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Optimum sizing of an autonomous wind–diesel hybrid system for various representative wind-potential cases

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Abstract

Official statistics estimate that almost two billion people worldwide have no direct access to electrical networks. Afar from decision centers and having limited political influence, isolated consumers are often abandoned, facing a dramatically insufficient infrastructure situation. In this context, a wind–diesel–battery hybrid system is one of the best alternative solutions to meet the electricity demand of numerous remote consumers, with rational first installation and operational cost, even at medium wind-potential areas. The basic idea of this effort, in comparison with previous works rejecting oil usage, is to use the minimum possible diesel-oil quantity and limit the battery bank dimensions. For the prediction of the optimum hybrid system configuration, an integrated numerical algorithm is developed, based on experimental measurements and operational characteristics by the hybrid system components manufacturers. During the calculations, a detailed energy-balance analysis is carried out for the entire time period examined, while the battery depth of discharge time evolution is also investigated. The developed model is successfully applied for three representative wind potential types. The results obtained are quite encouraging supporting the applicability of the proposed solution.

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1. Introduction

Official statistics estimate [1] that almost two billion people worldwide have no direct access to electrical networks, 500,000 of them living in European Union and more than one-tenth of the latter in Greece [2]. Afar from decision centers and having limited political influence, isolated consumers are usually abandoned, facing a dramatically insufficient infrastructure situation [3]. An autonomous wind-power system has been proven to be one of the most interesting and environmental friendly technological solutions for the electrification of remote consumers, especially in the presence of high wind potential [4,5].

On the other hand, in medium or low wind potential cases, the dimensions of a wind only stand-alone system are quite large [4], thus the corresponding first installation cost is almost prohibitive, despite the existence of remarkable subsidization [5]. For these reasons, most remote consumers cover their electricity demand using small oil-fired diesel-electrical generators, with minimal first installation cost and very high operational cost. In an attempt to obtain a realistic and environmental friendly solution, the idea of using a hybrid wind–diesel–battery system is hereby examined [6–8]. The basic idea of this effort, in comparison with previous works, by authors insisting on no oil usage, is to minimize the oil quantity used and limit the battery bank dimensions. Keep in mind that the lead-acid batteries used should be replaced approximately every 1200 operational cycles, and in no case being free of environmental impacts.

Analyzing the pros and cons of a wind–diesel and a wind-only system, one should mention that the first system presents increased reliability [9] to cover the load demand normally using smaller batteries than the second alternative, while a wind-only system consumes no fuel, having low environmental impacts. In any case, the proposed improved analytical model, used to estimate the optimum size of a wind–diesel hybrid system, takes into consideration the opportunity of zero oil-consumption.

2. Proposed solution

In an attempt to simulate the energy consumption profile of a remote consumer, a joint effort is made to settle the electricity-demand difficulty of a typical isolated consumer (e.g., a four to six member family), using a properly sized stand-alone wind–diesel system. After an extensive local market survey, a representative weekly electricity consumption profile [10–12] is adopted, being also dependent on the year period analyzed (i.e., winter, summer, other). The load profile used is basically a rural household profile (not an average load taken from typical users) selected among several profiles provided by the Hellenic Statistical Agency [4,5]. More precisely, the numerical load values vary between 30 W (refrigerator load) and 3300 W. According to the consumption profile approved, the annual peak load "N_p" does not exceed 3.5 kW, while the annual energy consumption "E_y" is almost 4750 kW h. Thus, the annual electricity consumption – on an hourly basis – is the first input of the present analysis, see also Fig. 1.

In order to meet the electricity demands of isolated consumers, an integrated energy production system is devised, similar to the one of Fig. 2. Hence, the proposed system comprises:

- A micro wind converter of rated power "N_o" and given power curve $N = N(V)$ for standard day conditions
- A small internal-combustion engine of "N^*" kW, able to meet the consumption peak load demand "N_p" (i.e., $N^* \geqslant N_p$), presenting a typical specific fuel-consumption curve versus partial loading of the engine, i.e., (SFC = SFC(N/N^*))
- A lead-acid battery storage system for "h_o" hours of autonomy, or equivalently with total capacity of "Q_{max}", operation voltage "U_b" and maximum discharge capacity "Q_{in}" (or equivalent maximum depth of discharge "DOD_L")
- An AC/DC rectifier of "N_o" kW and U_{AC}/U_{DC} operation voltage values
- A DC/DC charge controller of "N_o" rated power, charge rate "R_{ch}" and charging voltage "U_{CC}"
- A UPS (uninterruptible power supply) of "N_p" kW, frequency 50 Hz, autonomy time "δt" and operation voltage 220/380 V
- A DC/AC inverter of maximum power "N_p" able to meet the consumption peak-load demand, frequency 50 Hz and operational voltage 220/380 V

As it results from Fig. 2, the corresponding wind potential and ambient temperature and pressure are also necessary to integrate the system sizing calculations.

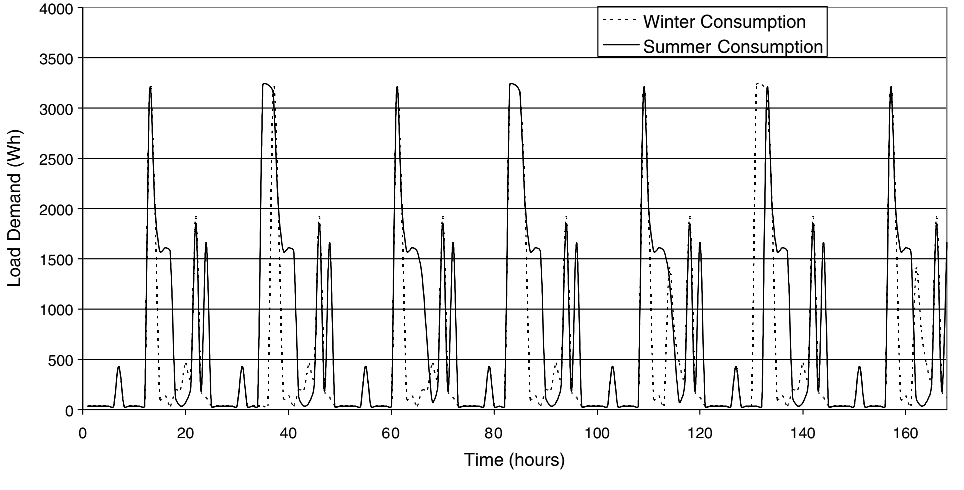

Fig. 1. Typical weekly electricity-demand profile of the remote consumer analyzed.

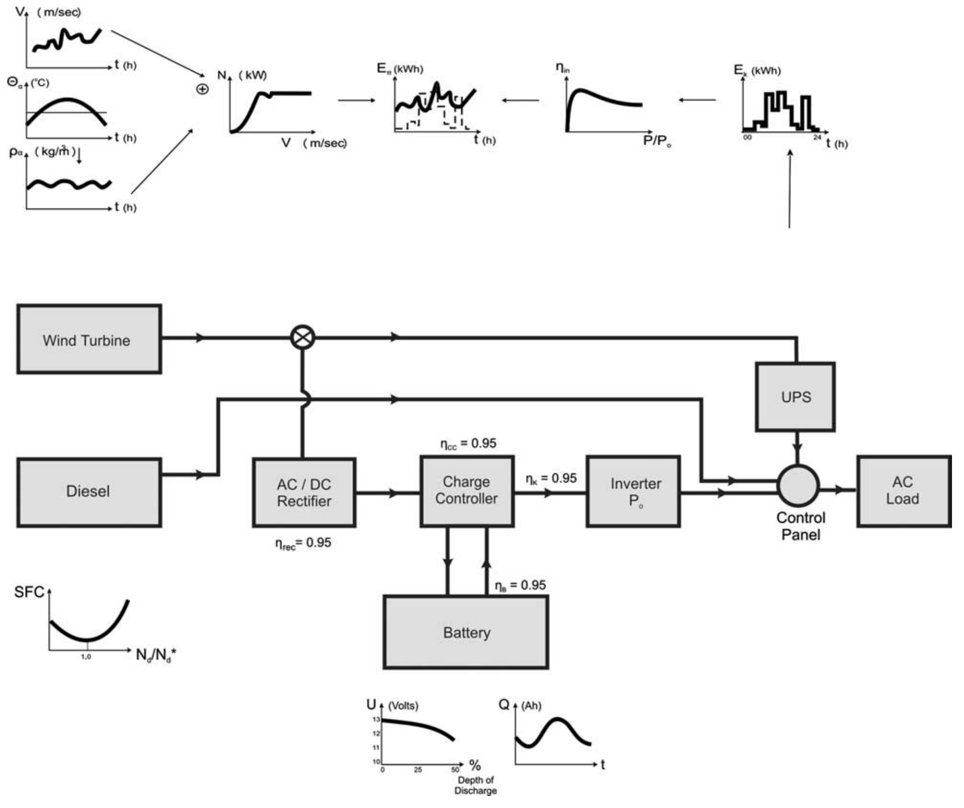

Fig. 2. Proposed autonomous wind–diesel hybrid system.

Finally, the operational characteristics of all components (e.g., wind-power curve at standard day conditions, diesel-generator's specific fuel-consumption, inverter efficiency, battery bank characteristic, etc.) composing the hybrid system under investigation are also required.

During the operation of the system, the following energy-production scenarios exist:

- Energy (AC current) is produced by the micro wind-converter, sent directly to consumers via the UPS
- Energy (AC current) is produced by the small diesel-generator and forwarded to consumers
- The energy output of the wind turbine (not absorbed by the consumption-energy surplus) is transformed to DC current (via an AC/DC rectifier), subsequently charging the batteries via the charge controller
- The battery is used to cover the energy deficit via the charge controller and the DC/AC inverter

In the present analysis, the diesel generator will not be used to charge the batteries via the AC/DC rectifier and the charge controller, as in any serious energy-deficit case, the diesel generator may directly cover the load demand, without energy storage losses.

Recapitulating, using the above-described configuration, it is possible to determine the appropriate system dimensions in order to fulfil the maximum load demand of the consumer, including a safety coefficient. For the present analysis, the optimum system-dimensions are defined using the relation between the battery capacity reduction and the annual diesel-oil consumption, i.e., (dQ_{max}/dM_f).

3. System sizing model

3.1. Proposed numerical algorithm

As mentioned above, the main scope of the present work is primarily to estimate the appropriate dimensions of a stand-alone wind–diesel system for every remote consumer examined, for a given annual diesel-oil consumption of the system. Accordingly, an effort is made to select the optimum combination of the stand-alone system dimensions and the annual diesel-oil consumption. The three governing parameters used during the optimization procedure are the rated power "N_o" of the wind turbine used, the battery's maximum necessary capacity "Q_{max}" and the annual mass fuel-flow consumption "M_f".

During the long-lasting operation of the proposed wind–diesel hybrid system, the following situations may appear:

- The power demand "N_D" is less than the power output "N_w" of the wind turbine ($N_w > N_D$). In this case, the energy surplus ($\Delta N = N_w - N_D$) is stored via the rectifier and the battery-charge controller. If the battery is full ($Q = Q_{max}$), the residual energy is forwarded to low priority loads.
- The power demand is greater than the wind-turbine power output ($N_w < N_D$), e.g., low wind-speed, machine non-available, etc. In similar situations, the energy deficit ($\Delta N = N_D - N_w$) is covered by the batteries via the battery-charge controller and the DC/AC inverter, under the precondition that the corresponding battery depth of discharge "DOD(t)" is lower than a given limit "DOD_1", i.e., $DOD(t) < DOD_1$.
- If this precondition is not fulfilled (i.e., $DOD(t) \approx DOD_1$), then the energy deficit is covered by the diesel generator at the expense of the existing oil reserves.
- In case of no further oil reserves, the energy deficit ($\Delta N = N_D - N_w$) is covered by the batteries via the battery-charge controller and the DC/AC inverter, violating the first degree battery protection precondition, i.e., accepting DOD(t) values greater than "DOD_1". However, if the battery's maximum depth of discharge "DOD_L" is exceeded, a load rejection takes place, underlining the necessity to increase the wind turbine's rated-power or the battery's bank-capacity or both of them.

In the real world, when the fuel reserves are zeroed and the battery is almost empty, an emergency energy-consumption management plan is applied: it should also be capable of facing unexpected energy-production problems related to "Force Majeure" events.

Under the above-described operational situations, the already presented [13] computational algorithm "WINDREMOTE-II" is substantially modified in order to take into account the existence of a small diesel generator. This new numerical code "WIND-DIESEL I" is used to carry out the necessary parametric analysis on an hourly energy production–demand basis, targeting to estimate the wind-turbine rated power "N_o" and the corresponding battery capacity "Q_{max}" given the annual permitted oil-consumption "M_f", see also Fig. 3.

More specifically, given the "M_f" value and for each "N_o" and "Q_{max}" pair, the "WIND-DIESEL I" algorithm is executed for all the time-period selected (e.g., for one month, six-months, one year or even for three years), while emphasis is laid on obtaining a zero-load rejection operation. More precisely, for every time-point analyzed, the system's energy-demand is compared with the wind-turbine's energy-production. The wind-turbine's output is defined by the wind speed, the ambient density and the manufacturer's power-curve.

In case (c), the energy deficit is covered by the diesel generator, if the corresponding oil reserves are not zero.

Finally, when the battery's maximum depth of discharge is exceeded (case (d)), load rejection takes place: hence the battery size is increased and the calculation is re-evaluated up to the case that the no-load rejection condition is fulfilled for the complete time period examined, i.e., $Q^* = \min\{Q_{max}\}$ verifying the following equation:

$$N_{exit}(t) \geqslant N_D(t) \quad \forall t \tag{1}$$

Next, another wind-turbine size is selected and the calculations are repeated. Thus, after the integration of the analysis a (N_o versus Q^*) curve is predicted under the no-load rejection restriction and a specific given annual mass fuel-consumption value "M_f". The calculations can be repeated for various "M_f" values in an attempt to estimate the optimum system configuration and the minimum oil-consumption.

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

$$\mathrm{DOD}(t) = 1 - \frac{Q(t)}{Q_{max}} \leqslant \mathrm{DOD_L} \quad \forall t \tag{2}$$

3.2. Governing parameters' initial values

Before the application of the above-presented analysis, in order to estimate the appropriate configuration of a wind–diesel system, one may give some details concerning the variation limits of the problem's main parameters. In this context, the minimum wind-turbine rated power results in the totally hypothetical situation of an absolute coincidence between the consumption load demand and the stochastic wind-energy production. In such a situation, one may write:

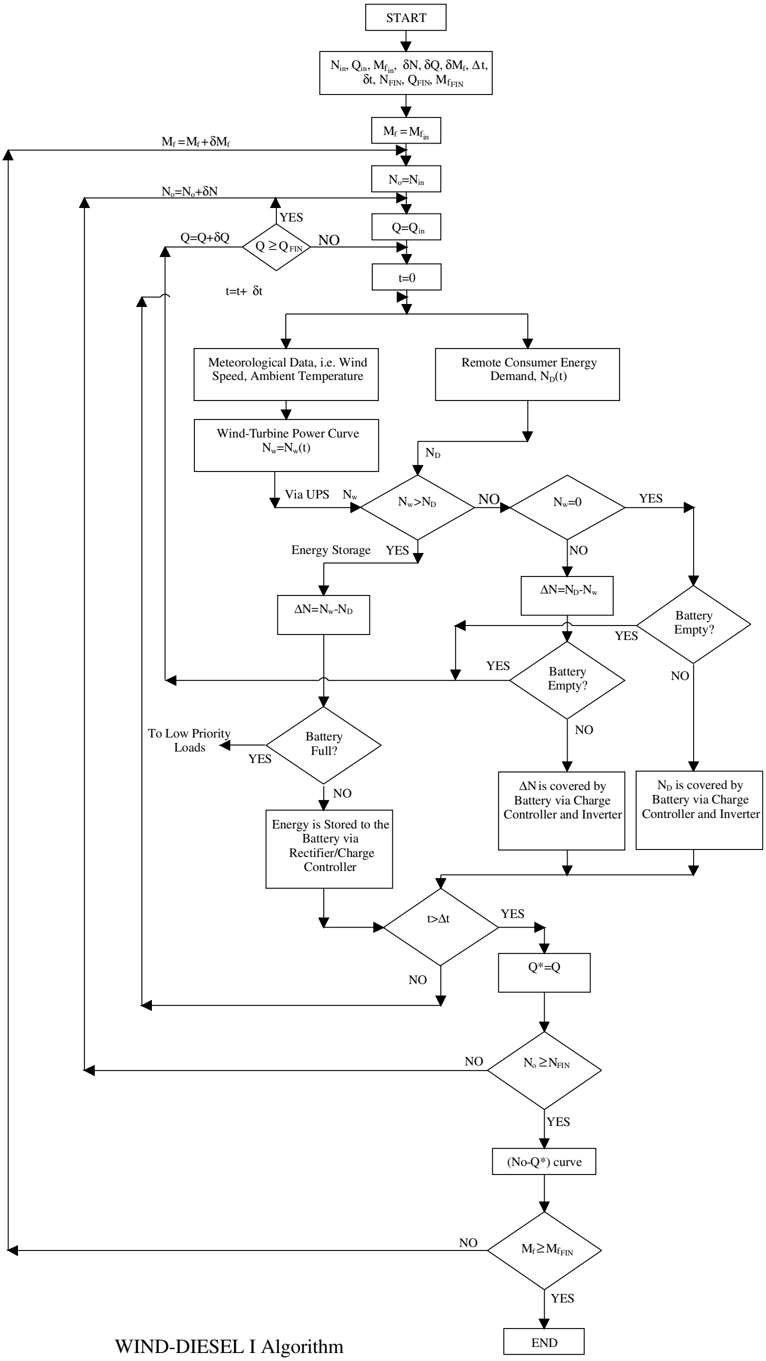

Fig. 3. WIND-DIESEL-I algorithm.

$$N_o \geqslant \frac{E_y}{8760 \text{ CF } \eta_{ups}} \tag{3}$$

where "E_y" ($E_y \approx 4750$ kWh) is the annual energy-consumption, "CF" is the mean annual capacity factor of the installation [14] and "η_{ups}" is the efficiency ($\eta_{ups} \approx 95\%$) of the UPS.

Similarly, the maximum annual fuel-consumption of the installation results in the theoretical case that the energy consumption is fulfilled only by the diesel generator; hence the corresponding annual fuel-consumption is limited by

$$M_f \leqslant \frac{E_y}{\eta_d H_u} \tag{4}$$

where "η_d" is the diesel-generator's electrical-efficiency ($\eta_d \approx 20$–30%) and "H_u" is the used oil's lower specific calorific-value ($H_u \approx 40{,}000$ kJ/kg).

Finally, the battery's bank-capacity depends mainly on the hours of the system's energy-autonomy "h_o" thus the expected mean battery capacity is estimated as

$$\bar{Q}_{max} = h_o \frac{E_y}{8760} \frac{1}{\eta_s \text{DOD}_L U_b} \tag{5}$$

where "η_s" is the efficiency ($\eta_s \approx 75\%$) of the energy-production branch (including battery-discharge loss, line loss, inverter loss, etc.) and "DOD_L" and "U_b" are described in section two.

4. Application results

Using the above information, we proceed to analyze representative wind–diesel hybrid systems located throughout Greece. The areas selected (Table 1) represent a high-wind potential area (Andros island), a medium-high one (Naxos island) as well as a low-wind potential case (island of Kea); see also Fig. 4.

Andros is a small medium-sized island (the second biggest one) of the Cyclades complex (population 12,000 habitants, area of 384 km^2), located in the middle of the Aegean Sea. The local terrain is very intense, including several rocky mountains with relatively sharp slopes. The island has one of the best wind-potentials in Greece ($\bar{V} \approx 10$ m/s), as the minimum monthly average wind speed exceeds the 6.5 m/s, Fig. 5. At the same time, the number of days with a daily average wind speed below 4.0 m/s (no wind production) is a minimum, see also Fig. 6, validating the fact that the maximum calm-spell period of the island is 37 h.

Table 1
Main characteristics of the regions investigated

Region	Area (km^2)	Population (cap)	Annual mean wind speed (m/s)	Max calm spells (h)
Andros	384	12000	9.5	36
Naxos	428	18000	7.4	104
Kea	103	2300	5.6	158

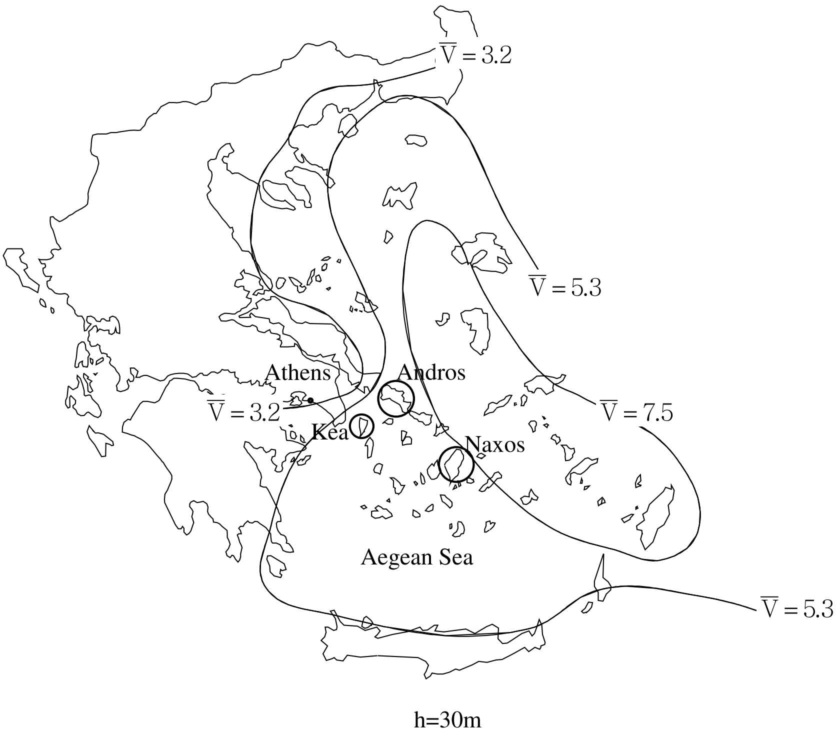

Fig. 4. Wind potential map for Aegean Sea area at 30 m height: $\bar{V}$ measured in m/s.

The results of the "WIND-DIESEL I" algorithm application to the Andros island case are demonstrated in Fig. 7 for various annual diesel-oil consumption levels. More precisely, each curve drawn corresponds to a given diesel-oil rate (e.g., $M_f = 100$ kg/y), while the x-axis describes the wind-turbine's rated power and the y-axis the corresponding battery capacity. In the same figure, the zero-diesel solution is also included. According to the results obtained, there is a considerable battery capacity diminution by accepting a minimum (25 kg/y) diesel-oil consumption, representing approximately 1% of the annual diesel-only system fuel-consumption, see Eq. (4). A significant battery capacity decrease is also encountered by accepting 100 kg/y diesel-oil consumption. For bigger diesel-oil quantities, the battery capacity is fairly reduced, excluding the configurations based on very small wind-turbines, i.e., rated powers below 3 kW.

Kea is a small island (2300 habitants, area 103 km^2) close to Athens: the topography of the island is typically Aegean, i.e., gentle slopes, absence of flat fields, low mountains and sparse vegetation, while the main economic activities of the local society are agriculture, cattle breeding, beekeeping and tourism. The corresponding wind-potential, although lower than the one of Andros, is good enough (annual mean wind speed ≈ 5.6 m/s, Fig. 8) to feed contemporary wind-turbines for electricity production.

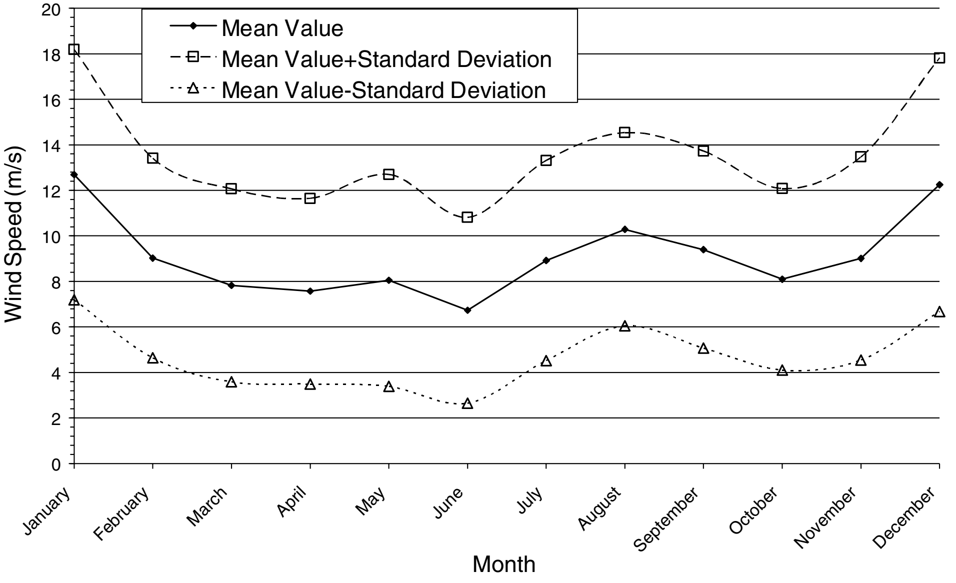

Fig. 5. Monthly averaged wind-speed values at Andros island.

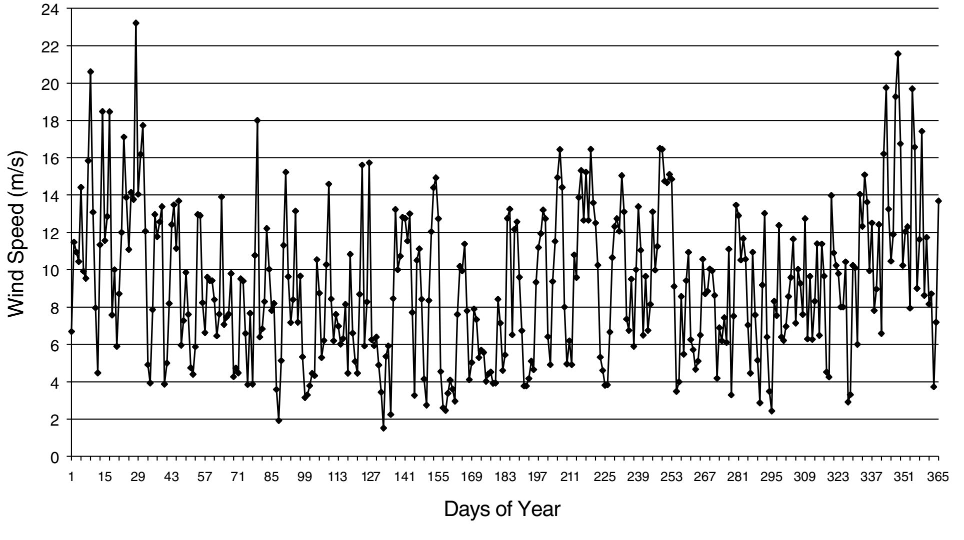

Fig. 6. Daily mean wind speed at Andros island.

In Fig. 9, one may see the calculated results concerning this relatively low wind-potential area. Using the information of Fig. 9, one may easily conclude that even by using remarkable diesel oil quantities, the system's dimensions (mainly battery capacity) are much larger than the Andros ones. On top of this, only by using

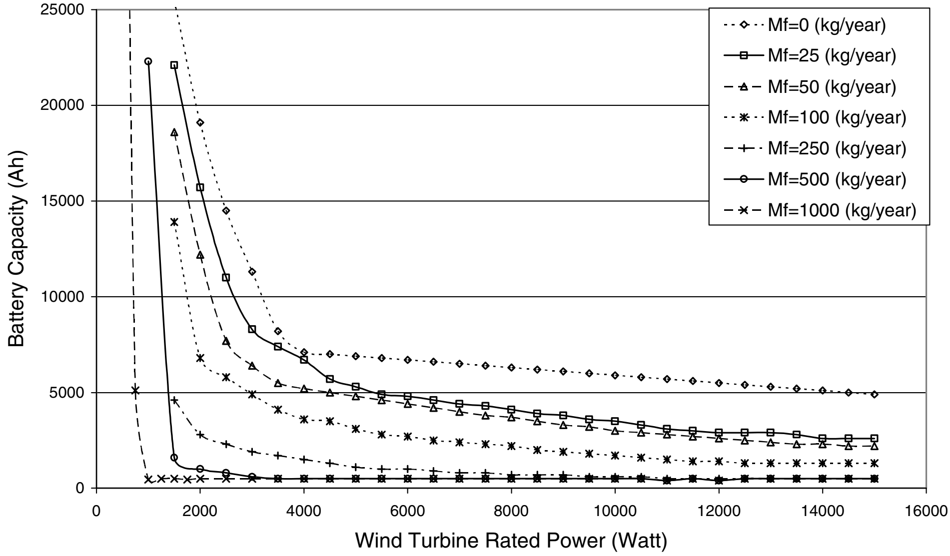

Fig. 7. Energy autonomous configuration for a wind–diesel hybrid system, Andros island.

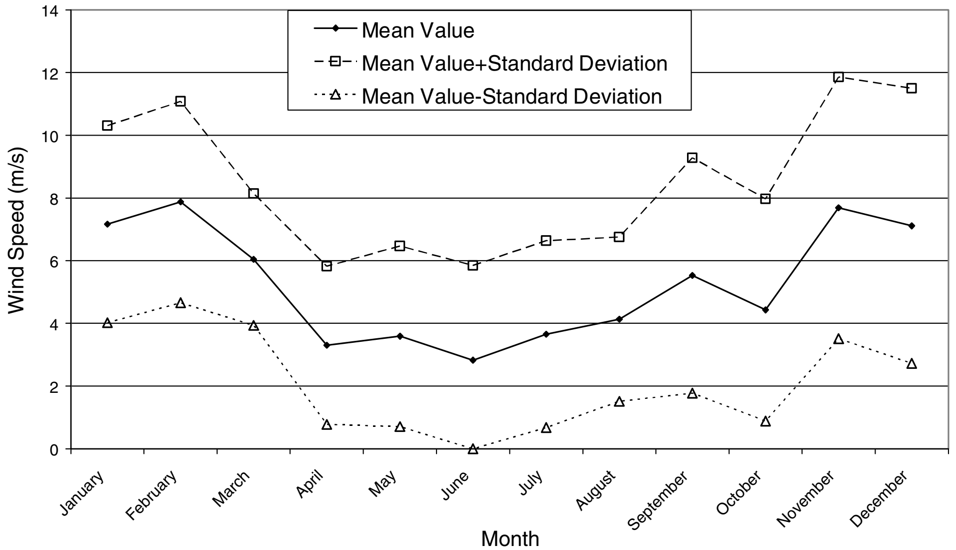

Fig. 8. Monthly averaged wind-speed values at Kea island.

significant annual diesel-oil quantities (e.g., $M_f = 250$ kg/y) is it possible to obtain a considerable battery-capacity reduction. Finally, one should use almost 1000 kg/y of diesel-oil in order to guarantee system autonomy, exploiting a relatively small

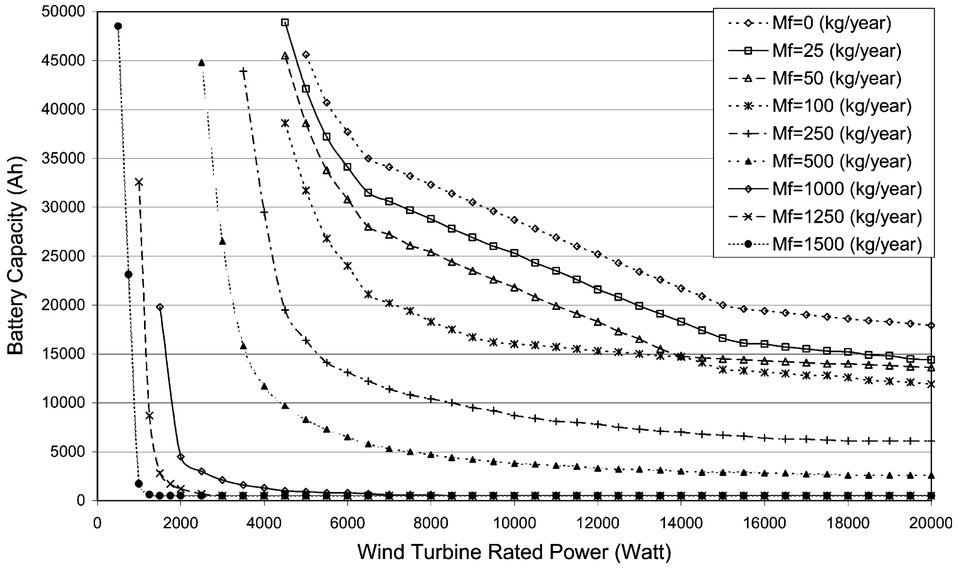

Fig. 9. Energy autonomous configuration for a wind–diesel hybrid system, Kea island.

wind-turbine (i.e., below 3 kW). This fact is clearly explained by comparing the wind potentials of the Andros and Kea islands, e.g., Figs. 5 and 8.

Finally, Naxos is also a medium-sized island (18,000 habitants, area of 428 km^2) in the central Aegean Sea, belonging to the Cyclades complex and presenting similar topography with Andros island. The island has an outstanding wind-potential, as in several locations the annual mean wind speed approaches 7.5 m/s, at 10 m height, Fig. 10.

In Fig. 11, one may see the calculated results concerning this relatively medium-high wind-potential area. According to the results of Fig. 11, one may state that, as in the Kea island case, one should use noteworthy diesel-oil quantities in order to remarkably decrease the system's dimensions (mainly battery capacity). Of course, the hybrid-system's dimensions are much smaller than the Kea ones. Besides, almost 250 kg/y of oil should guarantee the system's energy-autonomy using a reasonably small wind turbine (i.e., less than 3 kW). A rational explanation concerning the configuration of the above investigated cases may be evident by comparing the wind potentials of Andros, Kea and Naxos islands, i.e., Figs. 5, 8 and 10.

5. Discussion of the results

5.1. Selection of the solution

In order to select the best system configuration for each case investigated, the maximum battery-capacity diminution-rate versus the given annual oil-consumption

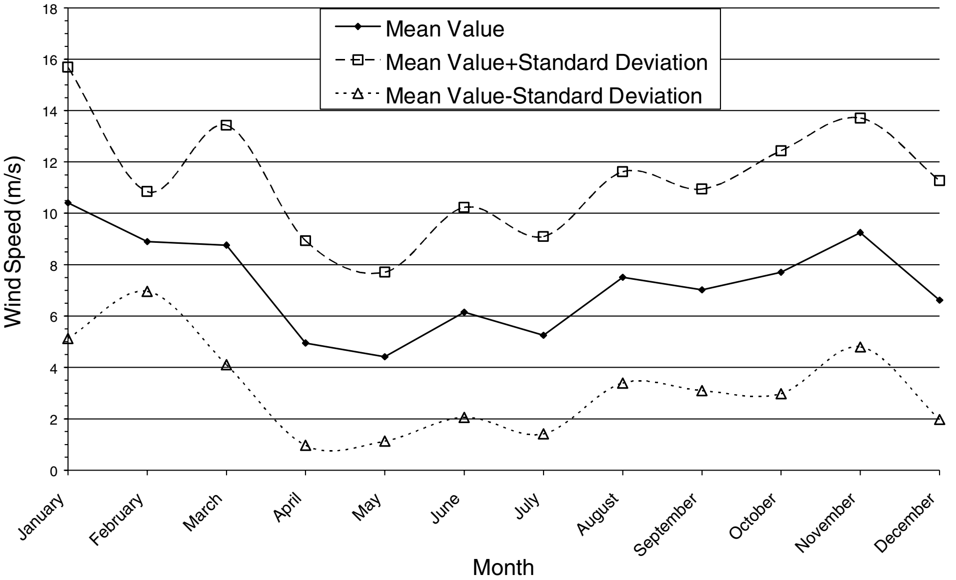

Fig. 10. Monthly averaged wind-speed values at Naxos island.

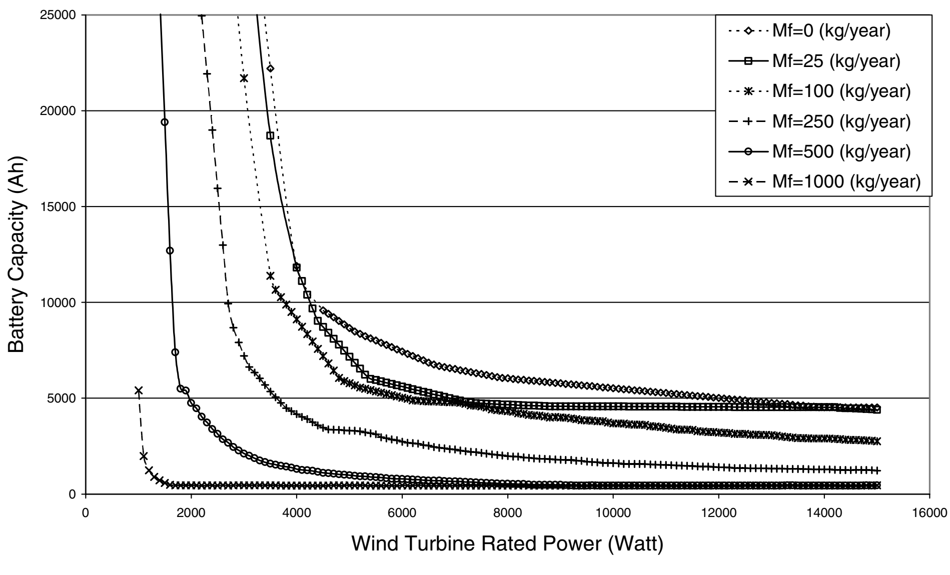

Fig. 11. Energy autonomous configuration for a wind–diesel hybrid system, Naxos island.

should be taken into consideration. For this purpose, Fig. 12 presents the battery capacity variation versus the annual diesel-oil consumption, for a given wind-turbine rated power, with respect to Andros island. According to the results obtained, there

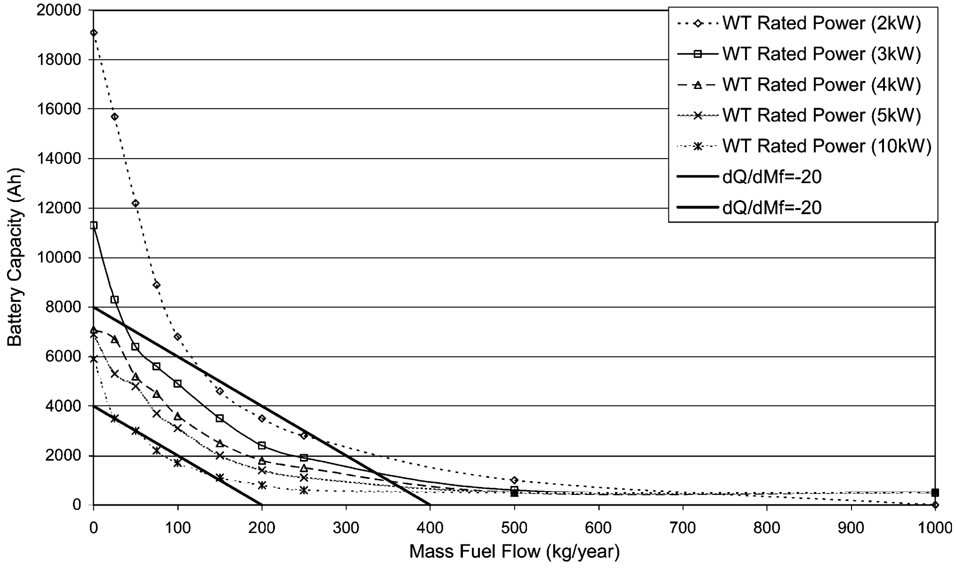

Fig. 12. Battery capacity decrease versus diesel-oil annual consumption, Andros island.

is a considerable battery size diminution when passing from a diesel-free to a wind–diesel hybrid system. This diminution is quite big in cases of relatively low diesel-oil contribution to the system's energy consumption (i.e., up to 200 kg/y or 10% of the diesel-only system's annual consumption (≈2000 kg/y)). For larger diesel oil consumptions, the battery capacity decrease is decelerated, since the battery capacity versus annual diesel-oil consumption distribution tends to an asymptotic value.

In this context, by setting the minimum acceptable (dQ_{max}/dM_f) value equal to (−20), see also Fig. 12, one may estimate the maximum necessary annual oil-consumption that minimizes the corresponding battery capacity contribution of the hybrid system under investigation. Bear in mind that the "$dQ/dM_f = -20$" value has been selected using the current oil market price at the specific isolated location (i.e., 1.5 €/kg of diesel oil) and the corresponding specific purchase cost (0.5 €/Ah; $U = 24$ V) of a lead-acid heavy-duty battery bank. According to the data of Fig. 12, once the wind-turbine's rated power of the hybrid system located in Andros island is equal to 3 kW, the optimum system configuration is obtained by using approximately 150 kg/y of diesel oil. In this case, the corresponding battery capacity is 3500 Ah, see also Fig. 7. On the other hand, when the wind-turbine's rated power is 10 kW, the maximum necessary annual oil-consumption may be equal to 50 kg/y, leading to a battery bank capacity equal to 3000 Ah.

Using the same methodology, the corresponding hybrid system's dimensions for the Naxos and Kea islands may be estimated, along with the maximum annual oil quantity required; see Table 2. As expected, given the annual mass fuel-consumption, the battery capacity reduction is in inverse proportion to the wind potential of the installation area; see also Figs. 13 and 14. Besides, larger annual

Table 2
Proposed optimum configurations

Region	Wind-turbine's rated power (kW)	Battery capacity (Ah)	Annual diesel-oil consumption (kg/y)
Andros	3	3500	150
	5	3700	75
	10	3000	50
Naxos	3	7210	250
	5	5780	100
	10	4150	50
Kea	5	8300	500
	10	8700	250
	15	13400	100

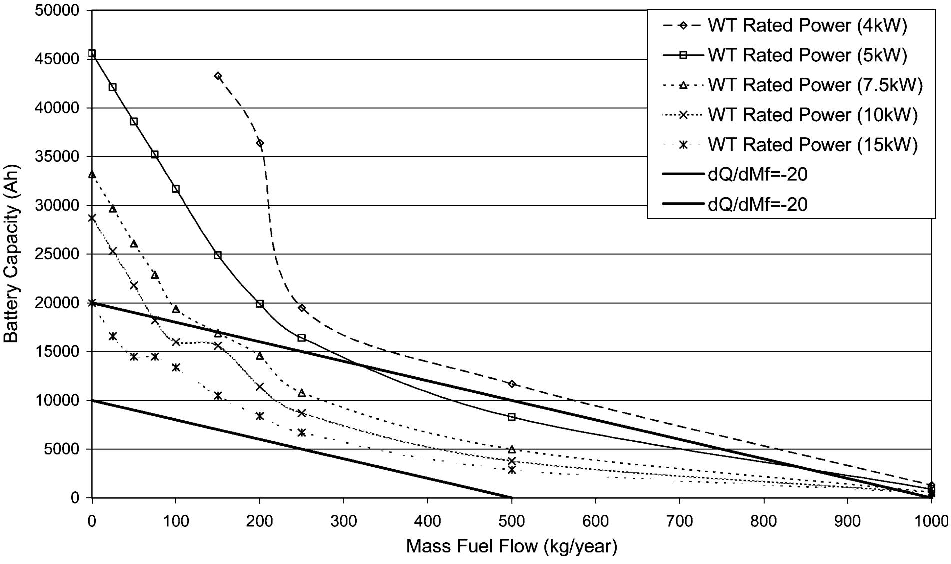

Fig. 13. Battery capacity decrease versus diesel-oil annual consumption, Kea island.

oil quantities are required in cases of small wind-turbines than in cases of relatively big ones. An integrated cost–benefit analysis on a ten or twenty-year operational period of the system may be used in order to obtain a most accurate long-term solution of the problem.

5.2. Energy balance

Another target of the present study is to extensively analyze the energy balance of the proposed wind–diesel hybrid-system for the complete time-period investigated.

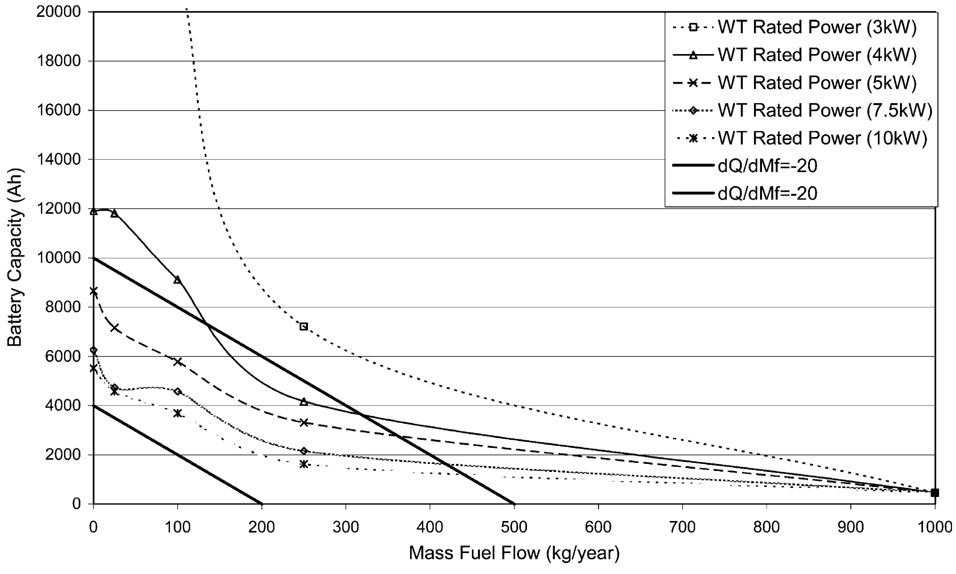

Fig. 14. Battery capacity decrease versus diesel-oil annual consumption, Naxos island.

To get a representative picture of the proposed system behavior, Fig. 15 presents the annual energy productions of typical energy autonomous hybrid-configurations located in Andros island. As is obvious from the results cited, the energy production is higher than the energy demand (≈4750 kW h) especially for low diesel-oil contributions. This might be the cost of reducing the battery size; hence one cannot store the entire wind-energy surplus. Only, at high diesel-oil penetration cases, the energy production fairly comparable with the energy demand and there is no extra wind-energy production.

This fact is also validated by Fig. 16, where the system's energy disposal is demonstrated. As it is clear from the data presented, a significant part of the energy production is finally rejected, being the direct result of wind-energy production and consumption demand incompatibility, along with limited energy-storage capacity. In any case, the diesel generator production represents a small part of the total system output, while the energy excess may be forwarded for additional energy-consumption, like water pumping for irrigation purposes [15] or small autonomous desalination installations [16].

This conclusion is clearly supported by inspecting Figs. 17(a)–(f), where the distribution of the wind-energy production of the wind–diesel hybrid system is demonstrated for zero, low and high diesel oil penetrations and for the two extreme wind-potential cases examined, i.e., Andros and Kea islands. As already mentioned at low diesel-oil penetration, a large portion of the wind-turbine production is finally rejected, while the internal system loss (i.e., rectifier and charge-controller losses, standing losses owing to the battery self-discharge, losses of the lines connecting

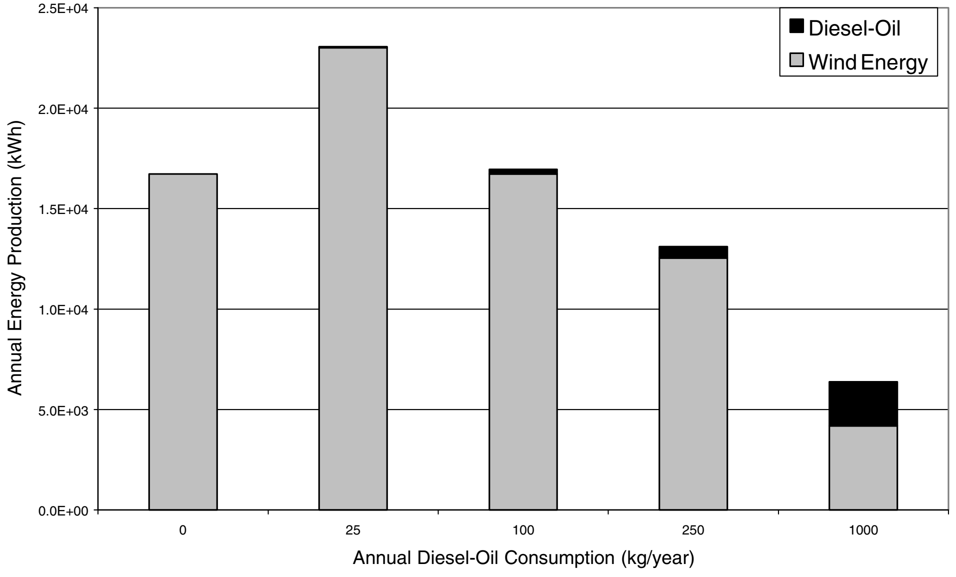

Fig. 15. Annual energy-production analysis for Andros wind–diesel hybrid system.

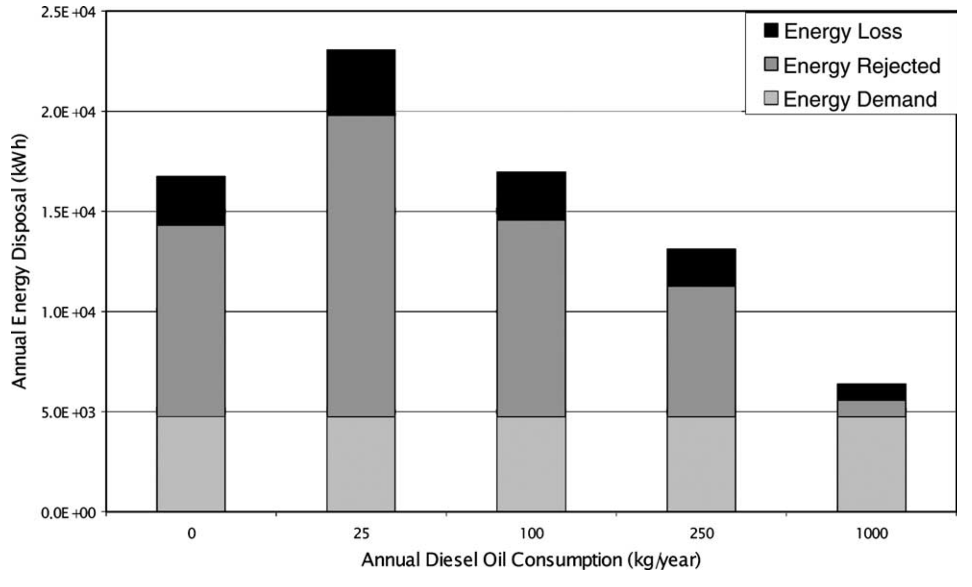

Fig. 16. Annual energy-production disposal for Andros wind–diesel hybrid system.

the installation apparatus, UPS and inverter loss) represents 14% of the wind-energy production for the Andros case. On the other hand, the wind-energy rejection for Kea island is quite low, while the internal system loss represents approximately one-third of the wind turbine production. Bear in mind that by increasing the

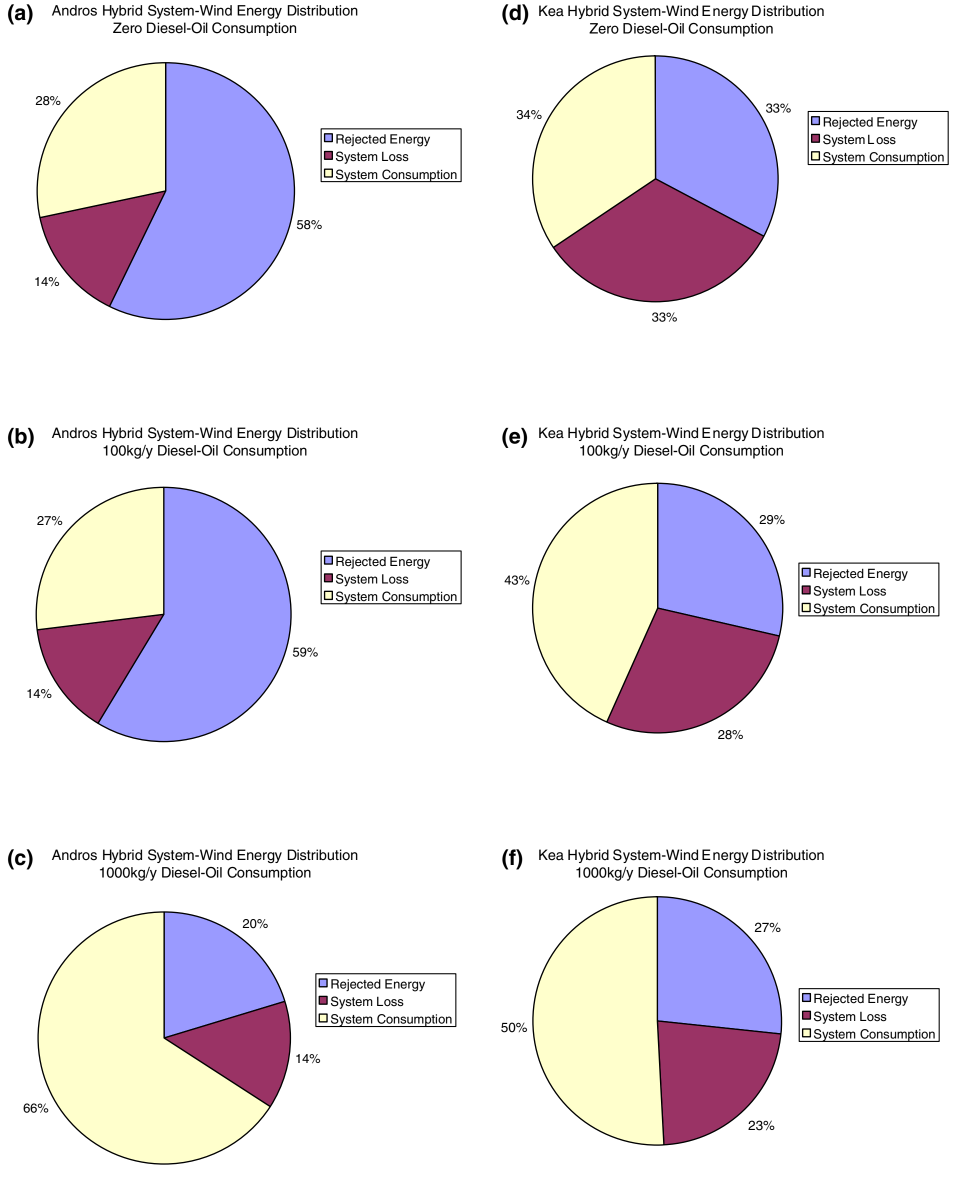

Fig. 17. Comparison between the wind-energy production disposal for a high and a low wind-potential region. (a) Andros island, zero oil-penetration. (b) Andros island, low oil-penetration. (c) Andros island, high oil-penetration. (d) Kea island, zero oil-penetration. (e) Kea island, low oil-penetration. (f) Kea island, high oil-penetration.

diesel-oil consumption, the wind-energy contribution is reduced to meet the consumption requirements, representing only 50% of the total annual consumption in the case of Figs. 17(c) and (f).

6. Conclusions

The central target of the present study is to estimate the optimum dimensions of a stand-alone wind–diesel hybrid system with energy storage, able to fulfil the energy requirements of a representative remote consumer. Thus, the optimum dimensions of a stand-alone hybrid system are defined for three representative wind-potential types, using long-term meteorological data. It is important to mention that the first case analyzed concerns a high wind-potential area, while the other two cases represent a medium-high and a medium-low quality wind-potential region.

The proposed hybrid system presents a first installation cost inferior to a stand-alone wind-power system and a considerably lower operational cost from a diesel-only installation. In addition, the existence of three independent power sources increases the system's reliability, while the usage of a limited diesel-oil quantity remarkably diminishes the corresponding battery size.

For the prediction of the optimum hybrid-system configuration, an integrated numerical algorithm is developed, based on experimental measurements and the operational characteristics by the hybrid system components manufacturers. During the calculations, a detailed energy-balance analysis is carried out for the entire time-period examined, in order to verify that – for every time point – the electricity requirement of the remote consumer is fulfilled by the proposed solution. Similarly, the battery depth of discharge (battery capacity) time evolution is also investigated, to ensure that the corresponding "DOD" value does not exceed the existing limiting value.

Finally, although no financial data are included in the present analysis, it is obvious that a wind–diesel–battery hybrid system is among the best alternative solutions facilitating the electricity demand of numerous remote-consumers with a rational first installation and operational cost, even for medium wind-potential areas. On top of this, subsidization possibilities – either by local authorities or via European funds – should greatly increase the economic attractiveness of similar stand-alone hybrid applications.

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References

[1] European Commission. Wind energy. The facts. A plan for action in Europe, printed in Belgium; 1999.
[2] Jensen ThL. Renewable energy on small islands, 2nd edition, Forum for Energy & Development, FED; 2000.
[3] Kaldellis JK, Vlachou D, Kavadias K. An integrated renewable-energy solution for very small Aegean Sea Islands, Renewable Energies for Islands, International Conference, Chania, Crete, Greece; 2001.

[4] Kaldellis JK. Parametric investigation concerning dimensions of a stand-alone wind-power system. J Appl Energy 2004;77/1:35–50.

[5] Kaldellis JK. Minimum stand-alone wind power system cost solution for typical Aegean Sea Islands. Wind Eng J 2002;26/4:241–55.

[6] Bowen AJ, Cowie M, Zakay N. The Performance of a remote wind–diesel power system. Renewable Energy 2001;22:429–45.

[7] Elhadidy MA, Shaahid SM. Role of hybrid (wind + diesel) power systems in meeting commercial loads. Renewable Energy 2004;29:109–18.

[8] Kaldellis JK, Vlachos GTh, Kavadias KA. Optimum sizing basic principles of a combined photovoltaic–wind–diesel hybrid system for isolated consumers. Proceeding of EuroSun 2002 International Conference, 2002. Paper W141, Bologna, Italy.

[9] Kaldellis JK. An integrated feasibility analysis of a stand-alone wind-power system, including no-energy fulfilment cost. Wind Energy J 2003;6/4:355–64.

[10] Lazou A, Papatsoris A. The economics of photovoltaic stand-alone residential households: a case study for various European and mediterranean locations. Solar Energy Mater Solar Cells J 2000;62/4:411–27.

[11] Beyer HG, Degner T, Gabler H. Operational behaviour of wind-diesel systems incorporating short-term storage: an analysis via simulation calculations. Solar Energy 1995;54/6:429–39.

[12] Notton G, Muselli M, Poggi P, Louche A. Sizing reduction induced by the choice of electrical appliances options in a stand-alone photovoltaic production. Renewable Energy 1998;15:581–4.

[13] Kaldellis JK. Optimum autonomous wind-power system sizing for remote consumers, using long-term wind speed data. Appl Energy 2002;71/3:215–33.

[14] Kaldellis JK, Vlachou DS, Paliatsos AG. Twelve years energy production assessment of Greek state wind parks. Wind Eng J 2003;27/3:215–26.

[15] Kavadias K, Komnimoglou A, Kaldellis JK. Wind energy surplus management for remote consumers using a water pumping storage system, European Wind-Energy Conference, Conference Proceedings. Bella Centre, Copenhagen; 2001. p. 972–5.

[16] Kaldellis JK, Kavadias KA, Kondili E. Renewable energy desalination plants for the Greek Islands, technical and economic considerations. Desalination J 2004;170(2):187–203.