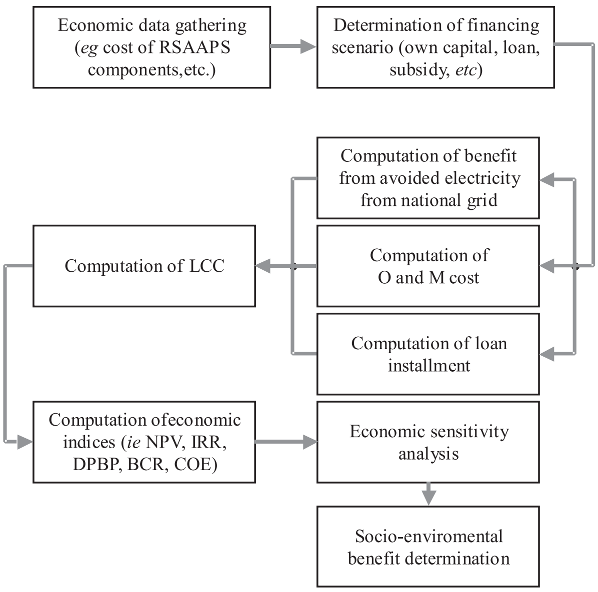

Fig. 11. A simplified representation of the proposed systematic procedure for performing economic analysis of a RSAAPS

quired to determine with precision the proper size of the PV generator and the battery storage system, in order to minimize the total cost of the system for a given loss of load probability (LLP). The models which may be used for the sizing of RSAAPS can be either empirical or numerical or analytical.

In this work the optimum RSAAPS size is based on the method described in [8], where at the beginning among a number of RSAAPS PV panels and batteries available in the world market the ones that satisfy certain necessary criteria are chosen. Then, the optimum size of these components is calculated and the type and properties of the other supplementary equipment, necessary for the complete RSAAPS installation, are identified.

Table 3. Determined four suitable RSAAPS using the proposed procedure (inverter input-output voltage and nominal power, number of batteries, number of PV panels, charger operating voltage and maximum current, maximum current of cables and fuses)

Suitable RSAAPS No	Inverter $U_{in} = 12$ V $U_{out} = 230$ V	PV panels	Charger 12 V I (A)	Cables (A)
1	408 W	6	26.4	45.5
2	408 W	6	26.4	45.5
3	832 W	13	30	92
4	832 W	13	30	92

In all RSAAPS there are 4 batteries

The main goal of the present case study is to design/install a RSAAPS in order to supply an AC load of 115 W (*eg* including a 60 W fan, a 40 W normal lamp, and a 15 W fluorescent lamp) for 10 hours daily (for the hours 9.00 to 18.00) and for 3 months of a year (June–July–August) with zero LLP. Based on pertinent technical and economic criteria two PV panel units (Unisolar US-64 [9] and Eurosolare PL810 [10]), and two battery units (Winner Apollo HGL100-12C [11] and Effecta BTL12-100 [12]) were chosen (from the available in the local market) to be evaluated for possible use. The complete investigation refers to the year 2006.

The investigation considered the four possible combinations of the above components, *ie*: (a) RSAAPS No.1 with Eurosolare PL810 and Winner Apollo HGL100-12C; (b) RSAAPS No.2 with Eurosolare PL810 and Effecta BTL12-100; (c) RSAAPS No.3 with Unisolar US-64 and Winner Apollo HGL100-12C; and (d) RSAAPS No.4 with Unisolar US-64 and Effecta BTL12-100. The obtained results of the examined four RSAAPS for the specified electric load and the above limitations are given in Table 3.

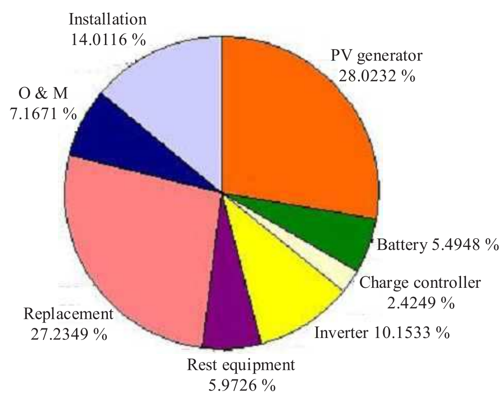

Fig. 12. Cost of every component of RSAAPS No.1 as percentage of its LCC

2.3 Description of the systematic procedure for economic evaluation of a RSAAPS

In general the Life Cycle Cost (LCC) of a RSAAPS has been reduced significantly over the last three decades, and this trend is expected to continue due to their mass production. RSAAPS use no fuel and are virtually maintenance free, but they have a high initial and non-recurring cost (equipment replacement, *etc*) a fact that may make them economically non viable. Moreover the €/kW cost for small-scale RSAAPS usually increases as the system size decreases. Thus, after the RSAAPS sizing procedure is completed, the economic evaluation of a number of RSAAPS candidates should be performed, and among them the most promising RSAAPS, *ie* the one with requiring minimum cost, is finally selected. This is accomplished by using the following well known economic indices [13, 14], *ie*: net present value (NPV), internal rate of return (IRR), benefit to cost ratio (BCR), discount pay back period (DPBP), and life cycle cost (LCC). In any energy production system/project, for competitive reasons, the associated cost of energy COE (€/kWh) is also computed. A simplified representation of the proposed systematic procedure for performing economic analysis of a RSAAPS is shown in Fig. 11.

Table 4. Applicable economic parameters and financing scenario

Parameters and financing scenario	Value	Units
Eurosolare PL810	391	€
Unisolar US-64	450	€
Winner Apollo HGL100-12C	115	€
Effecta BTL12-100	132	€
Siemens Atonic SR30	203	€
Sinewave IVT	850	€
Rest equipment	500	€
Installation cost	1173	€
Replacement cost 1*	2280	€
Replacement cost 2*	2415	€
O and M cost	30	€/year
Own capital (% of TIC**	100	%
Subsidy amount (% of TIC)	0	%
Loan amount (% of TIC)	0	%
Loan interest rate	5.652	%
Discount rate	5	%
Fuel inflation rate	2	%
Scale of taxation	40	%
Loan payback period	0	year
Economic life	20	year
Construction period	1	year
Purchase price of every kWh	0.069	€/kWh
Time period until first loan payment	0	year
Period of subsidy of loan interest	0	year
Interest rates subsidy	0	%
Purchase price of diesel	0.76	€/L
Distance from the grid	0	meter

* Where replacement cost is the cost of replacement for: (a) batteries (once every 5 years under normal operation); (b) inverter (once every 10 years under normal operation); and (c) Charge controller (once every 10 years under normal operation). Where replacement cost 1 is the replacement cost of the two RSAAPS with battery Winner Apollo HGL100-12C, and replacement cost 2 is the replacement cost of the other two RSAAPS with battery Effecta BTL12-100.
** Where TIC is the Total Initial Cost

Table 5. LCC values for the four examined RSAAPS

RSAAPS	No.1	No.2	No.3	No.4
	LCC (€)			
	8371.6	8573.3	11875	12077

In the present case study since the inverter and the charge controller of the four examined RSAAPS could have similar characteristics (see Table 3), two relatively inexpensive and reliable units are chosen from the local market, *ie* the Siemens Atonic SR30 charge controller [15] and the Sinewave IVT inverter [16]. After the necessary computations [13, 14], where the economic parameters and the financing scenario given in Table 4 are used, the values of Table 5 are obtained.

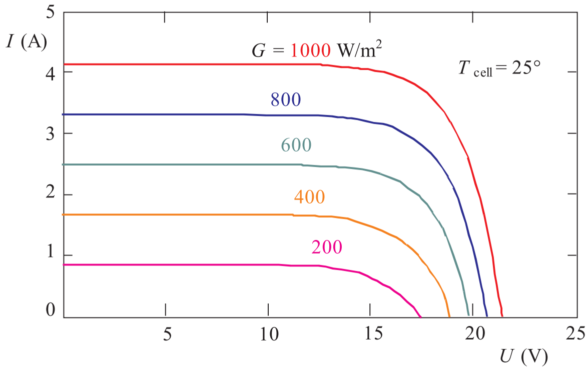

Fig. 13. I *vs* U characteristic curve of the PV panel for different values of total solar radiation $G\,(\mathrm{W/m^2})$ and fixed PV panel temperature T_{cell} = 25 °C, obtained from JPL model (the Lorenzo model and the associated measurements gave similar results)

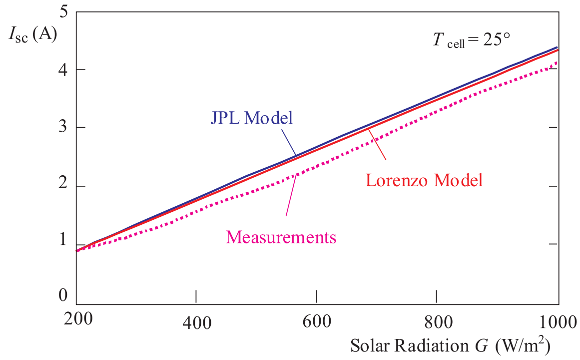

Fig. 14. Short circuit current I_{sc} of the PV panel for different values of total solar radiation G $(\mathrm{W/m^2})$ and for fixed PV panel temperature T_{cell} =25 °C obtained from JPL model, Lorenzo model and pertinent measurements

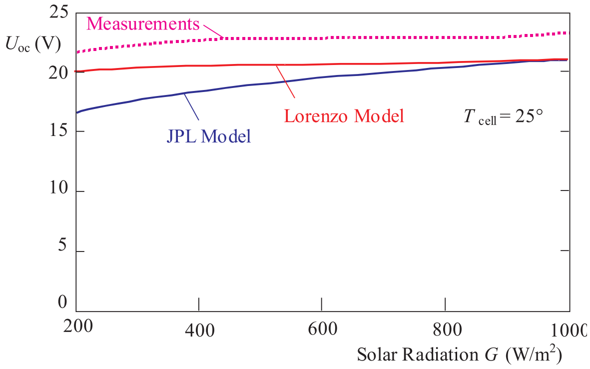

Fig. 15. Open circuit voltage U_{oc} of the PV panel for different values of total solar radiation G $(\mathrm{W/m^2})$ and for fixed PV panel temperature T_{cell} = 25 °C obtained from JPL model, Lorenzo model and pertinent measurements

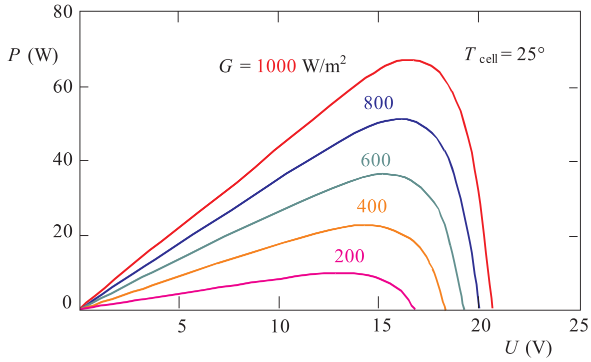

Fig. 16. P *vs* U characteristic curve of the PV panel for different values of total solar radiation G $(\mathrm{W/m^2})$ and fixed PV panel temperature T_{cell} = 25 °C, obtained from JPL model (the Lorenzo model and the associated measurements gave similar results)

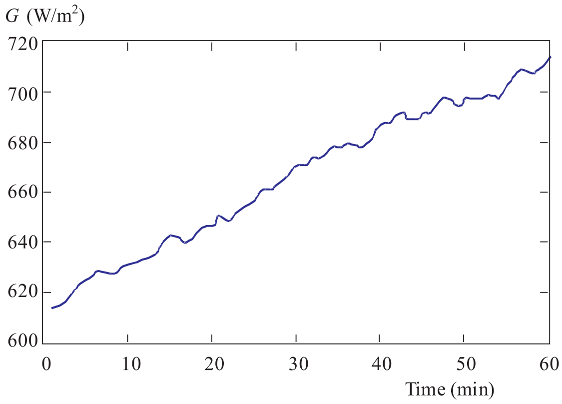

Fig. 17. Impinging total solar radiation G $(\mathrm{W/m^2})$ at the PV generator for a random period of one hour duration (*ie* from 9.00 *am* to 10.00 *am* on June 20, 2006)

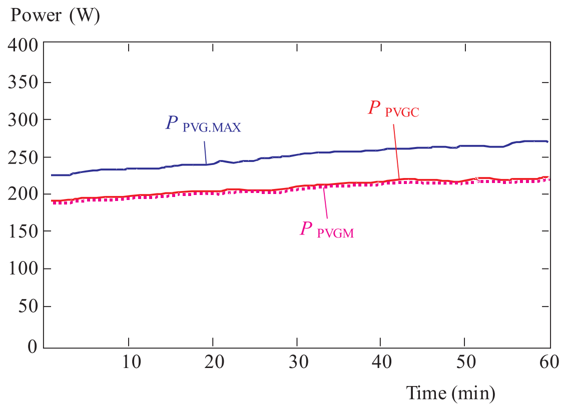

Fig. 18. PV generator measured output power P_{PVGM} (W), its computed (from the JPL model while the Lorenzo model gave similar results) output power P_{PVGC} (W) and its maximum (calculated with the Akbaba's model) output power $P_{\mathrm{PVG.MAX}}$ (W), for a random period of one hour duration (*ie* from 9.00 *am* to 10.00 *am* on June 20, 2006)

Table 6. Values of economic indices for RSAAPS No.1

IRR (%)	NPV (€)	BCR	DPBP (years)	COE (€/kWh)
4.9502	-36.7248	0.9896	>20	1.186

The economic parameters are based on the applicable latest electricity tariffs of the Greek Public Power Corporation (PPC), whereas the financing scenario follows the latest national development law and bank loan policy. From Table 5 it is clear that the most economically at-

Table 7. Sensitivity analysis of economic indices of RSAAPS No.1 as function of its PV generator cost (with respect to the base cost 391 €/PV panel)

ECR (%)	LCC (€)	IRR (%)	NPV (€)	BCR	DPBP (years)
0	8371.6	4.9502	-36.724	0.9896	>20
-10	8137	5.7502	193.406	1.0589	17.169
-20	7902	6.7502	423.538	1.1389	15.181
-30	7667	7.7502	653.669	1.2322	13.3707
-40	7433	8.9502	883.8	1.3425	11.7052
-50	7198	10.2502	1113.9	1.4748	10.1635

ECR = Expected cost reduction

Table 8. Sensitivity analysis of economic indices of RSAAPS No.1 as function of its distance of installation (L) from the electric grid

L (m)	LCC (€)	IRR (%)	NPV (€)	BCR	DPBP (years)
0	8371.6	4.9502	-36.724	0.9896	>20
31	8349.6	5.0502	-15.143	0.9957	>20
40	8151.6	5.7502	179.084	1.0543	17.3011
50	7931.6	6.5502	394.894	1.1283	15.4205
70	7491.6	8.6502	826.513	1.3132	12.1043
90	7051.6	11.2502	1258.1	1.5721	9.2558

Table 9. Sensitivity analysis of economic indices of RSAAPS No.1 as function of energy cost (€/kWh) of Greek utility (% variation from base tariff price 0,069 €/kWh)

Var (%)	LCC (€)	IRR (%)	NPV (€)	BCR	DPBP (years)
-6	8371.6	4.2502	-255.09	0.9275	>20
-3	8371.6	4.5502	-145.911	0.9585	>20
0	8371.6	4.9502	-36.724	0.9896	>20
3	8371.6	5.3502	72.462	1.0206	18.3202
6	8371.6	5.7502	181.649	1.0516	17.3781
9	8371.6	6.0502	290.836	1.0826	16.5289

Var= ± variation of grid energy tariff

tractive RSAAPS, among the examined four, is RSAAPS No.1. The selected RSAAPS (based on minimum LCC) should undergo further economic investigation. In order for this investigation to be complete, the following must also be determined:

- The cost of every component of the selected RSAAPS as percentage of its LCC (*eg* for RSAAPS No.1 see Fig. 12).
- The values of the economic indices of the selected RSAAPS (*eg* for RSAAPS No.1 see Table 6).
- The sensitivity analysis of the economic indices of the selected RSAAPS as function of the PV generator cost (*eg* for RSAAPS No.1 see Table 7).
- The sensitivity analysis of the economic indices of the selected RSAAPS as function of its distance of installation L from the electric grid (*eg* for RSAAPS No.1 see Table 8).
- The sensitivity analysis of the economic indices of the selected RSAAPS as function of energy tariff price (€/kWh) from electric utility (*eg* for RSAAPS No.1 see Table 9).
- The sensitivity analysis of the economic indices of the selected RSAAPS as function of percentage (%) of own capital, subsidy and loan ((*eg* for RSAAPS No.1 see Tables 10 and 11 under the assumption that the loan period is 6 years, the time period until the first loan payment is 1 year, and the investment's payment is 20 % per year for the first five years).

2.4 Description of the systematic procedure for socio-environmental benefits estimation of a RSAAPS

Based on the pertinent steps of [14, 17] the obtained important quantities from a detailed socio-environmental investigation are: (1) The avoided amount of diesel or lignite, which otherwise would have been consumed by a conventional (diesel or lignite) central electric power station for the production of an electric energy amount equal to that which is produced by the selected RSAAPS during its lifetime (*eg* for RSAAPS No.1 these quantities are 1.586 tones or 19.860 tones); (2) The associated avoided emissions during the lifetime operation of the selected RSAAPS, when compared to a power station mix (*ie* lignite and diesel) of a real electric power system (*eg* for RSAAPS No.1 and with respect to the Greek power system the relative avoided emissions are: CO_2 = 5996 kgr, SO_2 = 109 kgr, CO = 1.269 kgr, $N0_x$ = 8.465 kgr, and HC = 0.352 kgr); and (3) the associated annual social benefits (from avoided fuel and emissions) and their present value for lifetime operation of the selected RSAAPS (*eg* for RSAAPS No.1 these are 1102€ and 16162€, respectively).

Table 10. Sensitivity analysis of economic indices of RSAAPS No.1 as function of the percentage of own capital and subsidy (own/sub) with fixed loan 20%

own/sub (%)	LCC (€)	IRR (%)	NPV (€)	BCR	DPBP (years)
70/10	8371.6	8.3502	732.58	1.2974	12.783
60/20	8371.6	10.4502	1084.5	1.5136	10.3565
50/30	8371.6	13.2502	1436.4	1.8164	8.1841
40/40	8371.6	17.2501	1788.3	2.2704	6.2222

Table 11. Sensitivity analysis of economic indices of RSAAPS No.1 as function of the percentage of own capital and loan (own/loan) with fixed subsidy 20%

own/sub (%)	LCC (€)	IRR (%)	NPV (€)	BCR	DPBP (years)
70/10	8371.6	9.1502	907.69	1.3685	11.5408
60/20	8371.6	10.4502	1084.5	1.5136	10.3565
50/30	8371.6	12.0502	1261.3	1.7168	9.2362
40/40	8371.6	14.2502	1438	2.0216	8.1742

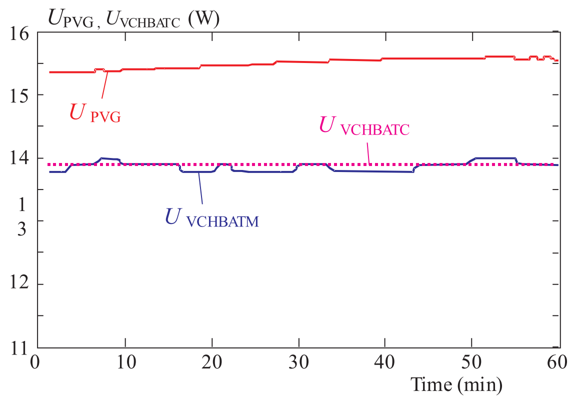

Fig. 19. Measured input voltage ($U_{\rm PVG}$) of charge controller, as well as its measured output voltage $U_{\rm VCHBATM}$ and its computed (from the model) output voltage $U_{\rm VCHBATC}$, for a random period of one hour duration (*ie* from 9.00 *am* to 10.00 *am* on June 20, 2006)

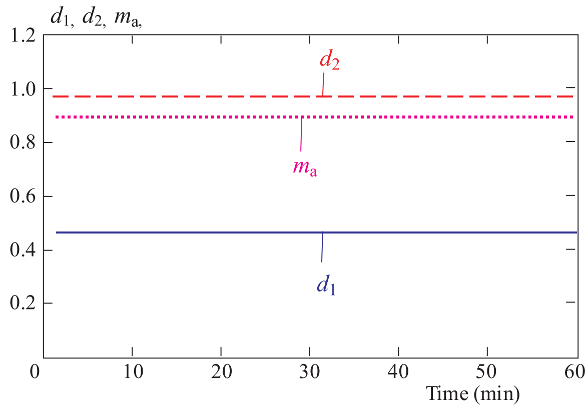

Fig. 20. Charge controller values of d_1 as well as inverter values of d_2 and m_a computed for a random period of one hour duration (*ie* from 9.00 am. to 10.00 *am* on June 20, 2006)

2.5 Description of the systematic procedure for energy assessment of a RSAAPS

A usual measure of the performance of a PV system is its conversion efficiency (CE), *ie* the ratio of its electric energy output divided by the energy of the falling sunlight on its PV generator:

$$CE = n_{pv}\, n_{BOS} = n_{pv}\left(n_{con} n_{bat} n_{inv} n_{cab}\right) \qquad (1)$$

where: n_{pv} is the efficiency of the PV generator/panel/cell, n_{con} is the efficiency of the charge controller, n_{bat} is the efficiency of the battery, n_{inv} is the efficiency of the inverter, and n_{cab} is the efficiency of the cables.

In the present case study, the efficiencies of BOS' components of the RSAAPS No.1 are: (1) $\eta_{con} = 90\%$; (2) $\eta_{bat} = 85\,\%$; (3) $\eta_{inv} = 94\,\%$; and 4) $\eta_{cab} = 97\,\%$. By substituting these manufacturer data in (1) the total BOS' efficiency is calculated and is $\eta_{BOS} = 69.7527\,\%$. Moreover, with additional input being the average monthly per day ambient temperature (°C), the average monthly per day temperature T_{cell} (°C) of the PV cell/panel/generator (assuming that the operating temperature of the PV generator is equal to the temperature of its panels and cells) and the average monthly per day efficiency $\eta_{PV}\%$ of the PV cell/panel/generator may be calculated [18, 19] (*eg* for RSAAPS No.1 see Table 12).

For the energy assessment procedure to be complete one uses the value of the total active surface F (m^2) of the PV generator (*eg* for RSAAPS No.1 it is $F = 4.045\,\mathrm{m}^2$) and the value of the dimensionless constant σ_p related to the degree of contamination of the PV generator (*eg* for RSAAPS No.1 it is $\sigma_p = 1$) and thus may compute [20] for the finally selected RSAAPS the values of monthly conversion efficiency CE, average daily per month electric energy output ADMEEA (Wh), average daily per month PV generator electric energy output $P_{\rm VGADMEEA}$ (Wh), average monthly per hour energy (Wh) available to charge the battery, and average monthly per hour energy (Wh) flowing directly from the PV generator to the AC/DC load (*eg* for RSAAPS No.1 see Tables 13 and 14).

Table 12. Average monthly per day ambient temperature (°C), average monthly per day temperature T_{cell} (°C) of the PV cell/panel/generator, and average monthly per day efficiency η_{PV} (%) of the PV generator/panel/cell

Year 2006	Ambient temp (°C)	Temp. (°C) computed	η_{PV} (%) computed	η_{PV} (%) measured
Jan	7.46	10.1123	10.68	10.3
Feb	3.419	7.9886	10.78	10.4
Mar	8.4539	13.4987	10.53	10.2
Apr	13.1684	18.1684	10.31	10.0
May	23.638	30.0871	9.77	9.6
Jun	27.5111	33.4792	9.61	9.5
Jul	28.1462	35.2428	9.53	9.5
Aug	29.5527	37.2421	9.44	9.4
Sep	22.5384	29.7306	9.78	9.6
Oct	16.3424	21.9119	10.14	10.0
Nov	12.4752	17.0848	10.36	10.1
Dec	8.3526	11.5249	10.62	10.3

2.6 Description of the systematic procedure for modeling of a RSAAPS

By following the modeling procedure of the RSAAPS one may forecast/understand the variation of its main variables. A brief description of each component model of the overall RSAAPS (shown in Fig. 1) is given below.

2.6.1 The PV panel/generator model

In order to compute the point values of the extremely nonlinear I *vs* U characteristic of a PV panel/generator (for various values of the impinging total solar radiation G (W/m^2) and PV cell/panel/generator temperature $T_{\rm cell}$), several mathematical models may be used. Two popular models are the JPL [3] and Lorenzo [19] ones. In Section 2.2 the sizing procedure was described where one chooses a PV panel unit and then calculates the needed number of such PV panels and also the way they should be connected, so as to synthesize the correct size of the PV generator. After this one can choose to use either the JPL or/and Lorenzo models, along with

Table 13. Computed and measured values of monthly conversion efficiency CE, average daily per month electric energy output ADMEEA (Wh), and average daily per month PV generator electric energy output P_{VGDAMEEA} (Wh)

Year 2006	Ce (%) computed	Ce (%) measured	(Wh) computed	(Wh) measured	P_{VG} (Wh) computed	P_{VG} (Wh) measured
January	7.45	7.2	382.85	370	491.62	474
February	7.52	7.25	736.68	710	826.13	797
March	7.34	7.1	816.31	790	877.45	850
April	7.19	6.9	1100.04	1056	1120.06	1099
May	6.81	6.7	1279.07	1258	1300.14	1278
June	6.70	6.6	1213.10	1195	1227.74	1214
July	6.64	6.6	1410.49	1401	1425.34	1421
August	6.58	6.5	1412.15	1395	1469.96	1463
September	6.82	6.7	1240.06	1218	1251.19	1228
October	7.07	6.9	883.99	863	929.61	917
November	7.22	7.0	669.08	649	796.98	777
December	7.40	7.2	441.54	430	506.43	491

the manufacturer data for the chosen PV panel (*eg* for RSAAPS No.1 it is the Eurosolare PL810) in order to model it.

For every component model one must validate the accuracy of its results by comparing them with the measured ones of the associated real component. Several on-site measurements can be made for this purpose using the real PV generator and high precision measurement instruments. Some related necessary information is:

i) The I *vs* U characteristic of the PV panel/generator for different values of total solar radiation $G\,(\mathrm{W/m^2})$ and for fixed PV panel temperature $T_{\mathrm{cell}} = 25$ °C (*eg* for RSAAPS No.1 see Fig. 13).

ii) The short circuit current I_{sc} and open circuit voltage U_{oc} of the PV panel/generator for different values of total solar radiation $G\,(\mathrm{W/m^2})$ and for fixed PV panel temperature $T_{\mathrm{cell}} = 25$ °C (*eg* for RSAAPS No.1 see Fig. 14 and Fig. 15).

iii) The output power P of the PV panel/generator as function of its output voltage U for different values of total solar radiation $G\,(\mathrm{W/m^2})$ and for fixed PV panel temperature $T_{\mathrm{cell}} = 25$ °C (*eg* for RSAAPS No.1 see Fig. 16).

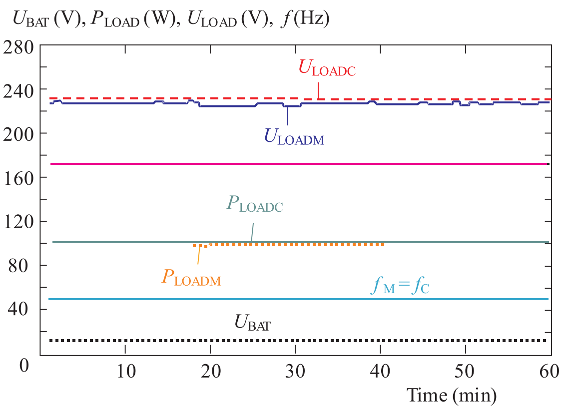

Fig. 21. Inverter measured input voltage (U_{BAT}) as well as its measured and computed (from the model) output power P_{LOAD}, output voltage U_{LOAD}, and frequency f

In the present case study, the RSAAPS No.1 does not include a MPP Tracker. Fig. 17 shows the values of the impinging total solar radiation $G\,(\mathrm{W/m^2})$ at the PV generator for a random period of one hour duration (*ie* from 9.00 *am* to 10.00 *am* on June 20, 2006) and Fig. 18 shows the associated values of the PV generator computed (from the JPL model while the Lorenzo model gave similar results) output power P_{PVGC} (W), its measured output power P_{PVGM} (W) as well as its maximum (calculated with the Akbaba's model [21]) output power $P_{\mathrm{PVG.MAX}}$ (W).

2.6.2 The charge controller model

In general the charge controller is a device which supplies the battery with its charging voltage U_{VCHBAT} (during normal charging), whereas it also protects the battery from overcharging (by switching accordingly the PV generator) and excessive discharging (by switching accordingly the DC loads). It can be modeled as a simple Buck - Boost DC-DC Converter [22], with a control unit, and a PWM generator being connected to the gate of its MOSFET (see Fig. 1). Thus, by knowing: (a) the PV generator output voltage U_{PVG} (being the input voltage of the charge controller); (b) the charging voltage of the battery U_{VCHBAT} (being the output voltage of the charge controller); and (c) the inductor (L_{CH}) and capacitor (C_{CH}) values of the Buck-Boost DC-DC Converter as well as the characteristics of its MOSFET and internal diode, then the charge controller unit of the RSAAPS can be modeled and the duty ratio d_1 values (given by $d_1 = \frac{U_{\mathrm{VCHBAT}}}{U_{\mathrm{PVG}}+U_{\mathrm{VCHBAT}}}$) of the PWM signal may be estimated.

In the present case study, the $U_{\mathrm{P\,VG}}$ is ranging from 0 to 21 V, $U_{\mathrm{VCHBAT}} = 13.8$ V, $L_{\mathrm{CH}} = 64.673\,\mu$H, $C_{\mathrm{CH}} = 10.33\,\mu$F, and the d_1 value was computed from the above expression using a divider (it was implemented via Matlab software, and in a real RSAAPS it may be a properly programmed microcontroller or DSP)

In order to validate the acceptable operation of the charge controller's model, one may connect a voltmeter to the input of the real charge controller and measure its input voltage U_{PVG}. At the same time, with another voltmeter connected to the output of the charge controller and in shunt with the battery (while not being fully charged), the output voltage of the real charge controller U_{VCHBATM} may be measured. Ultimately, the results obtained in this way should be compared with the corresponding ones computed from the model (*eg* for RSAAPS No.1 see Fig. 19 and Fig. 20).

2.6.3 The energy storage system (battery) model

The battery can be modeled using the Kinetic Battery Model (KiBaM) [23]. In this case the battery is considered as a generator, thus the charging current is negative and the discharging one is positive, while its internal resistance R_0 is considered to be constant. If the associated values of c (the fraction of the total charge in the battery that is readily available), k (the rate at which the available charge reverse is replenished from the chemical bound storage), $q_{\max}$ (maximum possible capacity of the battery), E_0 (extrapolated voltage at zero current of a fully charged battery), A (initial linear variation of internal battery voltage with state of charge), C and D (parameters reflecting the sharpness of end-of-discharge voltage drop), R_0 and the charging or discharging current of the battery are known, then the voltage of the battery and its state of charge (SOC) can be computed.

Table 14. Computed average monthly per hour energy (Wh) available to charge the battery, and average monthly per hour energy (Wh) flowing directly from the PV generator to the AC/DC load, for three months (of year 2006), where the RSAAPS No.1 supplies the load

	Energy		(Wh)	Energy		(Wh)
Hour	June	July	August	June	July	August
9.00	9.0	10.5	8.8	57.7	63.9	51.8
10.00	12.8	11.3	15.8	73.2	67.8	72.9
11.00	19.7	14.8	38.2	91.9	77.6	97.7
12.00	42.5	29.8	53.5	107.7	98.0	105.3
13.00	41.4	65.2	99.9	107.2	113.7	114.3
14.00	32.2	62.5	75.6	101.3	113.1	111.3
15.00	23.0	53.4	55.6	92.3	110.7	106.1
16.00	14.6	35.9	41.9	78.0	102.7	99.9
17.00	9.4	16.9	15.0	59.7	81.9	73.1
18.00	7.6	9.2	8.4	42.1	59.1	49.4

Table 15. Obtained results for the validation of the battery model (under discharge operation)

Load power (W)	Discharge current (A)	Battery voltage meas (V)	Battery voltage model (V)	SOC meas (%)	SOC model (%)
60	4	13	13.19	99	99
120	9	12.5	12.64	98	98
180	13	11.9	12.05	97	97

The values of the parameters k, c, $q_{\max}$ and R_0 of the model, being obtained from manufactures' data (or test data), can be assumed to be the same for charging and discharging (*eg* for RSAAPS No.1 they are $c = 0.416$, $k = 1.452$, $q_{\max} = 413.2$ and $R_0 = 0.0035\,\Omega$). Furthermore, by studying the manufacturer internal voltage curve of the battery as function of its state of charge the values of the additional parameters E_0, A, C and D can also be calculated (*eg* for RSAAPS No.1 and the discharging of the used battery they are: $E_0 = 13.6$ V, $A = -0.0066$, $C = -0.319$ and $D = 466.6260868$).

In order to validate the acceptable operation of the battery model, the battery voltage and its state of charge SOC can be measured (using proper instruments) from the real RSAAPS, by removing first the PV generator and the Inverter, and then connecting different DC loads on the terminals of the battery. If an ammeter is simultaneously connected in series with the battery, then its discharging current can be measured. Finally, the results obtained in this way should be compared with the corresponding ones computed from the model (*eg* for RSAAPS No.1 see Table 15).

2.6.4 The stand alone inverter model

Usually the stand alone inverter protects the battery from excessive discharging (by switching accordingly the AC loads) and at the same time supplies the needed AC power to the loads in compliance with all applicable power quality rules (*eg* in Greece these rules are: rms phase voltage $U_{\mathrm{INV,P,RMS}} = 230\,\mathrm{Volt} \pm 8\,\%$, frequency $f = 50 \pm 0.5$ Hz, power factor $\cos\varphi > 0.8$ (leading or lagging), and high harmonic purity). The stand alone inverter can be modeled as a forced-commutated, full-bridge, single-phase IGBTs voltage source inverter [22], with a Boost DC-DC Converter connected at its input (in order to increase/stabilize the input voltage of the inverter $U_{\mathrm{INV.IN}}$), a filter connected at its output, a control unit, and two PWM generators (one being connected to the gate of Boost DC-DC Converter MOSFET and the other one to the associated gates of the IGBTs), as shown in Fig. 1.

Therefore, by knowing: (a) the input voltage of the Boost DC-DC Converter (being the value of the battery voltage U_{BAT}); (b) its output voltage (being the input voltage of the inverter $U_{\mathrm{INV.IN}}$); (c) the inverter's rms phase output voltage $U_{\mathrm{INV,P,RMS}}$ and frequency f; d) the characteristics of the used IGBTs/MOSFET/internal diode, the inductor (L_{BC}) and capacitor (C_{BC}) values of the Boost DC-DC Converter, and the $L_F\, and\, C_F$ values of the used filter, then the inverter of the RSAAPS can be modeled and the duty ratio d_2 values (given by $d_2 = \frac{U_{\mathrm{INV.IN}} - U_{\mathrm{BAT}}}{U_{\mathrm{INV.IN}}}$) of the MOSFET PWM signal as long as the amplitude modulation index m_a values (for the linear region ($m_a \leq 1$) given by $m_a = \frac{U_{\mathrm{INV,P,RMS}}}{0.707 U_{\mathrm{INV.IN}}}$) of the IGBTs PWM signal may be estimated.

In the present case study, U_{BAT} ranges from 11.1 to 13.6 V, $U_{\mathrm{INV.IN}} = 360$ V, $U_{\mathrm{LOAD}} = U_{\mathrm{INV,P,RMS}} = 230$ V, $f = 50$ Hz, $L_{\mathrm{BC}} = 51.4\,\mu$H, $C_{\mathrm{BC}} = 9.2\,\mu$F, $L_F = 9$ mH, $C_F = 9$ nF, as well as the d_2 and m_a values were computed from the above expressions using two dividers (these two dividers were implemented via Matlab software, and in a real RSAAPS application they may be programmed using a microcontroller or a DSP).

In order to validate the acceptable operation of the inverter's model, one may connect a load to the output of the real inverter (*eg* for RSAAPS No.1 it is a 100 W AC lamp), and simultaneously measure with the use of appropriate measurement instruments: the battery voltage U_{BAT}, the inverter's output power P_{LOADM}, its output voltage U_{LOADM} and the frequency f_{M}. Eventually, the results obtained in this way should be compared with the corresponding ones (*ie* P_{LOADC}, U_{LOADC} and f_C) computed from the model (*eg* for RSAAPS No.1 see Fig. 20 and 21).

3 DISCUSSION

Based on the results of the solar potential evaluation it can be stated with certainty that in the specific site of Xanthi the solar potential is fairly high (with its highest values appearing during summer months) a fact which strengthens the suitability of PV system installations (particularly of grid-connected type), in order to essentially assist in meeting the continuously growing world electricity demand (usually at summer months). Moreover, it has (as expected) a statistical nature and is continuously fluctuating, a fact that mostly favours the grid-connected and/or hybrid PV systems for the purpose of covering high loads throughout the year and also with high reliability. The monthly change of the PV generator slope is considered beneficial, but if this slope is to remain fixed then its proper value is near to the latitude value (*eg* for the PV generator of RSAAPS No.1 this slope is $35°$).

The economic analysis shows, in practical terms, that small-scale RSAAPS (*eg* RSAAPS No.1) are not yet economically competitive by comparison to conventional electric grids when are constructed only with own capital and are placed near the electric grid. These RSAAPS become economically viable when the electric energy tariff of the electric utility is increasing and their distance of installation (L) from the electric grid is relatively long (*eg* for RSAAPS No.1 $L = 31.7$ m). In addition, the higher the applied percentage of subsidy or loan is the greater their economic viability becomes. If a small-scale RSAAPS were properly designed/constructed and some economic incentives (subsidy, loan, *etc*) were provided by national policy, then this may become an economically viable energy production scheme.

The cost associated with a small-scale RSAAPS is highly sensitive to the cost of its PV generator (which is the most expensive system component) and becomes economically viable when the PV generator cost is decreasing. In addition, a high percent of its LCC is spent for purchase, installation, maintenance and replacement of its batteries (this real disadvantage is sufficient to justify the use of a grid-connected PV system instead, wherever this is possible). On the other hand, the active participation of the users/owners of the system might help to improve RSAAPS operation and to reduce adequately its LCC (resulting in lower installation and maintenance cost). It is also to be noted that, nowadays, the remarkable actual decrease in the purchase price of BOS' components (due to their technological development and mass production) follow similar trends to those of PV modules during the last ten years.

From the obtained socio-environmental assessment results, it is clear that even in the case of a small-scale RSAAPS the associate electricity production is a highly clean process which really benefits the environment. In this investigation some secondary environmental factors (*ie* acoustic noise from conventional power stations, environmental impact from RSAAPS components manufacturing, *etc*) are not taken into consideration.

The performed energy assessment indicates that the efficiency of the PV generator/panel/cell is very low, whereas the small differences between measured and computed values are mainly due to the effect of aging, accumulation of dust and cooling effect of high wind speeds on the PV modules. Furthermore, the percentage of the PV generator electric energy output, which is available to charge the battery, is remarkably high and in conjunction with the low efficiency of the batteries makes the RSAAPS less efficient than the corresponding utility interactive system without batteries (since the electric grid transmission losses are much lower than the losses due to poor battery efficiency). Ultimately, the low CE and consequently the electric energy output of RSAAPS are evident, which necessitates the continuous optimization of the individual efficiencies of its components and the adaptation of an intelligent electric load demand site management.

It was proved that the models of the system components were sufficiently adequate. The possible small differences between the measured results and the associated computed ones (from the models) are mostly due to inherent imperfection of these models, the degree of accuracy of the measuring instruments being used, and also due to the time degradation of the real components. More specifically, the results obtained from JPL and Lorenzo models almost coincide (except in their U_{0C} values where the values of the Lorenzo model show better agreement with the associated measured ones) and generally show good agreement with the measured ones.

Finally, the produced electric energy from a PV panel/generator without using MPP Tracker is lower enough than the case where a MPP Tracker is present (for RSAAPS No.1 this difference reaches a maximum value of 20%). Moreover, after the construction of the RSAAPS its total electric energy production depends on its parameters and real climatic conditions, and it is not a function of the possible different used loads.

4 CONCLUSIONS

By all means a RSAAPS is a mature and rapidly improving technology suitable for a variety of applications (where all residential electrical/electronic appliances can be supplied with a RSAAPS). This system is expected to be competitive in the market of distributed energy generation in the foreseeable future. This work promotes RSAAPS exploitation by proposing a general and systematic procedure for thorough study (optimum sizing; technical, economic and socio-environmental assessment; and simulation of system operation) of such powerful sustainable energy supply systems. A case study of a real small-scale RSAAPS was extensively investigated using the proposed procedure and the relevant mathematical models were tested and amply validated, while the following were clearly demonstrated: a RSAAPS can have safe operation and it presents real potential to become an alternate and economically viable energy supply option with serious positive impact to the protection of the environment.

References

[1] PAPADOPOULOS, D. P.—SKRETAS, S. B.: A New Approach for Securing Efficient Operation of a Water-Pumping System fed by a PV Generator, ICEM XVII, Chania, Grete Island, Greece, 2-5 September 2006.

[2] ABDULLAH, A. H.—GHONEIM, A. A.—Al-HASAN, A. Y.: Assessment of Grid-Connected Photovoltaic Systems in the Kuwaiti Climate, Renewable Energy **26** No. 2 (2002), 189–199.

[3] BOROWY, B. S.—SALAMEH, Z. M.: Methodology for Optimally Sizing the Combination of a Battery Bank and PV Array in a Wind/PV Hybrid System, IEEE Transactions on Energy Conversion **11** No. 2 (1996), 367–375.

[4] LIU, B. Y. H.—JORDAN, R. C.: The Interrelationship and Characteristic Distribution of Direct, Diffuse and Total Solar Radiation, Solar Energy **4** No. 3 (1960), 1–19.

[5] TIRIS, C.—TIRIS, M.: Effect of Collector Orientation on Solar Energy Availability, Energy Conversion and Management **39** No. 8 (1998), 843–852.

[6] FIRATOGLU, Z. B.—YESILATA, B.: New Approaches on the Optimization of Directly Coupled PV Pumping Systems, Solar Energy **77** No. 1 (2004), 81–93.

[7] ZEROUAL, A.—ANKRIM, M.: The Diffuse – Global Correlations: Its Application to Estimating Solar Radiation on Tilted Surfaces in Marrakesh, Marocco, Renewable Energy **7** No. 1 (1996), 1-13.

[8] Sandia National Laboratories: Stand-alone photovoltaic systems. A handbook of recommended design practices, Photovoltaic design assistance center, Albuquerque New Mexico, March 1995.

[9] http://www.solion.com.gr/enversion/pdf/Unisolar%20US.pdf .

[10] http://www.photon.de/old-stuff/marktuebersichten/Solarmodule_Page23.htm .

[11] http://www.winnerbattery.net/.

[12] http://www.solion.com.gr/batteries_gr.htm.

[13] IRVING, G.: Modern CostBenefit Methods: an Introduction to Financial, Economic and Social Appraisal of Development Projects, Macmillan, London, 1978.

[14] KATSIGIANNIS, P. A.—PAPADOPOULOS, D. P.: A General Technoeconomic and Environmental Procedure for Assessment of SmallScale Cogeneration Scheme Installations: Applications to a Local Industry Operating in Thrace, Greece, Using Microturbines, Energy Conversion and Management **46** No. 20 (2005), 3150-3174.

[15] http://www.solarpower.co.il/PDF/steca-solarix.pdf.

[16] http://www.compasolar.gr/ivt.htm.

[17] SPIEGEL, R. J.—LEADBETTER, M. R.—CHAMU, F. Distributed Grid-Connected Photovoltaic Power System Emission Offset Assessment: Statistical Test of Simulated - and Measured - Based Data: Solar Energy **78** No. 6 (2005), 717–726.

[18] MATTEI, M.—NOTTON, G.—CRISTOFARI, C.—MUSELLI, M.—POGGI, P.: Calculation of the Polycrystalline PV Module Temperature Using a Simple Method of Energy Balance, Renewable Energy **31** No. 4 (2006), 553–567.

[19] LORENZO, E.: Solar Electricity, Engineering of Photovoltaic Systems, Institute of Solar Energy, Polytechnic University of Madrid, 1994.

[20] SORAS, C.—MAKIOS, V.: A Novel Method for Determining the Optimum Size of Stand-Alone Photovoltaic Systems, Solar Cells **25** No. 2 (1988), 127–142.

[21] AKBABA, M.—ALATTAWI, M. A. A.: A New Model for I-V Characteristic of Solar Cell Generators and its Applications, Solar Energy Materials and Solar Cells **37** No. 2 (1995), 123–132.

[22] MOHAN, N.—UNDERLAND, T. M.—ROBBINS, W. P.: Power Electronics Converters, Applications and Design, 2nd edition, John Willey and Sons Inc., 1995.

[23] MANWELL, J. F.—McGOWAN, J. G.: Lead Acid Battery Storage Model for Hybrid Energy Systems, Solar Energy **50** No. 5 (1993), 399-405.

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