INTEGRATED ELECTRIFICATION SOLUTION FOR REMOTE ISLANDS BASED ON WIND-PV HYBRID SYSTEM

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Abstract

Wind and solar driven stand-alone systems may suggest attractive electrification solutions for numerous isolated remote consumers. Nevertheless, due to the requirement of such systems for considerable energy storage capacity, diesel electrical generators are used instead. To minimize oil dependence, the idea of creating a combined wind - photovoltaic based hybrid system with the employment of an appropriate energy storage device is investigated. In this context, the main target of this paper is to estimate the appropriate dimensions of a similar system, able to meet the energy requirements of existing remote consumers, under the restriction of reasonable first installation cost.

Keywords: Isolated Consumer; Wind Turbine; Photovoltaic Generator; Lead Acid Batteries; Energy Autonomy

1. Introduction

Wind and solar driven stand-alone systems may suggest reliable electrification solutions for numerous isolated remote consumers [1-4]. Nevertheless, due to the requirement of such systems for considerable energy storage capacity, diesel electrical generators are either used to replace the specific systems or to comprise one of the system main components (wind-diesel and PV-diesel systems) [5-7]. In this context, apart from the excessive battery bank capacity required, increased first installation and operational costs may also comprise the direct result of such practices.

On the other hand, in several areas of our planet wind speed and solar radiation present redundant availability [8], hence the combined exploitation of available wind and solar potential may substantially reduce the energy storage requirements of stand-alone systems. A representative example encounters hundreds of scattered islands at the east side of the Greek mainland, i.e. in the Aegean Sea where a considerable number of isolated consumers reside, having no access to a constant and reliable electricity source [9]. In order to meet their electrification needs, remote consumers are obliged to use small diesel-electrical generators that consume considerable amounts of costly imported oil, contributing also to the degradation of the local environment due to the air pollution caused [10].

To eliminate oil dependence and improve the life quality of these remote consumers via the adoptions of RES-based electrification solutions [11], the idea of creating a combined wind-photovoltaic based hybrid system [12] with the employment of an appropriate energy storage device [13] is currently investigated. In this context, the main target of this paper is to estimate the appropriate dimensions of a stand-alone hybrid wind-photovoltaic (WT-PV) power system [12], able to meet the energy requirements of existing remote consumers, under the restriction of reasonable first installation cost.

For this purpose, an integrated methodology is applied, including the configuration of a new algorithm, able to provide autonomous WT-PV configurations, as well as the estimation of the respective first installation cost. As a result, minimum first installation cost configurations ensuring 100% energy autonomy for a typical remote consumer may be designated. Finally, for the validation of the proposed methodology two island cases are currently investigated, i.e. a medium-high and a medium-low wind potential areas, both determined by considerable solar potential.

2. Description of the Proposed Solution

2.1. Main components of a WT-PV system

To reduce any excessive battery bank capacity and eliminate the contribution of oil-based generation to cover the electricity demand of a typical remote consumer, an integrated WT-PV hybrid stand-alone configuration is currently proposed (Figure 1a). Note that the specific concept may equally well apply to a larger scale (Figure 1b), e.g. to cover the electricity requirements of an island region [14,15] via the minimization of the local oil-based electricity generation, provided that an appropriate energy storage system [13] is employed.

Anyhow, the main components of the stand-alone configuration currently investigated include the following:

- A small-scale commercial wind turbine of rated power “N_o” (kW)
- A photovoltaic system of “z” panels, properly connected (“z_1” in parallel and “z_2” in series) and corresponding to a total rated power of “$N_{pv}=N_{peak}\cdot z_1\cdot z_2$”; “$N_{peak}$” being the maximum power output of each panel (kW)
- A lead acid battery bank with a total capacity of “Q_{max}”, operation voltage “U_b” and 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 “$N_{cc}=N_o+N_{pv}$” rated power, charge rate “R_{ch}” and charging voltage “U_{cc}”.
- A DC/AC inverter of maximum power “N_{INV}” (kW) that is able to meet the consumption peak load demand “N_p”, increased also by an appropriate safety factor “SF” (e.g. SF=0.3), i.e. “$N_{INV}=N_p\cdot(1+SF)$”
- A UPS of rated power “N_{UPS}” (kW), able to meet the consumption peak load demand “N_p” at a frequency of 50 Hz and at an operational voltage of 220/380V.

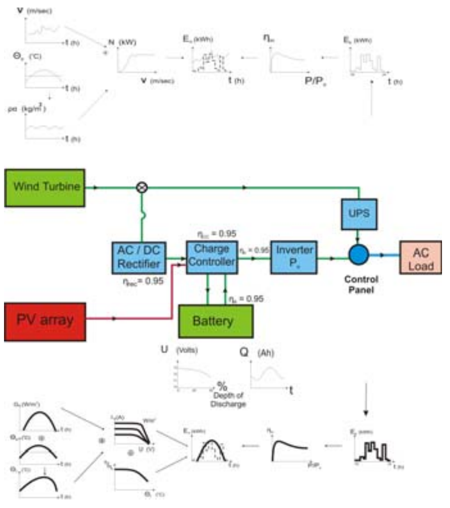

Figure 1a: WT-PV stand-alone solution for remote consumers

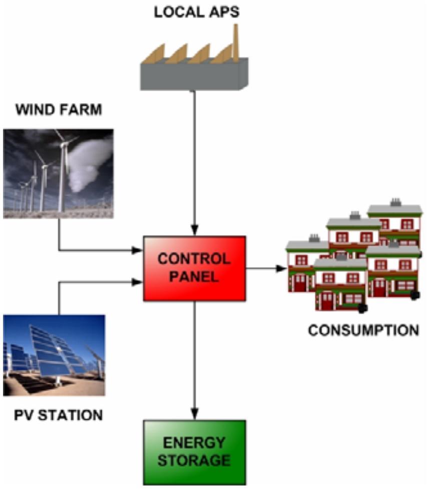

Figure 1b: Island-scale WT-PV energy autonomy solution

2.2. System operation scenarios

During the long-lasting service period of the proposed stand-alone system (20–30 years is assumed to be realistic), the following scenarios are possible:

- Energy (AC current) is produced by the small scale wind turbine and is sent directly to cover the remote consumer’s load demand via the UPS.
- Energy (DC current) is produced by the photovoltaic array and is sent directly to cover the remote consumer’s load demand via the charge controller and the inverter.

- The energy surplus of the wind turbine (i.e. wind energy production that cannot be absorbed by the load consumption) is used to charge the battery bank via the AC/DC rectifier and the charge controller.
- The energy surplus of the PV generator (i.e. PV energy production that cannot be absorbed by the load consumption) is used to charge the battery bank via the charge controller.
- Any energy deficit that cannot be satisfied by the energy production sum of the wind turbine and the PV generator is covered by the lead acid battery bank.

or differently put, the following two states may be encountered:

- The sum of power output by the wind turbine and the PV array "$\Sigma N_{RES}=N_w+N_{sol}$" exceeds the load demand "N_D" (i.e. $\Sigma N_{RES} > N_D$). In that case the accruing energy surplus is stored in the battery bank, either via the rectifier and the charge controller (wind turbine case) or directly via the charge controller (PV generator case), provided that the battery is not fully charged ("$Q=Q_{max}$"). Otherwise, any residual energy that cannot be stored in the battery bank is used to feed low priority loads.

- The power output of both the wind turbine and the PV generator "ΣN_{RES}" appears to be lower than the load demand "N_D" (i.e. $\Sigma N_{RES} < N_D$), thus, to meet the electricity demand successfully, energy is drawn from the battery bank via the charge controller and the DC/AC inverter. For this to happen however, the battery maximum depth of discharge condition should not be violated, otherwise a load rejection plan must be considered.

3. Applied Methodology

3.1. Sizing considerations

In order to determine the size of a WT-PV stand-alone system, a sequence of steps is considered: The photovoltaic generator's power "N_{pv}" is first selected from a given value range, while accordingly, a series of wind turbine power "N_o" and battery capacity "Q_{max}" pairs (i.e. N_o-Q_{max} combinations) ensuring zero load rejection all year round (i.e. 100% energy autonomy for the remote consumer investigated and the PV power adopted) are produced with the use of an appropriate algorithm. Obtaining the specific combinations, the next step calls for the estimation of the respective first installation cost "IC_o" that may eventually lead to the determination of minimum cost solutions.

In this context, there are three governing parameters that influence the final outcome of the sizing procedure, i.e. the rated power of the wind turbine "N_o", the lead acid battery bank maximum capacity "Q_{max}" and finally the PV array rated power "N_{pv}", while -as already mentioned- by applying the criterion of minimum first installation cost "$IC_o= IC_{omin}$", the most cost-effective solutions may be designated.

3.2. The WIND-PV III algorithm

To facilitate the simulation of the proposed system's operation, a new algorithm has been developed (Figure 2). The new numerical code WIND-PV III is used to carry out the necessary parametrical analysis on an hourly energy production-energy consumption basis in order to determine pairs of (N_o-Q_{max}), able to provide 100% electrical energy autonomy, always with regards to the PV rated power each time adopted.

More precisely, given the "N_{pv}" value, the algorithm is executed for each (N_o-Q_{max}) pair for the entire time period selected. When the zero load rejection condition cannot be satisfied, the battery bank capacity is increased up to the case that 100% energy autonomy is ensured, i.e. when $Q^*=\min\{Qmax\}$. Following, the rated power of the wind turbine is also increased and the calculations are repeated for several times, leading eventually to the configuration of a (N_o-Q^*) curve corresponding to a specific PV rated power "N_{pv}". Hence, by gradually increasing the PV rated power input, the desired number of (N_o-Q^*) curves may be generated.

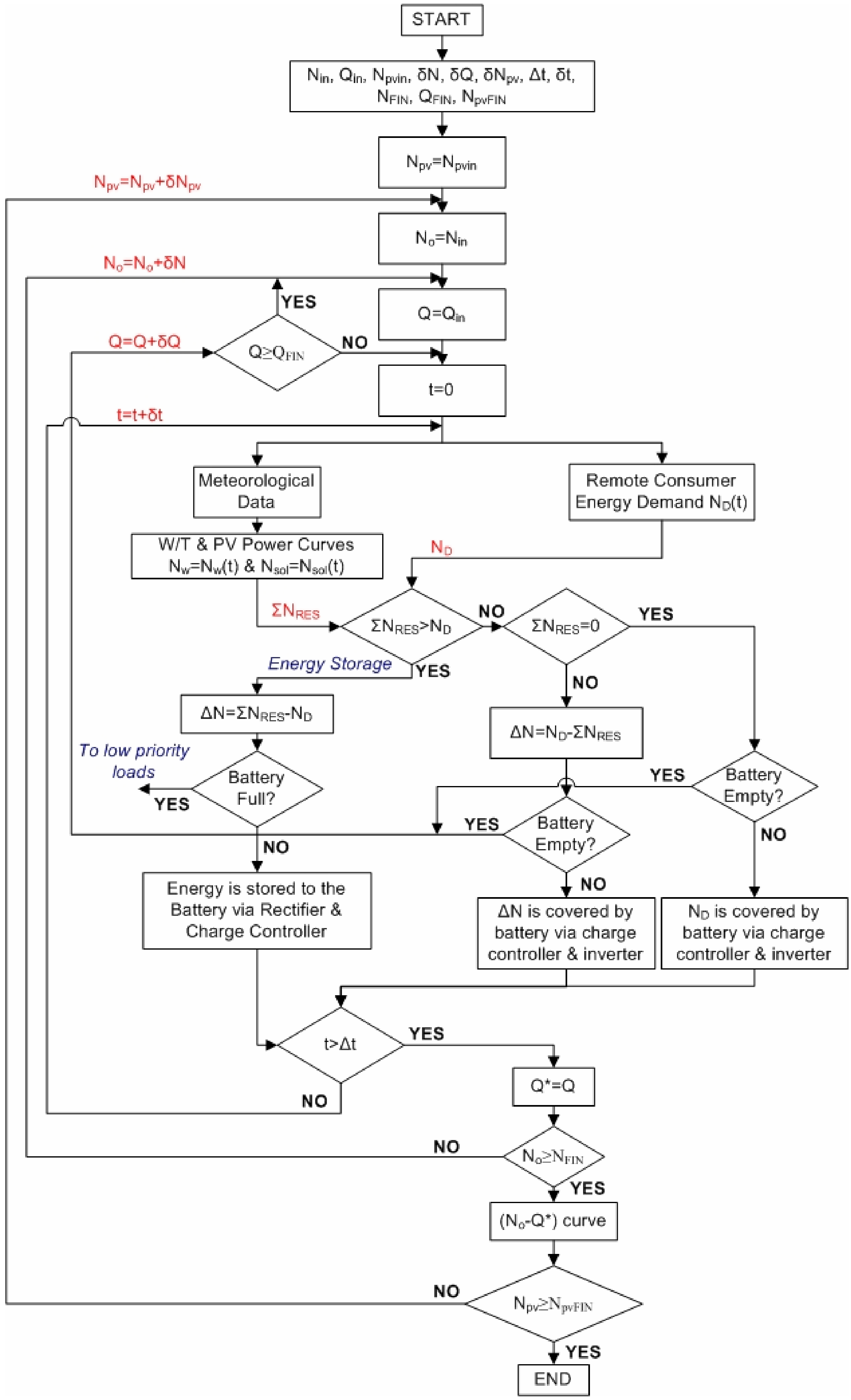

Figure 2: The WIND-PV III algorithm

Besides, among others, the sizing algorithm also takes into account the following necessary information:

- Detailed meteorological data, including wind speed “V” and solar radiation “G” measurements for a given time period (e.g. one year minimum).
- Ambient temperature “θ” and pressure “p” data for the entire period analysed.
- Operational characteristics of both the wind turbine (i.e. specific power curve for standard day conditions) and the photovoltaic modules (i.e. current, voltage, efficiency, usually in the form of I=I(U,G,θ)).
- Operational characteristics of all the other electronic devices of the installation, i.e. inverter efficiency, AC/DC rectifier performance, battery cell (Q-U;θ) curve etc.
- The electricity consumption profile of a typical remote consumer [3,4], being also dependent on the year period analyzed [16-18] (i.e., winter, summer, other), Figure 3. In particular, the annual peak load “N_p” of the remote consumer does not exceed 3.5 kW while the respective annual energy consumption “E_y” reaches approximately 4.75MWh.

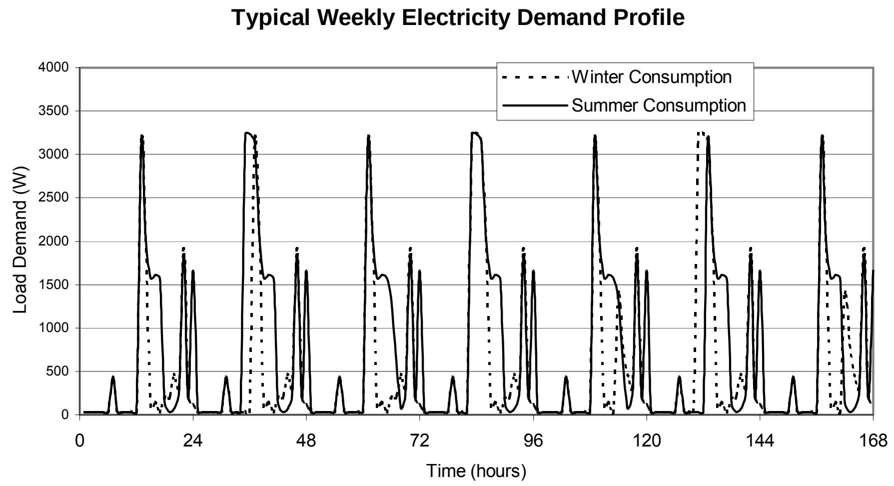

Figure 3: Electricity demand profile of a typical remote consumer

Finally, what is critical to mention is that in the specific study, optimum inclination angles minimizing the first installation cost of similar PV-stand alone systems have been adopted, based on the results of previous studies [4,19] carried out by the authors, concerning the electrification of remote consumers across Greece.

3.3. Estimation of the first installation cost

Using the calculation results provided by the WIND-PV III algorithm, the respective first installation cost “IC_o” for each of the combinations is given by equation (1):

$$IC_o = C_{WT} + C_{PV} + C_{bat} + C_{elec} + C_{BOS} \tag{1}$$

where “C_{WT}” and “C_{PV}” are the wind turbine’s and the photovoltaic modules’ ex-works cost respectively, “C_{bat}” is the battery bank buy cost, “C_{elec}” is the cost of all the major electronic devices included in the system (inverter, charge controller, rectifier) and “C_{BOS}” corresponds to the balance of the system (BOS) cost. Based on previous analyses conducted by the authors [19,20], equation (1) finally reads:

$$\begin{aligned} IC_o = &\left(\left(\frac{a}{b+N_o{}^x}+c\right)\cdot N_o\right)+\left(\zeta\cdot z\cdot P_r\cdot N_{peak}\right)+ \\ &+\left(c_b\cdot Q_{\max}\right)+\left(A+B\cdot(N_o+N_{pv})\right)+\left(f\cdot(C_{WT}+C_{PV})\right) \end{aligned} \tag{2}$$

Breaking down equation (2) we have that:

$$C_{WT}=\left(\frac{a}{b+N_o{}^{x}}+c\right)\cdot N_o \tag{3}$$

where α=8.7·10^5, b=621, x=2.05 and c=700, while

$$C_{PV}=\zeta\cdot z\cdot P_r\cdot N_{peak} \tag{4}$$

with "ζ" being a function of "z" (i.e. ζ=ζ(z)) that captures the scale economies for increased number of PV panels used and with "P_r" corresponding to the specific buy cost of a photovoltaic panel, usually ranging between 5,000 and 7,000 €/kW_p.

Following,

$$C_{bat}=c_b\cdot Q_{\max}=\frac{5.0377}{Q_{\max}{}^{0.0784}}\cdot Q_{\max} \tag{5}$$

where "c_b" is the respective battery specific cost, directly dependent on the battery capacity (€/Ah), and

$$C_{elec}=A+B\cdot(N_o+N_{pv}) \tag{6}$$

with A and B being the coefficients of the function relating the electronic equipment's cost to the wind turbine and the PV generator rated power (A=2200 Euros and B=380 €/kW).

Finally,

$$C_{BOS}=f\cdot(C_{WT}+C_{PV}) \tag{7}$$

where "f" is a coefficient regarding the contribution of the BOS components to the first installation cost, excluding the cost of electronic equipment and ranging between 5% and 15%.

4. Application Results

For the application of the proposed methodology, the case studies currently examined concern the Aegean Archipelagos region (Greece), where the insufficient infrastructure encountered in many islands [9] does not allow connection to a reliable electricity grid for several isolated consumers. On the other hand, the specific area is favored by appreciable wind speeds and considerable solar energy potential during the entire year [8] (Figure 4a), usually complementing one another (Figure 4b) and offering the opportunity for investigating the feasibility prospects of the proposed solution.

In order to evaluate the performance of a WT-PV stand-alone hybrid scheme, two islands of identical solar potential and different annual average wind speed are currently investigated; the first comprising a medium-high wind potential area (Kithnos) and the second suggesting a medium-low wind potential region (Kea). Annual wind speed and solar irradiance values on an hourly basis [8] along with the respective detailed electricity demand profile of a typical remote consumer (Figure 3) are used for the sizing methodology applied, while zero load rejection comprises the main constraint of the calculation procedure. Taking also into account the operational characteristics of all the system main components (wind-turbine, PV-module and battery type employed), several WT-PV stand-alone configurations, ensuring 100%

energy autonomy for the remote consumer and the area each time examined, may be generated by the WIND-PV III algorithm.

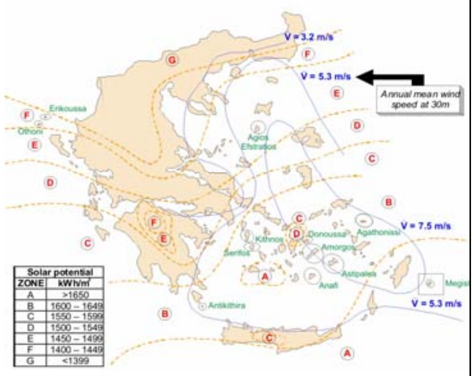

Figure 4a: Wind and solar potential of the Greek territory

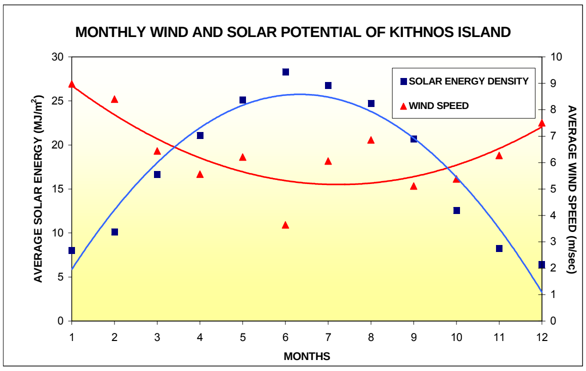

Figure 4b: Monthly wind and solar potential variation for the island of Kithnos

In this context, in Figures 5 and 6, one may obtain the energy autonomy curves for various PV power "N_{pv}" cases concerning to the island of Kithnos and the island of Kea respectively. From the comparison of results concerning the two areas investigated, it accrues that by exploiting a medium-high wind potential, substantial battery capacity reduction may be achieved. The difference noted becomes more evident in case that less PV power is used while the positive effect of the PV integration is even more reflected by the "wind-only" case considered.

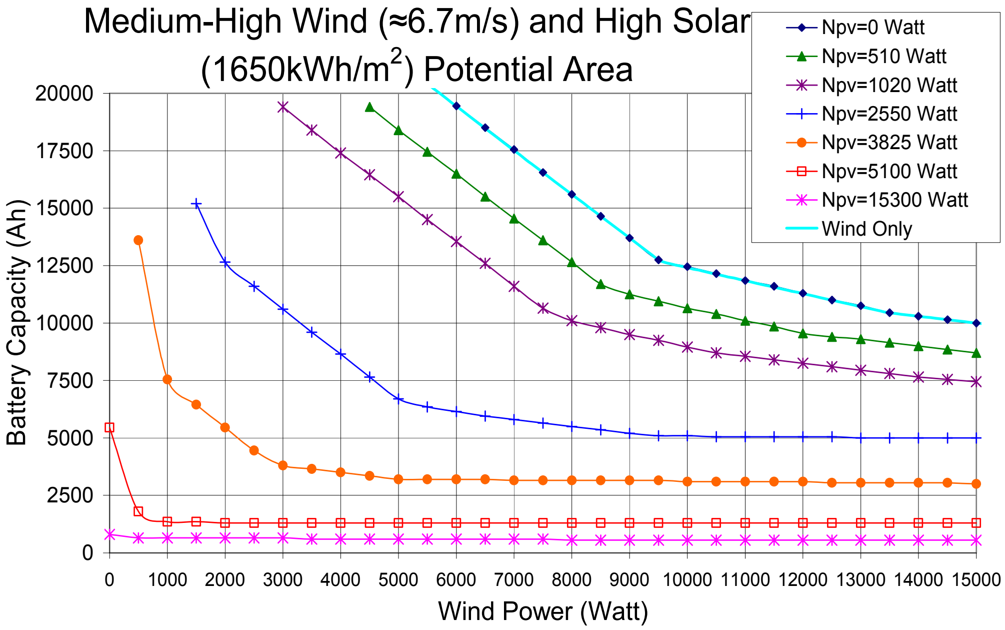

Figure 5: Energy autonomy curves for the island of Kithnos (medium-high wind case)

Taking for example the N_{pv}=510W curve, 18400Ah required for 100% energy autonomy in case that a 5kW wind turbine is used in Kithnos is remarkably less than the respective capacity of 23500Ah needed for Kea. On the other hand, if increasing the power output of the PV generator employed, the role of the wind turbine becomes less dominant and the battery capacity difference minimizes (e.g. in the case of the N_{pv}=15300W curve). Further, the positive impact of the PV integration on the battery capacity reduction is most reflected by the remarkable increase of the battery size in the "wind-only" cases. In fact, by only installing 510W of PV power, the battery capacity reduction exceeds 10% in the case of Kea and may even reach 25% in the case of Kithnos (for wind turbine power of 8.5kW) [21].

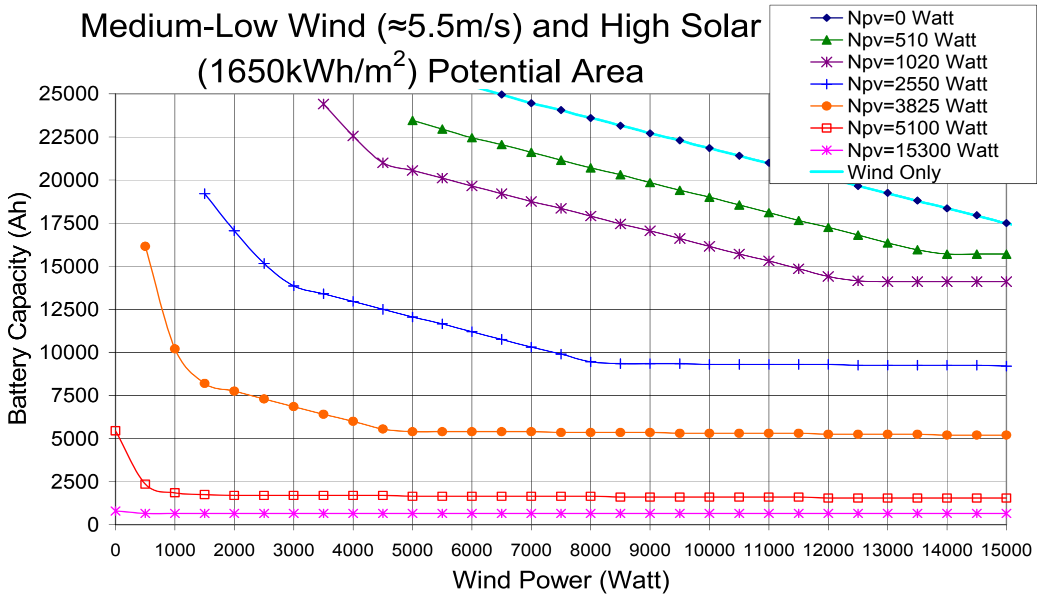

Figure 6: Energy autonomy curves for the island of Kea (medium-low wind case)

Next, in order to obtain minimum first installation configurations, the methodology of paragraph 3.3 is accordingly applied. According to the results obtained (see also Figure 7), by reducing the battery capacity up to a certain point (approximately between 1200Ah and 1800Ah) the initial cost of the installation minimizes. The opposite is valid in case that the battery capacity is further reduced (i.e. less than 1000Ah), this eventually leading to extreme fist installation costs due to the employment of an extremely large PV generator that may ensure 100% energy autonomy. On the other hand, if allowing the battery capacity to increase arbitrarily, the cost difference noted between the medium-high and the medium-low wind potential cases designate the importance of the PV integration for the elimination of the wind potential impact. Note finally that the minimum first installation cost value for the island of Kithnos yields 42,000 Euros for battery capacity of 1800Ah, while the respective value for Kea is equal to 42,270 Euros and corresponds to 1300Ah.

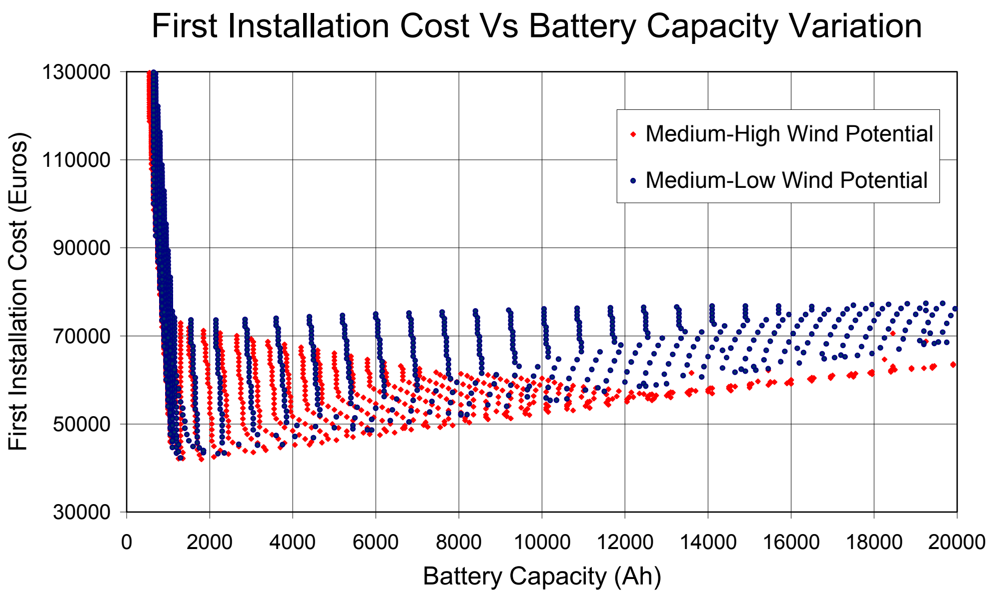

Figure 7: Firsts installation cost for autonomous WT-PV configurations as a function of the required battery capacity for both Kithnos and Kea islands.

Analogous conclusions may be drawn from Figure 8, where the first installation cost is plotted against the PV generator rated power. Although the increase of the PV power up to a certain point (in the area of 5kW) implies gradual reduction of the first installation cost, by increasing the photovoltaic power further than required, the initial installation cost becomes prohibitive. Besides, the gradual elimination of the wind potential impact by the integration of more PV power is again designated by the coincidence of cost values for PV power greater than 6kW.

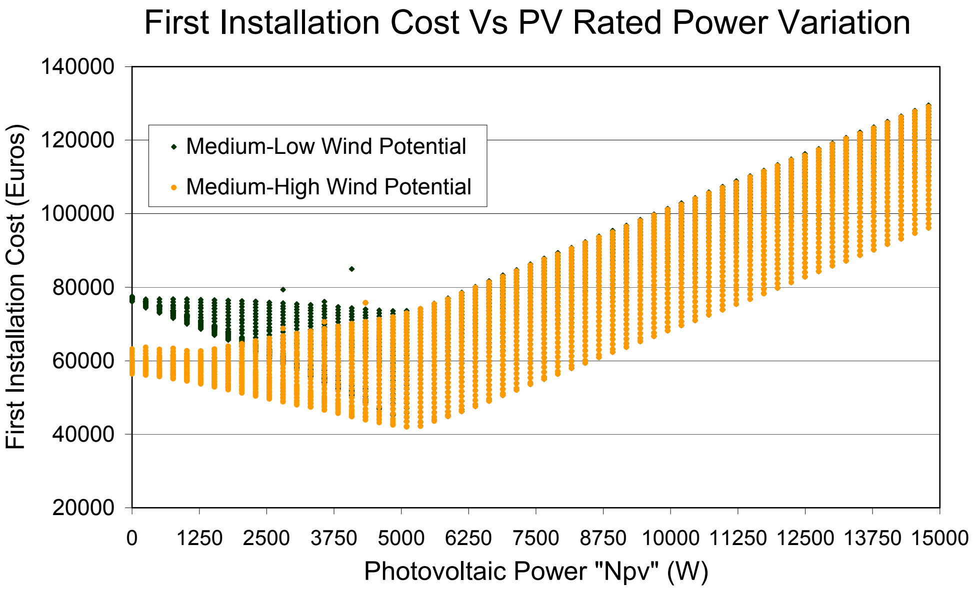

Figure 8: Firsts installation cost for autonomous WT-PV configurations as a function of the employed photovoltaic power for both Kithnos and Kea islands.

5. Conclusions

Based on the development of a calculation algorithm concerning the sizing of a WT-PV system, several WT-PV stand-alone configurations generated may be examined in terms of first installation cost. The integrated methodology is currently applied in an area of major interest, i.e. the Aegean Archipelagos islands, where one may encounter both numerous remote consumers and a considerable RES potential. Two island regions are investigated in order to obtain the impact of the local wind potential on the system size, while the developed algorithm is executed for several PV rated power cases.

According to the results obtained, the contribution of an appropriately sized PV generator may eliminate the effect of the local wind potential on the resulting first installation cost, reducing also the otherwise extreme battery capacity. Overall, what may be stated is that although the local RES potential is of high significance, optimum sizing of similar systems yields reasonable first installation cost values even in case of moderate conditions (e.g. medium wind potential or medium solar potential). Finally, what is also important to note is that according to the analysis undertaken, battery capacity should not be reduced arbitrarily since an over sizing of the PV generator required would have an adverse impact on the resulting first installation cost.

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