Renewable Energy 34 (2009) 65–70

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Reliability and economic evaluation of small autonomous power systems containing only renewable energy sources

Pavlos S. Georgilakis*, Yiannis A. Katsigiannis

Department of Production Engineering and Management, Technical University of Crete, University Campus, GR-73100 Chania, Greece

ARTICLE INFO

Article history:
Received 6 November 2007
Accepted 5 March 2008
Available online 11 June 2008

Keywords:
Autonomous power systems
Reliability cost
Reliability worth
Renewable energy sources
Sensitivity analysis

ABSTRACT

Evaluation of reliability performance in every power system has to be done within a cost–benefit framework. This approach, however, is a very time consuming task, especially for systems that contain a large number of possible configurations, so simpler techniques referred to the calculation of reliability indices are used. In small autonomous power systems (SAPSs), such an evaluation uses mainly deterministic criteria. This approach, however, cannot be applied in SAPS that contain only renewable energy sources, due to the intermittent nature of the provided energy. In this paper, a complete reliability cost and worth analysis is implemented for these systems, combined with the calculation of some basic probabilistic indices, in order to discover their performance and propose the appropriate of them as a criterion of optimal system configuration. This paper proposes that normalized energy reliability indices as system minutes and energy index of unavailability can be used as adequate criteria of system's optimal performance. This conclusion is validated through a large number of sensitivity analysis studies that are based on different maximum annual loads and different mix of load types.

1. Introduction

The basic function of a modern electric power system is to provide an adequate electrical supply to its customers as economically as possible and with a reasonable level of reliability [1]. Normally, system reliability increases with investment cost. Moreover, the customer damage cost decreases as the reliability level increases [2]. Reliability evaluation is crucial in small autonomous power systems (SAPSs), as they present some unique characteristics that are related with their distance from the electrical grid and the small amount of load that they have to serve.

Generally, there are three methods of supplying energy in rural areas: grid extension, use of fossil fuel generators, and hybrid power systems with renewable energy sources (RESs) [3]. In isolated or remote areas, the first two methods can be too expensive. Grid electrification is costing upwards 3000$ per connection [4], while the cost of fossil fuel delivery in these areas may be greater than the cost of the fuel itself. The use of decision support systems aims the multidimensional decision-making process regarding the choice of RES for energy supply in isolated regions [5].

RES can often be used as a primary source of energy in such systems, as they are usually present in geographically remote and demographically sparse areas. Moreover, RES is delivered to the site by nature, at no cost. However, since renewable technologies are dependent on a resource that is not dispatchable, there is an impact on the reliability of the electric energy of the system, which has to be considered. The basic way to solve this problem is to use storage as a type of energy-balancing medium [6]. In SAPS, either battery or flywheel storage can be used.

The fact that the cost of RES technologies (especially wind energy) has been significantly reduced recently, combined with the subsidy provided in many countries, makes their installation and operation very popular and attractive nowadays. This creates a need for developing comprehensive techniques that can be used to evaluate the economics involved [7] and the reliability of power supply that can be achieved from the utilization of these energy sources.

There are three basic approaches used in the reliability evaluation of power systems: (a) deterministic techniques, (b) probabilistic methods and (c) Monte Carlo simulation. Deterministic techniques are the basic criteria in SAPS, but they have the disadvantage that they did not recognize inherent uncertainties that have serious impact on reliability performance, such as random components' failure and customer load demands [8]. The basic deterministic criteria in SAPS are fixed capacity reserve margins, the loss of the largest unit and combinations of the two [9]. These criteria, however, cannot be applied in a system that contains only RES, since the capacity of such a system varies continuously with local atmospheric conditions and is not a fixed deterministic value. Probabilistic

* Corresponding author. Tel.: +30 28210 37312; fax: +30 28210 69410.
E-mail addresses: pgeorg@dpem.tuc.gr (P.S. Georgilakis), katsigiannis@dpem.tuc.gr (Y.A. Katsigiannis).

0960-1481/$ – see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.renene.2008.03.004

Table 1
Alternative cases of renewable resources

Case	Description
Case 1	Original wind and solar data of Kythnos island for year 2002.
Case 2	10% Increase on hourly solar energy and 10% increase on wind speed of Case 1 (+33% wind energy in comparison with Case 1).
Case 3	10% Decrease on hourly solar energy and 10% decrease on wind speed of Case 1 (−27% wind energy in comparison with Case 1).

methods overcome the problems of deterministic techniques, but they cannot completely recognize the chronological variation of intermittent sources such us wind speed and solar energy. These factors can be incorporated using the Monte Carlo simulation, which, however, increases significantly the computation time.

In order to evaluate the performance of a power system, probabilistic indices criteria are often used to determine the accepted adequacy criterion of the system. However, this criterion should be determined from a reliability cost and worth analysis or from planning experience [10].

Reliability evaluation of power systems with RES has attracted the interest of researchers worldwide. The impact of acceptable reliability level on a stand-alone photovoltaic system energy balance is examined in Ref. [11] and the conclusion is that a remarkable initial cost reduction is encountered as system reliability value drops from 100% to 95%. In Ref. [12], a complete study, from reliability point of view, is presented in order to determine the impact of interconnecting photovoltaic/wind system into utility grid. In Ref. [13], a methodology for reliability analysis of stand-alone proton exchange membrane fuel cell power plants is developed based on Markov model. Reliability improvement of isolated generation systems by photovoltaic ac fusion converters is studied in Ref. [14].

This paper proposes a reliability and cost evaluation methodology for SAPS that contain only RES. An extensive reliability cost and worth analysis has been applied for various load types that contain three possible renewable resource cases: normal (based on actual data), optimistic and pessimistic. For each case, five basic reliability probabilistic indices have been estimated, combined with a cost index of unsupplied energy. Then an inspection of the performance of these indices has been accomplished as measures of minimum system's overall cost, in order to use the appropriate of them as a direct criterion of evaluating system's optimum configuration, and bypass the time consuming stage of thorough inspection of these indices on a large number of feasible configurations. Finally, a comparison of resulted costs has been done.

The paper is organised as follows. Proposed methodology and considerations that have been made are presented in Section 2. Section 3 provides a brief description of the examined system. The obtained results and a wide sensitivity analysis are presented in Section 4. Section 5 concludes the paper.

2. Proposed methodology

The components of the studied SAPS contain a combination of ac wind turbines (WTs), photovoltaics (PVs) and battery storage. A converter that contains inverter and rectifier is also considered, so an optimum management of system's power flow can be achieved. The analysis refers only to generation facilities and neglects impacts from the transmission and distribution system. Moreover, no forced outage rate for any device of the system has been taken into account, in order to focus on the interruptions driven by the incapability of the system to meet the load demand.

For the calculation of system's overall reliability, an annual hourly simulation (8760 h) has been made, taking into account the renewable resources, the hourly load curve and the characteristics of the battery. More specifically, solar and wind resources were taken from measurements on Kythnos island for the year 2002. The hourly load curve follows the chronological load shape of the IEEE-RTS [15], while three different load types have been considered that will be described in Section 3. For each load type, a sensitivity analysis on the value of wind and solar resource has been made, as presented in Table 1. Finally, the capacity curve and lifetime curve of the battery have been considered during the simulation.

A variety of probabilistic indices can be calculated, in order to evaluate the performance of a power system in a reliability framework. The two basic probabilistic indices used are the loss of load expectation (LOLE) and the loss of energy expectation (LOEE). LOLE is defined as the average number of hours for which the load is expected to exceed the available capacity. On an annual basis, LOLE can be expressed mathematically as

$$\mathrm{LOLE} = \sum_{i=1}^{8760} t_{\mathrm{outage}}(i) \qquad (1)$$

where $t_{\mathrm{outage}}(i)$ is equal to 1 for the case that the load in hour i is greater than the generating capacity plus the battery storage level and 0 otherwise. LOEE is defined as the expected energy (in kWh) that will not be supplied when the load exceeds the available generation, and can be expressed as

$$\mathrm{LOEE} = \sum_{i=1}^{8760} e_{\mathrm{unserved}}(i) \qquad (2)$$

where $e_{\mathrm{unserved}}(i)$ is the energy not supplied in the hour i of the year. However, the actual benefits of a power system's operation can only be assessed by conducting relevant cost and reliability studies. It is therefore important to determine the optimal reliability level at which the reliability investment achieves the best results in reducing the customer damage costs due to power supply interruptions. This approach can be expressed mathematically as

$$\text{Minimize}: \quad \text{total cost} = \text{investment cost} + \text{customer damage cost} \qquad (3)$$

For the calculation of the expected customer damage cost, the customer damage functions (CDFs) have been used [16]. The CDF is

Table 2
CDF values ($/kW)

	Interruption duration		
User sector	1 h	4 h	8 h
Agricultural	0.649	2.064	4.120
Residential	0.482	4.914	15.690

Table 3
Periods of supplementary residential load in composite type

Period description	Days	Hours
New year's week vacation	1–7	1–168
Easter vacation (mid-April)	99–112	2353–2688
Summer vacation (June–September)	148–273	3529–6552
Christmas vacation	358–365	8569–8760

Table 4
SAPS component characteristics

Component	Minimum size	Cost ($)	O&M ($/yr)	Lifetime
WT	30 kW (rated)	60 000	400	20 Years
PV	1 kW	6000	0	20 Years
Battery	4 × 7.6 kWh	4000	40	4 × 10 500 kWh
Converter	2 kW	2500	0	20 Years

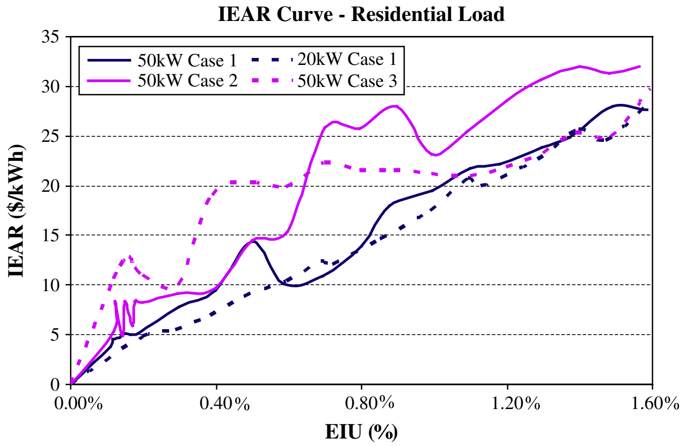

Fig. 1. IEAR curves for residential systems.

an index (expressed in $/kW) that depends on the type of user and the interruption duration. There is a small number of published studies that contain interruption cost data. Refs. [17] and [18] contain data for the power utilities of Canada and United Kingdom, respectively. Similar studies in Greece [19] have shown coincidence with the Canadian results. The values of CDFs, limited for the type of users that considered in our study, are presented in Table 2. Interruption costs for durations different than the values shown in Table 2 were estimated using the same slope of the straight line joining the two nearest duration values of Table 2.

In the case of multiple customer types that belong to the same service area, each sector CDF can be aggregated in order to produce the composite customer damage function (CCDF). The weighing used to produce the CCDF is usually done in terms of per-unit energy for each sector. The CCDF can then be converted into an extended index that links system reliability with customer interruption costs. One suitable form is the interrupted energy assessment rate (IEAR), expressed in $/kWh of unsupplied energy. The estimation of the IEAR indicates the severity, frequency and generation of the expected states of the generation model. In order to compute the IEAR, the expected customer interruption cost (ECOST) in $/yr must be estimated first, taking into account the duration of interruption, the value of CCDF and the unserved energy of each interruption. Then, IEAR can be calculated as follows:

$$\mathrm{IEAR} = \frac{\mathrm{ECOST}}{\mathrm{LOEE}} \tag{4}$$

Sensitivity analyses have shown that in a power system that consists of conventional generation sources, IEAR is reasonably stable and does not vary significantly with peak load or other operating conditions [16]. Such estimation simplifies significantly the calculation of total cost, as it can be deduced directly from investment cost and LOEE. The case of SAPS containing only RES can be fairly different, due to the intermittent nature of renewable resources as well as due to the fact that each component of the system is highly modular in the increment of its capacity. The variation of IEAR in such a system is examined in Section 4.1.

For the investigation of SAPS performance, five reliability indices have been selected: (1) LOLE, (2) EIU (energy index of unavailability), (3) SMs (system minutes), (4) DOI (duration of interruption), and (5) ENSI (energy not supplied index). More specifically, in the investigation of SAPS performance, LOLE is included as well as two energy indices different from LOEE, due to the fact that our study contains systems with different peak loads that have to be compared on equal basis. In order to achieve this, LOEE is normalized with total energy demand and with load peak demand to produce the energy index of unavailability (EIU) and system minutes (SMs), respectively [20]. EIU is calculated using

$$\mathrm{EIU} = \frac{\mathrm{LOEE}}{E} \tag{5}$$

where E is the total energy demanded, while SM is calculated using

$$\mathrm{SM} = \frac{\mathrm{LOEE}}{L_{\mathrm{p}}} 60 \tag{6}$$

where L_{p} is the peak load. Moreover, two additional indices have been calculated [16]: duration of interruption (DOI) and energy not supplied index (ENSI). DOI is expressed in hours per interruption (h/int) and has been selected in order to study the effect of long time interruptions in the evaluation of system's cost, while ENSI is expressed in kWh per interruption (kWh/int) and has been selected in order to study the effect of large amount of interrupted energy in cost estimation.

This study contains an evaluation of the described probabilistic indices, aiming to compare their performance in the calculation of the minimum system cost provided by Eq. (3). The results are validated through a large number of sensitivity analysis studies that are based on different maximum annual loads and different mix of load types.

Table 5
Optimal configuration of agricultural system

Case	Optimal configuration	EIU (%)	COE ($/kWh)
Case 1	3 WT, 1 kW PV, 128 bat., 16 kW conv.	0.48	0.393
Case 2	2 WT, 2 kW PV, 132 bat., 16 kW conv.	0.40	0.340
Case 3	3 WT, 12 kW PV, 132 bat., 16 kW conv.	0.49	0.476

Table 6
Optimal configuration reliability indices for agricultural system

Case	EIU (%)	SM	LOLE	DOI (h/int)	ENSI (kWh/int)
Case 1	0.48	1544	98	2.45	12.87
Case 2	0.40	1287	90	2.37	11.29
Case 3	0.49	1571	123	2.80	11.90

3. Case studies

For the SAPS study, three types of annual peak load demands have been considered. In the first type, the user is supposed to be agricultural with annual peak load demand of 20 kW, while in the second type the user is considered to be residential with annual peak load demand of 50 kW. Finally, in the third type the load is supposed

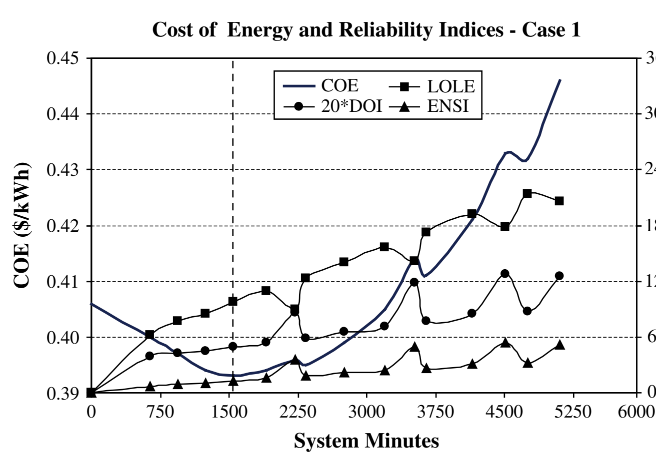

Fig. 2. Reliability indices performance for Case 1 of agricultural load.

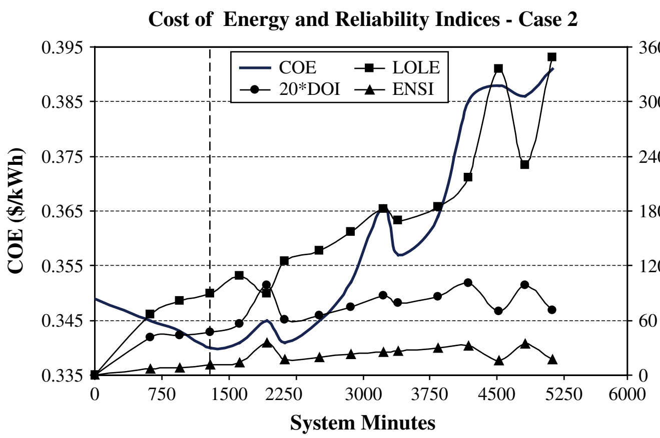

Fig. 3. Reliability indices performance for Case 2 of agricultural load.

Table 7
Optimal configuration of residential system

Case	Optimal configuration	EIU (%)	COE ($/kWh)
Case 1	7 WT, 15 kW PV, 328 bat., 48 kW conv.	0.00	0.403
Case 2	5 WT, 17 kW PV, 312 bat., 44 kW conv.	0.00	0.349
Case 3	9 WT, 15 kW PV, 384 bat., 48 kW conv.	0.00	0.481

to be composite that consists of agricultural and residential users. More specifically, the permanent population is supposed to be agricultural with annual peak load of 20 kW, while a temporary population of residential type is considered that is added in the periods described in Table 3 and has an annual peak load of 30 kW.

For each system configuration, the cost of energy (COE) has been calculated. The lifetime of the project is considered to be 20 years with an annual interest rate i of 8%. The rated power of WT is supposed to be 30 kW with cut-in speed at 4 m/s, rated wind speed at 8–22 m/s and cut-out speed at 24 m/s [21]. The basic assumptions containing minimum increments in each component size, initial cost, operation and maintenance (O&M) cost and lifetime are presented in Table 4. The efficiency of the PVs, the inverter, and the rectifier is 15%, 90%, and 85%, respectively, while no tax reductions or subsidies are considered.

4. Results and discussion

4.1. Variation of IEAR

The variation of IEAR in relation with EIU for the case of residential systems is presented in Fig. 1. The depicted curves represent the three cases of Table 1 for the 50 kW residential system, while a modified version of Case 1 for the 20 kW system has been considered, in which the customer type is supposed to be residential (instead of agricultural). Although there is an increasing trend in each one of the curves, their shape varies significantly for different operating conditions (50 kW curves), as well as for different peak loads (Case 1 curves). Similar conclusions can be obtained from the study of the remaining load types. As a result, IEAR does not remain stable for systems containing only RES, and has to be calculated separately for each configuration.

4.2. Agricultural load

Table 5 shows the configurations with the lowest COE of a 20 kW agricultural system for the three cases of solar and wind data of Table 1. As expected, COE has smaller value for Case 2, while EIU has similar values for all configurations and presents a small incremental trend as the solar and wind potential is decreased.

Table 6 presents the values of the five reliability indices for the optimal configuration described in Table 5. Figs. 2–4 show the variation of LOLE, DOI (multiplied by 20) and ENSI for different levels of power interruptions, expressed as a function of SM. Although EIU can be also used as a power interruption index that gives similar results, SM index is preferred because of its larger range of values. The vertical dotted line in Figs. 2–4 represents the point with the lowest COE for each case. From the study of Figs. 2–4, it is concluded that none of the three fluctuating reliability indices (LOLE, DOI, and ENSI) can be used as criterion of optimal system configuration. On the other hand, SM (and consequently EIU) presents nearly constant values for the three cases at their lowest COE: 1500 for SM and 0.50% for EIU.

4.3. Residential load

The case of residential customers has the characteristic that the lowest cost is achieved when no power interruptions exist, so all reliability indices are equal to 0. As can be seen from Table 7, the optimum value of COE is slightly increased in comparison to the corresponding values of agricultural customers. Fig. 5 compares the increase of COE in relation with SM. It can be deduced from Fig. 5 that Case 3 has the trend to increase its COE with higher rates, as the amount of interrupted energy increases.

4.4. Composite load

The optimal configuration of each case for the composite load scenario is presented in Table 8. The value of COE is significantly

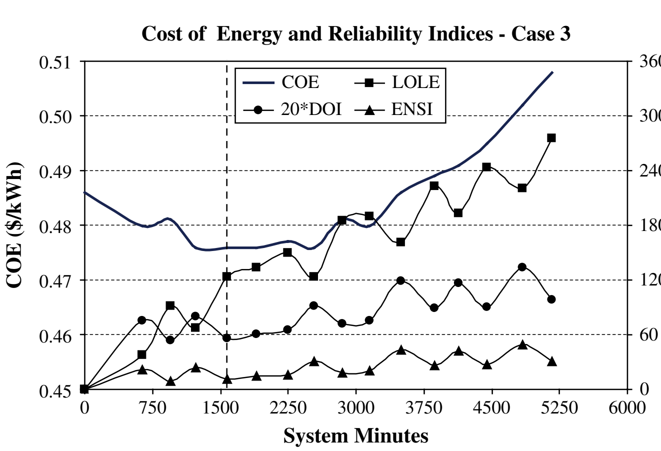

Fig. 4. Reliability indices performance for Case 3 of agricultural load.

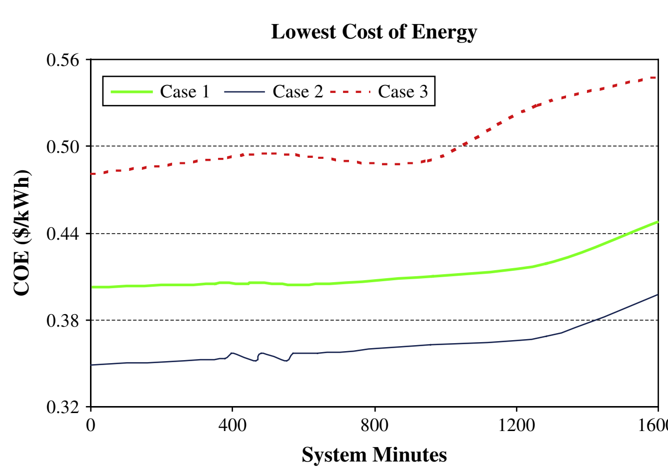

Fig. 5. Evolution of COE for the residential system.

Table 8
Optimal configuration of composite system

Case	Optimal configuration	EIU (%)	COE ($/kWh)
Case 1	6 WT, 45 kW PV, 160 bat., 40 kW conv.	0.29	0.566
Case 2	5 WT, 36 kW PV, 160 bat., 40 kW conv.	0.20	0.493
Case 3	7 WT, 45 kW PV, 240 bat., 40 kW conv.	0.39	0.679

larger than the other load scenarios, while the EIU level stands between them. As a result of the increased summer demand of electric power caused by the temporary residential population, the quantity of the PV panels is significantly larger. Table 9 shows the values of the reliability indices for optimal configuration of each considered case, while Figs. 6–8 depict the variation of LOLE, DOI (multiplied by 20) and ENSI. LOLE and DOI present nearly constant values in each optimal configuration. Nonetheless, in some cases they present significant fluctuations near this value, so they cannot be considered as reliable and adequate criteria. On the other hand, SM and EIU present values that are included in the neighbourhood of the optimal values of COE: 600 for SM and 0.30% for EIU. Finally, it has to be noted that all power interruptions that have been presented in this scenario occurred during the period that residential population is added.

4.5. Analysis of results

From the results presented in Sections 4.1–4.4, it is concluded that the use of the normalized energy reliability indices SM and EIU can provide an initial and quite accurate assessment of the optimal configuration in SAPS containing only RES. SM index also presents another interesting characteristic, as its optimal configuration value for the composite load can be calculated directly from the corresponding values of the combined load scenarios. More specifically, in the agricultural scenario the critical value of SM is 1500 and in the residential scenario is 0. Taking into account that in the composite scenario all interruptions happen in the high load periods (where the residential users are present), and during these periods the ratio of agricultural energy demand is by definition 40%, the threshold value of SM can be calculated through a linear function of the combined scenarios' SM threshold values, as follows $SM = 0.4 \times 1500 + 0.6 \times 0 \Rightarrow SM = 600$. In order to generalize this conclusion, however, a significantly larger number of alternative scenarios have to be studied.

4.6. Economic evaluation of COE

In order to achieve a realistic sense of SAPS performance containing only RES, a cost comparison with other isolated systems has to be done. Table 10 presents the variation of COE for different types of Greek isolated island systems. It is concluded that each scenario of Sections 4.2–4.4 presents much lower COE in comparison with the energy cost in Greek islands (except of the case of large island), even if the pessimistic values of Case 3 are being used. Taking into account that the COE of our study can be reduced significantly due to subsidies or tax reductions, such an SAPS can be always a very attractive solution for an isolated region.

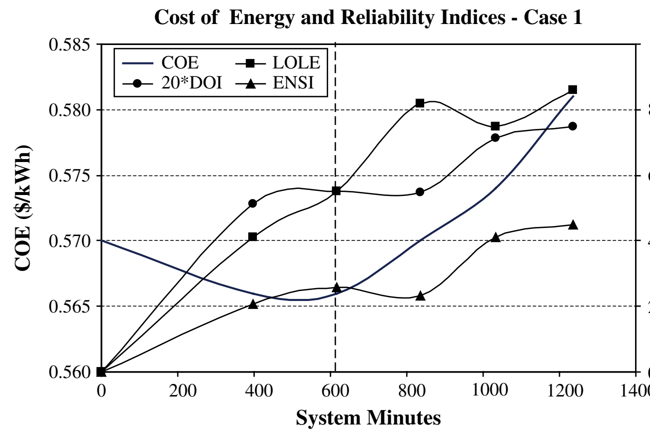

Fig. 6. Reliability indices performance for Case 1 of composite load.

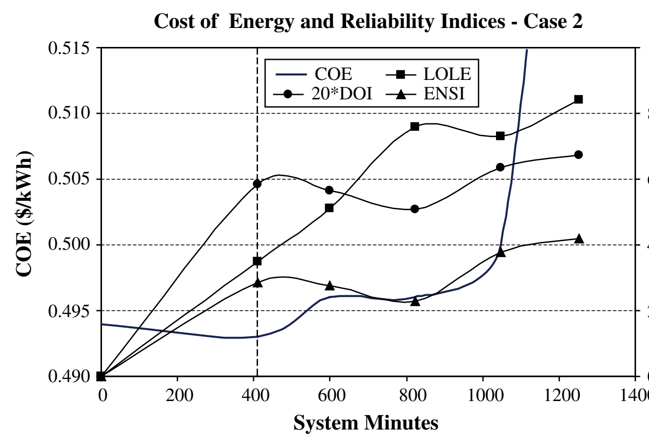

Fig. 7. Reliability indices performance for Case 2 of composite load.

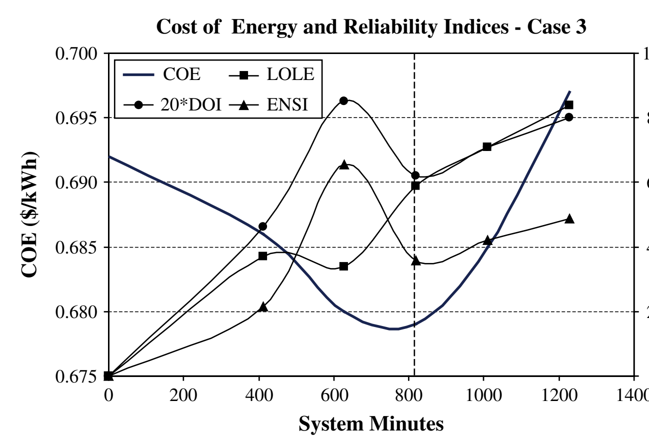

Fig. 8. Reliability indices performance for Case 3 of composite load.

Table 9
Optimal configuration reliability indices for composite system

Case	EIU (%)	SM	LOLE	DOI (h/int)	ENSI (kWh/int)
Case 1	0.29	617	55	2.75	25.71
Case 2	0.20	411	35	2.92	28.52
Case 3	0.39	819	59	3.11	35.91

Table 10
Energy cost in Greek islands

Island type (isolated systems)	COE ($/kWh)
Lowest COE value (large island)	0.28
Mean COE value	1.64
Highest COE value	6.02

5. Conclusions

The optimal configuration of small autonomous power systems containing only renewable energy sources through a reliability cost and worth analysis is a time consuming task, due to the intermittent nature of renewable resources, their variation, and the high modularity of each part of the system. Such systems also present extra difficulties compared with conventional systems, related with the inability of using simple deterministic indices as reliability criteria, as well as the nonstable value of the interrupted energy assessment rate for different operating conditions and different loads. This paper proposes that normalized energy reliability indices as system minutes and energy index of unavailability can be used as adequate criteria of system's optimal performance. This conclusion has been validated through a large number of sensitivity analysis studies that are based on different maximum annual loads and different mix of load types.

Acknowledgements

This work has been performed within the European Commission (EC) funded RISE project (contract number FP6-INCO-CT-2004-509161). The authors wish to thank the RISE partners for their contributions and the EC for partially funding this project.

References

[1] Wacker G, Billinton R. Customer cost of electric service interruptions. Proceedings of the IEEE 1989;77:919–30.
[2] Billinton R, Zhang W. Cost related reliability evaluation of bulk power systems. Electrical Power and Energy Systems 2001;23:99–112.
[3] Kaldellis JK. An integrated model for performance simulation of hybrid wind–diesel systems. Renewable Energy 2007;32:1544–64.
[4] Ackermann T. Wind power in power systems. Chichester: John Wiley & Sons; 2005.
[5] Georgilakis PS. State-of-the-art of decision support systems for the choice of renewable energy sources for energy supply in isolated regions. International Journal of Distributed Energy Resources 2006;2:129–50.
[6] Swift-Hook DT, Ter-Gazarian AG. The value of storage on power systems with intermittent energy sources. Renewable Energy 1994;5:1479–82.
[7] Swift-Hook DT. The whole life costing of wind energy. Renewable Energy 1997;10:247–51.
[8] Bagen YC, Billinton R. Incorporating well-being considerations in generating systems using energy storage. IEEE Transactions on Energy Conversion 2005; 20:225–30.
[9] Newfoundland & Labrador Hydro. Isolated systems generating planning practices: a survey of Canadian utilities 1995.
[10] Karki R, Billinton R. Cost effective wind energy utilization for reliable power supply. IEEE Transactions on Energy Conversion 2004;19:435–40.
[11] Kaldellis JK, Koronakis P, Kavadias K. Energy balance analysis of a stand-alone photovoltaic system, including variable system reliability impact. Renewable Energy 2004;29:1161–80.
[12] El-Tamaly HH, Mohammed AAE. Impact of interconnection photovoltaic/wind system with utility on their reliability using a fuzzy scheme. Renewable Energy 2006;31:2475–91.
[13] Tanrioven M, Alam MS. Reliability modeling and analysis of stand-alone PEM fuel cell power plants. Renewable Energy 2006;31:915–33.
[14] Desouki H, Lotfi AA. Reliability improvement of isolated generating systems by photovoltaic ac fusion converters. Renewable Energy 2001;23:391–7.
[15] The IEEE reliability test system – 1996. IEEE Transactions on Power Systems 1999;14:1010–20.
[16] Billinton R, Allan RN. Reliability evaluation of power systems. 2nd ed. New York: Plenum Press; 1996.
[17] Tollefson G, Billinton R, Wacker G, Chan E, Aweya J. Canadian customer survey to assess power system reliability worth. IEEE Transactions on Power Systems 1994;9:443–50.
[18] Kariuki KK, Allan RN, Palin A, Hartwright B, Caley J. Assessment of customer outage costs due to electricity service interruptions. In: Proceedings of CIRED '95, paper number 2.05; 1995.
[19] Koskolos NC, Megaloconomos SM, Dialynas EN. Assessment of power interruption costs for the industrial customers in Greece. In: Proceedings of ICHQP '98, Athens, Greece; 1998.
[20] Allan R, Billinton R. Probabilistic assessment of power systems. Proceedings of the IEEE 2000;88:140–62.
[21] Vernados PG, Katiniotis IM, Ioannides MG. Development of an experimental investigation procedure on double fed electric machine-based actuator for wind power systems. Sensors and Actuators Part A: Physical 2003;106: 302–5.