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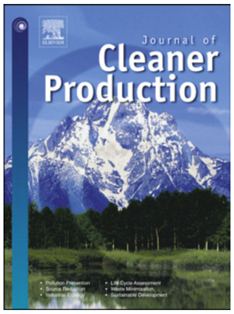
Published in:
Journal of Cleaner Production

Link to article, DOI:
10.1016/j.jclepro.2012.07.014

Publication date:
2013

Citation (APA):
Xydis, G. (2013). On the exergetic capacity factor of a wind – Solar power generation system. Journal of Cleaner Production, 47, 437–445. DOI: 10.1016/j.jclepro.2012.07.014



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PII: S0959-6526(12)00352-6

DOI: 10.1016/j.jclepro.2012.07.014

Reference: JCLP 2969

To appear in: *Journal of Cleaner Production*

Received Date: 22 January 2012

Revised Date: 22 June 2012

Accepted Date: 5 July 2012

Please cite this article as: Xydis G, On the exergetic capacity factor of a wind – Solar power generation system, *Journal of Cleaner Production* (2012), doi: 10.1016/j.jclepro.2012.07.014.

On the Exergetic Capacity Factor of a Wind – Solar Power Generation System

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Abstract

In the recent years, exergy analysis has become a very important tool in the evaluation of systems' efficiency. It aims on minimizing the energy related-system losses and therefore maximizing energy savings and helps society substantially to move towards sustainable development and cleaner production. In this paper, a detailed exergetic analysis aiming to identify the overall Exergetic Capacity Factor (ExCF) for a wind – solar power generation system was done. ExCF, as a new parameter, can be used for better classification and evaluation of renewable energy sources (RES). All the energy and exergy characteristics of wind and solar energy were examined in order to identify the variables that affect the power output of the hybrid system. A validated open source PV optimization tool was also included in the analysis, It was shown that parameters as e.g. air density or tracking losses, low irradiation losses play a crucial role in identifying the real and net wind and solar power output while planning new renewable energy projects and in fact do play a significant role on the wind – solar plant's overall exergetic efficiency. In specific, it was found that air density varies from site to site influencing productivity. A difference of 6.2% on the productivity because of the air density was calculated. The wind and solar potential around a mountainous area were studied and presented based on field measurements and simulations. Since the number and the size of RES projects, over the last few years, are continually increasing, and new areas are required, the basic idea behind this research, was not only to introduce ExCF, as a new evaluation index for RES, but also

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to investigate the combined use of wind and solar energy under the same area and the benefits coming out of this combination.

Keywords: Exergetic Capacity Factor; Wind – Solar Systems; System Losses

Nomenclature

A	wind turbine rotor swept area (m^2)
AM	Air Mass coefficient
Ci	installed capacity of the wind farm (MW)
G_{sc}	solar constant which equals 1,367 W/m^2
H	monthly average daily solar radiation on a horizontal surface
h	altitude (m)
H_d	daily diffuse radiation
H_0	extraterrestrial radiation on a horizontal surface
h_{km}	the location height above sea level (km)
K_T	monthly average clearness index
l	cable length (km)
L	transmission loss (W)
$\dot{m}$	air mass flow (kg/s)
n	the day of the year
P	power load (kW)
P_m	the nominal maximum power output from a PV(kW)
P_{real}	actual PV power output (kW)
R	resistance (Ohm/km)
R_b	the ratio of beam radiation on the PV array to that on the horizontal
S	the solar radiation on the panel surface
T	air temperature (ºC)
T_{cell}	the PV cell temperature (ºC)
T_{NOCT}	Nominal Operating Cell Temperature (ºC)
U	voltage (kV)
V_R	wind speed (m/s)

Greek letters

β	panel inclination

δ	solar declination angle
λ	the maximum power temperature coefficient (PV)
ρ	air density (kg/m^3)
ρ'	albedo of the ground
φ	phase angle between active and reactive power (rad)
ψ	latitude
ω_s	solar hour angle
ω'_s	tilted sunset hour angle

List of Acronyms

AEP	Annual Energy Production
AExP	Annual Exergy Production
ExCF	Exergetic Capacity Factor
HV	High Voltage
LV	Low Voltage
MV	Medium Voltage
PV	Photovoltaic
PVGIS	Photovoltaic Geographical Information System
RES	Renewable Energy Sources
WF	Wind Farm

1. Introduction

Extensive solar studies and wind resource analyses based on measurements and simulations are undoubtedly necessary for the efficient exploitation of renewable energy sources. Solar characteristics are usually found and analyzed based on solar maps, software tools such as Photovoltaic Geographical Information System (PVGIS) (Huld et al., 2006) or PVsyst (PVsyst User's Guide, 2012). Wind characteristics measured usually include wind speed with anemometers at different heights, wind direction using wind vanes at different heights and temperature (using thermometers) according to the international standard IEC 61400-12-1 (IEC, 2005).

In this paper a mountainous area was thoroughly energetically and exergetically wise studied. The air flow study showed that the proposed Wind Farm (WF) polygon area set for the WF installation on the hillcrest of the under examination mountain is advantageous for wind farms as they tend to increase the wind speed (compared to the incoming air flow) because of the obstructions on the incoming wind and therefore are usually preferable compared to flat terrains in order the power output to be increased (wind speed-up effect) (Røkenes and Krogstad, 2009; Lubitz and White, 2007; Pellegrini and Bodstein, 2004; Lemelin et al., 1988; Miller and Davenport, 1998; Capon, 2003). Installing PV projects at the same areas, could increase power output and at the same time combine two RES in the same polygon dispensable area. In this paper this combination was thoroughly investigated and all projects were included. The goal was to indentify the way these parameters influence the exergetic efficiency of combined wind and solar projects. A draft literature review, site experimental results, the wind – solar power system planning, exergetic analyses and conclusions follow in the upcoming sections.

2. Previous Studies on Exergy Analysis of Renewable Energy Sources

A large body of literature concerning the applications of exergy analysis has been carried out during the past decades. However, exergy analyses and studies on wind and solar energy concerning advances on exergetic efficiency are not that many. Koroneos *et al.* (2003) dealt with the three kinds of RES in terms of exergetic aspects including wind energy. In this research the authors concluded for different wind turbines (600 kW – 1 MW) that while the wind speed changes from 5 m/s to 9 m/s, the available wind potential for electricity use changes from 35% to 45% due to exergy losses mainly because of the rotor, the gearbox and the generator. A solar thermal power system was also exergetically examined within this paper. Şahin *et al.* (2006) estimated mean exergy and energy efficiencies in relation to the wind speed and suggested that exergy efficiency should be used for wind energy sitting in order modelling to be more realistic. Under the same concept, Xydis *et al.* (2009) implemented the exergy analysis methodology as a wind farm sitting tool in Central Peloponnese, Greece, an analysis which showed that gross Annual Energy Production (AEP) & net AEP may differ significantly based on other parameters variation like transmission losses, air density losses, topographic losses (wake effects) and wind turbine availability. Şahin *et al.* (2006) used exergy analysis for each system, applying a point-by-point map analysis giving another approach to wind power systems as exergy maps provided even more useful information (compared to energy analysis) regarding losses. Ozgener O. and Ozgener L. (2007) carried out an exergy and a reliability analysis of a wind turbine proving – among others – and showed that exergy efficiency changes between 0% and 48.7% at different wind speeds, considering pressure difference from the state point. Hepbasli (2008) in his important review on exergetic analysis and assessment of renewable energy resources pointed out that differences between energy and exergy efficiencies were proved to be 40% at low wind speeds and up to nearly 55% at high wind speeds. In the same analysis, a comparison of energy and exergy efficiency values of solar collector, photovoltaic and hybrid collector was done where it was shown that the exergy efficiencies of solar collector, PV and hybrid solar collector were found to be 4.4%, 11.2% and 13.3%, respectively (Saitoh *et al.*, 2003; Fujisawa and Tani, 1997). Ozgener *et al.* (2009) investigated exergetic efficiency and various thermoeconomic values of a small wind turbine and as Baskut *et al.* (2010; 2011) did point out the importance of various meteorological parameters with respect to wind speed. Öztürk (2011) calculated energy and exergy efficiencies at 10, 25 and 50 m for 23 different wind-monitoring stations in Turkey and stressed the importance of air temperature and pressure at inlet and outlet of a wind turbine. Ahmadi and Ehyaei (2009) have dealt with an improved approach for exergy analysis of the wind. Based on the same type of installed wind turbine, by varying the cut in rated and "furling" speeds, showed that the energy production can vary a lot while the entropy generation could be decreased up to 76.9%. However, not all types of analyses do take into account the terrain. What is probably of great value is the effect on the exergetic efficiency of the ground combined with the meteorological effects not just refering to a site but to a whole area. Based on Hepbasli's review exergy is a measure of the maximum useful work that can be done by a system while Van Gool (1997) has reported that the maximum improvement in the exergy efficiency for a specific process can be achieved when exergy losses or irreversibilities are minimized. Joshi *et al*. (2011) implemented an analysis of exergy efficiency for hybrid PV/T systems while Yilanci *et al*. (2011) included also an environmental analysis in a photovoltaic-hydrogen production system. Coskun *et al.* (2011) and Coskun (2010) have found that intensity of global solar irradiance affects energy and exergy efficiencies and therefore the efficiency of the collectors. De An and Singh (2011) analysed a solar-wind hybrid power plant for Malaysia based on the NREL's HOMER software results. PV exergy efficiency in terms of the inclination of the solar irradiation and time and in terms of exergy losses was calculated using computer programs written in Matlab-Simulink software environment (Akyuz *et al.*, 2012; Namjoo *et al.*). Mahmoud and Abdel-Akher (2010) tried to present the effect of allocation of photovoltaic and wind generation units in electrical distribution networks after many tests. Studies (Zhou *et al.*, 2010; Bekele and Palm, 2010; Yang *et al.*, 2009) were focused in optimizing (technically and economically) different hybrid stand-alone or grid connected solar-wind power generation systems. Boroumandjazi *et al.* (2012) reviewed how the technical characteristics of a renewable based system can affect the exergy efficiency of the system more than the energy efficiency. Saidur *et al.* (2012) compared the thermal and the exergetic efficiency of systems and proved that thermal efficiency is not sufficient as a system characteristic to choose the proper system.

To fill the gap in the literature related to wind – solar units and exergy analysis aiming at optimizing the generated power by optimizing the sitting and the operation of a wind – solar farm minimizing at the same time exergy losses or irreversibilities in a specific area, an innovative study has been carried out and is described in this paper.

3. Wind – Solar Power System Planning

3.1 Wind Speed Measurements

Wind measurements were carried out for 3 years using two (1) 40 m. meteorological mast on the east of Mt. Didimo, on the south of Saronic Gulf, in eastern Peloponnese (Figure 1). Site coordinates, period of measurement, average velocity, and height above ground level are shown on Table 1. Tools used for elaborating all the measurements and produce estimates of wind speed/energy output (at various distances from the measuring meteorological masts) were WindRose (WindRose, 2010) and WAsP (Mortensen *et al.*, 1993).

Vector Hellenic Windfarms S.A. operates a certified laboratory (Laboratory of Wind Measurements) from Hellenic Accreditation System S.A. (E.SY.D.) in Greece and the meteorological stations were under the laboratory's supervision.

Table 1. Main measured characteristics of the site in the area

Site / Code	**Latitude (°)**	**Longitude (°)**	**Mean speed ($m \cdot s^{-1}$)**	**Period of data analysis**	**Height (m.a.g.l.)**
L1	37.29°N	23.17°E	5.80 at 40 m.	2 Oct ’05 – 2 Oct ’08	595

Fig. 1. Area for wind-solar power generation system under examination

The wind was studied for 3 years (Oct ’05 – Oct ’08). One (1) 40 m. mast was installed made out of steel in tubular form kept in vertical position using tense wires. Anemometers and vanes were placed every ten meters (20; 30; 40). A data logger connected to the available sensors of the mast stored and sent the data to the responsible laboratory using the GSM method (a method for transmitting digital data). The uncertainty of the measured wind speed for the masts “L1” was calculated using the WindRose software at 0. 2.

3.2 Area’s Solar Characteristics

However, within the polygon for the WF investment, not only because of the prerogative orientation of part of the designed WF, but also because of the solar irradiation levels, it was decided a PV park to be built inside the polygon as well. Based on the free web based software PVGIS developed from the Joint Research Centre (JRC), and the free open source excel-based tool developed from the author an estimation of the solar (PV) production output in kW per m^2 is done. The solar characteristics of the wider area are shown on Figure 2.

Fig 2. Solar characteristics of the wider area

The average daily and monthly electricity production (in kWh) and the average daily sum of global irradiation per square meter of a given system (in kWh/m^2) will be calculated and the Exergetic Capacity Factor (ExCF) of the PV park, $(ExCF)_{PV}$ will be found if losses are calculated and excluded.

It has been decided by an Independent Power Producer in this area a wind – solar power generation system to be developed. The total capacity of the initially proposed power generation system is 18 MWs (of 9 wind turbines 2 MWs each) and 1,91488 MW of PV park totalling 19.91488 MWs. All project construction works necessary for the implementation of the project like road works; Medium Voltage/High Voltage (MV/HV) lines, possible substations locations, PV park and WF are drawn and shown in Figure 3. Therefore calculating the ExCF of both the PV park and WF, $(ExCF)_{WF-PV,}$ the exergetic efficiency of the wind – solar power generation system will be found.

Fig 3. , PV park and WF and needed construction works to be done in the area

4. Exergetic Analysis and Results

The concepts of exergy, available energy, and availability are similar. Exergy is a measure of the maximum useful work that can be retracted by a system (Hepbasli, 2008). Dincer *et al.* (2004) reported that for an efficient and effective use of fuels, it is essential to consider the quality and quantity of the energy used to achieve a given objective. Van Gool (1997) has also proposed that maximum improvement in the exergy efficiency for a process or a system is obviously achieved when the exergy loss or irreversibility is minimized. In this regard, it is easily understood that the first law of thermodynamics deals with the quantity of energy and asserts that energy cannot be created or destroyed, whereas the second law of thermodynamics deals with the quality of energy. Therefore, it can be said that exergy analysis can be used to measure and evaluate interconnected WFs or PV parks considering their losses (topographic & wake losses, air density losses cable losses, transformer or substation losses, technical availability losses, shadow losses, PV panel temperature losses etc) revealing the maximum useful work that can be derived from a wind or PV farm and not just evaluate the maximum work extracted from it. In the research implemented and presented in this paper the focus was on identifying the losses due to seasonal variation of the air density and PV panel temperature variation and exergetically find the effect of it in the net production of a proposed wind and PV farm.

4.1 Exergetic Analysis of the proposed WF

The available output from the proposed wind farm could be determined based on the flow rate passing through the rotor (swept area) of the turbine. The kinetic energy E_k is:

$$E_k = \frac{1}{2} \cdot \dot{m} \cdot V_R{}^2, \qquad (1)$$

where V_R *and* $\dot{m}$ are the wind speed and the air mass flow rate respectively, and

$$\dot{m} = \rho \cdot \mathrm{A} \cdot V_R, \qquad (2)$$

where ρ is air density, A is the wind turbine rotor swept area equals $\pi \cdot R^2$.

Thus, $$E_k = \frac{1}{2} \cdot \rho \cdot \pi \cdot R^2 \cdot V_R{}^3 \qquad (3)$$

something which means that if the wind speed is measured, the kinetic energy can be defined, for a given wind turbine, and since the kinetic energy is a form of mechanical energy it can be converted to work unconditionally, then the exergy output it is also known.

Following this concept, a WAsP based wind resource analysis (Mortensen *et al.*, 1993) in the project area (Figure 4) was done and shows the average kinetic energy per unit area (in particular 30 m X 30 m) perpendicular to the wind flow measured in [W/m^2]. Based on this analysis the energy output of each unit area is calculated with a mean value of 195 W/m^2 (41 - 417 W/m^2) and the maximum wind speed on this terrain, after the spatial analysis, is 6.49 m/s. The terrain is rough and the hub heights of the proposed wind turbines to be installed vary from 560 m to 620 meters above ground level (m.a.g.l.). It needs to be noted that because of the terrain high complexity, the ruggedness index (RIX) was taken into account for the planning of the wind turbines.

Fig. 4. Wind resource analysis and WF planning

In general it is known that the wind turbine is designed to operate at a design conditions including constant air density. Thus, once the air density has changed, the output of wind turbine will certainly change. Lower density may cause a loss in power output of the wind turbine. In this case, taking into account the altitude of the investment an average air density of 1.151 kg/m^3 was taken into consideration and inserted into the model for the analysis. This has a significant effect on the final production from the proposed wind farm. It is seen that in general follow the same trend.

Taking into account also the Wind Turbine Power Calculator of Danish Wind Industry Association (Wind turbine power calculator, 2012) and the Swiss Wind Power Data Website (2012) an updated power map was produced which included not only the topographical and wake effects as usual, but the losses due to air density variation (Figure 4).

Based on this resource grid analysis the produced power map gives the ability to the wind developer not only to optimally plan the farm taking into consideration the topographical and wake effects but also the air density losses (which is usually neglegted). Adding up also the electrical losses (internal interconnection medium voltage losses and transformer losses) and the wind turbine technical availability losses a fixed percentage for the proposed wind farm, usually provided from the wind turbine manufacturer it is possible to calculate the exergetic efficiency of the WF.

Following the analysis of Vogstad (2010) and Jones (2010), the electrical losses are taken into account the cable transmission losses based on the equation:

$$L = k \cdot P^2 [W], \tag{4}$$

where $$k = \frac{R \cdot l}{U^2} \cdot (1 + \tan^2 \phi) \tag{5}$$

L is the transmission loss [W] along the cable segment, P is the power load [kW]. R represents resistance in [Ohm/km], l cable length [km], φ phase angle [rad] between active and reactive power and U the voltage level [kV]. The electrical losses were estimated taking into account the fact that the wind farm is planned to be 18 MW, and therefore the overall electrical losses will be specified from the medium voltage losses for the interconnection of the wind turbines and the distribution power station (20/150kV 25 MVA transformer) losses. Based on Eq. (4) and (5), (Xydis *et al.*, 2009; Xydis, 2012a; Xydis, 2012b; Schneider Electric, 2012) the initial planning (Fig. 3 and 4) and the length of the medium voltage cabling, the cable losses were calculated at 2.05%. Adding up the average losses for each Wind Turbine of the internal Low Voltage/Medium Voltage (LV/MV) transformer (0.6%) and the wind farm MV/HV substation (0.45%) (Wind turbine power calculator, 2012), the sum of the electrical losses is 3.1% for the proposed WF. An exergetic Sankey flow diagram below shows all average losses on the proposed wind farm (Figure 5).

Fig. 5. Sankey flow diagram describing the losses of the proposed WF

Following the approach of Xydis *et al.* (2009) and Hepbasli and Alsuhaibani (2011), exergy efficiency of the proposed wind farm, including all losses can be estimated by using the equation

$$\text{Exergy Efficiency} = \frac{\text{NetAEP}}{8760 \cdot Ci} \cdot 100\%, \qquad (6)$$

where *Net AEP* is the Net Energy [MWh] produced, *8760* h are the total hours within a year (365 days x 24 hours), and C_i the installed capacity of the wind farm [MW].

It was found after the simulations, that the net Annual Energy Production (AEP) or more accurately the Exergetic Capacity Factor (ExCF) of the WF is 39.93 GWh (Table 2).

Table 2. ExCF of the WF

Site	X-location [HGRS '87]*	Y-location [HGRS '87]*	Elev. [m]	Speed [m/s]	Net AExP [GWh]	Wake losses [%]
WT 1	437642.5	4147642	560	6.09	4.32	1.55
WT 2	436470.2	4148934	580	6.23	4.39	3.22
WT 3	436371	4149069	560	6.04	4.24	0.94
WT 4	436766.2	4148257	580	6.27	4.28	6.74

WT 5	436925.2	4148091	590	6.32	4.54	2.83
WT 6	437169.9	4148045	620	6.45	4.73	2.30
WT 7	436702.8	4148480	600	6.12	4.30	2.38
WT 8	437324	4147899	600	6.38	4.63	2.38
WT 9	437508.4	4147798	576	6.23	4.50	1.34
TOT					39.93	

*Hellenic Geodetic Reference System *1987*

4.2 Exergetic Analysis of the proposed PV Park

Photovoltaic panel electrical performance depends on environmental conditions such as the temperature, solar irradiation, angle-of-incidence, and the types of PV cells. In this project specifically, the angle, the type of the PV cell and the solar irradiation (since the project is in a specific area) are known. Temperature plays a very important role on the efficiency of the modules and consequently on the PV park efficiency. It will be allowed not only to calculate how much module power will be lost or gained due to temperature variation but also based on the wind how much will be saved. For the photovoltaic panel efficiency, based on several research findings (Sarhaddi *et al.*, 2010; Burger, and Ruther, 2006; Skoplaki and Palyvos, 2009; Ross, 1980) the actual PV power output, P_{real}, can be estimated based on the equation:

$$P_{real} = P_m \cdot \frac{S}{1000} \cdot \left[1 - \lambda \cdot (\mathrm{T}_{cell} - 25)\right], \tag{7}$$

and $$T_{cell} = T + \frac{S}{800} \cdot (T_{NOCT} - 20), \tag{8}$$

where P_m is the nominal maximum power output from a PV, S is the solar radiation on the panel surface, T_{cell} is the cell temperature, T is the ambient temperature, T_{NOCT} is the Nominal Operating Cell Temperature, and λ the maximum power temperature coefficient.

The proposed park consists of 9,328 panels of 205 W_p each (including 8 inverters of output 250KW each). The maximum energy efficiency of the inverters according to the technical description of the manufacturer is 95.2%. The required land for the development of the PV park is 13,852.08 m^2 of net space.

A simple excel-based tool was developed to calculate the solar radiation on the panel surface based on Duffie and Beckman (2006). In order to calculate the solar declination angle, δ:

$$\delta = 23.45 \cdot \sin \cdot \left[360 \cdot \frac{284 + n}{365} \right], \tag{9}$$

where *n*, the day of the year (e.g. i.e. n =2 for January 2, n = 33 for February 2, etc.).

For the solar hour angle, ω_s (the solar hour angle at the time when the sun sets):

$$\omega_s = \arccos(-\tan \psi \cdot \tan \delta), \tag{10}$$

where ψ is the latitude.

For the extraterrestrial radiation (which is needed for the calculations) on a horizontal surface, H_0, for day *n* it can be calculated from the following equation:

$$H_0 = \frac{86400 \cdot G_{sc}}{\pi} \left[1 + 0.033 \cdot \cos\left(2\pi \frac{n}{365} \right) \right] (\cos \psi \cos \delta \sin \omega_s + \omega_s \sin \psi \sin \delta), \tag{11}$$

where G_{sc}, the solar constant which equals 1,367 W/m^2 and π the known mathematical constant. However, the solar radiation is usually “weakened” by the cloudiness. Therefore, the monthly average clearness index, K_T, should be introduced which can be computed by dividing the monthly average daily solar radiation on a horizontal surface, *H*, by H_0. Therefore, there is:

$$K_T = \frac{H}{H_0}, \tag{12}$$

H is important in order to calculate the monthly average daily diffuse radiation H_d. The equation used was the one proposed by Lalas *et al.* (1982):

$$\frac{H_d}{H} = 1.446 - 2.965 \cdot K_T + 1.727 \cdot K_T{}^2 , \qquad (13)$$

In order to complete the tilted irradiance calculation, R_b (the ratio of beam radiation on the PV array to that on the horizontal) is needed to be calculated from:

$$\mathrm{R}_b = \frac{\cos(\phi-\beta)\cdot\cos\delta\cdot\sin\omega'_s + (\pi/180)\cdot\omega'_s\cdot\sin(\phi-\beta)\cdot\sin\delta}{\cos\phi\cdot\cos\delta\cdot\sin\omega_s + (\pi/180)\cdot\omega_s\cdot\sin\phi\cdot\sin\delta} , \qquad (14)$$

where ω'$_s$ is the tilted sunset hour angle calculated from:

$$\omega'_s = \min\left\{\omega_s , \arccos(-\tan(\phi-\beta)\cdot\tan\delta\right\} \text{ and } \beta\text{, the panel inclination.} \qquad (15)$$

This way the calculation of hourly irradiance in the plane of the PV array, H_T, can be computed.

$$\frac{H_T}{H} = (1-\frac{H_d}{H})\cdot R_b + \frac{H_d}{H}\cdot(\frac{1+\cos\beta}{2}) + \rho'\cdot(\frac{1-\cos\beta}{2}) , \qquad (16)$$

where ρ' is the albedo of the ground. Therefore, H_T can be calculated for the specific month since H is already known. The gross AEP can be found by adding up the months and multiplying by the panels' efficiency excluding losses. On the website http://www.uest.gr/ppt/Solar_Irradiation_eng.xls there is open source accessible and validated (based on PVsyst results) AEP excel-based calculator developed from the author, aiming in the designing of a cost-effective and efficient PV system.

The nominal efficiency of the panels to be used under STC conditions is 13.7% (measurements in 1000 W/m^2, Air Mass, AM, equal to 1.5 and panels' temperature 25°C). Regarding the effects of altitude on solar irradiation it has been observed that the sunlight intensity increases with the height above sea level. A simple empirical formula to calculate the sunlight intensity, I_D, (accurate to a few kilometres above sea level) is given from Meinel, A. B. and Meinel, M. P. (1976) and Laue (1970):

$$I_D = 1.353 \cdot [(1 - ah_{km}) \cdot 0.7^{(AM^{0.678})} + ah_{km}) \,, \qquad (17)$$

where a = 0.137 and h_{km} is the location height above sea level in kilometres (in the under examination case study h_{km} = 0.59). By replacing, the I_D= 0.8870kW/m^2, while for the sea level the I_D= 0.846 kW/m^2 (4.8% increase).

Fig. 6. Planning of PV park

Based on research findings (Sarhaddi *et al.*, 2010; Skoplaki and Palyvos, 2009; Rahman *et al.*, 2010; Garcia *et al.*, 2009; Bücher, 1997; Kaldellis, 2011; Redpath, 2011) regarding losses there is:

- √ Temperature correction factor - losses due to temperature increase: -1.3%
- √ Optical losses factor (ash accumulation losses etc): -2%
- √ Inverter losses: -4.8%
- √ Wiring, protection devices, data receivers etc. losses: -8%
- √ Energy transfer losses: -0.5%
- √ Transformer losses: -0.6%
- √ PV modules aging: -1%
- √ Sunlight intensity factor: +4.8%

Adding up those losses, the total exergetic efficiency of the PV park now is *78.4%*. (table 3), and replacing in the Eqs. (7), (8) and knowing T_{cell}, T, T_{NOCT}, and λ, we can calculate the available PV power output as in table 3.

Table 3. Table of annual exergy produced from the PV power generation system

A/A	Gross AEP (GWh)	Inverter Losses	MV Grid losses	Sunlight intensity	Optical losses factor	Aging coeff.	Wiring, protection devices, data receivers etc.	Net AEP (GWh)	(kWh/ kW)
P_{real}	**3.295**	*0.952*	*0.995*	*1.048*	*0.98*	*0.90*	*0.90*	**2.583**	**1350.9**

Similarly to the WF and since exergy efficiency is the ratio of the total outgoing exergy flow to the total incoming exergy flow during a process (Amini, 2007), the Exergetic Capacity Factor (ExCF) of the PV park, *(ExCF)*$_{PV}$, can be calculated based on the equation (6).

$$(\mathrm{ExCF})_{\mathrm{PV}} = \frac{2583\ \mathrm{MWh}}{(8760\ \mathrm{h})\cdot(1.91 MW)}\cdot 100\% = 15.4\% \ , \tag{18}$$

and the the ExCF of the WF, *(ExCF)*$_{WF}$, is:

$$(\mathrm{ExCF})_{\mathrm{WF}} = \frac{39930\ \mathrm{MWh}}{(8760\ \mathrm{h})\cdot(18 MW)}\cdot 100\% = 25.32\% \ , \tag{19}$$

Therefore, the Wind – Solar Power Generation System, *(ExCF)*$_{WF\text{-}PV,}$ is:

$$(\mathrm{ExCF})_{\mathrm{WF\text{-}PV}} = \frac{42513\ \mathrm{MWh}}{(8760\ \mathrm{h})\cdot(19.91 MW)}\cdot 100\% = 24.37\% \ , \tag{20}$$

The interconnection proposed for the wind – solar power generation project is the PV park to be connected with the proposed WF and the whole system to be connected to the Greek grid.

Conclusions

In this paper a study on the exergetic efficiency of a proposed wind farm and PV park was done through a wind and solar analysis based on the variation of the proposed plants' properties. Exergetic efficiency power density maps were produced to provide a common basis for project developers and to point out parameters neglected so far as the impact on the exergetic efficiency of a plant.

This paper presents the results of an innovative methodology to the problem of the accurate estimation of power forecasting of combined wind and solar projects in mountainous areas. Calculating the exergetic efficiency of a wind farm or a solar park is of great importance, as up to now there are analytical ways to estimate losses of the project's output under normal conditions and only (usually) up to what's "coming out" of the PV or the wind farm.

Air density losses were included in the used software which was used to produce the power density maps. Air density varies from site to site (because of altitude changes within the proposed WF) which has an effect on the WF productivity. A 6.2% on the productivity only because of the air density was calculated. It should be noted that this is happening in an area with average altitude of 600 m. In areas with higher altitude this site, the air density losses will be even greater especially during summer months when humidity ratio is higher than winter.

A validated open source tool was developed and used for the calculation of the solar irradiation and consequently the PV park output. It was proved that because of the altitude the solar irradiation intensity is higher than in coastal areas. This study helps decision makers and project owners, following the proposed methodology, to identify the final output of their project. It could help PV developers to take into consideration that implementation of projects to sites with significant altitude is advantageous as it increases the overall power output.

These results could be used from wind and solar project developers for a more precise and accurate prediction of all power generation systems worldwide. The global applicability of the methodology implemented in this paper is based on projects' exploitation (specifically implemented on windy coastal sites) under the most effective way.

Acknowledgements

The preparation of this paper would not have been possible without the support of the Certified Laboratory of Wind Measurements of Vector Hellenic Windfarms S.A.. The used data array was made up of the average (1 value per second – 600 values in 10 min) and maximum 10-min wind speed values in the sites monitored by the laboratory of Wind Measurements of Vector – Hellenic Wind Farms S.A.

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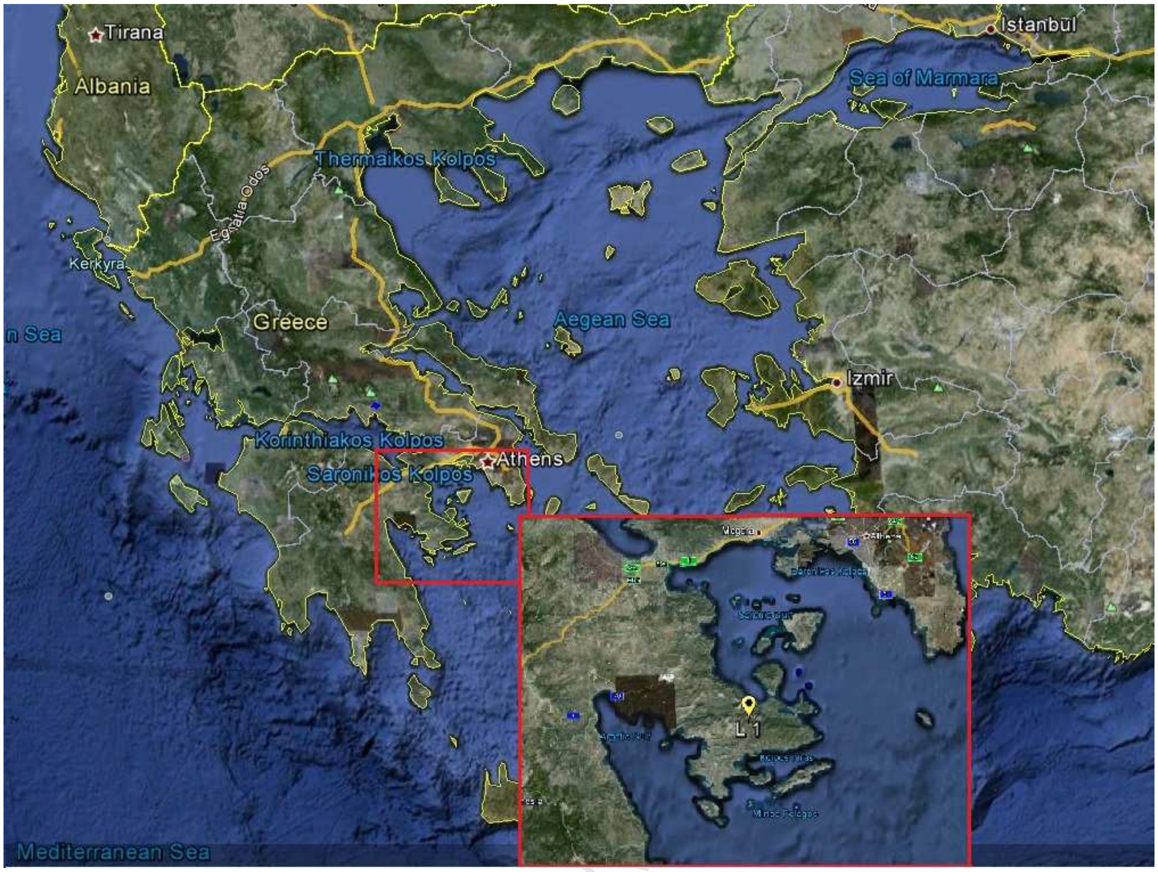
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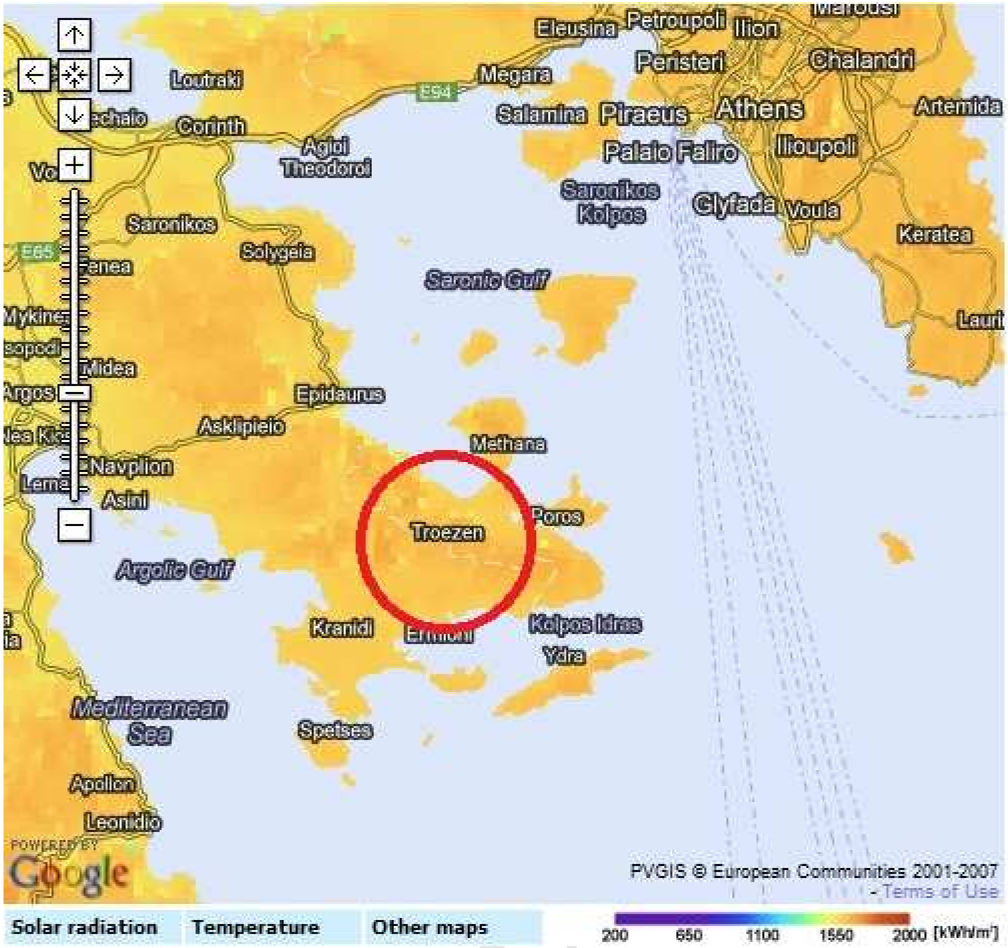
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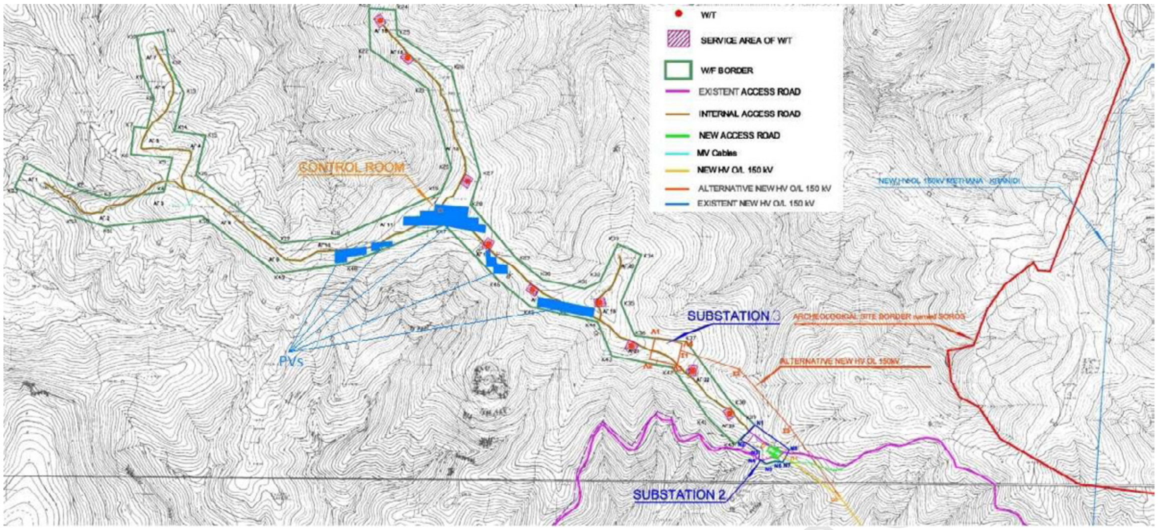
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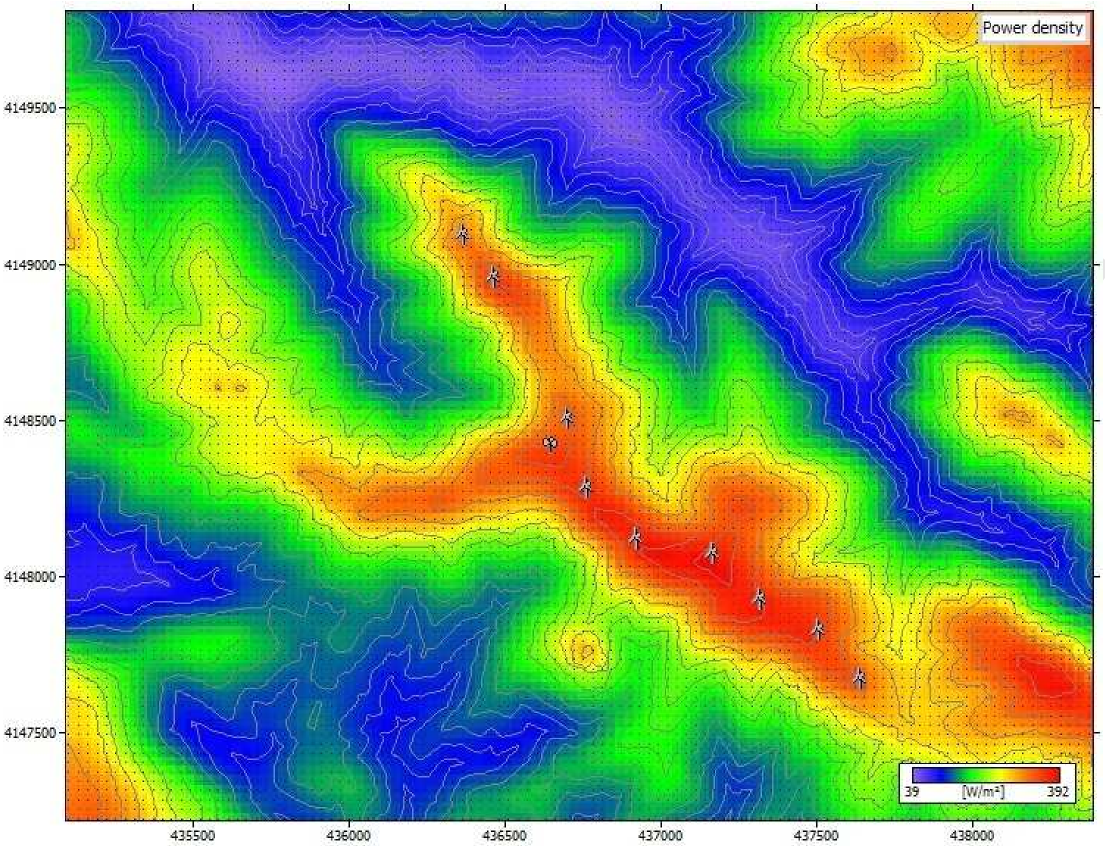
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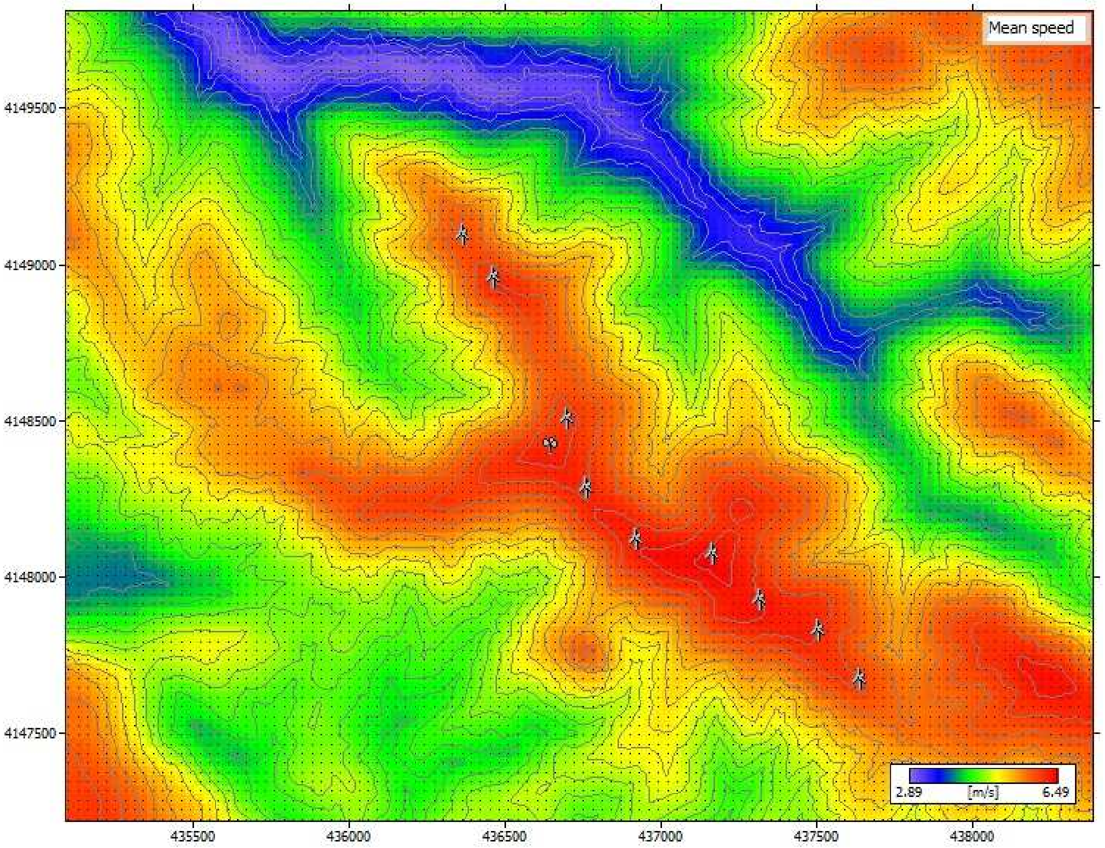
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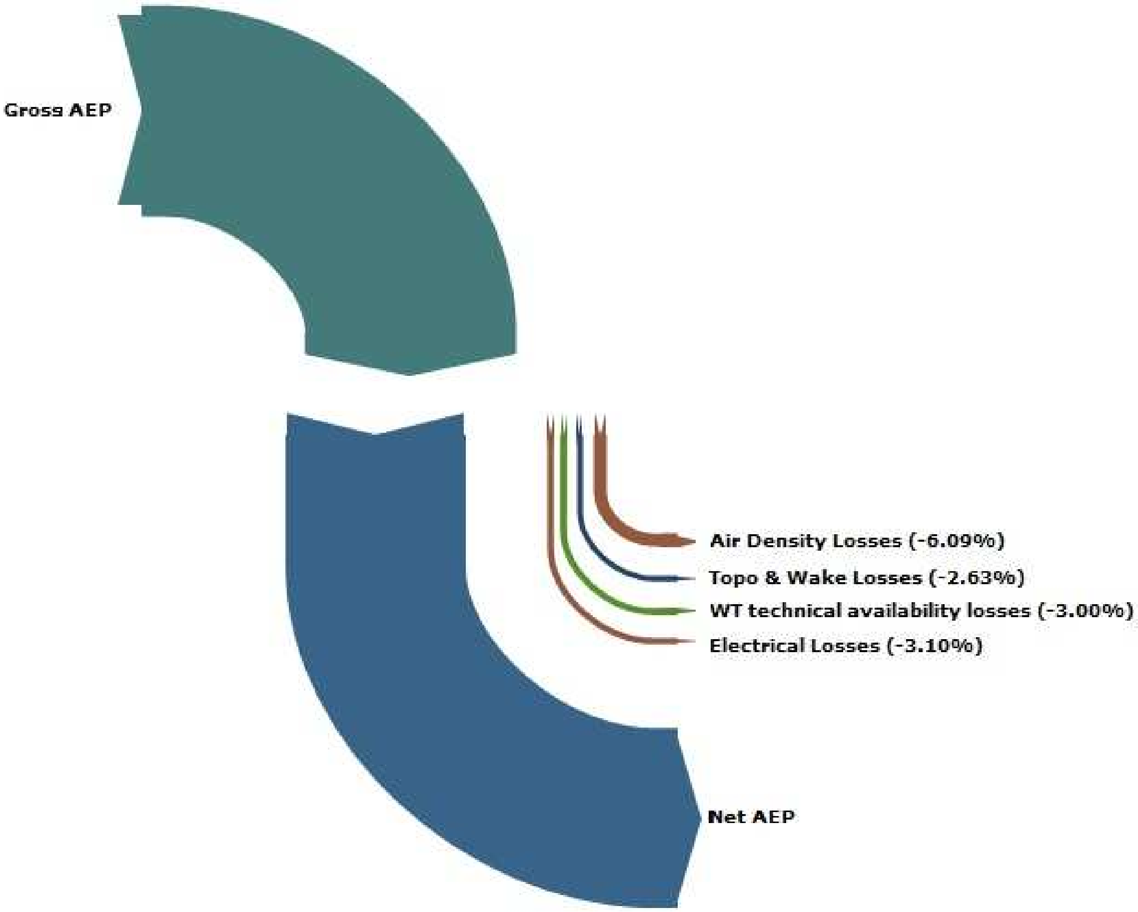
Gross AEP
Air Density Losses (-6.09%)
Topo & Wake Losses (-2.63%)
WT technical availability losses (-3.00%)
Electrical Losses (-3.10%)
Net AEP