Wind park reliable energy production based on a hydrogen compensation system. Part I: Technical viability.

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Abstract

Power production from renewable energy resources is increasing day by day. In the case of Spain, in 2009, it represents the 26.9% of installed power and 20.1% of energy production. Wind energy has the most important contribution of this production. 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. Weather forecast systems have errors in their predictions depending on wind speed. Thus, if wind energy becomes an important actor in the energy production system, these fluctuations could compromise grid stability. In this study technical and economical viability of a large scale compensation system based on hydrogen is investigated, combining wind energy production with a biomass gasification system. Combination of two systems has synergies that improve final results. In the economical study, it is considered that all hydrogen production that is not used to compensate wind energy could be sold to supply the transportation sector.

Keywords

Hybrid system; Wind energy; Biomass; Fuel cell; Renewable energy; Energy Storage; Economical Viability;

1. Introduction.

Contribution of renewable energy sources to electrical power production is becoming an important part of the energy production mix in many countries. In the case of Spain, in 2009, the 26.9% of installed power was from renewable sources (20% corresponding to wind energy) and the 20.1% of the electrical energy demand was covered by this kind of energy (13.8% corresponding to wind energy) [1]. Spanish wind power plans are not completed yet, so we can assume that, in the next years, percentage of wind energy production will be increased. As it is well known, the two main problems of this renewable energy source are impact on the grid and availability, due to its inherent variable behavior. Stability on the grid could be compromised if there is a substantial increment of wind power installed. Energy production should be fit to energy consumption in order to guarantee the stability. Weather forecast systems can predict (one day before) wind speed with an error that varies in the range of 10% to 15%, depending on the wind speed. If energy from wind power systems is a considerable part of total energy production, this percentage of uncertainty could have a negative impact on the remaining energy production systems. So, it is necessary to implement an energy storage system that could compensate the deviations of the prediction of the wind park, using the energy produced by the park in the valley hours. Authors demonstrated the viability of the use of hydrogen as energetic vector to achieve this objective in [2], but there are a lot of more recent studies that agree with this concept (i.e. [3], [4], [5]).

Conclusion of the mentioned study was that conversion to and from hydrogen should increase its efficiency to be competitive. For this reason, in [6] we studied the use of synthesis gas (syngas) from a biomass gasification system to compensate the wind park, establishing synergies between the two energy production systems. Biomass gasification is a mature technology with acceptable conversion efficiency. One of the conclusions of this study was that the syngas deposit (calculated for optimum behavior of the system) remained full during long periods of time, doing unnecessary the use of the gasifier upgrade. Moreover, energy produced by the wind park during valley hours (i.e. during the night) could not be profitable for energy storage.

These two reasons caused that we considered hydrogen as a more profitable energetic vector to compensate the wind park. On the one hand, it can be obtained from water electrolysis, taking advantage of the wind park´s excess of energy (i.e. during valley hours). On the other hand, it is possible to extract the hydrogen from the syngas obtained by gasifying biomass with steam water. This gasification technique allows obtain up to 64% in volume of hydrogen from the syngas flow [7], with a minimum of 51% [8].

In this case, if hydrogen deposit is full, excess can be sold to hydrogen fuel stations, supposing that hydrogen car (or transport in general) was a reality in the near future. In this way, gasifier upgrade considered to increase syngas production is used continuously, increasing global efficiency of gasifier compared it with its partial use when the deposit was full in [6].

There are a lot of studies that take into account hydrogen as a fuel to transportation sector. In [9] plans of the European Parliament are shown, not only to the development of fuel cell vehicles but also to the development of hydrogen filling stations. In the paper, hydrogen is produced from photovoltaics, wind and biomass. In [10], a prediction of the behavior of the passenger transport sector towards 2050 is presented. The study addressed the need for investments in R&D, demonstrations, skilled people and infrastructure required for the development of fuel cell technologies and transition from petroleum to hydrogen in a significant percentage of vehicles sold by 2020. Other studies considered hydrogen rail transportation ([11], [12]), comparing it with the current diesel fuel supplying system in Ontario.

Spain has a great potential of renewable energy sources (RES) for clean production of hydrogen in the future [13]. There are a lot of activities that focus on R&D of the electrolyzer and their components. Spain has also an important potential in biomass from the agricultural sector for electricity production and bio-fuels and it has been involved in demonstration projects for transport applications. Hence, the objective of this paper is to study the system considering the Spanish market, due to its relevant characteristics and all concerning aspects.

This study comprises a 2-paper companion set of papers. The first paper shows the technical viability study of a system that compensates the deviation of the wind prediction of a 40 MW wind park by means of two complementary systems: a production-consumption hydrogen system based in a set of electrolysers and a set of solid oxide fuel cells; and a steam water biomass gasification system that can contribute with a high percentage of hydrogen. It is extracted from the syngas by means of a PSA system. In the second paper we show the results of the economical viability of the systems that had the best technical behavior.

The paper is structured as follows. In the second section we present a complete system description, with a definition of used technologies and possible synergies between all of them. In the third section it is described how the technical analysis is made, defining the study variables and the calculation procedure. Fourth section shows the results and their discussion. Finally, conclusion of the study will show the best technical scenarios that it will be interesting doing the economical study.

2. System description.

As it is described in the previous section, the objective of the system is to guarantee that energy from a wind park, compromised one day before, is delivered to the grid independently of the error in the prediction. Compensation system is based on a hydrogen production and conversion system to compensate the differences between the forecasted energy output and real energy output. Hydrogen is produced by the electrolysis of water when there is an excess of energy in the wind park (in the valley hours, when energy is not injected into the grid, or when prediction was lower than the real wind speed), and by means of extraction of it from the syngas obtained by gasifying biomass with steam water. Figure 1 shows the block diagram of the complete system considered. In the following explanation we will describe, for each block in the figure, its characteristics, used technology, assumptions for the calculation and possible synergies with other components of the systems.

Wind park. It is considered a 40 MW wind farm. The hourly energy output data is obtained from real data in the experimental Sotavento Wind Park (24 MW_{el} extrapolated to 40 MW_{el}) [14] and a complete year is considered. Error in the one day advanced predictions was calculated in the same way that in [6]: for low wind speeds (< 6m/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; for medium wind speeds (> 6m/s and < 9m/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; for high wind speeds (> 9m/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.

Electrolyser. Commercial technologies currently used are alkaline electrolysis with 25-30 % caustic potash (KOH) or polymer electrolyte membrane electrolysers. Large scale electrolysers, typically, are alkaline ones that are well known and exist for more than 30 years, including low maintenance costs [15][16]. A special type of electrolysers that is used in this study is the LURGI-System from Industrie Haute Technology (IHT) that works under pressure conditions about 32 bars. Using this kind of electrolyser the products can be directly used for further processes and do not have to be pressurized. The chosen electrolyser from IHT has a nominal hydrogen production of 760 Nm^3/h including an oxygen production of 380 Nm^3/h and operates with nominal efficiency at part-loads between 25 and 100 % of its nominal capacity. Table 2 shows a detailed set of electrolyser technical data. Produced oxygen can be used in the gasification system to improve the efficiency of the process.

Fuel Cell. There are several types of fuel cells supplied by different fuels like hydrogen, methanol or methane in form of natural gas. All of them have as exhaust gases steam water, that can be used as input in the biomass gasifier to increase the percentage of hydrogen in the resulting syngas. This is an advantage over other electricity generation systems as gas turbines. In stationary applications, the more used technologies are

Molten Carbonate (MCFC) and Solid Oxide fuel cells (SOFC). Advantages of SOFC over MCFC are the following: they are more efficient (fuel input to electricity output) and do not have problems with electrolyte management. Moreover, they have a potential long life expectancy of more than 40,000–80,000 h [17]. Nevertheless, very high operating temperature force to use special materials to guarantee a long durability and a very long time to start-up (about 20 hours). This last characteristic obliges to maintain fuel cell operating continuously with a minimum consumption of hydrogen (a 10% of maximum output power is assumed) in order to be prepared to compensate the wind park. Output water byproduct of the fuel cell reaction can be used moreover to feed the electrolyser.

Biomass gasification system. The biomass based hydrogen production can be divided into two main routes, thermo-chemical and bio-chemical [18], [19]. Bio-chemical methods are namely fermentation, photolysis or biological water gas shift reaction and practical applications still need to be demonstrated. Thermo-chemical processes are namely pyrolysis, gasification and super critical water gasification (SCWG). Pyrolysis is the conversion of biomass into synthesis gas with heat in absence of oxygen. For the SCWG, water is miscible with organic substance above the critical point. This method is preferred especially for high moisture biomass. Gasification with air is the cheapest and easiest one and the gasification with oxygen-enriched air or pure oxygen leads to a higher low heating value (LHV) of the synthesis gas than for air gasification (3 – 8 MJ/Nm³ daf - dry ash free-) because of the absence or less amount of nitrogen in the product gas. The most efficient method related to the hydrogen yield is the gasification with steam and oxygen whereby the steam (H_2O) also is split into hydrogen and carbon monoxide or dioxide. With this gasification method also a higher LHV of about 10 – 16 MJ/Nm³ of dry ash free biomass is obtained [20], [21]. In this study an atmospheric downdraft gasifier with an additional CO-shift to augment to hydrogen yield is considered. This gasifier consists in five different zones: in the drying zone at the top with temperatures about 150°C to 300°C the wet biomass will be dried before it reaches the pyrolysis zone where at temperatures of about 600°C the pyrolysis of the biomass begins to produce the reaction products like char, tar and gases (equation 1), which as well represents the general reaction equation. With the addition of air or oxygen and/or steam the biomass starts to combust (combustion zone) which is necessary to generate the heat for catalysis and cracking reforming and tar decomposition in the reduction and catalyst zone. Table 3 shows the composition of the synthesis gas obtained with the chosen gasifier and their characteristics.

$$\text{Biomass} + \text{heat} + \text{steam} \rightarrow$$

$$\rightarrow \text{char} + \text{tar} + \text{gases}\ (CO_2, CO, H_2O, H_2, CH_4, C_nH_m) \tag{1}$$

The base size of the biomass installation is chosen to 4.5 MW. This power corresponds to the gasifier, the combustion engine and electrical generator group that is generating energy continuously and injecting it to the grid. So, all the systems of this installation are self founding with the benefits by selling the energy. It is not considered the increment of energy content of the syngas because it is obtained by gasifying with steam water. This increment can be used to pay the maintenance task in the gasifier upgrade and its deposit.

Upgrade of biomass installation consists in a over dimensioning gasifier and a hydrogen separator PSA (that is described below). The size of the gasifier upgrade is one of the variables of the study.

Pressure Swing Adsorption (PSA). It is a widely used, highly efficient and highly selective gas-cleaning process to obtain pure gases. It is based on the on the selective accumulation or adhesion of one or more components of a gas mixture on the surface of a micro porous solid [22]. To obtain hydrogen from syngas the adsorption process is one of the three main processes used in industry for separating hydrogen from other gases like light and heavy hydrocarbons and methane. Also, it is used to obtain nitrogen and oxygen. For hydrogen production by a PSA a minimum pressure ratio of approximately 4:1 between the purging and adsorption pressure is required. The optimal purging pressure is as low as possible: it can be atmospheric pressure or even go lower down to 0.1 to 0.35 bar. The hydrogen purity for four bed processes ranges from 99 vol % up to 99.9999 vol % and the hydrogen recovery under optimal conditions is about 70 % - 92 % [19]. We selected the system that provides the high purity. All the other gases resulting from separation are feed to the biomass generation system. Preliminary results of simulations showed that there was not enough oxygen from electrolysis to supply the complete gasifier. So, besides hydrogen separation from syngas, another PSA system is used to obtain extra oxygen from air. In this study, PSA's efficiency is assumed to be 80% and the own demand of energy is given with 0.5 kWh/Nm^3 H_2 or O_2.

Hydrogen storage. The best storage density can be obtained with metal hydride storage systems but they require a long and complex filling process and are still very expensive [23]. For station applications, pressurized tanks with volumes up to 10,000 m^3 are the simplest and cheapest solution because it only requires a storage vessel and a compressor [24], [25]. In this study a medium pressure storage system is chosen that harmonizes with the chosen electrolyzer such that no additional compressor is necessary and compression energy will be saved. The storage tank's size will be adjustable between 5,000 Nm^3 and 50,000 Nm^3 in steps of 5,000 Nm^3 based on the gas storage size of 36,000 Nm^3 applied in a previous study [6]. For hydrogen compression only two compressors are needed: one for low compression up to 32 bars to compress the hydrogen coming from the gasification process and separated in a pressure swing adsorption (PSA). The other one is for high compression up to 200 bars to compress the hydrogen that will be sold to fill the hydrogen transport trucks [26]. The maximum amount of hydrogen per hour to sell will be about 2,000 Nm^3, so that a high pressure compressor (HP-compression) Type CT from the Greenfield AG is used. For low pressure compression (LP-compression) the compressor size depends on the amount of hydrogen delivered by the gasification process and PSA. For the 1.5 MW and 1.0 MW gasification installation the high pressure compressor Type CT and Type CU respectively from the Greenfield AG will be used. Although it seems oversized these compressors require less energy than a similar low pressure compressor: Type CT needs 200 kW for compression of 1,600 Nm^3/h and a low pressure compressor Atlas Copco P37 needs 280 kW for 1,500 Nm^3/h. For the 0.5 MW gasification installation a low pressure compressor P 10 from Atlas Copco will be installed using less energy than a similar high pressure compressor. In table 4 it is shown an overview of the compressor's technical data.

3. Simulation procedure.

Objective of this first part of the study is to demonstrate the viability of wind park compensation using the proposed solution. Due to the high number of systems that are taking part in the solution, other objective is to find the optimal technical scenario. So, it is necessary to determine the variable that we wish to optimize of. Taking into account the main objective, this variable can be "Compensation factor" ($f_{H2,compensation}$). This parameter represents the amount of wind park energy that can be compensated with this system. It is possible that hydrogen stored was not enough to compensate all the energy required by the wind park or instantaneous power required by the wind park was greater than the compensation system installed power. In these cases, wind park is not compensated and compromise of energy is not accomplished. But other variables allow us to evaluate the system behavior. Below it is shown and described characteristic variables of the system:

- Electrolyzer's capacity utilization factor $f_{EL,util}$: amount of wind-energy E_{H2} that is transformed into hydrogen via electrolysis related to maximum possible energy to transform.
- Fuel cell's capacity utilization factor $f_{FC,util,}$: annual used energy for compensation related to maximum possible energy to compensate.
- Hydrogen to sell $V_{H2,sell}$.
- Percentage of time that hydrogen deposit is empty: $f_{H2,dep,empty}$
- Oxygen utilization factor $f_{O2,util}$
- Necessary water to add to process $V_{H2O,add}$/ excessive water to sell $V_{H2O,sell}$

In order to find the best technical scenario, four parameters of the system are defined. In Table 5 it is shown the name, the range and the step of change made in the different simulations.

In all the technical scenarios analyzed, the hourly energy fluxes delivered by the wind park are calculated as well as the forecasted data. Starting data were wind speed (m/s), date and obtained energy from the wind park ($E_{WP,real}$(t), kWh). Further, the energy required by the fuel cell to compensate is calculated. With these energies the hourly mass fluxes of hydrogen, oxygen and water needed to operate and obtained by the processes of electrolysis, biomass gasification and hydrogen conversion via fuel cell are calculated. In addition, the hydrogen, oxygen and water deposit contents comparing the necessary to the produced quantities are computed. Table 6 shows the list of parameters calculated to obtain the value of defined variables. Procedure of calculation is illustrated in figure 2.

With the given wind park data and the four adjusted parameters the available energies are calculated and the constant energies for LP-compression and for the hydrogen PSA are already considered. Now hydrogen and oxygen mass fluxes are obtained by operating the electrolyser with the calculated energy and by operating the gasification plant. Then hydrogen storage content, fuel cell mass fluxes and finally, the resulting parameters including water circuit and oxygen system are calculated. A more detailed explanation of how all these data are calculated is shown next.

Wind park energies. As it is commented above, from data of Sotavento real wind park, it is calculated the prediction considering the wind speed. Distinguishing between hours of hydrogen production t_{H2}, hours of electricity input into the grid t_{grid}, considering the energy delivered by the wind park E_{WP} and the forecasted energy E_{fc} one can calculate the energy supplied to the grid E_{grid}. With these data also the useable energy for hydrogen production E_{H2} and the necessary energy for compensation in cases of higher forecasted values than delivered energies $E_{comp,req}$, are calculated.

Hydrogen production. There are two ways to calculate hydrogen production: excess of wind energy and from biomass. In the case of electrolysis, before using the energy E_{H2} for electrolysis the system's own demand in form of hydrogen-PSA and LP-compression will be subtracted as it will be explained below. It is also necessary to consider the range of part-loads in which the electrolyser cannot be operated. According to this, a partial load factor f_p for minimal power to operate the electrolyser can be introduced:

$$V_{H2,WP}(t) = P_{H2}(t) \cdot f_{n,kWh \rightarrow Nm^3} \qquad for \qquad P_{H2} \geq P_{El,max} \cdot f_p$$

$$V_{H2,WP}(t) = 0 \qquad for \qquad P_{H2} < P_{El,max} \cdot f_p \tag{2}$$

where $P_{H2}(t)$ is the power that could be applied to the electrolyser in a concrete hour.

To calculate hydrogen from biomass gasification ($V_{H2,BM}$), it is necessary to consider the hourly demand of biomass of the additional gasifier capacity (m_{BM}), syngas yield (Y_{gas}– Nm^3 synthesis gas per kg wet biomass), percentage of the biomass installation in use for hydrogen production, percentage of obtained hydrogen (f_{H2}) and pressure swing adsorption efficiency (η_{PSA}), as it is showed in equation 3.

$$V_{H2,BM}(t) = \dot{V}_{H2,BM} = m_{BM} \cdot Y_{gas} \cdot \frac{P_{H2,BM,add}}{P_{H2,BM,basic} + P_{H2,BM,add}} \cdot f_{H2} \cdot \eta_{PSA} \tag{3}$$

Hydrogen storage and consumption. To calculate the quantity of hydrogen in the storage tank at the end of every hour $V_{H2,deposit}(t)$ the hourly generated hydrogen $V_{H2,prod}(t)$, the amount of hydrogen utilized by fuel cell $V_{H2,comp,FC}(t)$, the quantity of hydrogen in the tank at the end of the previous hour $V_{H2,deposit}(t-1)$and the size of the tank $V_{H2,dep-size}$ have to be considered. Consumption come from compensation, thus, hydrogen volume requested by the wind park for compensation $V_{H2,comp.req}$ can be calculated by equation 4, considering minimal and maximal consumption of hydrogen $V_{H2,FC,min}$ and $V_{H2,FC,max}$ as the upper and lower limit of $V_{H2,comp,req}(t)$. These limits are determined by the fuel cells operational range introduced above.

$$V_{\mathrm{H2,comp,FC}}(t) = \frac{E_{\mathrm{comp,req}}}{\rho_{\mathrm{H2}} \cdot \eta_{\mathrm{FC}} \cdot d_{\mathrm{H2}}} \qquad with \qquad \dot{V}_{\mathrm{H2,FC,min}} \leq V_{H2,comp,FC}(t) \leq \dot{V}_{\mathrm{H2,FC,max}} \tag{4}$$

where ρ_{H2} is the hydrogen mass, d_{H2} is hydrogen energy density and η_{H2} is fuel cell's efficiency.

Oxygen system and water circuit. The oxygen generated by the electrolyser is stored in an oxygen storage tank and used for the steam/oxygen gasification process. Actual oxygen tank content $V_{O2,deposit}(t)$ is calculated taking into account produced amount of oxygen $V_{O2,prod}(t)$ from electrolysis and oxygen required for the gasification process $V_{O2,gasif,req}(t)$. If there is not enough oxygen it has to be generated by an air-PSA that is included in the gasification installation.

To operate the electrolyser and the biomass gasification installation water is necessary. Water generated by the fuel cell can be stored in a water tank and could be used for these two installations. Water is calculated from the real amount of hydrogen used for compensation $V_{H2,comp,real}(t)$.

Systems own demand. Two compressors and two pressure swing adsorption systems have an hourly energy own demand that has to be considered. The energy own demands are determined as given in equations 5 to 8

$$E_{\mathrm{PSA,H2}} = \sum_{i=1}^{8760} V_{\mathrm{H2,BM}}(t) \cdot c_{\mathrm{PSA,H2}} \tag{5}$$

$$E_{\mathrm{PSA,O2}} = \sum_{i=1}^{8760} V_{\mathrm{O2,PSA}}(t) \cdot c_{\mathrm{PSA,O2}} \tag{6}$$

$$E_{\mathrm{LP-compress}} = \sum_{i=1}^{8760} V_{\mathrm{H2,BM}}(t) \cdot c_{\mathrm{LP-compress}} \tag{7}$$

$$E_{\mathrm{HP-compress}} = \sum_{i=1}^{8760} V_{\mathrm{H2,sell}}(t) \cdot c_{\mathrm{HP-compress}} \tag{8}$$

where c is the conversion factor for each system. If there is not enough energy to compensate the system's own demand excessive fuel cell energy will be used for it ($E_{FC,min}$).

4. Results and discussion.

To determine the most efficient and competitive system five technical scenarios with a range of four to twelve hours of wind park energy consumption for electrolysis will be analyzed. Scenarios does not only consider the nightly hours for hydrogen production, they also use daily hours in the afternoon for hydrogen production because of low energy prices at this time and higher prices in the beginning of the night until 11 p.m.

In order to calculate all possible parameter combinations and plot their belonging resulting parameters a programming in Microsoft Visual Basic is developed. Showing all the results obtained requires a synthesis effort. For this reason, we had to fix the value of some variables. Based in the results obtained in [6], it seems that power of systems that could make possible the compensation is the parameter with smaller variation. Figure 3 shows the variation of the compensation factor $f_{H2,comp,max}$ and the maximum fuel cell's capacity utilization factor $f_{FC,util,comp,max}$, for different fuel cell power. It can be seen that with a 5 MW fuel cell power, compensation factor is near 90% and utilization factor is in the middle of the range. More fuel cell power guarantees a little increment in the compensation factor with a light drop of utilization factor, so it is considered that it is not worth increasing fuel cell power.

It is impossible to show in this paper all the results of the study because of evident space reasons. As an example of the results obtained, we will show those extracted of the scenario number 1, considering a 5 MW set of fuel cells. But discussion will include all the scenarios calculated.

Results are organized showing the behavior of each parameter under study with the variation of upgrading gasification power, number of electrolysers and hydrogen storage tank size. As it is not possible to obtain a four-dimensional graph, four three-dimensional graphs are plotted, each of them corresponding to the biomass gasification upgrade considered power. A brief discussion of the parameter result is included.

Compensation factor. Figure 4 shows the simulation results for different biomass upgrade gasifier power. No biomass upgrade (0 MW) corresponds with the case of exclusive use of wind park remaining energy to compensate the wind park. Basic biomass power plant would take advantage of synergy with the system. Only a maximum of 65 % is reached in this case. With P_{BM} = 0.5 MW, the maximum is already about 82 % reached with a large electrolyser (4 ones). However, with P_{BM} = 1.0 and P_{BM} = 1.5 MW the final compensation maximum of 86.6 % is already achieved with two and one electrolyser, respectively. It can be concluded that the 1.0 MW and 1.5 MW gasification configurations seem to be more efficient because of higher compensation factors for less electrolyser power and for smaller hydrogen tanks.

Fuel cell capacity utilization. In figure 3 the maximum fuel cell capacity utilization factor of 18.94 % for a 5 MW fuel cell is already shown and is also found in figure 4.c and 4.d. For no gasification plant (P_{BM} = 0 MW) and P_{BM} = 0.5 MW a maximum factor of only 14 % and 18 % respectively is achieved (figure 4.a and 4.b). This results from less hydrogen to convert via fuel cell. Later on it will be shown that there are always times of an empty storage tank for $P_{BM} = 0.5$ MW, so that hydrogen is missing and maximum capacity utilization is not achieved.

Percentage of hours of compensation for one year is about 34.26 %. Hence, in 64.74 % of the annual hours fuel cell is only operating under minimal conditions and just using 10% of its nominal power. Thus, the capacity utilization in general is very low and not exceeding 20 %.

Excess of hydrogen. When hydrogen deposit is full, we can continue producing it for selling purpose. The maximum annual amount of hydrogen to sell varies between 5 million standard cubic meters for no additional gasification plant to 6 and 7.5 million up to 9.5 million standard cubic meters for the 0.5 MW, 1.0 MW and 1.5 MW gasification installations respectively. The smaller the hydrogen tank is the higher the amount to sell is because less hydrogen can be stored and the deposit is nearly always full.

Water flow. This concept describe water in excess (positive) or that it is necessary to add (negative) to the system, but only supplying the additional gasification plant and the electrolyser. It is considered that water necessary for basic biomass plant is funding by the energy selling produced by it. The amount of produced water is rising with the maximum gasification power and the hydrogen tank size. In these cases more hydrogen that originates from the biomass is obtained by gasification process and converted into water via fuel cell. With larger tank volumes more hydrogen is stored and the tank is less times empty. This leads to a higher fuel cell capacity utilization and water production – also shown by higher compensation factors. With the increasing number of electrolysers less excess water exists because of a higher demand by the electrolyser.

Oxygen needed. In the simulations, it was clear that not all the oxygen generated by electrolysis could supply the biomass gasifier completely. So, it was necessary to add an oxygen generator from the air. The bigger the gasification installation the more oxygen is necessary – always getting to the maximum of 100 % for no electrolysers. With many electrolysers a lot of oxygen can be supplied so that the percentage is decreasing. Examining figure 8 it can be concluded that a percentage of at least less than 40 % or better less than 20 % should be aimed for.

As a resume of all results from this scenario number 1, it can be said that configurations with only one hydrogen production method are not viable because of a lack of hydrogen. In addition, scenarios with gasification plant powers of $P_{BM} = 0.5$ MW will be difficult to realize and will not be considered anymore. The hourly hydrogen production of 305.49 Nm³ ($P_{BM} = 0.5$ MW) is lower than the necessary feed in into fuel cell under minimal conditions of 351.42 Nm³ for a 5 MW fuel cell. Additionally, the compensation factor is higher for the two bigger gasification plants or can be reached with smaller installations. A maximum compensation percentage of 86.6 % ($P_{BM} = 1.0$ and 1.5 MW) compared to 82 % ($P_{BM} = 0.5$ MW) is reached and a percentage of 80 % or more can be achieved with only two electrolyzer and a storage tank volume of 20,000 Nm³ ($P_{BM} = 1.0$ MW). To reach a compensation factor of 80 % or more with

P_{BM} = 0.5 MW, four electrolyzers and a 35,000 Nm³ tank are necessary. As well only with P_{BM} = 1.0 and 1.5 MW a never empty storage tank is possible. With smaller installations (No_{EL} = 1; V_{H2} = 20,000 Nm³) very low percentages of an empty storage tank (< 5 %) will not be a problem.

Having seen all the results it is also concluded that the optimal configurations are already attainable for one or two electrolyzers and storage tank volumes of between 20,000 Nm³ and 30,000 Nm³. Hence, the focus will be on these installation sizes that are also shown in table 8.

Considering other hourly scenarios, compensation factor in the scenarios with P_{BM} = 1.0 MW decreases a lot. With only one or two electrolyzers the 80 % of compensation are not reached. For the hourly scenarios of 18/06 and 20/04 f_{comp} not even reaches percentages of 70 %. Hence, these scenarios can also be excluded. Further, the scenario 20/04 with P_{BM} = 1.5 MW is not adequate because of its maximal compensation of less than 75 %. This results from the very low hydrogen production; thus, there is not enough hydrogen and in many times compensation will not be effective.To summarize the results table 9 give an overview of the optimal scenarios with compensation percentages higher than 85 % or higher than 80 % for scenario 18/06. It has to be kept in mind, that there are more or even better scenarios with larger storage tanks or more electrolyzers. However, they are not optimal due to low advancement compared to the depicted ones. Optimal scenarios for 20/04 are not found.

The results also shows that for 12/12 and 14/10 there are optimal scenarios with only one electrolyzer, but for 16/08 already two electrolyzers have to be installed. For 18/06 the compensation percentage is even not possible to reach. It can be concluded that 14/10 with less hours of hydrogen production and 12/12 are the optimal hourly scenarios.

Conclusion.

In this study the technical viability of a wind park energy compensation system is proven using hydrogen as energy storage. System could supply the difference between compromised wind park energy production one day before, basing it on forecast software, and real production. Different installations (wind park, biomass gasifying, fuel cell, PSA, hydrogen storage) and their synergies are explained and demonstrated. Data of wind park production come from a real system (Sotavento wind park). Systems used in the study are commercial and data of their behavior is extracted from information published by the builder, except in the case of steam water biomass gasifying. In this case data come from contrasted bibliography.

In order to optimize the configuration, a set of initial parameters and output variables were defined. These variables gave an idea of the behavior of the system. The most important in this technical study was Compensation Factor, that shows percentage of time that wind park needed compensation and our system was able to compensate it.

Five hourly scenarios were defined to study all the possibilities of hydrogen production, with a range of four to twelve hours of wind park energy consumption for electrolysis. In the case of scenario number 1, where there was 12 hours dedicated to hydrogen production, configurations with only one hydrogen production method (just electrolysis or just biomass gasification) were not viable. Compensation factor was higher for the two bigger gasification plants. To reach a compensation factor of 80 % or more with P_{BM} = 0.5 MW, four electrolyzers and a 35,000 Nm³ tank are necessary. Optimal configurations were already attainable for one or two electrolyzers and storage tank volumes of between 20,000 Nm³ and 30,000 Nm³.

In other scenarios, where number of hours dedicated to electrolysis were lower, compensation factor in the scenarios with biomass upgrade gasifier with P_{BM} = 1.0 MW decreases a lot. With only one or two electrolyzers the 80 % of compensation are not reached.

For 12/12 and 14/10 scenarios there were optimal configurations with only one electrolyzer, but for 16/08, two electrolyzers had to be installed. For 18/06 the minimum compensation percentage is even not possible to reach. It can be concluded that 14/10 with less hours of hydrogen production and 12/12 were the optimal hourly scenarios.

As final conclusion, this study demonstrates the technical viability of wind park compensation using a biomass gasification system and an electrolysis hydrogen generation system, but it is incomplete with any economical study to demonstrate its economical viability. This is the objetive of the second paper of this brief series.

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Figures

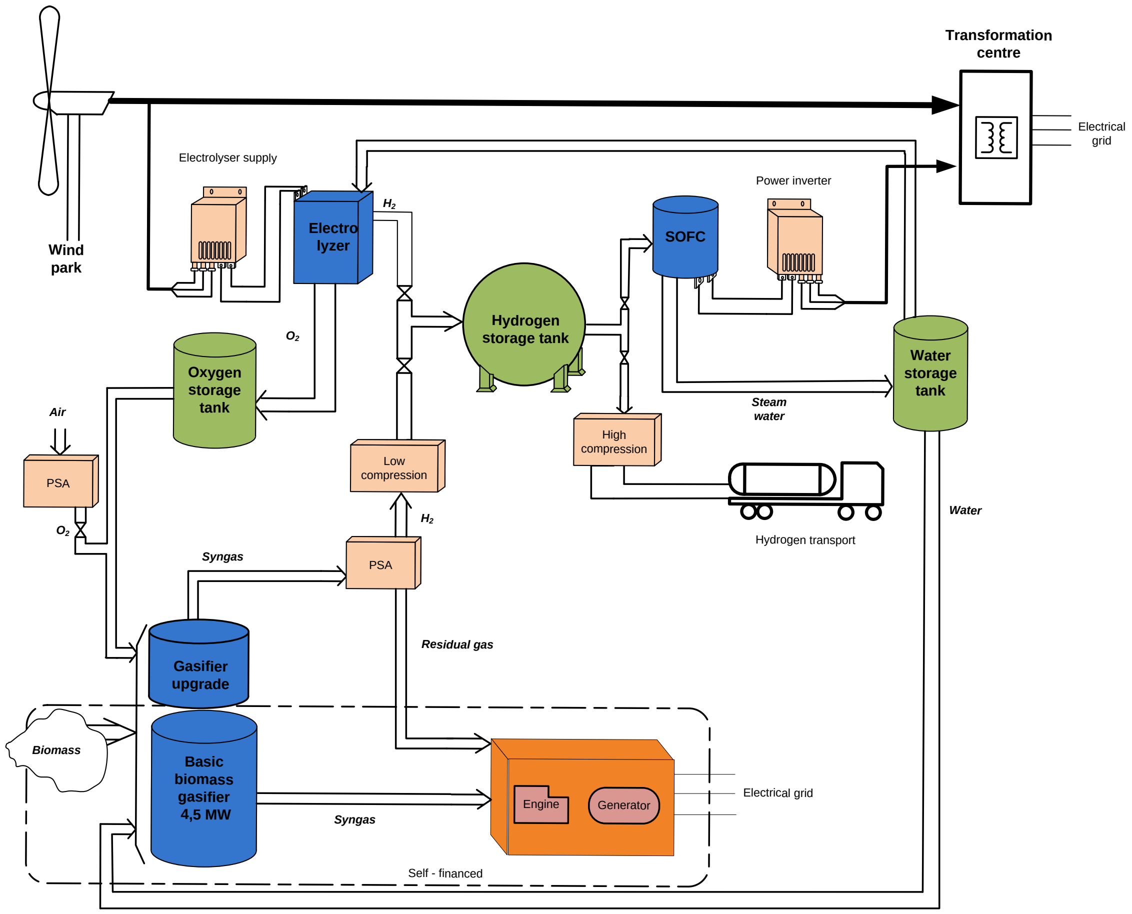

Figure 1: Diagram block of the complete system.

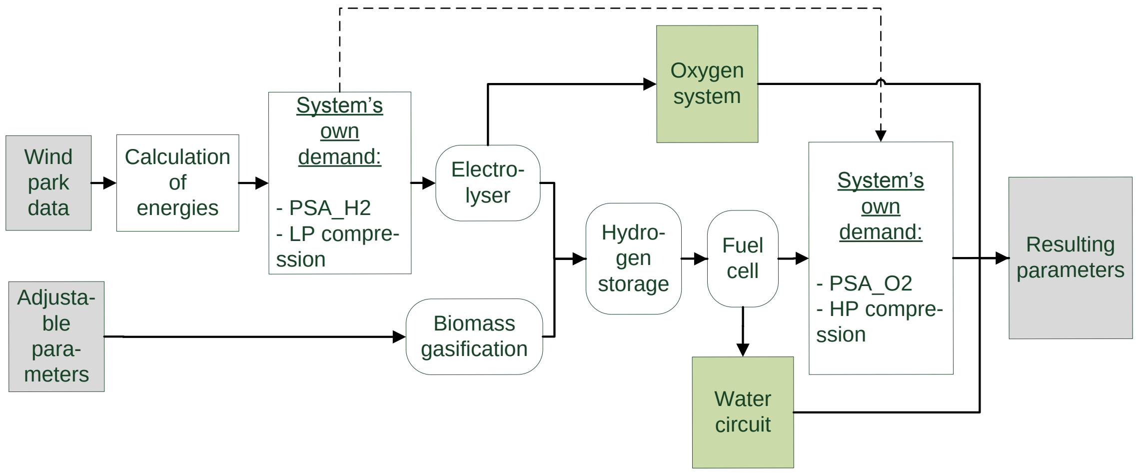

Figure 2: Calculation scheme.

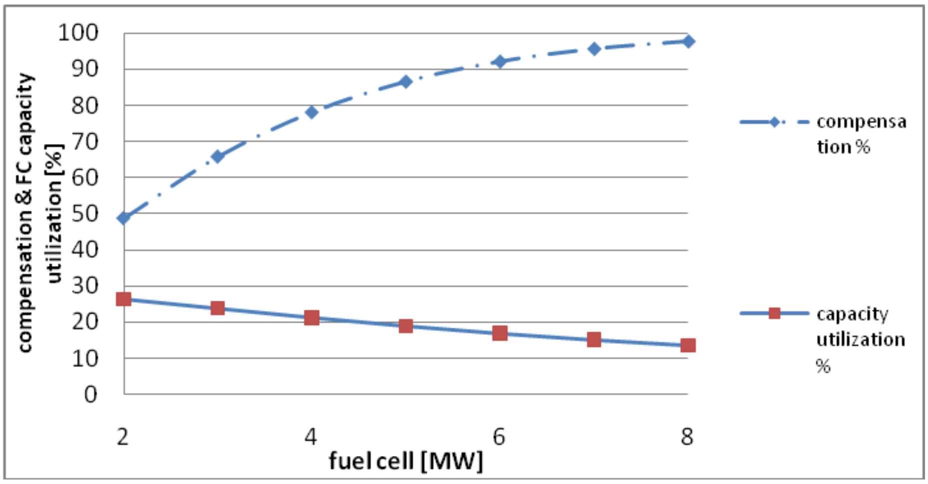

Figure 3: Maximum **c**ompensation factor and fuel cell´s capacity utilization factor for different fuel cell power in the scenario number 1: 12/12.

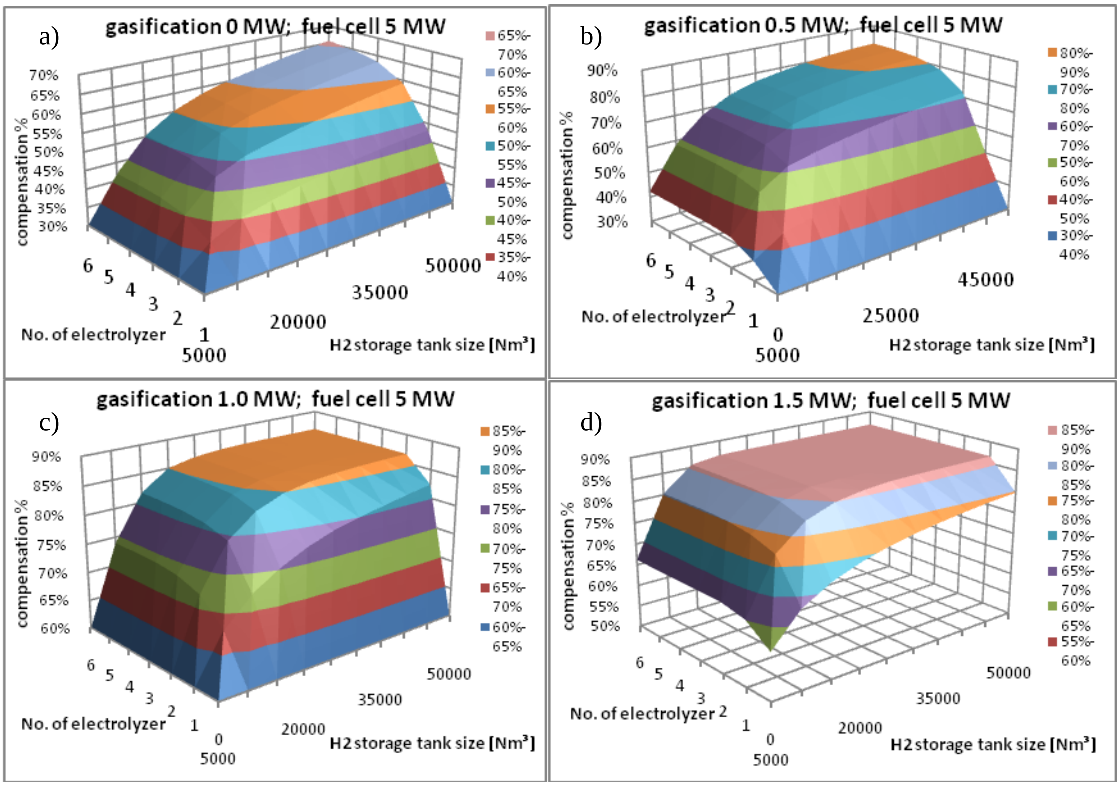

Figure 4: Compensation factor of the system for different biomass upgrade gasifier power: a) 0 MW, b) 0.5 MW, c) 1 MW and d) 1.5 MW, with 5 MW fuel cell set power. Scenario number 1: 12/12.

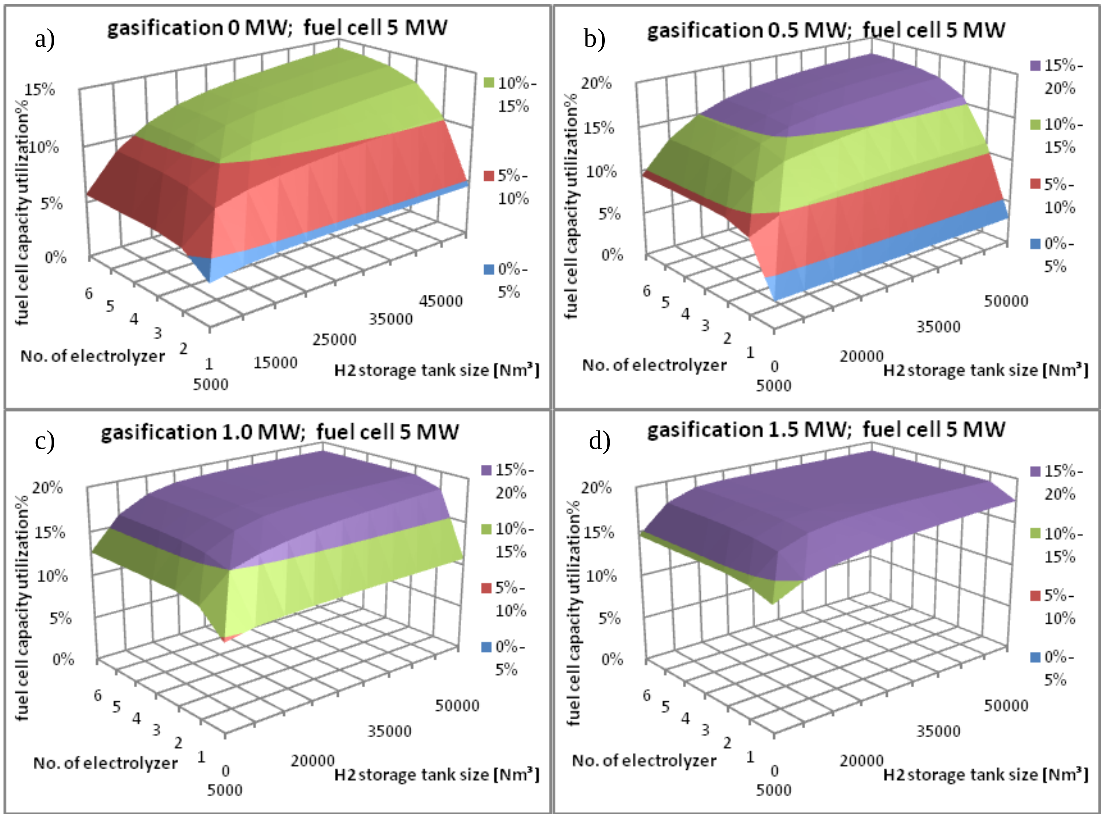

Figure 5: Fuel cell capacity utilization for different biomass upgrade gasifier power: a) 0 MW, b) 0.5 MW, c) 1 MW and d) 1.5 MW, with 5 MW fuel cell set power. Scenario number 1: 12/12.

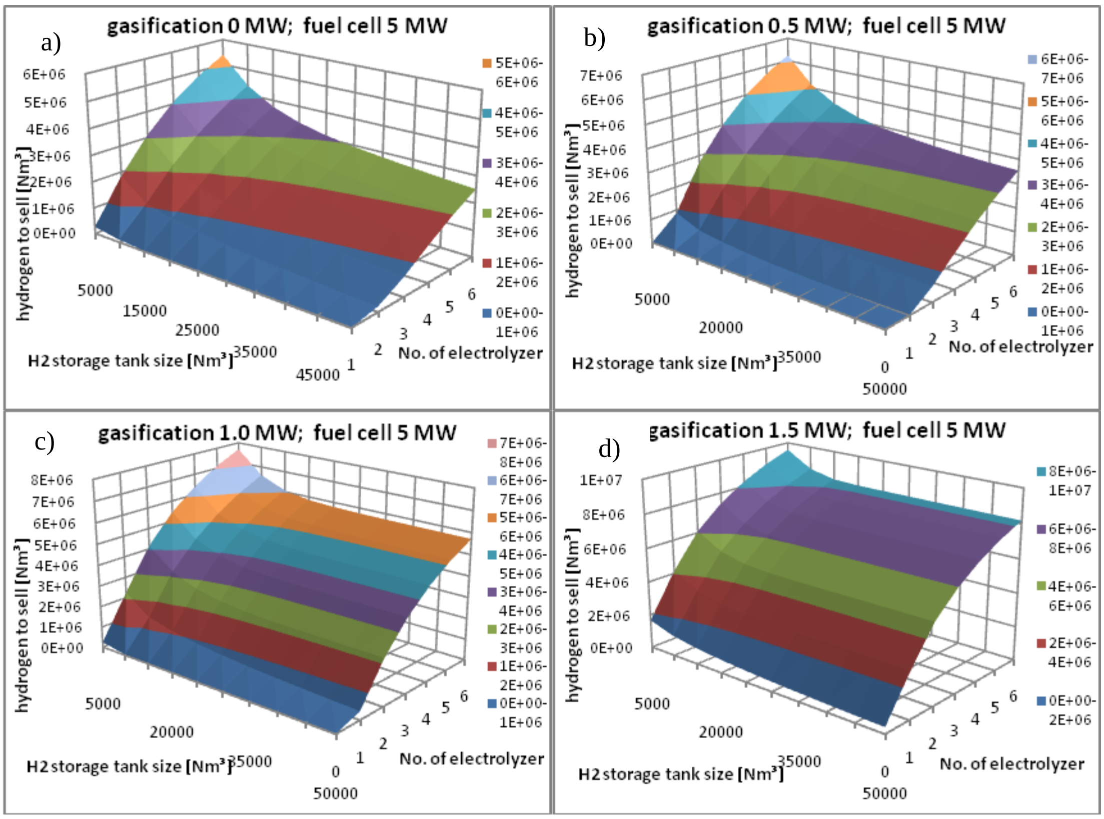

Figure 6: Excess of hydrogen production for different biomass upgrade gasifier power: a) 0 MW, b) 0.5 MW, c) 1 MW and d) 1.5 MW, with 5 MW fuel cell set power. Scenario number 1: 12/12.

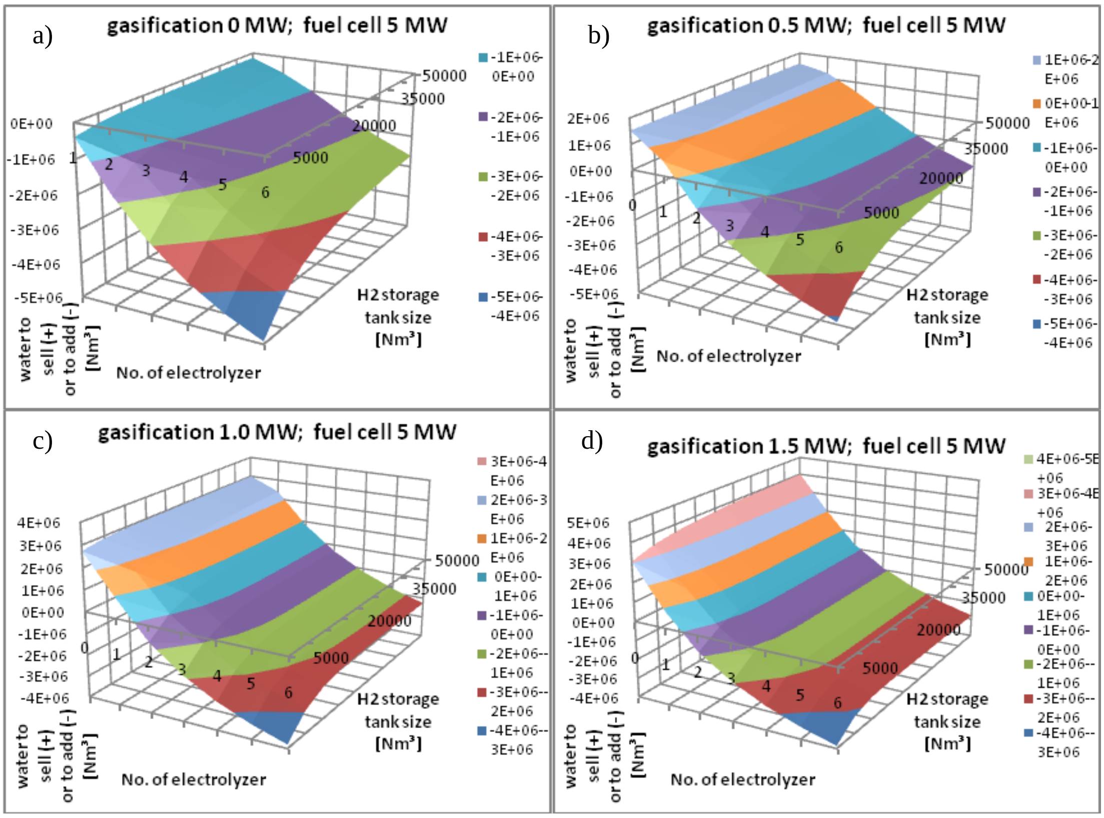

Figure 7: Flow of water in the system (excess is positive and defect is negative) for different biomass upgrade gasifier power: a) 0 MW, b) 0.5 MW, c) 1 MW and d) 1.5 MW, with 5 MW fuel cell set power. Scenario number 1: 12/12.

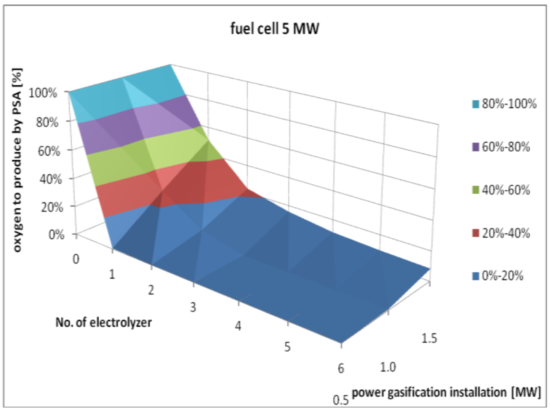

Figure 8: Percentage of oxygen produced by the PSA system from the air that gasifier need, for different biomass upgrade gasifier power and number of electrolysers, with 5 MW fuel cell set power. Scenario number 1: 12/12.

Tables.

Table 1. List of symbols

Latin symbols		
a	%	average percentage for fuel cell determination
c	kWh/Nm³	specific energy consumption to operate (own demand)
d	kWh/kg	energy density
E	kWh	energy
f	%	factor
fa	%	average factor of every hour
LHV	MJ/Nm³	lower heating value
m	kg/h	mass flow
M	g/mol	molar mass
n	-	number of times
p	%	part-load
P	W	capacity/power
t	h	time
V	Nm³	volume
$\dot{V}$	Nm³/h	flow rate
w	-	weighting factor for fuel cell determination
Y	g /kg or m³/kg	hydrogen or syngas yield per kg biomass
Greek symbols		
η	%	efficiency
ρ	g/Nm³	density
Volumes		
$V_{\mathrm{H2,BM}}$	Nm³	hydrogen produced by biomass gasification and obtained by pressure swing adsorption
$V_{\mathrm{H2,comp,real}}$	Nm³	hydrogen used for compensation – related to fuel cell's minimal and maximal consumption and deposit content
$V_{\mathrm{H2,comp}}$	Nm³	hydrogen used for power compensation only related to fuel cell's maximal power
$V_{\mathrm{H2,comp,FC}}$	Nm³	hydrogen needed for power compensation that one is able to compensate – related to fuel cell limits
$V_{\mathrm{H2,comp,req}}$	Nm³	hydrogen requested for power compensation related to wind Park energy

		output $E_{comp,req}$ and forecast data
$V_{H2,deposit}$	Nm^3	amount of hydrogen in hydrogen deposit
$V_{H2,dep\text{-}size}$	Nm^3	size of hydrogen deposit
$\dot{V}_{H2,FC,min}$	Nm^3/h	minimal hydrogen consumption of fuel cell
$\dot{V}_{H2,FC,max}$	Nm^3/h	maximal hydrogen consumption of fuel cell
$V_{H2,prod}$	Nm^3	hydrogen produced by wind park and biomass
$V_{H2,WP}$	Nm^3	hydrogen produced by electrolyser with wind park energy

Indexes

add	additional	H2	hydrogen
BM	biomass	hp	high pressure
comp	compensate	inst	installation
compress	compression	lp	low pressure
conv	converted	n	nominal
E	energy	O2	oxygen
El	electrolyser	p	partial
eng	engine	PC	power converter AC/DC or DC/AC
ex	excessive	prod	produced
fc	forecast	real	real
FC	fuel Cell	spec	specific
gasif	gasification	util	utilization
grid	electricity grid feed-in	WP	wind park

Table ¡Error! No hay texto con el estilo especificado en el documento.**:** Technical data of electrolyzer

Part-load between 25 % and 100 %	
max. production capacity	760 Nm³/h H_2
max. production capacity	380 Nm³/h O_2
electrical energy consumption $C_{n,kWh \rightarrow Nm^3}$	4.6 kWh/Nm³ H_2
maximal power	3,496 MW
Other data	
operational pressure	32 bar
hydrogen purity	99.8 to 99.9 % vol.
oxygen purity	99.3 to 99.6 % vol.
Residual impurity	
H_2O	approximately 1 to 2 g/Nm³
KOH	less than 0.1 mg/Nm³
feed water	0.85 l/Nm³ H_2
cooling water	40 l/Nm³ H_2 (Δt = 20°C)
partial load factor f_p	0.25

Table 3: Parameters of oxygen/steam gasification

Name	Unit	Value
Biomass LHV	MJ/kg, dry basis	18.87
Cold gas efficiency (% based on LVH)	%	69.9
Biomass feed rate (dry basis)	kg/h	266.7
$f_{moisture}$	%	8
Biomass feed rate (wet basis)	kg/h	289.89
Oxygen flow	m³/h	68.7
Steam rate	kg/h	45.8
Synthesis gas flow	Nm³/h	427
Lower heating value	MJ/Nm³	8.24
Product gas composition	vol%, dry basis	
$H_2 = f_{H2}$		56.3
CO		8.9
CH_4		2.3
CO_2		28.1
N_2		4.2
C_xH_y		0.2
Nominal capacity for hydrogen production ($P_{H2,BM}$)	kWh	1,500
Energy to Biomass conversion factor($f_{E\text{->}BM}$)	kWh/kg Biomass	3.37
Efficiency of gas engine (η_{eng})	%	35
Synthesis gas yield (Y_{gas})	m³/kg Biomass	1.6
Hydrogen yield (Y_{H2})	g H_2 / kg biomass (wet, 8%)	74.53
Efficiency of hydrogen PSA ($\eta_{PSA,H2}$)	%	80

Table 4: Compressor's technical data

	Type CT	Type CU	Type P 10
Working pressure Flow rate Motor power	up to 401 bar up to 1,600 Nm^3/h max. 200 kW	up to 501 bar up to 850 Nm^3/h max. 110 kW	up to 40 bar up to 315 Nm^3/h max. 75 kW
Used for	HP-compression	-	-
	LP-compression for P_{BM} = 1.5 MW	LP-compression for P_{BM} = 1.0 MW	LP-compression for P_{BM} = 0.5 MW

Table 5: Input parameters of the simulation.

Adjustable parameters		**Range**	**Step**
electrolyzers	Number.	1 - 6	1
fuel cell power	MW	2 - 8	1
hydrogen storage size	Nm^3	5,000 - 50,000	5,000
size of additional part of biomass gasification	MW	0 - 1.5	0.5

Table 6: Calculated parameters

Energies [MWh]:		**Mass flux**		**Storage vessels**	
		<u>Electrolysis:</u>		<u>Hydrogen:</u>	
Extrapolated energy (40MWh)	$E_{WP}(t)$	Needed water	kg	Actual content	Nm^3
		Produced oxygen	Nm^3	Quantity to sell	Nm^3
Forecasted energy	$E_{fc}(t)$	Produced hydrogen	Nm^3		
Energy feed-in into grid	$E_{grid}(t)$	<u>Fuel cell:</u>		<u>Water:</u>	
		Needed hydrogen	Nm^3	Actual content	liters
		Produced energy	MWh	Quantity to add	liters
Energy used to operate electrolyser	$E_{H2}(t)$	Produced water	kg		
		<u>Gasification process:</u>		<u>oxygen:</u>	
Necessary energy to compensate via fuel cell	$E_{comp}(t)$	Needed oxygen	Nm^3	Actual content	Nm^3
		Needed steam	kg	Quantity to add or sell	Nm^3
		Produced hydrogen	Nm^3		

Table 7: Distribution of time for each scenario considered.

Scenario	Hours of electricity grid feed-in t_{grid}	Hours of hydrogen production t_{H2}
1	12	12 (from 2 p.m. to 5 p.m. and 11 p.m. to 8 a.m.)
2	14	10 (from 2 p.m. to 4 p.m. and 11 p.m. to 7 a.m.)
3	16	8 (from 11 p.m. to 7 a.m.)
4	18	6 (from 12 a.m. to 6 a.m.)
5	20	4 (from 2 a.m. to 6 a.m.)

Table 8: Optimal system configurations (scenario 12/12)

El [no]	*P*_FC [MW]	*P*_BM [MW]	*V*_H2 [Nm³]	*f* comp [%]	*f* FC,util [%]	*V* H2,sell [Nm³]	tank empty [%]	*f* O2,util [%]	*V* O2,sell [Nm³]	*V* H2O,sell [m³]
1	5	1.5	25,000	86	18.8	2,759,526	0.3	49.3	1,545	1,972
2	5	1	30,000	85.8	18.7	2,264,027	0.4	92	732,730	765
2	4	1.5	25,000	78.2	21.3	5,736,820	0.0	77	242,689	-568
3	4	1.5	25,000	78.2	21.3	7,007,070	0.0	84.3	684,131	-1,676

Table 9 Optimal configurations for scenarios 2 to 4.

El [no]	*P*_FC [MW]	*P*_BM [MW]	*V*_H2 [Nm³]	*f* comp [%]	*f* FC,util [%]	*V* H2,sell [Nm³]	tank empty [%]	*f* O2,util [%]	*V* O2,sell [Nm³]	*V* H2O,sell [m³]
Scenario 14/10										
1	5	1.5	40,000	85.6	21.8	1,752,445	0.7	45	1,043	2,786
2	5	1.5	30,000	86.5	22.1	3,506,269	0.3	72.7	138,866	1,260
3	5	1	50,000	86	21.9	2,092,421	0.4	94.5	1,017,492	843
Scenario 16/8										
2	5	1.5	40,000	85	24.4	2,534,840	1.1	67.8	71,619	2,061
2	6	1.5	35,000	85.5	20.6	2,107,831	3.5	67.8	71,619	2,408
3	5	1.5	30,000	84	24.1	3,493,800	1.7	74.4	326,817	1,239
Scenario 18/6										
2	5	1.5	45,000	80.1	26.4	1,628,542	4.5	60.5	38,664	2,819
3	5	1.5	40000	80.9	26.6	2,210,827	3.9	68.5	146,325	2,311