Modeling, comparative simulation and practical performance analysis of a stand-alone PV hybrid power system in Turkey

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This study aims to analyze and compare the performance of a stand-alone PV hybrid system located in Fethiye, Turkey. The system was built in off-grid configuration employing a wind turbine - diesel generator hybrid auxiliary supply. System performance was calculated both by simulation and real life measurements. Simulation results and actual performance has been compared for determining the factors affecting the overall performances of PV and/or hybrid power systems. The impact of the meteorological conditions, load demands, and the characteristics of system components were also analyzed. The results were reported using the international evaluation parameters.

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Keywords: Photovoltaics, Wind energy, Renewable hybrid power systems

1. Introduction

With a population reaching 75 million, Turkey's electricity production and consumption based on primary energy resources are continuing to increase. Gross electric energy consumption of Turkey was 229,3 TWh in 2011 and increased by 9,0% in reference to 2010. Although PV market in Turkey is still fairly small, a highly competitive market is expected to emerge soon with the grid-parity is reached. Estimated cumulative installed PV power in Turkey is about 6,5-7 MW [1]. The off-grid applications account for around 90% of cumulative installed PV capacity. However, the share of the grid-connected PV power systems will rapidly grow in near future in Turkey.

In addition to PV generators, hybrid systems combining diesel generators, wind turbines, small hydro turbines, and other sources with storage components can be used for meeting the energy demand of remote or rural areas. Before developing a hybrid electric system for a specific site, it is essential to know the particular energy demand profile and the resources available at that site. Therefore, it is strongly needed to predict the system's performance and to monitor and analyze the real-life operation.

This study aims to analyze the performance of a stand-alone PV hybrid system located in Fethiye-Turkey and compare the results with the simulated performance of the same system. Methods explained in "*TS EN 61724: Photovoltaic system performance monitoring – Guidelines for measurement, data exchange and analysis*" are used in the evaluation and comparison processes. This International Standard recommends procedures for monitoring energy-related PV system characteristics such as in-plane irradiance, array output, storage input and output and power conditioner input and output; and for the exchange and analysis of monitored data. The purpose of these procedures is to assess the overall performance of PV systems configured as stand-alone or grid-connected, or as hybridized with non-PV power sources such as engine generators and wind turbines [2].

The stand-alone PV hybrid power system installed in Kızılada-Fethiye, Turkey includes PV and wind generators and a diesel generator (Fig.1 & Fig.2). This PV hybrid system was installed by Girasolar Energy Ltd. in collaboration with Ege University Solar Energy Institute.

The system was planned to meet the whole electrical energy consumption of a restaurant with a hybrid power system during the touristic season. Considering the daily energy requirements, the capacities of power sources are defined as: 17,82 kWp multi-crystalline solar modules, 15 kW wind turbine, 70 kVA diesel generator, 48 V 3 000 Ah battery capacity. The system was designed in ac coupling topology. The main components are listed below and the specifications of the system components are explained in Table 1.

- *PV modules:* 108 pieces 165 W modules.
- *Solar inverters:* 3 pieces (SMA SMC6000A). (Three PV arrays are used and each of them covers 3 strings connected in 12 modules serially).
- *Wind turbine:* 1 unit (STEP V2 15 kVA)
- *Wind inverters:* 3 pieces (SMA WB 5000A).
- *Battery group:* 2 clusters are used and each of them has 48 V 1 500 Ah capacity. Each cluster covers 24 pieces batteries (MUTLU AKÜ) which has 2 V 1 500 Ah capacity.
- *Control board:* 1 unit switchboard (SMA SI5048 MC-Box 6) is used to enable the synchronization of two battery clusters.
- *Bi-directional inverters:* 6 pieces bi-directional inverters (SMA SI 5048) supply the loads on the stand-

alone ac grid side and charge battery banks with the energy from grid-feeding units connected on the ac side.

- *Other components:* A solar irradiation sensor (SMA Sunny Sensor Box), an anemometer sensor, ambient and module temperature sensors are also included to the system.

Fig.1. An off-grid PV hybrid system in Fethiye, Turkey.

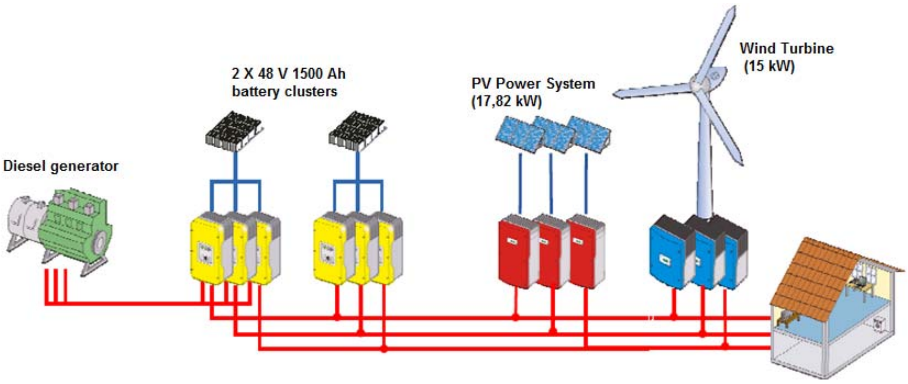


Fig. 2. The flow diagram of PV hybrid system in Fethiye, Turkey.

Table 1. The specifications of the components used in PV hybrid system in Fethiye, Turkey.

PV modules:

	Pmpp (W)	Isc (A)	Voc (V)	Impp (A)	Vmpp (V)	Module Efficiency (%)	Area (m^2)
PHOTOWATT (108 pieces, multicrystalline silicon modules)	165	5,1	43,2	4,8	34,4	12,3	1,34

Inverters:

	SI5048 (6 pieces)	SMC 6000A (3 pieces)	WB 5000A (3 pieces)
Max. dc input power	12 800 W	6 300 W	5 750 W
Max. input voltage	230 V/172,5 V – 264,5 V [ac.]	600 V	600 V
MPP voltage range/rated input voltage	-	246 V – 480 V/246 V	246 V – 600 V/270 V
Min. input voltage/initial input voltage	-	211 V/300 V	300 V
Max. input current	56 A [ac]	26 A	26 A
Rated output power	5 000 W	6 000 W	5 000 W
Max. output current	100 A	26 A	26 A
Max. efficiency/European weighted efficiency	95%	96,1 %/95,3 %	96,1%/95,3%
Operating temperature range	-25°C ... +60°C		
Dimensions (W/H/D)	467/612/235 mm	468/613/242 mm	468/613/242 mm
Weight	63 kg	63 kg	62 kg

Battery:

- OpZs block series stationary (standby) batteries which are the products of a Turkish manufacturer (MUTLU AKÜ) are used. With their separator and alloy features they infrequently require maintenance and have a long life as 1 200-1 599 duty cycles.
- Each battery has 2 V and 1 500 capacity.
- Dimensions (Width/Length/Height/Height with polarhead): 215/277/800/875 mm
- Weight with electrolyte (max): 116 kg

Wind turbine:

- Rated power output: 15 kW/230 V 50 Hz
- Start: 2-3 m/s, Rated: 11 m/s, Cut out: 25 m/s, Survival: 50 m/s
- Total weight (15 m/18 m mast height): 1 890/2 000 kg
- Blades: 3, Rotor diameter: 8,4 m, Rated rpm: 100 rpm
- Synchronous generator, Rated rpm: 1 500, Electrical Power: 16 kVA, Voltage output: 0-400 V [ac], Efficiency: 84%.

2. Performance Prediction

The design of a stand-alone system should consider providing all energy demand of the site. Energy planners must study the solar, wind and other available potential resources with the energy demand. This will allow them to design the proper hybrid power system that meets the demands of the facility at best. Based on the technical data of the components having the international qualification approval, the renewable sources such as solar radiation and wind speed should be evaluated with the user load demand to make accurate predictions for the hybrid system requirements. The meteorological input parameters for the simulation study could be provided by the national and international reliable measurement databases.

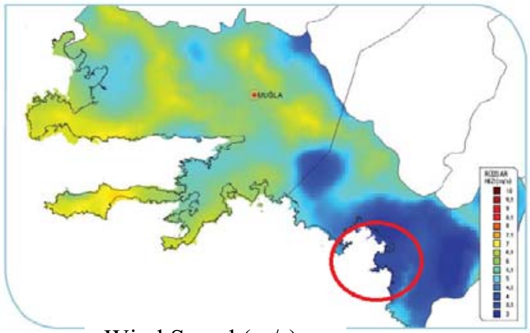
2.1 Weather Data

The weather parameters required for the PV hybrid system analyzed in this work are the solar radiation [W/m²], the ambient temperature [°C] and the wind speed [m/s]. The solar radiation values provided by European Commission – Joint Research Center - Photovoltaic Geographical Information System (PVGIS) are referred often as reliable resources. According to PVGIS, Turkey's global irradiation and optimal-inclined solar electricity potential are 1 400-2 000 kWh/m^2 and 1 050-1 500 kWh/(kW_{rated}.y), respectively. PVGIS estimates of long-term monthly averages in Fethiye are shown in Table 2. By using these inputs, the annual global irradiation is calculated as 1,96 MWh/(m^2.y) in Fethiye.

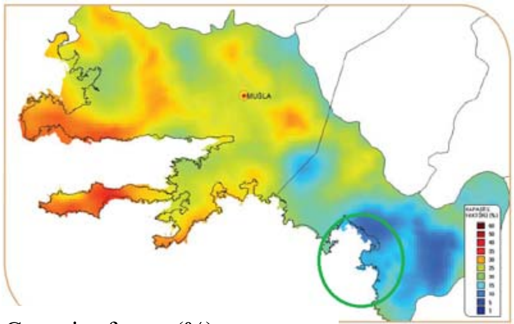
Table 2. PVGIS Estimates of long-term monthly averages in Fethiye,Turkey[3].

	Optimal inclination angle [°]	Irradiation on optimally inclined plane ($Wh/m^2/day$)	Irradiation on horizontal plane ($Wh/m^2/day$)	24 hour average of temperature (°C)
January	60	3 660	2 360	10,5
February	52	4 520	3 240	10,8
March	40	5 570	4 600	12,6
April	23	5 980	5 680	15,7
May	9	6 180	6 500	20,6
June	2	6 470	7 130	25,1
July	7	6 420	6 900	27,8
August	18	6 360	6 270	27,7
September	35	6 310	5 420	24,3
October	49	5 520	4 080	20,2
November	58	4 170	2 720	15,4
December	61	3 220	2 040	12
Year	33	5 370	4 750	18,5

Wind speeds registered at EİE-REPA* database may be used for wind energy simulation. The wind energy potential is calculated by considering the wind turbine's mast height, power factor (Cp) and the capacity factor of the location. The values for the wind speed and the capacity factor at 50 m height are shown in Fig. 3. The red circle shows the location of Kızılada-Fethiye. EİE emphasizes that the locations which have 7 m/s or higher wind speeds or 35% capacity factor at 50 m height may be evaluated as economically feasible [4]. The annual average wind speed and capacity factor in Kızılada-Fethiye are 4,5-5 m/s and ≈ % 15, respectively. Therefore, the wind energy potential of this location may not be considered feasible.



Wind Speed (m/s)



Capacity factor (%)

Fig. 3. The annual wind speed and capacity factor average at 50 m height in Fethiye, Turkey [4]

In this study, the measured values at EİE & MGM† Metering Stations at 10 m height are used. Since the height of the wind turbine's mast used in Fethiye is 15 m, these measured values are simulated to 15 m height by using Hellmann coefficient (Table 3).

$$V_r(m/s) = V_{rref}(m/s)\left(\frac{h(m)}{href(m)}\right)^{\alpha}$$

V_r: Wind speed at desired height (m/s), Vr_{ref}: Wind speed at referenced/known height (m/s), h: The desired height for the simulation (m), h_{ref}: The referenced height (m), α : Helmann coefficient. The Hellman exponent depends upon the coastal location and the shape of the ground terrain, and the stability of the air.

* EİE-REPA: General Directorate of Electric Power Resources Survey and Development Administration – Wind Energy Potential Atlas. EİE renamed as Renewable Energy General Directorate in 2011.

† MGM: General Directorate of Meteorology

Table 3. Simulated wind speeds by considering EİE-MGM's measured values in Fethiye, Turkey.

	Jan.	Feb.	March	April	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Year
A	2,53	2,85	2,72	2,6	2,75	3,83	3,36	4,24	3,72	3,11	2,8	1,57	3
B	2,72	3,07	2,93	2,80	2,96	4,12	3,61	4,56	4,00	3,35	3,01	1,69	3,23

A: Average monthly wind speeds measures at EİE & MGM Metering Stations at 10 m height [m/s]
B: Simulated wind speeds at 15 m height by using Hellmann Equation (α =0,18)

2.2 Predicted Solar Electricity Generation

By considering the solar irradiation potential in Table 2 and the efficiencies of the system components predicted in Table 4, the simulation of the PVPS energy generation and performance analysis may be calculated (Table 5).

Table 4. The predicted efficiencies of the PVPS components.

Rated power / Application type / Topology:	17,82 kW / Off-grid / ac coupling
PV efficiency (η_{PV}):	12,3%
Power conditioning unit efficiency (η_{PCU})*:	a) 96,1% or b) 86,7%
Battery efficiency (η_{B})*:	a) – or b) 70%
Cable losses:	2%
Other losses (temp., dust etc.):	10%
PV system efficiency (η_{SP})*:	**a) 10% b) 7%**

* a) The load demand is directly provided. b) The load demand is provided over the battery group (Fig.4).

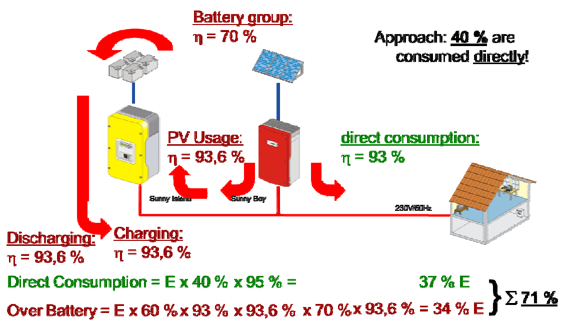


Fig. 4. Efficiency with ac coupling.

The ac coupled system topology has a superior performance compared to the dc coupled configuration since each inverter can be synchronized to its generator so that it can supply the load independently and simultaneously with other inverters [6]. It is possible to use 40% of the generated energy directly with ac coupling (Fig. 4). This topology has several advantages compared to the dc coupled topology such as higher overall efficiency, smaller sizes of the PCUs while keeping a high level of energy availability, and optimal operation of the diesel generator due to reduced operating time and consequently less maintenance cost. On the other hand, the operation and control of this topology are more sophisticated due to the synchronization process required between the components. The development of an advanced PCU simplifies the control and the load dispatch problem [7].

Table 5. PVPS simulation results in Fethiye, Turkey

System performance indices:	
Reference yield (Y_r), [$kWh/d/kW_{rated}$]:	5,37
Array yield (Y_a), [$kWh/d/kW_{rated}$]:	4,83
Array capture losses (L_c), [$kWh/d/kW_{rated}$]:	0,54
Balance of System (BOS) losses (L_{BOS}), [$kWh/d/kW_{rated}$] 1):	a) 0,47, b) 1,77
Performance ratio (PR), [%] 1):	a) 81, b) 57
Final PV system yield (Y_f), [$kWh/y/kW_{rated}$] 1):	a) 1591,18 b) 1113,83

a) The load demand is directly provided. b) The load demand is provided over the battery group (Fig. 4).

In this study, it is assumed that 40% of the energy generation is directly consumed and the following system performance indices may be achieved: BOS efficiency [η_{BOS}] = 74%, PV system efficiency [η_{SP}]=8%, Performance ratio [PR]=66,6%, Final PV system yield [Y_f]=1 304,77 $kWh/y/kW_{rated}$.
The monthly energy prediction is shown in Table 7.

2.3 Predicted Wind Energy Generation

Rayleigh distribution enables to estimate the energy recovered by a medium sized wind turbine. The related equations are explained below.

$$h_r = 24 \cdot \left(\frac{\pi}{2}\right) \cdot \left(\frac{k}{(V_r)^2}\right) \cdot e^{-\frac{\pi}{4}\left(\frac{k}{V_r}\right)^2}$$

$$P_r = C_{pBetz} \cdot 0,5 \cdot \rho \cdot A \cdot (V_r)^3 = 0,5 \cdot \rho \cdot \frac{\pi \cdot D^2}{4} \cdot (V_r)^3 C_p$$

$$E_r = h_r \cdot C_p \cdot 0,5 \cdot \rho \cdot A \cdot (V_r)^3$$

h_r: Wind blowing hours (h), k: Calculated wind speeds (1-25 m/s), V_r: Mean wind speed (m/s), P_r: Wind turbine power (W), E_r: Wind energy generation (Wh), A: Cross-sectional area (m^2), D: Diameter (m), ρ : Density of air (1,23 kg/ m^3), C_{pBetz} : Betz coefficient (0,5926), C_p: Power factor, (max. %59,26)

The wind energy generation potential was calculated with these equations by using the wind speed values shown in Table 3 and also the wind turbine's average speed-electrical power graphs given in the product data sheet (Table 6).
The monthly energy prediction is also shown in Table 7.

Table 6. Wind power system simulation results in Fethiye, Turkey

Wind turbine:	15 kVA STEP V2
Application type:	Off-grid ac coupling
Power Conditioning Unit (PCU) Efficiency1[1)]:	a) 96,1%, b) 86,7 %
Other losses (control board etc.)	90%
Battery efficiency (η_B) [1)]:	a) –, b) 70 %
Cable losses:	2%
Wind turbine BOS efficiency [1)]:	a) 84,8%, b) 53,5%, c) 66%
Wind power system output energy (kWh/y) [1)]:	a) 9769,84, b) 6172,10, c) 7611,20

[1)] a) The load demand is directly provided. b) The load demand is provided over the battery group (indirect usage). c) % 40 direct usage and % 60 indirect usages are considered.

Table 7. Montly energy prediction of PV and wind power system in Fethiye, Turkey.

	Off-grid PVPS*	Off-grid Wind Power System*
	17,82 kW	15 kVA
[kWh/m]	ac coupling	ac coupling
January	1 346,43	313,51
February	1 501,89	475,20
March	2 049,08	405,48
April	2 128,95	346,02
May	2 273,49	421,08
June	2 303,39	1 160,69
July	2 361,78	799,71
August	2 339,71	1 509,27
September	2 246,43	1 071,83
October	2 030,69	630,81
November	1 484,57	447,73
December	1 184,57	29,87
TOTAL	23 250,97	7 611,20
kWh/kW$_{rated}$/y	**1 304,77**	**507,41**

* % 40 direct usage and % 60 indirect usages are considered.

3. Operation Results

The monitoring period of the system is between July 1st, 2008 and December 31st, 2010. Beside the inherent measurement uncertainties the analysis includes some special sources of failures which are described below. The comparisons were made by normalizing the values to 1 kW.

Following to the initial operation, the wind turbine was disabled on September 18th, 2008. Since the touristic season is closed, the wind turbine could be operated again on July 11th, 2012. Due to a lightning streak, one blade was broken on September 12th, 2009 and then the wind turbine was totally disabled, considering its insufficient potential at site. Therefore, the measured values for the wind turbine cover only two intervals of July 1st and September 17th (2008) and July 11th and September 11th (2009).

Since one solar inverter was disabled on June 9th, 2009 and it was enabled again on July 17th, 2009, only the 11,88 kW PVPS could be monitored in this period. The second failure was observed on July 6th, 2010 and again the 11,88 kW PVPS could be monitored until the end of 2010.

3.1 Analysis of Weather Data

PV modules are placed on the optimum angle (33°). By using the SMA Sunny Sensor Box and its accessories, the solar irradiation on plane (W/m^2), the ambient and module temperatures (°C) and the wind speed (m/s) are measured. The calculated global solar irradiation based on real measurements is compared with the PVGIS database in Fig. 5. The real-time and the predicted values are 5,15 [kWh/(m^2.d)] and 5,37 [kWh/(m^2.d)], respectively. The annual mean temperature based on the real-time measurements is 19,9° C and it is higher than the PVGIS prediction (18,5 °C). The module temperatures are measured among 48-60 °C [8].

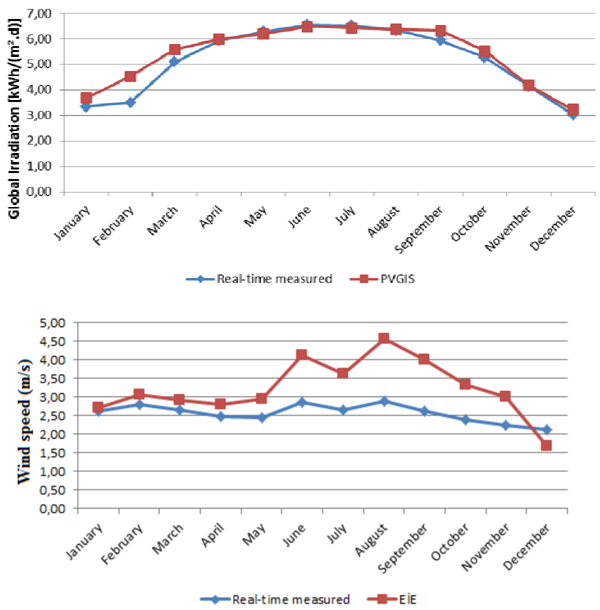


Fig. 5. The comparison of real-time global solar irradiation and wind speed with the predicted ones.

The monthly averages of the measured wind speeds are also compared with the predicted ones in Fig. 5. The predicted values are provided from Table 3. The actual and the predicted values are 2,57 m/s and 3,23 m/s, respectively [8]. Although there is a significant difference between these values, the annual variation pattern is similar.

3.2 Analysis of Load Demand

In Kızılada-Fethiye implementation, there is a load demand difference between winter and summer periods (Fig. 6). The customer needs energy only in spring and summer, since they run the restaurant only in touristic season. The summer and winter load demands are 155-280 kWh/d and 14-25 kWh/d, respectively. The peak power drawn is also measured as 23 kW in summer and 4,4 kW in winter [8].

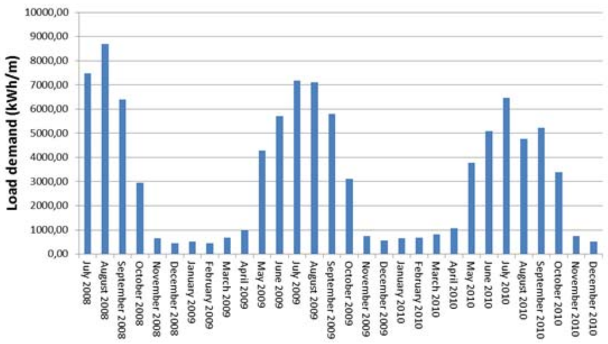


Fig. 6. The monthly load demand.

3.3 Analysis of Solar Electricity Generation

In comparison with the low wind energy potential, Kızılada-Fethiye location has a significant solar energy potential. The predicted and measured solar electricity generations based on 1 kW rated PVPS are compared in Fig. 7 and the performance ratio (PR) for the practical analysis is shown in Fig. 8. As seen in these figures, the system performance is significantly decreased due to the low load demand in winter periods.

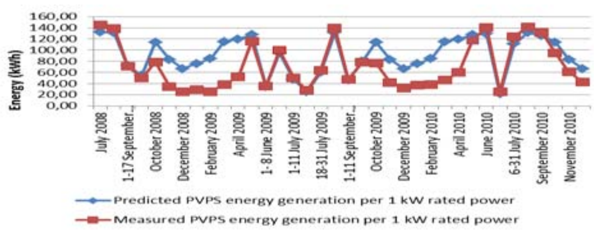


Fig. 7. Comparison of predicted and measured PVPS energy generation in Fethiye, Turkey.

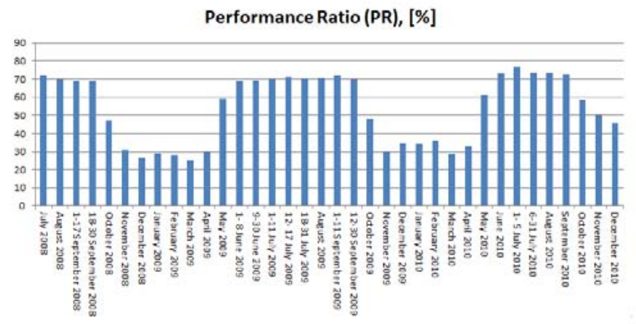


Fig. 8. Performance ratio (PR) of the PVPS.

The direct usage percentage was calculated based on measured values. The average direct usage of the generated energy was observed 43% during the monitoring period. It is significantly increased during the summer due to the high load demand during the high solar energy generation periods. With the decreasing load demand in winter, the direct usage is stopped. (Fig. 9). The system performance indices are summarized in Table 8.

Table 8. Annual system performance indices in Fethiye, Turkey.

	η_{SP} [-]	Yr [h.d^{-1}]	Ya [h.d^{-1}]	Yf [h.d^{-1}]	Lc [h.d^{-1}]	PR [%]	Final yield (Yf), [kWh/y/kW$_{rated}$]
2009	0,065	5,43	4,86	3,062	0,58	52,85	952,61
2010	0,068	5,29	4,73	3,057	0,56	55,10	1 059,99

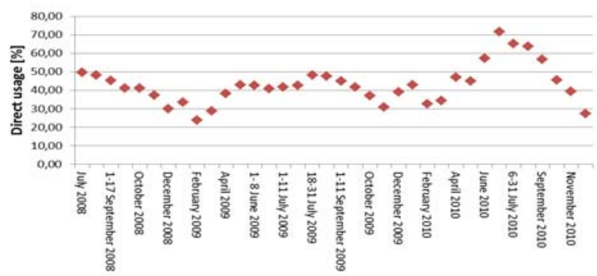


Fig. 9. Direct usage [%].

3.4 Analysis of Wind Energy Generation

During the monitoring periods, the measured and the calculated energy values are shown in Table 9. Since the low wind speeds caused an interrupted operation of the turbine, there is a significant difference between the measured and predicted values.

Table 9. Energy generation of the wind turbine.

Monitoring period:	Mean wind speed (m/s):	Wind turbine's output energy calculated by Rayleigh Distribution (kWh):	The measured energy at the input of wind inverters (kWh):	The measured energy at the output of wind inverters (kWh):
July 2008	2,50	301,94	254,23	177,96
August 2008	2,70	409,51	327,61	176,91
1-17 September 2008	2,51	168,30	143,06	74,39
12- 17 July 2009	2,70	79,26	64,20	38,52
18-31 July 2009	2,70	184,94	159,05	84,30
August 2009	2,72	420,98	370,46	203,75
1-11 September 2009	2,60	125,51	104,17	60,42

3.5 Analysis of the energy generation of the diesel generator

The energy output and the running time of the diesel generator are shown in Fig. 10. The daily energy generation supplied by diesel generator was measured as 100-245 kWh/d among July-September period. During the monitoring period between 1 July 2008 and 31 December 2010, 6 5185 kWh total energy was generated and the running time was 2 960,6 h.

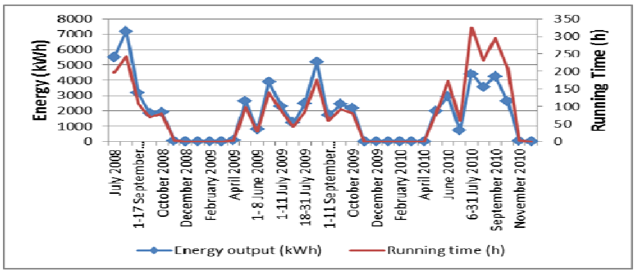


Fig.10. The energy output and running time of the diesel generator.

4. Conclusion

The remarkable results of this study are summarized below:

The global solar irradiation values based on PVGIS database are coherent with the site-measured values. The values are 5,37 [kWh/(m2.d)] and 5,15 [kWh/(m2.d)], respectively. The annual mean temperature based on the measurements is 19,9 °C and it is over the PVGIS prediction (18,5°C). The measured module temperatures are among 48-60°C.

The actual and the predicted mean wind speeds are 2,57 m/s and 3,23 m/s, respectively. Although there is a significant difference between these values, the monthly variation is close. Since the low wind speeds caused an intermittent operation of the turbine, there is a significant difference between the measured and predicted energy values.

The average direct usage of the generated energy was observed 43% during the monitoring period. It is significantly increased during the summer due to the high load demand during the high solar energy generation periods. With the decreasing load demand in winter, the direct usage is stopped.

The prediction for the PV system efficiency, the performance ratio, and the final yield is consistent with the measured values in June-September period (Fig. 7 & Fig. 8). However, a significant difference is observed in the rest of the time. The main reason of this is the energy generation is limited due to the low energy demand. There is 22% difference between the predicted potential compared to the actual generation. The comparison of the actual and predicted values is summarized in Table 10. The present solar energy potential could not be used since the batteries are fully charged and there is not any load demand.

Table 10. The comparison of the real-time and predicted values in Fethiye, Turkey.

	Off-grid PVPS, Kızılada-Fethiye		
	Simulation (1 year)	Real Measurement (2009)	Real Measurement (2010)
Topology	ac	ac	ac
Inclination angle	33°	33°	33°
Global irradiation [kWh/(m^2.d)]	5,37	5,43	5,29
Direct usage [%]	40	39,01	48,35
PVPS Performance Ratio (PR), [%]	67	52,85	55,10
PV system efficiency [η_{SP}]	0,08	0,065	0,068
PV final yield, [kWh/y/kW$_{rated}$]	1 305	952,61	1 059,99

The results shown in this study would help to improve the accuracy of the evaluation of photovoltaic system performance parameters.

Acknowledgements

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