Hybrid biomass-wind power plant for reliable energy generation

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A B S T R A C T

Massive implementation of renewable energy resources is a key element to reduce CO_2 emissions associated to electricity generation. Wind resources can provide an important alternative to conventional electricity generation mainly based on fossil fuels.

However, wind generators are greatly affected by the restrictive operating rules of electricity markets because, as wind is naturally variable, wind generators may have serious difficulties on submitting accurate generation schedules on a day ahead basis, and on complying with scheduled obligations in real-time operation.

In this paper, an innovative system combining a biomass gasification power plant, a gas storage system and stand-by generators to stabilize a generic 40 MW wind park is proposed and evaluated with real data. The wind park power production model is based on real data about power production of a Spanish wind park and a probabilistic approach to quantify fluctuations and so, power compensation needs. The hybrid wind-biomass system is analysed to obtain main hybrid system design parameters. This hybrid system can mitigate wind prediction errors and so provide a predictable source of electricity.

An entire year cycle of hourly power compensations needs has been simulated deducing storage capacity, extra power needs of the biomass power plant and stand-by generation capacity to assure power compensation during critical peak hours with acceptable reliability.

1. Introduction

In the actual energy production market, if a reduction of greenhouse effect gases is desired, it is necessary to promote energy production scenarios where renewable energy sources had more and more importance. As it is well known, the main drawback of renewable energies is the inherent variable behaviour. In the scientific literature we can find examples of systems that try to take advantage of some kind of storage system. Most simple examples use traditional storage system [1,2] based in batteries. Advanced systems use hydrogen as energetic vector [3–6] taking advantage of different fuel cell technologies (from Proton Exchange Membrane technology to Solid Oxide Fuel Cell technology). These studies emphasize control necessities to optimise energy production.

Another way to solve the raised problem is to combine different kind of renewable resources, so problem could be reduced. Tan-rioven [7] describes a wind and solar photovoltaic hybrid plant with diesel generator and a fuel cell system as energy backup. Dufo-López et al. [8] describe a Solar photovoltaic system used in combination with a diesel generator and a mixed backup systembattery-fuel cell. Fiedler et al. [9] show an example of combining solar thermal energy with a biomass power lant, using solar battery-fuel cell. Fiedler et al. [9] show an example of combining solar thermal energy with a biomass power plant, using solar battery-fuel cell. Fiedler et al. [9] show an example of combining solar thermal energy with a biomass power plant, using solar energy to dry biomass and increase power plant efficiency.Finally, Othman et al. [10] show a photovoltaic-thermal solar combining to produce heat and electricity with the same system.

All systems described below have a common characteristic: they work in an isolated system or in an internal grid. This situation could promote distributed generation, because renewable system could reach a full predictable system. Distributed generation has a lot of advantages. For example, it reduces transport losses and it improves energy quality there where generation is located [11,12]. However, there are not so many studies, combining renewable resources to profit the synergy between each other, to stabilize renewable power plants connected to the grid.

To become competitive in a liberalized market, wind energy reliability requirements should be guaranteed [13]. Wind power can change substantially along the day, as proved by Fig. 1 where data on daily maximum (P_{max}) and minimum (P_{min}) values of output power, as a percentage of the total installed wind power in a 40 MW park, are plotted for a 60 days period [14].

Reliability will be even more necessary in the near future when wind generation is going to increase substantially its share in the electricity generation portfolio in many countries, i.e.: in the case of Spain, it can be more than double in the immediate future, reaching

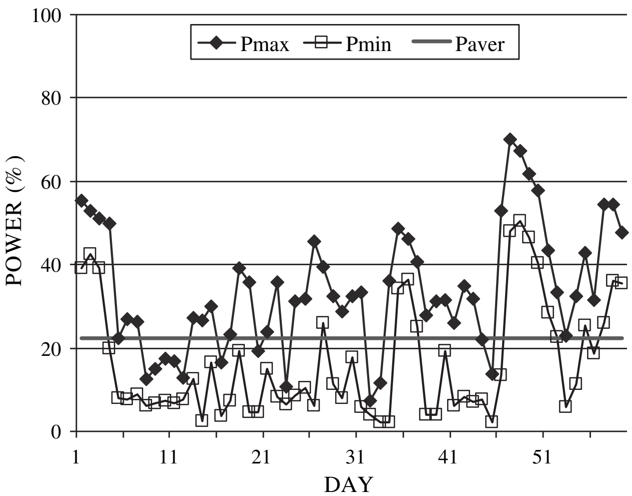

Fig. 1. Fluctuations in wind park power output [14].

a 20 GW level by 2010. Nowadays, when the wind energy is subsidized due to its green character, this lack of reliability is not a big problem, but once the total wind power level becomes an important fraction of the total electricity generation system, reliability will become a must and, in addition, subsidies could not be possible anymore.

Wind generated electricity to become competitive in a free energy market framework, should be able to cope with very short advanced requirements of stable power levels. So, a reliable prediction of the wind park energy production is an important element, constituting a tool that will allow managing the electric power system in a more effective way, by providing the capacity to forecast the park generation and facilitating offers of energy that mean a rising added value for this type of generation. Nevertheless, even with very good wind prediction codes, differences will appear between those predictions and the real energy production from the wind park that will require some kind of energy storage system to compensate the generated wind power when it is below the compromised offer to the system operator based on the predictions.

Biomass energy generation systems could be complementary taking into account their different properties in reliability when compared to wind energy systems. Its main problems are related to fuel availability and storage, but, once these problems are solved, reliability is not a question and energy can be provided on request up to the maximum level of the biomass plant. So, it is worthy to study the capability of a biomass system to provide the backup needed by the wind park to cover the possible misadjustments between the predicted and real values of its power output, analysing in detail the capabilities and behaviour of a hybrid system composed by a wind and a biomass plant and the possible synergies between the two systems. To optimise the use of the biomass plant we are assuming this plant installed in the site of the wind park and working all the time to produce electricity, but overdimensioning it to be able to cope with a compensation role when the wind park is asked for more energy than it can provide at that moment. In this approach it could be possible to share by the two plants some of the system of connection to the grid and the additional capital investment for the reliability improvement will be only the cost of the overdimensioning, in relation to the biomass plant alone, of the components. In this paper, we have selected a biomass plant based on a gasifier and an internal combustion engine where the gasifier could be operated up to one third above of the nominal value required by the biomass plant, that is in accordance with the nowadays available technologies, and this increase in gas generation can be used for a second internal combustion engine when wind energy compensation is needed. Fig. 2 shows a diagram of the proposed system.

Paper is structured as follows: Section 1 analyses the hybrid wind-biomass system and develops a design criteria for the interaction that is used for the choice of the main hybrid system design parameters. Section 2 shows the results of the simulation of the system for a long period of time using as input real data of a wind park operation. Technical requirements and their availability for the system are discussed in section 3 and finally, in section 4, the economical viability of this solution is analysed.

2. Hybrid system conceptual design

Assuming a hybrid system as showed in the diagram of Fig. 2 composed by a wind and a biomass plants with nominal powers P_e and P_b, respectively, the fraction of P_e that can be compensated, f, can be defined as:

$$f = P_c/P_e = \Delta P_b/P_e \tag{1}$$

where P_c is the compensation power, and in the considered hybrid system, we are assuming it coming from the overdimensioning of the biomass power plant, ΔP_b.

The biomass power plant capacity is mainly defined by the rated capacity of the biomass gasifier so, if r_g is the overdimensioning factor of the gasifier, we can relate the fraction f with the power of the biomass plant by the following equation

$$f = r_g \cdot P_b/P_e \tag{2}$$

The value of r_g is usually fixed by the gasifier manufacturer according to partial load performance of the equipment, values of r_g in the range 0.2–0.3 are usually recommended by the manufacturers.

For power decrements bigger than $f \cdot P_e$ the gasifier overdimensioning is not enough and supplementary gas should be obtained to supply the internal combustion engine in the compensation branch of the system. Fig. 3 plots the $f \cdot P_e - P_b$ domains of a wind park in a particular case ($P_e = 40$ MW, $f = 0.1$, $r_g = 0.25$) for operation in two different regimes: direct and storage based compensation, the last one uses a gas storage system to be filled out by the gasifier in the periods of time when no compensation is required. This need to refill the gas deposit so the system is ready to be used the next day requires that the two times to consider t_c (compensation time) and t_r (refill time) should comply with:

$$t_c + t_r = 24 \tag{3}$$

where these times are measured in hours.

Eq. (3) fixes the volume of the deposit to use for the gas of the backup system. The gas flux needed by the second engine is given by:

$$\phi_m = q \cdot f \cdot P_e \tag{4}$$

and the gas flux provided by the gasifier to the compensation branch is:

$$\phi_g = q \cdot r_g \cdot P_b \tag{5}$$

where q is the energy equivalent of the gas used by the engine, that we are going to assume identical to the gas generated by the

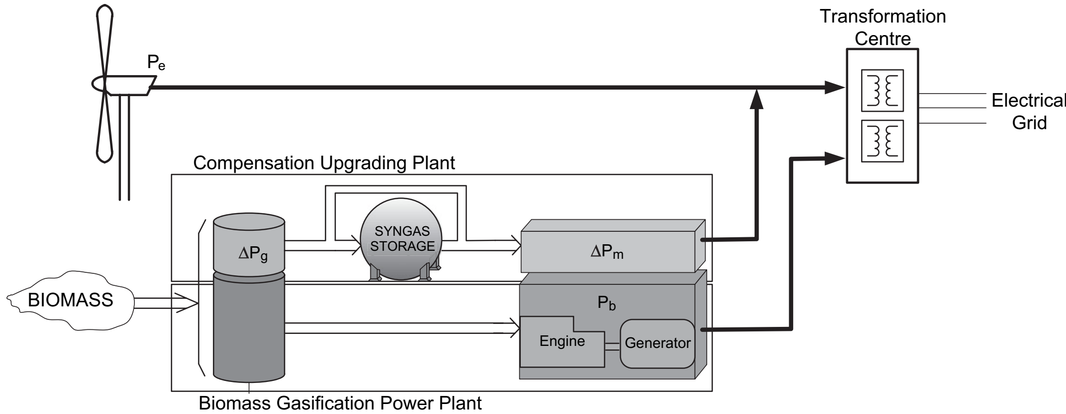

Fig. 2. Proposed hybrid wind-biomass system.

gasifier, both in the order of 2000 Nm^3/MWh. This value is obtained considering a higher heating value (HHV) of 5 MJ/Nm^3 [15] for the gas obtained typically from an air blown fluid bed gasifier and efficiency of internal combustion engine of 36% (on HHV basis) [16].

If this second flux is not enough, because the power to compensate exceeds the direct compensation limit ($f \cdot P_e > r_g P_b$), the gas flux to be provided from the deposit is given by:

$$\phi_d = q \cdot (f \cdot P_e - r_g \cdot P_b) \quad (6)$$

So, if we have to compensate during a t_c period of time, the required gas to take from the deposit will require a volume for the deposit given by:

$$V_c = q \cdot (f \cdot P_e - r_g \cdot P_b) \cdot t_c \quad (7)$$

Nevertheless, there is no sense to increase the volume over the value that is possible to refill, during the period of time that the system is not compensating and the upgrading of the gasifier can be used for gas reposition.

$$V_r = \phi_g \cdot t_r = q \cdot r_g \cdot P_b \cdot t_r \quad (8)$$

By imposing $V_c = V_r$ and substituting in Eq. (3) the values of t_c and t_r deduced from Eqs. (7) and (8), respectively, we can deduce the value of the minimum value of the volume for the storage deposit:

$$V_{\text{lim}} = 24 \cdot q \cdot r_g \cdot P_b \cdot (f \cdot P_e - r_g \cdot P_b)/(f \cdot P_e) \quad (9)$$

Fig. 4 plots the dependence of this V_{lim} with the power of the biomass plant. The V_{lim} contour contains the intersection points of the V_r and V_c curves for such t_c and t_r values that together sum 24 h.

Using t_c from Eq. (7) and V_{lim} from Eq. (9), we can deduce:

$$f \cdot P_e \cdot t_c = 24 \cdot r_g \cdot P_b \quad \text{if } P_b < f \cdot P_e / r_g \quad (10)$$

So, a triple compensation factor, defined as the product of the fraction of the wind park energy output to be compensated times the park nominal power times the number of compensation hours, is only dependent on the characteristic of the biomass plant (power and overdimensioning) and introduces a compromise between the size of the wind park and the fraction of power and the period of time to apply compensation (Fig. 5).

Eqs. (9) and (10) will be the essential elements to take into account when designing the compensation branch of the hybrid wind-biomass system. The third element, the internal combustion engine for compensation purposes, whose rated power can be considered as an overdimensioning respect to the engine already existing in the original biomass power plant, should be dimensioned taking into account the maximum power of the instantaneous power to compensate. In fact, f, fraction to compensate in Eq. (10) is an average value defined as $\langle f \rangle$, the ratio between the mean value of the distribution of power expected from the wind and the nominal power of the park. Nevertheless, to compensate any decrement whatever its value is, with a certain probability, we should considered the maximum value for f deduced from such probability distribution. Fig. 6 plots the distribution with indication

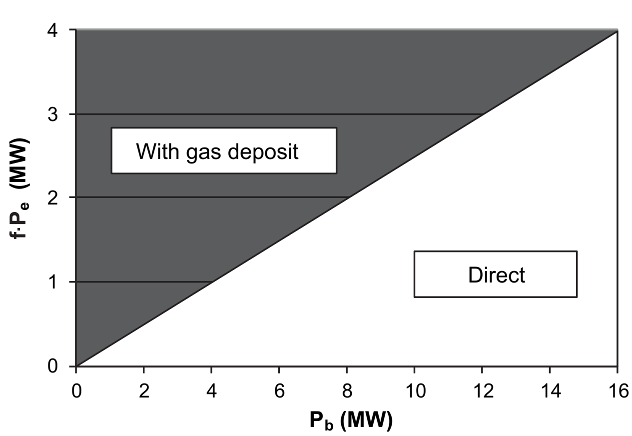

Fig. 3. Operation regimes ($f = 0.1$, $P_e = 40$ MW, $r_g = 0.25$).

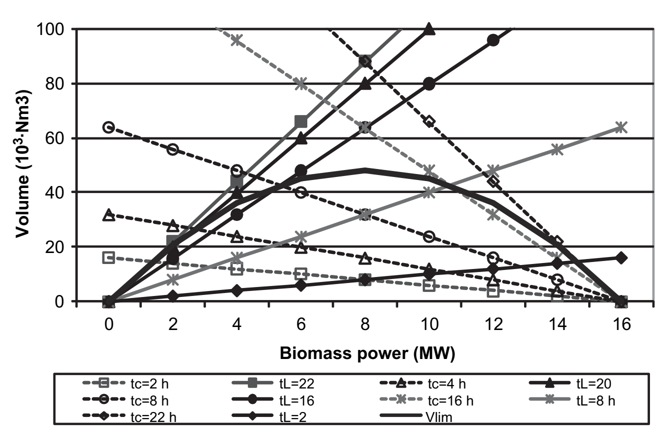

Fig. 4. Storage volume ($f = 0.1$, $P_e = 40$ MW, $r_g = 0.25$).

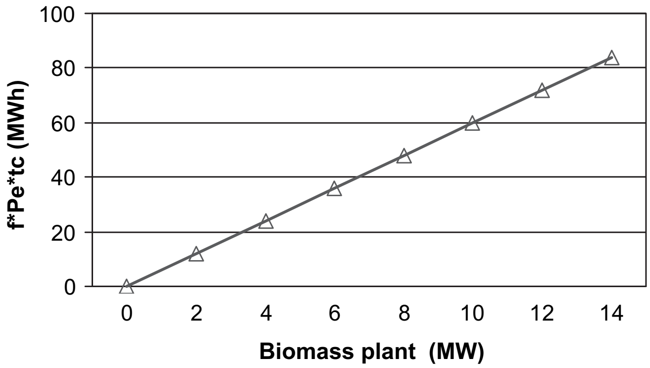

Fig. 5. Triple compensation product ($r_g = 0.25$).

of the two values, $<f>$ and f_{max}, this last one for a 93% probability to succeed in compensation. The power, ΔP_m ,of the required internal combustion engine to make possible this compensation will be given by:

$$\Delta P_m = f_{max} \cdot P_e \tag{11}$$

3. Simulation and results

3.1. Wind park

The behaviour of the proposed hybrid system has been simulated using real data from a 40 MW wind park in Spain [17]. This data provides the output power of the park along one entire year with a 1 h time resolution, and so allow computing the error in the one day advanced predictions for the power output were calculated using the following criteria [18], where three main error categories have been considered:

1. For low wind speeds (<6 m/s): generated power is highly overestimated by the wind prediction program, so an 100% estimated error in the predicted powers obtained from these speeds is used.
2. For medium wind speeds (>6 m/s and <9 m/s): generated power is also overestimated by the wind prediction program, so an 45% underestimated error in the predicted powers obtained from these speeds is assumed.
3. For high wind speeds (>9 m/s): generated power is underestimated by the wind prediction program, so a 25% overestimated error in the predicted powers obtained from these speeds is used.

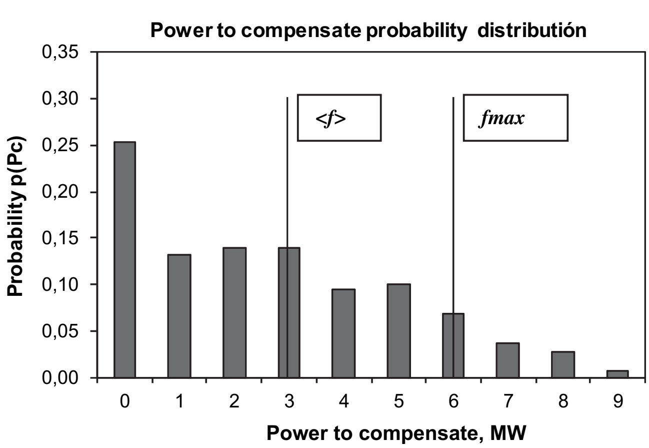

Fig. 6. Compensating fractions.

This criteria has been obtained from the results of a study performed using various wind prediction programmes in seven wind parks of Spain [18].

Fig. 7 shows a comparison between the generated power curve and the predicted power curve, for the 40 MW wind park, using the above described error criteria, and also the compensated power required from the biomass plant.

Looking at the data for the entire year, the wind variations between two consecutives measurements, at a rate of 1data/hour are less than 10%. An occurrence of wind variations higher than 20%, that can result in power variation of 0.1 MW/minute is very unusual, less than 0.3%, so we can assume this variation rate as the upper limit to the wind speed change rate for the design of the hybrid system.

3.2. Biomass gasification power plant and compensation upgrading plant

The design parameters of the hybrid system were calculated using design criteria described in the previous section. Assuming a hybrid system composed by a wind park with a nominal power of 40 MW to be compensated up to 12 h in an average fraction $<f> = 7.5\%$ with a biomass plant with a gasifier overdimensioned in a 33%, we can deduce from Eq. (10) that such biomass plant should have a nominal power of 4.5 MW. The gasifier should reach 6 MW and the internal combustion engine, for $f_{max} = 15\%$ (93% probability of compensation) will be also a 6 MW unit. Eq. (9) gives for these conditions a deposit volume of $36 \cdot 10^3$ Nm^3. Table 1 summarises the characteristics and parameters of the designed system.

For the biomass gasification power plant it has been assumed the following features:

1. Efficiency of the whole biomass plant has been considered 25% referred to HHV (higher heating value) of input biomass.
2. Changes in requested power for compensation purposes (power compensation ramp) purposes can be followed by the system.

For the compensation upgrading plant it has been considered the following assumptions.

1. If syngas deposit contains enough gas to cover compensation needs of the hour ahead, syngas flow can be served as fast as requested (maximum power compensation expected slope is <0.15 MW/min, which implies a syngas flow slope <300 Nm^3/min)
2. Simulation starts with the syngas deposit full.
3. No energy consumption for storing the gas has been considered as it is very low pressure storage (pressure < 0.1 bar, typical storage employed for biogas from anaerobic digestion).
4. Extra gas provided by the gasifier overdimensioning follows the following rule:
   - during night (20:00 PM–07:00 AM), as no compensation is required, it is stored.
   - during day (08:00 AM–19:00 PM), if no compensation is required or it is lower than 1.5 MW, but the deposit is not completely full, it is stored.

These assumptions allow computing the hourly energy balance of the hybrid system according the power compensation needs.

3.3. Results

Fig. 8 plots the evolution along the year of the stored gas in the proposed hybrid system under the conditions outlined at the two

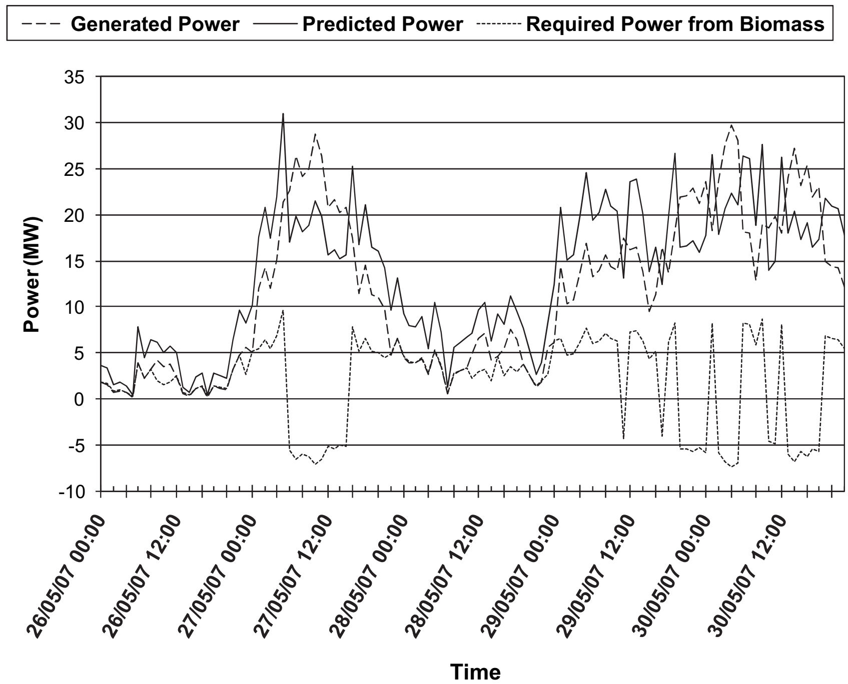

Fig. 7. Wind park power curves.

previous paragraphs. Small dips in the plot indicate those specific times when the system has not enough gas to compensate for the requested power. They are very few along the year and are quantified in Fig. 9 where the effective compensation time, total time in which requested gas from storage for compensation purposes was available, over the total one required is plotted as function of the volume of the gas storage system. Considering an storage capacity of 36×10^3 Nm^3 of hydrogen and a real whole year cycle, a 90% of compensation is obtained. Saturation in the storage system indicates those situations where the capability of the system to generate gas and fill up the deposit exceeds the available volume. This could suggest increasing that volume, but Fig. 9 shows that increases over the design value deduced using Eq. (9) do not change substantially the compensation probability, already close to 100% with those design values, so, given the economical and logistics problems derived from an increase in size of the storage tank, there is no sense in such increase for a so small increase in compensation capabilities. Under these design characteristics, the oversized gasifier is only partially working to keep the gas deposit full and ready for the next day operation. Fig. 10 details the evolution for the utilization factor of the gasifier along the year.

Table 1
Parameters of the simulated hybrid system.

Parameter	Description	Value
Wind Park		
P_e	Wind park power	40 MW
$<f>\cdot P_e$	Average value of compensated power	3 MW
$f_{max}\cdot P_e$	Peak value of compensated power	6 MW
t_c	Compensation time	12 h
Biomass Gasification Power Plant		
P_b	Biomass plant power (gasifier & engine)	4.5 MW
Compensation Upgrading Plant		
ΔP_g	Gasifier overdimensioning power	1.5 MW
ΔP_m	Internal combustion engine overdimensioning power	6 MW
V	Gas storage deposit volume	36×10^3 Nm^3

Fig. 11 details with higher time resolution the three different compensation situations that could appear in the operation of the system:

(a) Covering total compensation needs, where the requested power to compensate prediction errors is fully provided by the system.
(b) A failure situation, where due to lack of gas in the deposit, not enough power can be supplied.
(c) Peak compensation, where however there was not enough gas in the deposit, real power compensation requirement exceed maximum compensation capacity (6 MW) assumed in the system design.

Considering the whole year cycle, situation (a) happens 86.4% of the time and situation (b) and (c) happens 10.4% and 3.2% of the time respectively. Considering situation (c) as acceptable situation because there is no lack of gas, it can be concluded that effective compensation was achieved almost 90% of the total operation time of the wind park.

4. Technical implementation

The proposed hybrid system can be arranged using elements already available. Biomass plants with energy output in the range of several MWs are available, using as standard elements gasifier up to 6 MWs and engine and generator in this range.

Gasifier is used in partial load when it is not necessary to produce synthesis gas in excess to store (i.e. when the storage in full). In this case, working below the nominal power could imply an efficiency reduction. Technical characteristics of gasifiers ensure that the efficiency does not decreases substantially when it is used at 70% of nominal power.

In the case of the group engine-generator there is a similar limitation. When the generator is used up to 50% of nominal power, efficiency of the group is in the range 32–33%. But when it is used at a lower fraction of the nominal power, efficiency falls dramatically.

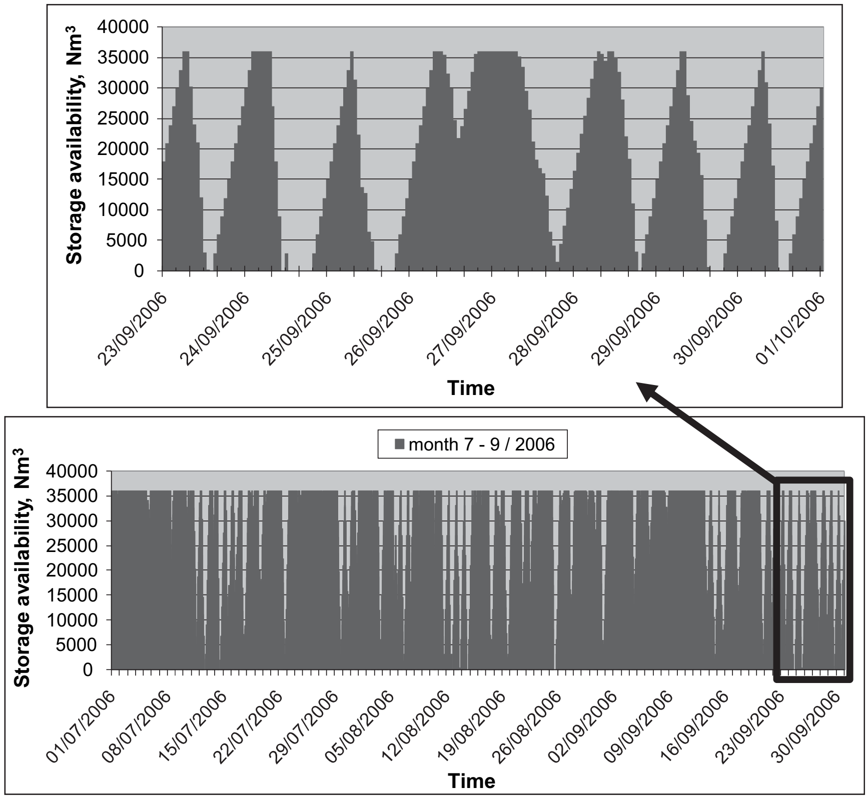

Fig. 8. Evolution of stored gas availability along the year.

So, if the compensation is implemented using a unique generator, efficiency of this group will be very low, because in most cases operating power output will be below the 50% of nominal power. It is a better choice to install different groups (two or three would be enough) working all of them in partial load (always above 50%) to produce the biomass power plant nominal power. When compensation is needed, generation is increased in the same proportion in all the groups. This kind of operation ensures a higher efficiency in all the cases.

In order to ensure correct wind power compensation, it would be necessary that all power variations from the wind park were properly compensated just in time. In the system described in this paper, maximum compensation power from biomass plant is 6 MW. Taking into account that this is the maximum variation in the compensation power in an hour, it corresponds to a 0.1 MW/min slope. Engine-generator system can guarantee a change in its operation power point of 0.5 MW/min in worst conditions, when syngas comes from storage tank. If we consider that storage tank is empty, slope of power changes is limited by the gasifier response. In this case, maximum power slope is 0.15 MW/min, enough to accomplish the maximum power slope defined. Wind parks are located in geographical locations where wind speed is quite constant. So that, no large wind speed variations are expected. In the concrete case of Sotavento wind park, we analysed data along a year and all wind power compensation needs had a variation rate lower than 0.1 MW/min.

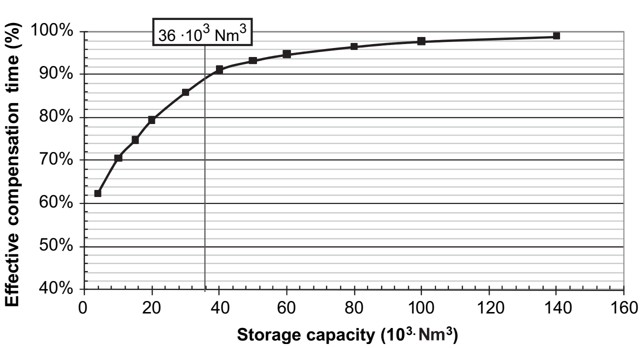

Fig. 9. Effective compensation time for one year operation.

A third element to consider is the availability of biomass resources to feed the compensation system. Assuming a wind park located in an almost flat area with a surface occupation of 8–14 ha per MW, we can assume our wind park has a surface in the order of 300–500 ha. If energy crops are grown in the park, assuming a production in the order of 15 t/ha [19,20] and an energy content of around 4.75 kWh/kg (on HHV basis), typical value for the cynara cardunculus, we can obtain a total amount of 21.4–35.7 GWh of biofuel which, considering 25% HHV of electric efficiency, could be enough for the required compensation energy deduced from our simulation of the operation for the entire year that reaches an electric energy value of 8.2 GWh.

Waste biomass from forestry and agricultural crops (tree prunnings and cereal straw) can also be employed. In previous projects [21] it has been observed that in Mediterranean rural areas (60–90% of area is forest or cropland) available biomass density is around 0.2–2 t/ha. A biomass power plant of 4.5 MW with a 25% HHV of electric efficiency would need around 40,000 tons of wet biomass (30% of moisture) and considering a waste biomass density of 0.5 t/ha, it would need around 805 km^2 of area equivalent to an approximate maximum transport distance of around 25 km [22].

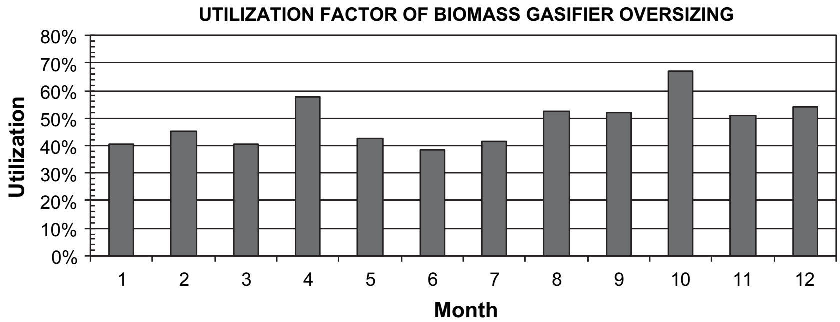

Fig. 10. Evolution of the utilization factor of the oversized gasifier along the year.

5. Economical viability

The combined use of a biomass power station to compensate the prediction errors in the electric power production of the wind parks, allows them working under market conditions with a great reliability, (in the case studied for a 40 MW wind park, with a biomass power station that can compensate up to 6 MW, this reliability reaches a 93%), that moreover of the intrinsic benefit in the kWh price working to market tariff, avoids the penalties by production deviations. The annual benefits (R) of the considered wind park are:

$$R = E_e \cdot (c_m - c_d) \tag{11}$$

Where: c_m is the kWh price working to market tariff, c_d is the kWh price working to fixed rate and E_e is the annual net park electricity production.

In the case of Spain, $c_m = 9.0448$ cent € and $c_d = 6.534$ cent €. Considering that the average operational period of the wind park is 2200 h/year, which means a real power of this park of about the 25% of its nominal installed power, we can obtain an benefit of 2.2 M€, and assuming that the difference $(c_m - c_d)$ will not change, the benefit will be similar each year. Also according the results (3.3) "effective compensation was achieved almost 90% of the total operation time of the wind park", the penalties to be paid for non-covering the prediction when there is not enough power to compensate prediction errors (10% of the total operation time of the wind park) are estimated about 0.2 M€/year (year energy not supplied × 10% c_m). So, the annual benefit is estimated in 2.0 M€.

The extra maintenance cost of hybrid system due to the supplementary equipment has been considered negligible.

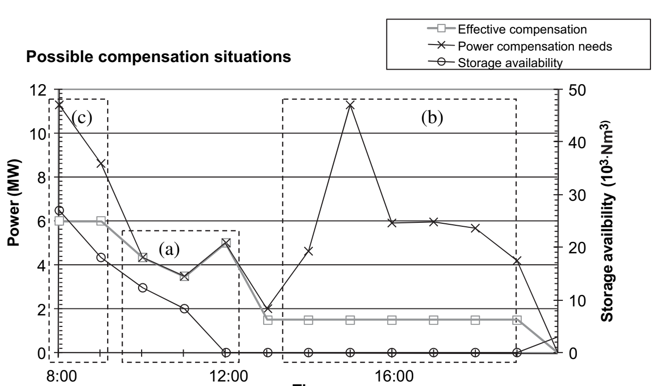

Fig. 11. Different compensation situations in a critical day: (a) Total compensation, (b) Storage tank is empty, and (c) Maximum compensation capacity of 6 MW.

The extra cost for the considered hybrid system is due to the oversizing of the biomass power plant specifically the gasifier and the generation system based on an internal combustion engine which implies around 7.8 M€, so that the investment paying-off period would be 4 years approximately.

This "oversizing" cost of the biomass plant has been deduced considering a scale value of 2000 €/kW [23] for the generation system and the gasifier upgrading (1.5 MW). The cost of the electric generation system increment, based on a second internal combustion engine until reaching the 6 MW to cover the power peaks, it is calculated using a scale value of 500 €/kW [24]. And the cost for the gas storage system has been deduced from a unit price of 50 €/Nm3, that is typical for the range of volume we are considering in this application.

The extra investment to carry out to allow for this compensation scheme, 7.8 M€, represents about a 15% of the total investment in the wind and the biomass power plants, considering for both elements of the hybrid system the following costs: 46 M€ for wind park and 9 M€ for biomass plant, deduced from an economic scale of 1150 €/kW the wind park [24] and 2000 €/kW the biomass plant [16].

6. Conclusions

In the near future wind energy will have an important share in electricity generation scenario forcing to solve the reliability problem of this energy source. A hybrid system, combining a biomass gasification and a wind generation plants, could alleviate these problems by means of installation on the location of the wind park a biomass power plant and the oversizing of its gasifier, so this extra power could be devoted to generate gas to be stored and used by a generation system based on a internal combustion engine to compensate the deviations in the wind generation to the 24 h in advance predictions made to the grid operator. A methodology has been derived to design the main parameters of this hybrid system and applied to a 40 MW wind park, deducing that a biomass power plant with a power one order of magnitude below the nominal power of the wind park and about 30% oversizing in the gasifier could reach this objective. Simulation of the hybrid system behaviour using as input real wind park data for an entire year of operation proves the capability of the system to compensate the wind park in a 90% of the deviation cases with a utilization factor for the use of the oversized gasifier in the order of 50% of the time. The designed hybrid system can be built using already available technologies and the time response is high enough for the expected wind change rates deduced from the available wind park data. Economical studies prove an investment paying-off period of about 4 years. Biomass logistics studies indicate for standard production of biomass the need to use the production in the area with an average of 25 km around the plant for the normal operation of the plant. The extra demand due to the compensation system will require an additional 25% of biomass, and so longer transport distances, but could be also covered by the use of the own land of the wind park for energy crops growth. This compensation hybrid system is perfectly adequate to the use of renewable energy sources in a future sustainable energy scenario where renewable energies should play an important role with contributions in the order of 30% of the total primary energy demand and prove that, by complementing different renewable sources, it is possible to avoid the drawbacks of each of them.

References

[1] Denny E, ÓMalley M. Wind generation, power system operation and emissions reduction. IEEE Trans Power Syst 2006;21(1):341–7.
[2] Ashok S. Optimised model for community-based hybrid energy system. Renew Energy 2007;32:1155–64.
[3] Garcia RS, Weisser D. A wind-diesel system with hydrogen storage: joint optimisation of design and dispatch. Renew Energy 2006;31:2296–320.
[4] Kasseris E, Samaras Z, Zafeiris D. Optimization of a wind-power fuel-cell hybrid system in an autonomous electrical network environment. Renew Energy 2007;32:57–79.
[5] Nelson DB, Nehrir MH, Wang C. Unit sizing and cost analysis of stand-alone hybrid wind/PV/fuel cell power generation systems. Renew Energy 2006;31:1641–56.
[6] Zoulias EI, Lymberopoulos N. Techno-economic analysis of the integration of hydrogen energy technologies in renewable energy-based stand-alone power systems. Renew Energy 2007;32:680–96.
[7] Tanrioven M. Reliability and cost-benefits of adding alternate power sources to an independent micro-grid community. J Power Sourc 2005;150:136–49.
[8] Dufo-López R, Bernal-Agustín JL, Contreras J. Optimization of control strategies for stand-alone renewable energy systems with hydrogen storage. Renew Energy 2007;32:1102–26.
[9] Fiedler F, Nordlander S, Peresson T, Bales C. Thermal performance of combined solar and pellet heating systems. Renew Energy 2006;31:73–88.
[10] Othman MY, Bakar MN, Sopian K, Yatim B. Performance analysis of a double-pass photovoltaic/thermal (PV/T) solar collector wit CPC and fins. Renew Energy 2005;30:2005–17.
[11] Pregelj A, Begovic M, Rohatgi A. Quantitative techniques for analysis of large data sets in renewable distributed generation. IEEE Trans Power Syst 2004;19(3):12–7.
[12] Lund H. Large scale integration of optimal combinations of PV, wind and wave power into the electricity supply. Renew Energy 2006;31:503–15.
[13] Segura I, Pérez-Navarro A, Sánchez C, Ibáñez F, Payá J, Bernal E. Technical requirements for economical viability of electricity generation in stabilized wind parks. Int J Hydrogen Energy 2007;32:3811–9.
[14] 2006IEAWind Energy Annual Report, <www.ieawind.org.>; 2006.
[15] Castells XE. Treatment and waste-to-energy valorisation of waste materials (in Spanish). Madrid: Ediciones DÍAZ De Santos; 2005.
[16] US Environmental Protection Agency. Combined heat and power partnership anon. Catalogue of CHP Technologies 2002.
[17] Sotavento experimental wind park, www.sotaventogalicia.com.
[18] AEE, Asociación Empresarial Eólica. Prediction exercise: final report (in Spanish). Madrid, http://www.aeeolica.es/doc/informe_final_prediccion.pdf; 2006.
[19] Venturi P, Venturi G. Analysis of energy comparison for crops in European agricultural systems. Biomass and Bioenergy 2003;25:235–55.
[20] Fernandez J, Curt MD, Aguado PL. Industrial applications of *Cynara cardunculus* L. for energy and other uses. Ind Crops Prod 2006;24:222–9.
[21] Alfonso D, Peñalvo E, Pérez-Navarro A, Rodríguez J. Study of biomass resource evaluation at the mediterranean area. In: Proceedings of 9th world renewable energy congress. Florence, Italy; 19–25 August 2006.
[22] Alfonso D, Perpiñá C, Pérez-Navarro A, Peñalvo E, Vargas C, Cárdenas R. Methodology for the evaluation of distributed biomass resources and optimization of its management and energy use. In: Proceedings of 2nd international congress of energy and environment engineering and management, Badajoz; Spain, 6–8 June 2007.
[23] Alfonso D, Perpiñá C, Pérez-Navarro A, Peñalvo E, Vargas C, Cárdenas R. Methodology for optimization of distributed biomass resources evaluation, management and final energy use. Biomass and Bioenergy 2009;33: 1070–9.
[24] Eólica 2006. Wind power 2006, asociación empresarial eólica (AEE), www.aeeolica.org; 2006.