Study of power fluctuations and their compensation in a hybrid system with renewable energy sources

Hristiyan Kanchev, Bruno François, Zahari Zarkov, Ludmil Stoyanov, Vladimir Lazarov

This paper deals with the combined influence of photovoltaic and different wind energy potentials and respectively the produced energy on the operation of an autonomous hybrid system. The studied system comprises a PV generator, a wind generator and three micro gas turbines (MGT) supplying power to residential loads. The installed power of the PV and wind generators varies for each studied case. The solar energy distribution is identical for all simulations while three different cases of the wind speed distribution are used. The system control is realized with planning of the MGT power references for 24 hour ahead using dynamic programming. The objective is to minimize the CO_2 equivalent emissions by decreasing the MGT startups and shutdowns. The results analysis allows determination of the optimal installed power of renewable generators taking into account the primary potential and the load curve.

Keywords: *hybrid system, renewable energy, storage, optimization, gas turbine*

Изследване на флуктуациите на мощността и тяхното компенсиране в хибридна система с възобновяеми източници на енергия (Християн Кънчев, Брюно Франсоа, Захари Зарков, Людмил Стоянов, Владимир Лазаров). *В статията е разгледано комбинираното въздействие на слънчевия и вятърния потенциал и съответно произведената енергия върху работата на автономна хибридна система. Изследваната система включва ФВ генератор, вятърен генератор, три газови микротурбини и товари. Инсталираната мощност на възобновяемите източници се изменя за различните изследвани случаи. Разпределението на слънчевата енергия е еднакво за всички симулации, докато за скоростта на вятъра са използвани три различни разпределения. Управлението на система е осъществено чрез планиране на заданията за мощността на газовите микротурбини за 24 часа, използвайки динамично програмиране. Целта е минимизиране емисиите на CO_2 еквивалент чрез намаляване на пусканията и спиранията на газовите турбини. Анализът на резултатите позволява определяне на оптималните инсталирани мощности на възобновяемите генератори, вземайки предвид първичния потенциал и товаровия график.*

Ключови думи: *хибридна система, възобновяеми източници, запасяване на енергия, оптимизация, газови турбини*

1. Introduction

Electricity generation and transmission infrastructure has a crucial importance for satisfying the global energy demand and environmental objectives required for ensuring our sustainable development. For over a century, large-scale electrical systems had no major evolution before the penetration of a considerable amount of Distributed Generation (DG) with small power. In the recent years a change is underway - the classical structure of a hierarchical electricity generation, transmission and distribution system is being replaced by the concept of smart grid. This means an intelligent electrical system composed of conventional power plants, loads and a significant number of clusters of loads and DG that can operate autonomously or connected to the distribution system and are able to be dispatched as a consumer or generator and thus contributing in the overall electrical system optimization. Each local cluster of generators (conventional and/or renewable energy-based) and loads, supervised by local energy management system and being able to operate in autonomy or connected to the distribution grid, can be called a Hybrid System (HS) or a microgrid. The Hybrid System Central Energy Management System (HSCEMS) has the functionality to optimize the operation of a Hybrid System for different criteria such as emissions reduction, optimal use of the storage or optimal energy exchange with the rest of the distribution system and also to be dispatched by the distribution system operator. As already mentioned, nowadays the electrical transmission and distribution networks are still rather passive and centralized from a supervision point of view. This makes the coordination of DG in the grid difficult and leads to suboptimal operation of large-scale hierarchical electrical systems [1]. In order to coordinate power generation and consumption in an optimal way and to improve efficiency, power supply reliability and security, the grid organization should incorporate distributed intelligence, autonomy and interactive communication at all levels of the grid [2], [3].

The studied hybrid system (fig. 1) comprises a wind generator, a PV generator, three micro gas turbines (*MGT_i*) with a nominal power output of 30kW, 30kW (with different CO_2 equivalent emission characteristics) and 60kW and households following a typical domestic load curve with a peak consumption of 110 kW. Each generator is connected to the system through electronic converters (LCS – Local Control System). A similar system, but with only photovoltaic or only wind generators as a renewable energy source has already been studied in previous works [3], [4] and [5].

The theoretical distribution of the solar irradiation is well-known but in reality the weather conditions influence this distribution. However it can be predicted with relatively good precision. In the case of the wind energy its distribution can consist several peaks during the day and they can influence the control of the whole system. The complementarity of both renewable energies is studied in previous authors' work [6] without taking into account the load curve.

The objective of this paper is a study of the influence of the wind speed distribution in time on the operation of an autonomous HS comprising micro gas turbines, PV and wind generator, energy storage system and loads. The performance criteria are the CO_2 equivalent emissions and the fuel consumed by the micro gas turbines, taking into account the combined influence of the PV and wind energy potentials during a given 24 hour period.

2. Assessment of the primary potential

Three cases of wind speed variation over a given time period are considered, while the solar potential of the site is considered identical. It may be assumed that the peak of the wind speed for the three cases of distribution is as follows (fig. 2-a):

- "Case 1" – the peak coincides with the consumption peak;
- "Case 2" – the peak coincides with the solar radiation peak;
- "Case 3" – the peak is after the maximal consumption.

On fig. 2-b is presented the on-site PV production forecast for a PV installation with peak power P_c=60kW and the load curve used in this study.

The model of Pallabazer [7] is used to determine the wind generators productivity. The model is presented by the formulae:

$$(1)\quad p = \begin{cases} 0 & if \quad V \le V_{cut-in} \\ \dfrac{V^2 - V_{cut-in}^2}{V_{nom}^2 - V_{cut-in}^2} & if \quad V_{cut-in} < V < V_{nom} \\ 1 & if \quad V \ge V_{nom} \end{cases}$$

where $V_{cut\text{-}in}$ is the cut-in speed of the generator, V is the wind speed and V_{nom} is the rated wind speed of the generator.

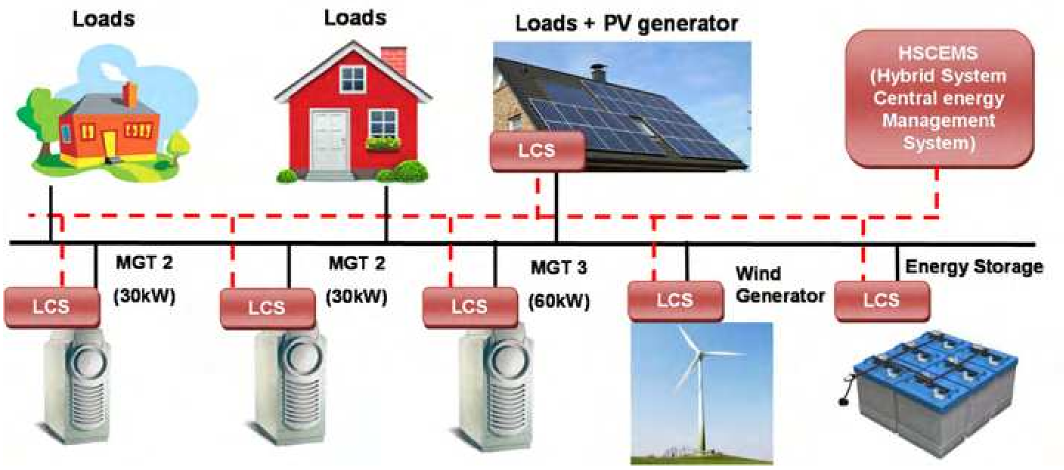
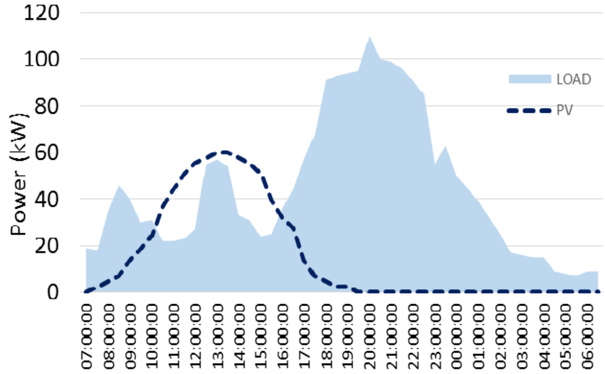


Fig. 1. The system under study.

a)



b)

Fig. 2. a) Variation of the wind speed for the 3 studied cases; b) Production forecast for a 60kW PV generator and the load curve

The energy produced by the photovoltaic generator is calculated on the base of data for solar radiation G_β and ambient temperature T_a with the Durisch's model [8]. The efficiency is calculated by:

$$\eta_{pv} = p\left[q\frac{G_\beta}{G_{\beta,ref}} + \left(\frac{G_\beta}{G_{\beta,ref}}\right)^m\right]\times \tag{2}$$
$$\times\left[1 + r\frac{T_{cell}}{T_{cell,ref}} + s\frac{AM}{AM_0} + \left(\frac{AM}{AM_0}\right)^u\right]$$

where the reference values of the solar radiation, the cell temperature and the air mass are $G_{\beta ref}$=1000W/m^2, $T_{cell,ref}$ = 25°C and AM_0 = 1.5, while the real values of the cell temperature are determined from the ambient temperature T_a with the Ross' formula (3) and of the air mass AM – with the Karsten's formula (4) where the zenith angle θ_Z is in degrees [8].

$$T_{cell} = T_a + h_R G_\beta \tag{3}$$

$$AM = \frac{1}{\cos\theta_Z + 0.50572(96,07995 - \theta_Z)^{-1.6364}} \tag{4}$$

The coefficients of the model are empirical and for the polycrystalline Si technology the values are: p=15.39, q=-0.1770, m=0.0794, r=-0.09736, s=-0.8998, u=0.9324 and h=0.026.

When the efficiency is determined, the produced energy is calculated as the multiple of the panels' area, the solar radiation and the efficiency. The calculated power for the PV installation with a peak power of 60kW are presented on Fig. 2b.

3. Hybrid system management

The hybrid system central energy management system assigns power references and other appropriate control signals to all generators in the studied HS. The requirements for the HSCEMS operation are:

- To supply power to the loads without interruptions;
- To increase the use renewable generators in the energy mix;
- To minimize the energy cost and the CO_2 equivalent emissions of gas turbines by controlling their power references following an algorithm for minimal pollution and minimum start-ups and shutdowns.

The nature of the Renewable Energy Based Generated (REBG) power implies the use of gas turbines to fulfil the load requirements because the REBG power is rarely sufficient. There are different strategies for the management of the gas turbines with minimum start-ups and shutdowns. The operation schedule and the energy management are complex problem defined as a Unit Commitment Problem (UCP). The small computation time of the dynamic programming makes this approach preferred for solving the problem [3], [4]. The management system define the power references for all gas turbines and for the energy storage device for 24 hour ahead. The time step is 30 minutes. The algorithm calculates the needed power to supply the load after the use of forecasted REBG power and the charge level of storage device. The power references for the MGT ensure minimum of CO_2 equivalent emissions (fig.3).

The needed power is compared with each MGT and combination of MGT's minimum and maximum power outputs. All feasible solutions (power between the minimum and the maximum power output) are evaluated and HSCEMS chooses the optimal one using recursion starting from time step 48 backwards. To minimize the number of startups and shutdowns

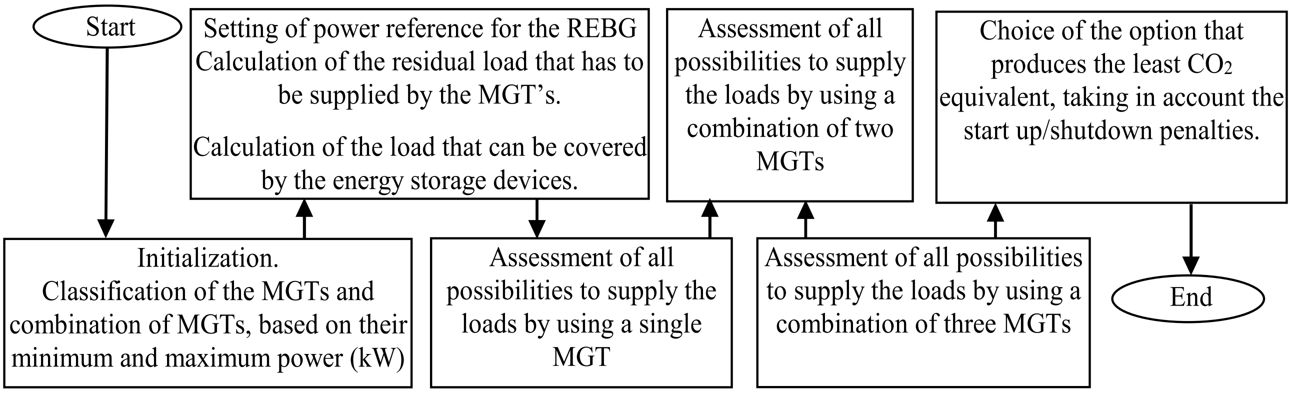


Fig. 3. Framework of the power planning algorithm.

penalties are used if the state of the unit changes in the period *t+1*. Thus the emissions are decreased and MGT's exploitation life is increased.

The optimization objective function, expressed as a UCP is:

$$S_{CO2}(t)=\sum_{t=1}^{48}\sum_{i=1}^{M}(\delta_i(t).CO_{2\_i}(P_{MGT\_i}(t),t)+C_{pe\_co2i}(\delta_i(t),t) \tag{5}$$

where $CO_{2\_i}(P_{MGT\_i}(t))$ is the characteristic of the CO_2 equivalent emissions. $P_{MGT\_i}(t)$ is the generated power, which varies at each time step *t, i* is the unit number.

During the system operation the forecasted values of REBG power can change. In this case short-term power balancing is performed in the local controllers using primary voltage and frequency control.

4. The micro gas turbines and their fuel consumption and emissions

Micro Gas Turbines consist of a small power electrical generator (a high speed permanent magnet synchronous machine with fluid bearings), driven by a gas turbine. The high frequency output voltage passes through power converters (a rectifier and an inverter) in "back-to-back" configuration. Thus the MGT can be connected to the hybrid system's grid. The converters are controlled by a local generation control system which ensures the normal system operation.

The micro gas turbines have lower emissions than a diesel generators and they are preferred for use in the modern hybrid systems. Moreover the micro gas turbines provide flexibility in the connection methods (autonomous or grid-connected), the ability to be arranged in parallel to serve higher loads. The MGT's have fast response and can compensate the fluctuations of the REBG power in the hybrid systems. Because of their fast response the gas turbines are used in large-scale electrical systems for peak-shaving to reduce electricity generation costs.

The MGT's fuel consumption is calculated from the partial load efficiency characteristics. The operational cost of the gas turbine is determined as a function of the generated electric power $P_{MGT\_i}(t)$, taking into account the cost of the consumed gas per produced kWh [4]:

$$C_i=f(P_{MGT\_i}(t)) \tag{6}$$

The pollutant gases have different weights in the CO_2 equivalent emissions. The weights are related with their global warming potential. The mass of the exhaust gases (NO_x, CO and CO_2) are calculated in kg/kWh as a function of the generated output power [4], [5]:

$$m_x(t)=\mu_x\, E_{MGT\_i}(t)=\mu_x\, P_{MGT\_i}(t)\,\tau \tag{7}$$

where μ_x [kg/kWh] is the emission factor (or specific emissions) for the pollutant to produce the generic useful electrical energy output $E_{MGT\_i}(t)$ and $m_x(t)$is the mass of the emitted pollutant.

The characteristic of CO_2 equivalent emissions of each MGT is expressed as a non-linear function of its power output through a polynomial interpolation.

5. Case study results

The system operation is simulated using the system model and control algorithm, presented in previous studies [3], [4] and [5]. The operation is simulated with three different wind power distributions shown in fig.2a. The rated power of the wind generator in the hybrid system varies from 30 to 60 kW with step of 5kW. The rated power of the PV generator in the system is always the same as of the WG. The following hypotheses are assumed:

- The algorithm uses the average values of powers in each time period of 30 minutes during the 24 hour power planning.
- The PV and wind generators aren't limited by technological constraints.
- The charge and discharge power of the storage device and its capacity are without limits because the device is idealized.
- The initial and the final state of charge of the storage device are identical (in the beginning and at the end of the considered 24 hour period).
- All simulations use the same load profile.
- The HSCEMS cannot control the loads in the hybrid system.

The simulation results are presented in Table 1. The price of the natural gas is accepted to be 0,04EUR/kWh. It is used for calculation of the fuel cost.

The energy analysis for the different studied cases is presented in Table 2. EPV and EWG are the energies generated by the PV and wind generator. EMGT1, EMGT2 and EMGT3 are the energies generated by the micro gas turbines 1, 2 and 3 respectively. On figures 4 and 5 are presented the powers generated and consumed in the hybrid system in the wind speed distributions "case 1" and "case 2" with PV and wind generator having a nominal power output of 30kW each. Fig. 6 presents the power flows in the system for "case 3" wind speed with 55kW PV and WG power. The CO_2 equivalent emissions and the consumed fuel can be used for assessment of the system performance. Analysis of the results shows that the most economic cases on CO_2 equivalent emissions and fuel

Table 1

CO_2 equivalent emissions and fuel consumption

	Wind speed case 1		Wind speed case 2		Wind speed case 3	
WG and PV generator peak power	CO2 eq. (kg)	Fuel cost (EUR)	CO2 eq. (kg)	Fuel cost (EUR)	CO2 eq. (kg)	Fuel cost (EUR)
30 kW + 30kW	1230	79.3	828	96.2	473	86.4
35 kW + 30kW	1095	62.6	**995**	79.8	**381**	67.9
40 kW + 40kW	1080	42.2	613	60.9	391	49
45 kW + 45kW	**1112**	21.7	513	40.74	172	30.7
50 kW + 50kW	580	2	361	21	909	10.5
55 kW + 55kW	0	0	0	0	0	0
60 kW + 60kW	0	0	0	0	0	0

Table 2

Energy analysis for the various cases with PV and WG

		Wind speed case 1				Wind speed case 2				Wind speed case 3			
WG and PV generator peak power	E_{PV} kWh	E_{WG} kWh	E_{MGT1} kWh	E_{MGT2} kWh	E_{MGT3} kWh	E_{WG} kWh	E_{MGT1} kWh	E_{MGT2} kWh	E_{MGT3} kWh	E_{WG} kWh	E_{MGT1} kWh	E_{MGT2} kWh	E_{MGT3} kWh
30 kW + 30kW	182	317	231 14h	33 1.5h	250 5h	228	234 11.5h	79 3.5h	287 5.5h	298	168 7h	22.6 1h	351 6.5h
35 kW + 35kW	212	370	143 10h	0	257. 5.5h	266	175 9h	45 2h	271.8 5.5h	347	124 5.5h	11.47 0.5h	288 5.5h
40 kW + 40kW	242	422	118 9h	0	159 3.5h	304	129 7h	23 1.5	212 4.5h	397	94 5h	11.5 0.5h	194 4h
45 kW + 45kW	273	475	69 7.5h	0	78 2h	342	83 5h	11 0.5	161 3.5	447	70 3h	0	114 2.5h
50 kW + 50kW	303	528	16 1h	0	0	380	64 4h	11 0.5h	59 1.5h	497	26 1.5h	0	33 1h
55 kW + 55kW	333	581	0	0	0	418	0	0	0	546	0	0	0
60 kW + 60kW	364	634	0	0	0	456	0	0	0	596	0	0	0

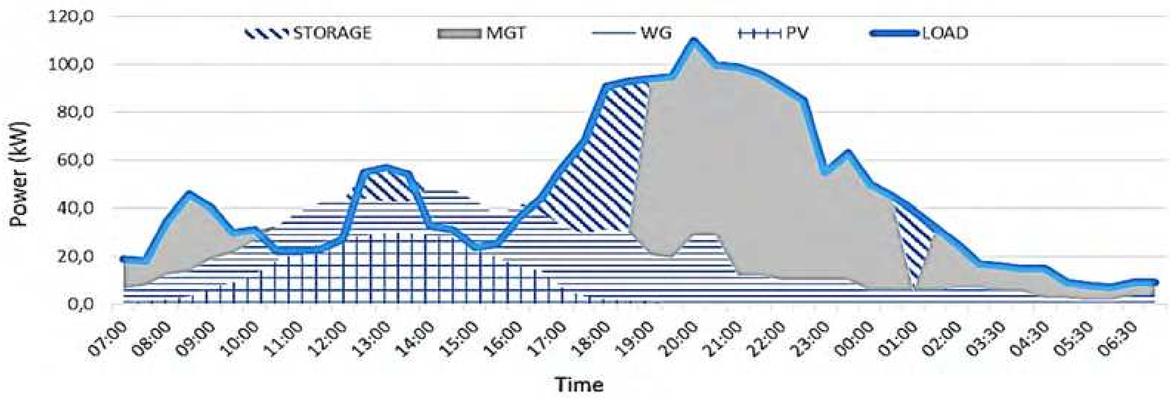


Fig. 4. Power flows in the HS, wind speed “case1” and 30kW+30kW WG and PV generators.

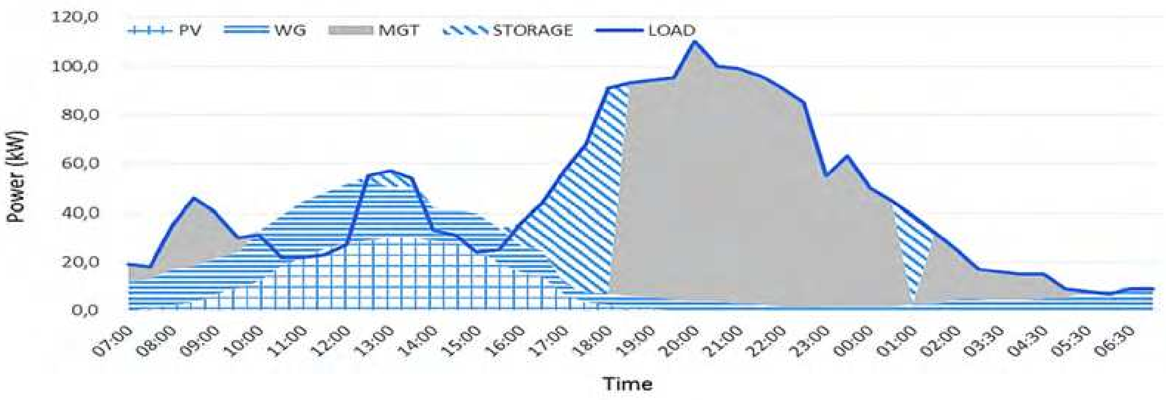


Fig. 5. Power flows in the HS, wind speed “case2” and 30kW+30kW WG and PV generators.

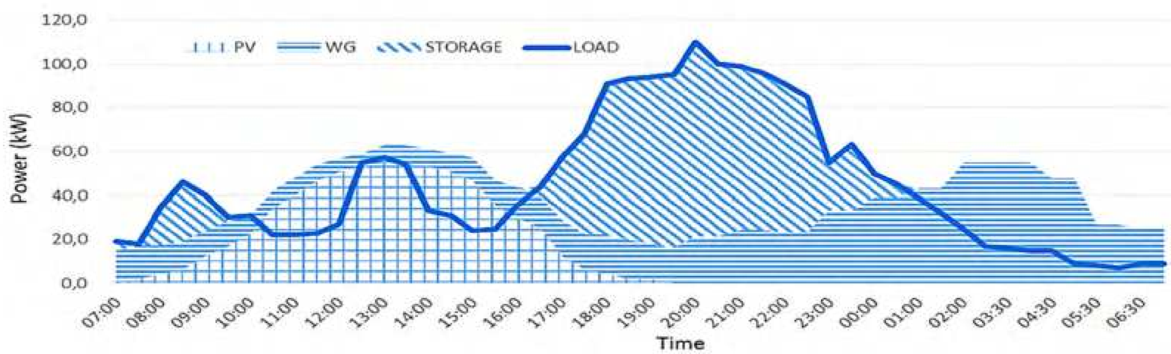


Fig. 6. Power flows in the HS, wind speed “case3” and 55kW+55kW WG and PV generators.

cost are those with amounts of stored energy allowing for the shutting down all the micro gas turbines during most or even all of the time steps. At contrary, when renewable energy is present but insufficient to supply the totality of loads, the micro gas turbines are forced to operate at a low power level (i.e. 5-10kW) with much greater amounts of CO_2 equivalent emissions (see bolded numbers in Table 1).

6. Conclusions

The paper presents a study of the influence of combined solar and wind energy distribution on the operation of an autonomous hybrid system with a wind generator, PV panels, micro gas turbines and energy storage system. The system operation has been simulated with wind and PV generators with different rated powers from 30 to 60kW using 30-minute average values. All of the cases use the same load curve, PV primary potential curve and three different cases of wind speed distribution in time. The power planning is done by an algorithm of unit commitment with a dynamic programming-based optimization procedure. Considering both the CO_2 equivalent emissions and consumed fuel, the following conclusions can be made.

More renewable energy in the wrong moment could result in more CO_2 equivalent emissions and in general less efficiency. This is due to the fact that when available renewable energy power can't supply the totality of the loads, the micro gas turbines are forced to operate at a low power level where their efficiency is not optimal and the CO_2 equivalent emissions are much greater (for example in the "case 1" wind speed profile with 45+45kW wind and PV generators).

The wind speed distributions which have a peak before or after the load curve peak lead to lower CO_2 equivalent emissions because in certain periods the energy from the storage device and the renewable sources is sufficient to supply all the loads in the system and to shut down some of the micro gas turbines (example "case 2"and "case 3 scenarios").

The results demonstrate that for ensuring an optimal management strategy of a hybrid system, an infra-hourly analysis of renewable energy primary resource and the load curve can be of greater interest than simply oversizing the renewable energy generators and/or the energy storage devices while using average daily energy values.

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Hristiyan Kanchev, *PhD, assistant professor in the Faculty of Electrical Engineering, Technical University of Sofia. His field of interest includes renewable energy sources (electrical aspects), distributed electricity generation, energy management and micro grids.*

Phone: +359-2-965-24-65 e-mail: hkanchev@tu-sofia.bg

Bruno François, *PhD, Professor at the Department of Electrical Engineering of Ecole Centrale de Lille. He is a member of Laboratory of Electrical Engineering (L2EP), Lille. He is currently working on advanced energy management systems.*

Phone: +33-3-20-33-54-59 e-mail: Bruno.francois@ec-lille.fr

Zahari Zarkov, *PhD, Associated professor in the Faculty of Electrical Engineering, Technical University of Sofia. His field of interest includes renewable energy sources (electrical aspects), electronic power converters for RES, integration of energy converters using RES.*

Phone: +359-2-965-24-61 e-mail: zzza@tu-sofia.bg

Ludmil Stoyanov, *PhD, Associated professor in the Faculty of Electrical Engineering, Technical University of Sofia. His field of interest includes renewable energy sources (electrical aspects), modelling of electric generators and energy conversion systems with RES.*

Phone: +359-2-24-65 e-mail: ludiss@tu-sofia.bg

Vladimir Lazarov, *PhD, Professor in the Faculty of Electrical Engineering, Technical University of Sofia. His field of interest includes renewable energy sources (electrical aspects), electric machines with electronic commutation and electrical machines for information.*

Phone: +359-2-965-24-59 e-mail: vl_lazarov@tu-sofia.bg

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