Performance Evaluation of a Hybrid Photovoltaic-Wind- Fuel Cell System

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Abstract: - The paper introduces hybrid photovoltaic-wind-diesel generation systems for supplying remote power plant taking into account the enhancement of the sustainable energy on the economic point of view. The possibility to introduce a Fuel Cell generation device in a photovoltaic-wind existing plant for supplying Telecommunication apparatus is also investigated and the results are reported and discussed in the paper. Furthermore, starting from measured data, a control system is realized in order to verify the functionality of the plant.

Key-Words: - Fuel cells, new/alternative energy resources, photovoltaic power systems, system costs, hybrid system

1 Introduction

A High Integrated Hybrid System (HIHS) can be seen as a way, using renewable sources, to produce electric energy without pollution.

The PhotoVoltaic (PV) energy production has been mainly used:

- in the industrialized country for supplying remote loads with reduced consumption;
- in underdeveloped countries for generating electricity with reduced need of maintenance and with low operation costs.

Research and development made PV technology suitable for industrial applications related to telecommunications, water pumping, water purification, public light, etc.

In Europe (where the weather conditions are really variables and the forecast are available for limited period ahead of time) the PV system needs to be oversized and integrated with batteries and Diesel Generator Set (DGS) for back-up purpose [1,2]. Because of these limits the PV has been rarely chosen as energy supply in off grid industrial application which requires more than a few kWh/day. The Wind Generator (WG), despite of its reduced power cost comparing to the PV solution, is not so diffused in Europe because of the weather conditions. The European weather conditions, in fact, do not allow designing PV only and/or WG only stand alone plants, although these technologies are available for energy supplying in off grid system. The HIHS instead permits to design a power supply system able to guarantee the continuity of the supply mixing the different renewable energy resources – like PV, WG (even micro-hydro if possible) – limiting the DGS use for little period during winter and/or for back-up purpose only.

On the design point of view the optimization of the generators size of the HIHS plant is very important, leading to a good ratio between cost and performances [3]. The HIHS is usually designed to decrease the fuel consumption of the diesel-machine in the range of 70-90%, as compared with only battery-diesel supply architecture overcoming the DGS drawbacks [4]. Therefore, the primary source of electric energy for the plant becomes the renewable one, while the diesel machine constitutes the auxiliary source in case of emergency or for battery charge. Furthermore the hybrid systems can be very effective in terms of sustainable energy development, permitting a generation of electric energy with a minor environmental interference.

In this paper, a technical-economic analysis of a real HIHS plant is presented [5]. The plant under study is used to supply a telecommunication system. The use of this plant for the community and for emergency purposes makes unacceptable possible black outs: the main characteristic of this system is the need of continuity in the power supply. On the economic point of view, an over sizing of the system leads to an excessive increment of the produced energy cost.

Furthermore, an improved HIHS composed by PV, WG, hydrogen Fuel Cell (FC), water electrolyser, batteries and - as backup devices – DGS is presented and analyzed on economical and technical point of view. In the future both DGS and batteries could be removed or reduced according to the collected working data and the operation experience on FC devices. In fact, FC devices are very attractive option to be used with intermittent sources of generation like the PVs because of high efficiency, modularity and fuel flexibility. A preliminary test of such possibility is carried out realizing a control system that simulates the operation of the plant working with FC starting from the measured data. The technical literature in this field presents hybrid systems with FC dedicated together with one renewable source only (PV or WG) and economical analysis are seldom dealt with [3,4,6].

2 Hybrid system

2.1 System layout

The commonly used plant layout, according to Fig.1, is made up of a set of photovoltaic modules (PV), a wind generator (WG), batteries and a diesel generator set (DGS). The DGS works for little period during winter and for backup purposes. Furthermore, its presence increases the overall system reliability. The batteries are used for the storage of the energy on the short time and for realizing the decoupling of the energy production from the consumed one. The system is managed and controlled by a complete controller, developed for these applications [7].

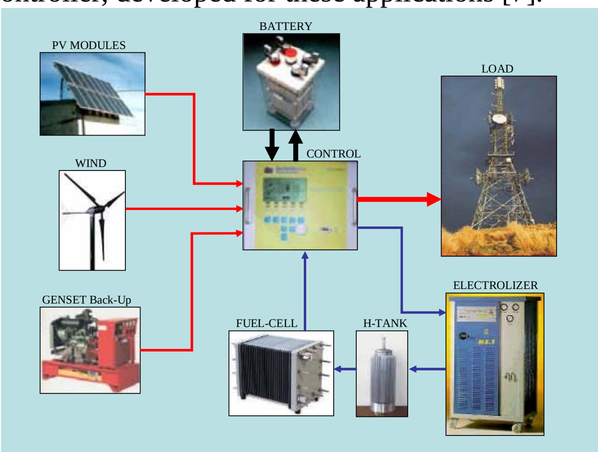

Fig.1. Hybrid complete system layout

2.2 System sizing

The required inputs for the overall system sizing are substantially three: the load diagram, the solar exposition diagram and the wind diagram. Based on these diagrams, it is possible to calculate the PV module size and number, and the WG size. As the system sizing is quite simple the optimization is a little bit difficult because of the large number of possible choices. In fact, it is possible to supply most of the needed energy with one kind of renewable sources, but in this way the system will not be optimized.

Focusing on system optimization, it is possible to note that in the considered site PV and WG gives their peak production in different period of the year. Typically the PV reaches the best performance during spring and summer while WG has his peak production during winter time.

Starting from the load diagram shown in Fig.2, from the local solar radiation diagram and from the wind map, accounting all the cost of installation and operation, the overall system optimization is made by following these steps:

1. PV modules sized for a 100% load supply from April to September. The result of this sizing brings to a PV array made by 64 modules, 75Wp and 48Vdc each one. The total power is 4800Wp. Fig.2 shows mean monthly PV energy production in kWh/month.
2. WG sized to supply the lack of PV power from October to March. The wind generator is of 500Wp because it produces power with wind speed lower than 7km/h and higher than 150km/h. Fig.2 shows the mean monthly energy production [8].[1]
3. DGS sized for backup purposes and expected to work for little period during winter but also to guarantee the necessary system reliability. This leads to rate a DGS with 5kW and fuel consumption of 3000g/kWh. In this way, neglecting possible black-out, the DGS normal working time is about 47h/year, with the need of 104 litres/year of diesel fuel, one maintenance operation and two refuelling per year.

Fig.3 shows the mean monthly energy balance – based on 2005 data - between the energy production and consumption of the hybrid PV-WG-DGS system sized.

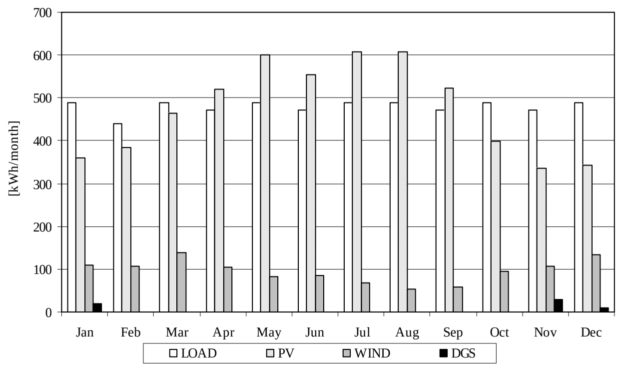

Fig.2. Load diagram and energy production of PV, WG and DGS of the HIHS.

It is possible to see that an energy surplus is present for almost all the year. The use of this surplus and

[1] Comparing the PV and WG energy production it is possible to see that even if the WG size is about 1/10 of the PV size, its contribution to the energy production is about 1/5 of the PV production.

the control of all the operation parameters is done by an electronic control and monitoring system designed for the operation of an HIHS that has been presented in [7]. Thanks to this monitoring system, it is possible to manage the HIHS and to modify, if necessary, the control algorithm in order to optimize the system work with respect to the local conditions.

3 Fuel Cell system

During the system optimization, the chosen layout leads to an energy production surplus (Fig.3). This surplus – calculated neglecting the possible DGS production - is due to renewable production.

Several energy storage techniques, like batteries, flywheels and hydrogen production are available for system integrators when energy storage is needed [2]. The main considered parameters during sizing are energy storage capacity, source availability, and response time of the energy source.

Normally batteries present good modularity, fast time response and good energy-mass ratio storage, but they need maintenance and are subjected to fault. In addiction batteries performances depend on working temperature that has to be controlled during operation time. These characteristics make batteries suitable for hybrid systems.

Considering a fly-wheel it presents little modularity, very fast time response, but the stored energy is available for the system for very little time with respect to batteries; on the other hand a plant with a fly-wheel presents less system complexity and practically minimal or no maintenance [9].

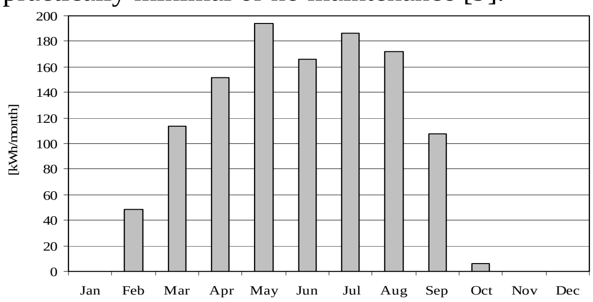

Fig.3. Energy surplus of the build system.

A FC, compared with the two previous techniques, presents modularity and the possibility of partial load working; good energy storage capability that can be simple obtained with correct hydrogen tank sizing. One main week point of the FC is its very slow dynamics. Maintenance problems of fuel cell are still an open problem because of the presence of the catalyst that must be substituted after its working life-time [10,11].

A way to increase the effectiveness of the system consists in substituting the DGS backup set with a FC. In this way, it is possible to use the energy surplus to produce, by a hydrolysis process, the hydrogen needed from the FC.

3.1 System layout

The system layout remains the same to previous one except for the presence of the fuel cell, hydrogen and water tanks (see Fig.1). The FC is assumed to substitute the DGS. The DGS presence is related to the lack of practical experience in systems with FCs and their reliability. Using this plant as a test prototype it is possible to verify the energy availability all over the year. A further step for this plant design, after a data collection phase on plant operation during some years, can be a plant design without the DGS backup set.

3.2 System sizing

The hydrogen can be produced, during the surplus of energy production, from water by an electrolyser and stored in a container for further use. Assuming a hydrogen production rate of about 0.018 m^3/kWh, the surplus energy can be used to produce about 18.6 m^3/year. With low temperature fuel-cell, neglecting the use of thermal energy, its efficiency can be considered to be about 30%. The lower heating value of hydrogen is 10.72 MJ/m^3 (38.6 kWh/m^3) [11]. Therefore the total electric energy that can be produced by the FC is:

$$E_{H2} = \eta \cdot V_{H2} \cdot LHV_{H2} = 215 \ kWh/year \qquad (1)$$

In this way, although the hydrogen can be produced only during spring and summer and needs storage, the use of a FC can lead to a complete autonomy of the plant (Fig.4).

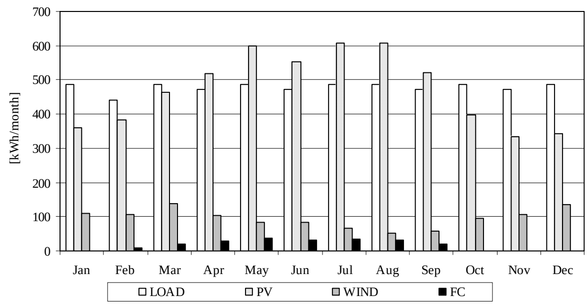

Fig.4. Energy production (WIND and PV) and energy consuming (LOAD and FC) of the HIHS + FC plant.

The plant, including PV generator, wind generator and DGS with the mentioned characteristics, it's already in function. The FC and electrolyser implementation are at the moment in phase of study.

Before the experimentation on field it is necessary an economical evaluation and a preliminary study of the complete system that must clarify the technical problems that can occur. For this reason a simple control system - starting from monthly/daily mean data measured on the existing plant in 2005 - is realized. The model allows studying the systems with FC and electrolyser shown in Fig.1 even if with some approximation.

4. Economic analysis

Scope of this section is to estimate the kWh cost and therefore the economic convenience by using the Unit Electricity Cost (UEC) method referring to the analyzed different plants solution [5, 12].

The first step for the economic analysis consists in the evaluation of the overall costs of the three plants under examination: PV+DGS, HIHS and HIHS+FC type. Table 1 sensitizes the data obtained for the three different plant calculated taking into account the cost of diesel generator, fuel and maintenance costs, photovoltaic modules, batteries, wind generator and Fuel Cell and installation.

Table 1. Plants costs

Plant	Installation [€]	Hardware [€]	O&M [€]	Total [€]
PV + DGS	5770	32625	6925	45360
HIHS	5770	36840	1150	43760
HIHS + FC	5770	48250	4040	58060

Table 2. UEC For different Type of plants

Plant	UEC [€/kWh]	UEC with environmental costs [€/kWh]
PV + DGS[2]	1.562	1.566
HIHS	0.440	0.442
HIHS + FC	1.047	1.049
HIHS + FC (no DGS)	0.849	0.850

A comparison of the Table 1 data shows that the Operation and Maintenance (O&M) cost of a HIHS is cheaper than the other plants. This is substantially due to the reduction of periodic maintenance and refuelling operation. In the case of FC, the costs are higher because of the absence of a real market for FC maintenance. FC cost will be reduced in the next years because of the increase of the FC production.

The evaluation of the cost of the produced energy by the real plant is made by using the Life Cycle-Costing (LCC) [5,12] which leads to the UEC. The UEC for the three considered plants are reported in Table 2. These values have been calculated accounting only the costs reported in Table 1 and adding the environmental costs [5].

Data reported in Table 2 show that HIHS lead to the lower UEC. Anyway, the HIHS+FC plant, even if it is a prototype, is cheaper than the PV+DGS plant. Furthermore, comparing the data reported in Table 2 with the ones reported in [5], it is possible to assert that the environmental cost is strictly related to the DGS emissions.

Finally, the UEC in the case of HIHS+FC without DGS, are evaluated. These costs are today only a tentative, but in the future, when FC will have a market spread with reliable operation, the economic impact will be more precisely set.

5 The control system

In this section, we briefly discuss the simulation model used in this paper. The simulation will be extended for a temporal window of 24 hours in two different conditions: one regarding a typical day of May when the energy production is high, the other one corresponding to a typical day of November when the energy production is not enough to power the load. In the first case the regulator deviates the energy overproduction towards the aqua electrolyser, storing hydrogen on the tank. In the second case the FC will provide the lack of energy taking the hydrogen from the tank. Furthermore, the system analysis will be done considering initially the plant including battery, but without the DGS. Subsequently it will be discussed the possibility of eliminate the battery too. The models of the different part of the system are shown in Fig.5.

Considering the typical day of May, when the energy production is high because of the PV production, the controller is programmed for use the energy overproduction towards the aqua electrolyser in order to store hydrogen in the tank. The simulation model used in this condition includes the load power regulator, the generators, the model of the battery charge state and the aqua electrolyser.

The energy supplied in the first hours of the day is not enough to cover the entire requirements of the load, therefore this will be supplied from the battery that in the meantime endures a partial discharge. When the PV production rises, the power generated becomes greater than the energy required so the battery can be recharged. When this process is finished the energy in excess (Fig.6) is deviated towards the aqua electrolyser which produces the hydrogen for the FC: for the considered day the system can produce and store almost 0.112 m^3 of hydrogen. This means a corresponding energy per year estimated in 1148.74 kWh.

It must be noted that the control system is studied to guarantee a high battery charge level in order to always be able to constitute a supply for four or five days in case of breakdown or particularly unfavorable environmental conditions.

In a typical November day, of when the energy production is low, the controller will provide the lack of energy taking the hydrogen from the tank and using it in the fuel cell. The simulation model used in

[2] For PV+DGS without WG system the DGS normal working time is about 460h/year, with a fuel consumption of 1010 litres/year. This implies 9 maintenance operations and 20 refuelling of the tank per year.

the second condition is made up of the load power regulator, the generators, the model of the battery charge state and the FC. The results obtained from the simulation are synthesized in Fig.7. In the early morning the discharge of the battery is limited by the FC, in order to avoid the slow but progressive discharge of the battery, that in the arc of some days - above all if unfavorable to WG or FV - would carry to the impossibility of feeding the load correctly.
However in few hours the power production raises because of the PV energy so the FC can be turned off and the battery partially recharged. The hydrogen consumed during the entire day is approximately 0.07m^3. The annual total energy that the FC consumes is approximately 54.24kWh.
Therefore it can be observed that the hydrogen amount produced in the summery months exceeds the necessary one to the single function of supply, even if it must be considered eventual conditions of breakdown that could lead to various energetic balances. Moreover is useful to emphasize that the use of FC leads to the same result as the use of DGS do. In fact, it would work in the winter months with almost identical modalities of the FC, while in the summer months the energy must be wasted.
It is finally analyzed the possibility to eliminate the battery group and use the FC also for the management on the short period of the energy. This would mean at the same time an increase of the annual use of the devices more technologically advanced and expensive. From the simulation is possible to observe that in order to cover the demand, an excessive over-sizing of the PV plant would be necessary, with a consequently not convenient increase of costs. In fact, during a typical day of May, the system needs almost 0.13m^3 of hydrogen more, corresponding to energy excess from PV of 7.2kWh/day. During a typical day of November, this amount increase to 2.2m^3, corresponding to energy excess of 122kWh/day.
These results are in agreement with that obtained by other Authors [3, 4]. In fact a typical self-sufficient HIHS supplying remote plant must include short-term and long-term energy storage. The combination of a battery bank - commonly used for short-term energy storage – with long-term energy storage in the form of hydrogen can significantly improve the performance of stand alone renewable energy systems.

6 Conclusion

The paper deals with a technical and economical analysis of possible implementation of renewable energy sources on an existing plant for supplying isolated telecommunication devices. The photovoltaic and wind energy sources are implemented in the considered installation.
In particular the possibility of substituting the Diesel Generator backup group with a Fuel Cell is investigated both through the energy balance and as an economic investment.
The results show that the energy balance is satisfied and the plant can work properly with the two configurations. The energy storage is done with a diesel oil tank for the first layout, and with hydrogen,

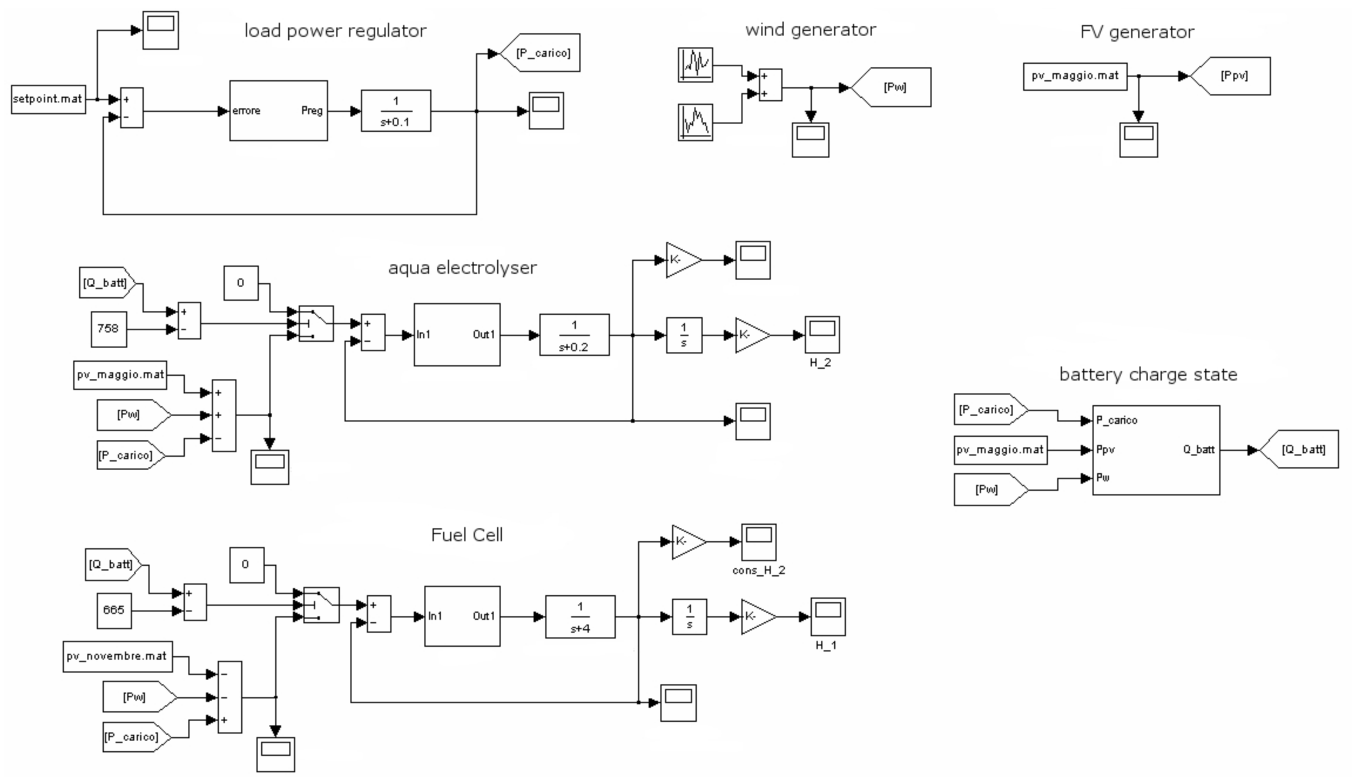

Fig.5. Control and simulation system.

and the necessary water tank, for the second one. The water tank is necessary only in order to improve the autonomy of the plant. Maintenance and refueling of the plant with the diesel generator are the major problems because of the periodic maintenance required by the diesel generator, which works only during winter time. Using the fuel cell technology, the need of periodic maintenance and refueling operation is limited or removed.
The real case application permits to quantify economical indices that show the advantages of the High Integrated Hybrid Systems.
Furthermore accounting environmental cost, the photovoltaic-wind- fuel cell configuration, having this latter near-zero emission, permits an increasing of environmental sustainability and then a decreasing of the increment due to external costs in the electric power generation.
Finally the possibility of substituting the battery with fuel cell is analyzed. Unfortunately with the present technologies and the efficiency that they correspond, such substitution is not possible neither from the technological point of view nor from the economic one. In spite of that the future developments appear feasible; it can not be excluded that substantial progresses will be done in the next few years.

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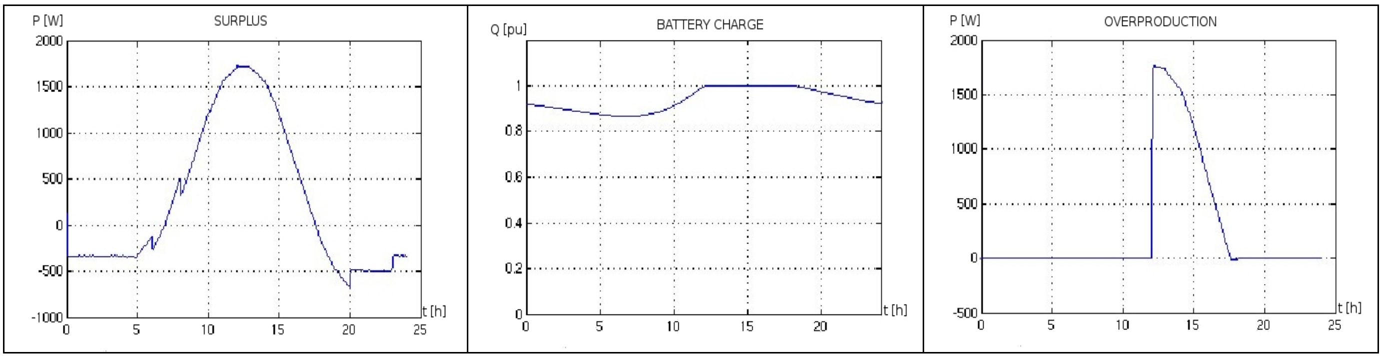

Fig.6. Most significant data obtained in May.

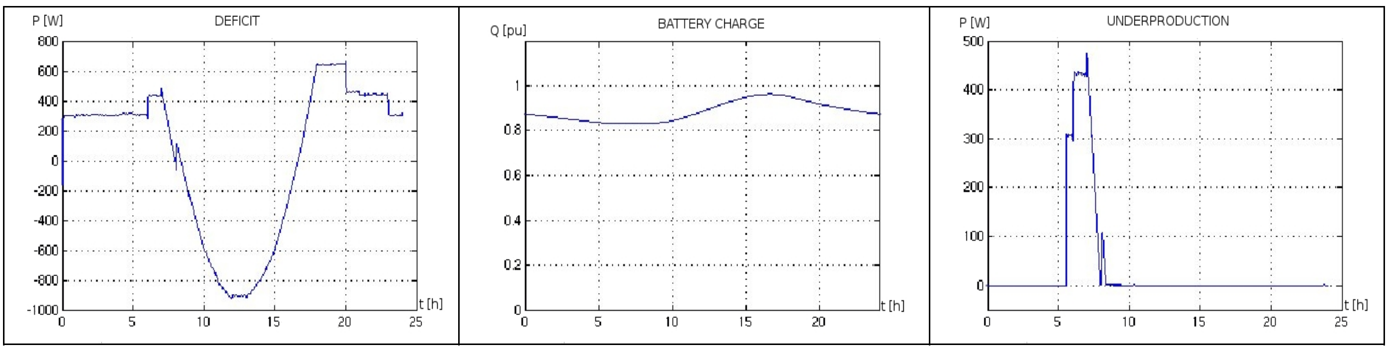

Fig.7. Most significant data obtained in November.