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Optimal Single Wind Hydro-Pump Storage Bidding in Day-Ahead Markets including Bilateral Contracts

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***Abstract*—The present evolution of fuel prices together with the reduction of premiums for renewable energies make it of vital importance to improve renewable production management. This paper proposes a model of a single renewable power producer to compete more efficiently against other generators. The single unit is composed of a wind power producer and a hydro-pump storage power producer. The synergies between both renewable producers make relevant the possibility of mitigating wind power uncertainty, and due to this, the imbalances of the wind power producer will be reduced. The reduction of wind imbalances can come from deviating part of the excess of wind generation through a physical connection towards the pumping system or by increasing hydro generation to mitigate the lack of wind generation. To evaluate the problem, stochastic mixed integer linear programming is proposed to address the problem of selling the energy from the single renewable unit through a bilateral contract and in the day-ahead market, as a new contribution to earlier studies. Furthermore, a balancing market is considered to penalize the imbalances. The decision is made to maximize the profit, considering risk-hedging through the Conditional Value at Risk. The model is tested and analyzed for a case study and relevant conclusions are presented.**

***Index Terms*—Bilateral contract, day-ahead electricity market, risk aversion, single wind hydro-pump storage, power producer.**

NOMENCLATURE

Indexes

i	Index referring to a hydro unit.
l	Index referring to each block resulting from the linearization of the production curve of a hydro turbine.
t	Index referring to a period [hour].
w	Index referring to a scenario.

Parameters

α	Per unit confidence level.
$b^+_{t,w}$	Upper limit of the wind farm power offer in period *t* and scenario *w* [MW].
$b^-_{t,w}$	Lower limit of the wind farm power offer in period *t* and scenario *w* [MW].
$B0_i$	Hydro unit *i* power capacity [MW].
β	Risk aversion of the producer, $\beta \in (0,1)$.
c_i	Start-up cost of hydro unit *i* [€].
c_i^H	Generating cost of hydro unit *i* [€/MWh].
c_i^p	Pumping cost of hydro unit *i* [€/MWh].
cv	Conversion factor [Hm^{3}s/m^{3}h].
c^W	Wind farm generation cost [€/MWh].
eff	Hydro pumping efficiency.
$gw_{t,w}$	Power produced by the wind farm using a Weibull distribution in period *t* and scenario *w* [MW].
$if_{t,i,w}$	Incoming flow associated with hydro unit *i*, period *t* and scenario *w* [Hm^3/h].
LL^{Bil}	Lower limit of the energy sold in the physical bilateral contract [MWh].
$\lambda_{t,w}$	Day-ahead market price in period *t* and scenario *w* [€/MWh].
$\lambda^+_{t,w}$	Positive imbalance market price in period *t* and scenario *w* [€/MWh].
$\lambda^-_{t,w}$	Negative imbalance market price in period *t* and scenario *w* [€/MWh].
λ^{Bil}	Bilateral contract price [€/MWh].
$Pmax$	Maximum installed power of the wind farm [MW].
$porhoh_i$	Minimum power of hydro unit *i* for the upper curve [MW].
$porhol_i$	Minimum power of hydro unit *i* for the lower curve [MW].
$porhom_i$	Minimum power of hydro unit *i* for the intermediate curve [MW].
ppm_i	Pumping upper limit of hydro unit *i* [MW].
ρ_w	Probability of occurrence of scenario *w*.
$r_{0,i}^{initial}$	Initial reservoir volume of hydro unit *i* [Hm^3].
$rhoh_{l,i}$	Slope of block *l* of hydro unit *i* for the upper curve [MW/(m^3/s)].
$rhol_{l,i}$	Slope of block *l* of hydro unit *i* for the lower curve [MW/(m^3/s)].
$rhom_{l,i}$	Slope of block *l* of hydro unit *i* for the intermediate curve [MW/(m^3/s)].
$rhopp_i$	Conversion factor from total hydro unit *i* capacity in MWh to m^3/s [MW/(m^3/s)].
UL^{Bil}	Upper limit of the energy sold in the physical bilateral contract [MWh].
$umax_i$	Maximum water discharge of hydro unit *i* [m^3/s].
$umin_i$	Minimum water discharge of hydro unit *i* [m^3/s].

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$umax_{l,i}$	Maximum water discharge of block l of hydro unit i [m^3/s].
$vc1_i$	Lower level of the reservoir associated with hydro unit i used in the discretization of the hydro production curves [Hm^3].
$vc2_i$	Upper level of the reservoir associated with hydro unit i used in the discretization of the hydro production curves [Hm^3].
$Vmax_i$	Maximum volume of the reservoir of hydro unit i [Hm^3].
$Vmin_i$	Minimum volume of the reservoir of hydro unit i [Hm^3].

Continuous Variables

$b_{t,i}^{DA}$	Joint power offer in the day-ahead market associated to the wind farm and hydro unit i in period t [MW].
b_t^{Bil}	Joint power offer in the bilateral contract associated to the wind farm and hydro unit i in period t [MW].
$CVaR$	Conditional value at risk [€].
$\Delta_{t,i,w}$	Imbalance between the actual joint production and the joint power offer of hydro unit i in period t and scenario w [MW].
$\Delta_{t,i,w}^-$	Negative imbalance between the actual joint production and the joint power offer of hydro unit i in period t and scenario w [MW].
$\Delta_{t,i,w}^+$	Positive imbalance between the actual joint production and the joint power offer of hydro unit i in period t and scenario w [MW].
η_w	Auxiliary variable in scenario w used to compute the CVaR [€].
$g_{t,w}^{DA}$	Power produced by the wind farm used in the day-ahead market in period t and scenario w [MW].
g_t^{Bil}	Power produced by the wind farm used in the bilateral contract in period t [MW].
I^{DA}	Sum of all incomes (or cost) of the wind farm and hydro units of the day-ahead market [€].
$I_{t,i=1,w}^{DA}$	Incomes (or cost) at each period t of the wind farm and hydro unit i in scenario w of the day-ahead market [€].
I^{Bil}	Sum of all incomes of the wind and hydro units of the bilateral contract [€].
I_t^{Bil}	Incomes at each period t of the wind farm and hydro units of the bilateral contract [€].
$np_{t,i,w}$	Power produced by hydro unit i in period t and scenario w to eliminate the negative imbalance [MW].
$p_{t,i,w}$	Power produced by hydro unit i in period t and scenario w [MW].
$P_{t,i=1,w}^{DA}$	Power produced in the day-ahead market by hydro unit i unit, in period t and scenario w [MW].
$P_{t,i=1}^{Bil}$	Power produced in the bilateral contract by hydro unit i, in period t and scenario w [MW].
$pn_{t,i,w}$	Net pumping of hydro unit i in period t and scenario w [MW].
$pr_{t,i,w}$	Auxiliary variable associated with $pp_{t,i,w}$ [MW].
PF	Sum of all profits of the wind and hydro units [€].
$pp_{t,i,w}$	Total pumping of hydro unit i in period t and scenario w [MW].
$ppb_{t,i,w}$	Power purchased by hydro unit i, in the day-ahead market that is pumped in period t and scenario w [MW].
$ppw_{t,i,w}$	Power produced by the wind farm that is pumped to hydro unit i in period t and scenario w [MW].
$ppw_{t,i,w}^{\pm}$	Auxiliary variable associated with $ppw_{t,i,w}$ [MW].
$ppw_{t,i,w}^-$	Wind power that is pumped by hydro unit i when there is a joint offer to purchase power in period t and scenario w [MW].
$ppw_{t,i,w}^+$	Excess wind power that is pumped by hydro unit i, when there is a joint offer to sell power in period t and scenario w [MW].
$ppwm_{t,i,w}$	Excess of wind power that can be pumped by hydro unit i in period t and scenario w [MW].
$r_{t,i,w}$	Reservoir of hydro unit i in period t and scenario w [Hm^3].
$s_{t,i,w}$	Spillage of hydro unit i in period t and scenario w [m^3/s].
TC	Sum of all total costs of wind and hydro unit [€].
$TC_{t,i=1,w}$	Total costs of wind and hydro unit in period t, hydro unit i and scenario w [€].
$u_{t,i,w}$	Water discharge of hydro unit i in period t and scenario w [m^3/s].
$ul_{l,t,i,w}$	Water discharge of block l of hydro unit i in period t and scenario w [m^3/s].
VaR	Value at risk [€].
$wf_{t,i,w}$	Water flow pumped by hydro unit i in period t and scenario w [m^3/s].

Binary Variables

$a_{t,i,w}$	0/1 variable that is equal to 0 if hydro unit i, pumps in period t and scenario w and 1 otherwise.
$bd_{t,i}$	0/1 variable that is equal to 1 if there is joint sale in period t, and 0 otherwise (purchase).
$d_{t,i,w}^1$	0/1 variable used in the discretization of the hydro production curves of hydro unit i in period t and scenario w.
$d_{t,i,w}^2$	0/1 variable used in the discretization of the hydro production curves of hydro unit i in period t and scenario w.

$d_{t,i,w}$	0/1 variable that is equal to 1 if the imbalance is negative, and 1 if the imbalance is positive.
$v_{t,i,w}$	0/1 variable that is equal to 1 if hydro unit *i* generates in period *t* and scenario *w* and 0 if the unit is pumping.
$w_{l,t,i,w}$	0/1 variable that is equal to 1 if the water discharged by hydro unit *i* has exceeded block *l* in period *t* and scenario *w* and 0 otherwise.
$y_{t,i,w}$	0/1 variable that is equal to 1 if hydro unit *i* is started-up in period *t* and scenario *w* and 0 otherwise.
$z_{t,i,w}$	0/1 variable that is equal to 1 if hydro unit *i* is shutdown in period *t* and scenario *w* and 0 otherwise.

I. INTRODUCTION

Electrical systems have been in constant evolution since the 1990s, where wind power introduction has been a challenge since then. Renewable energies experienced a substantial growth after the Kyoto Protocol, initially adopted in December 1997. Since then, other protocols have been signed with new specifications and mechanisms, responding to the problems of every age. The high penetration of intermittent generation like photovoltaic and wind power is the current main challenge. The evolution of wind power capacity around the world ranges from 17.5 GW in 2000 to 370 GW in 2014. To mitigate the problem of intermittence together with uncertainty, storage systems are being developed, especially in the last years. Thus, storage systems can help the electric system to match demand and generation, and the differences in the demand between peak and valley hours are mitigated with them. In context of this paper, a wind power farm is linked with a hydro-pump power unit to sell the generation in the day-ahead electricity market and through a bilateral contract where the imbalances are penalized in the balancing market. This new unit is called Single Wind Hydro-Pump Storage (SWHPS) unit.

A. Literature Review

Currently, wind technology [1] and hydro-pump storage technology have reached maturity to be incorporated in electric systems. Such technologies have been used in the context of electricity markets [2] in the last decade. Wind and hydro pump storage generation present three kinds of uncertainties: i) market prices [3], ii) wind generation [4] and iii) water reserves. On the other hand, stochastic programming has being used to model wind generation trading in day-ahead markets [2] [5]. Mathematical programming [6] and, specifically, mixed integer linear programming is regularly used to model hydro power scheduling [7] and a generic storage system in electricity markets is presented in [8]. Wind power has significant interest for short-term trading [9], including short-term probabilistic forecasts of wind power [4], and risk mitigation of wind producers in an electricity market [10]. In addition, hydro power optimal scheduling can be modeled linearly [7] and non-linearly [11]. Because of wind uncertainty, researchers have been seeking several dispatchable energies to mitigate wind imbalances. Hydro and wind generation are combined in [12], while [13] links wind and hydro generation comparing the uncoordinated and coordinated operation, in [14]–[16] real projects on wind-hydro units are shown. Reference [17] evaluates a coordination of both energies, while [18] improves the risk profile of the energy inflows. In the same line of research, some authors include risk [19], and a single offer is used in [20] where risk-hedging is modeled through Conditional Value at Risk (*CVaR*). Reference [21] considers one week as long-term to evaluate a virtual power plant formed by dispatchable and non-dispatchable technologies, adding a bilateral contract for a period of 168 hours. Bilateral contracts are described in [2], [22], and [23]. A forward bilateral contract and a day-ahead market including value-at-risk is modeled in [24], and a new dynamic risk-constrained approach for a wind power producer is developed in [25]. With respect to risk, reference [26] is the seminal paper on Conditional Value at Risk (*CVaR*).

B. Aims and Contributions

Stochastic programming is used to solve the problem proposed of maximizing the profits from selling the energy in a bilateral contract and in the day-ahead market for a time frame of 168 hours. The SWHPS power producer has to determine the best quantity to offer in each hour, what quantity is destined to reduce the imbalances by means of hydro pump storage and the energy that is sent to the bilateral contract and the day-ahead market. The SWHPS power producer is composed of two renewable sources, wind and hydro-pump energy units; the hydro-pump storage can reduce the imbalances coming from the wind generation uncertainty due to the advantages of the water discharge and its known reservoir level. The real problem is the uncertainty in wind generation when there is a physical bilateral contract. Due to the wind generation uncertainty, the energy of the bilateral contract that has to be supplied cannot be satisfied, so wind generation is associated to the hydro-pump power unit to potentially mitigate part of the volatility. In this way, a stochastic mixed integer linear programming model is created to study the behavior of the offers in the day-ahead market with a penalization mechanism (imbalances) and through a physical bilateral contract until the SWHPS generation can meet the physical bilateral contract. The day-ahead market is also necessary to compensate for part of the wind generation volatility.

The aim is to evaluate this type of offering strategy because wind power can be sold in a bilateral contract as a consequence of being supported by the hydro pump storage unit.

Our contributions are fourfold:

i) Model and simulation of a SWHPS power producer using two options, through a bilateral contract and in the day-ahead market.

ii) Model of the SWHPS producer behavior against risk.

iii) Incorporation of the effects of the bilateral contract in the day-ahead market offer.

iv) Reduction of the total uncertainty in the profits due to the incorporation of the physical bilateral contract.

This paper evaluates a new approach for a wind and hydro-pump power unit allowing it to sell energy in the day-ahead

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market and in a physical bilateral contract, reducing a part of the uncertainty of the profits from selling the energy generated.

C. Paper Organization

This paper is organized as follows: Section II describes the main idea of the paper, Section III shows the objective function subject to constraints, Section IV presents the main inputs needed in the model and the parameters used for the analysis of the problem, Section V the results are shown, in Section VI the results are discussed, and Section VII collects the main conclusions proved in previous sections.

II. DESCRIPTION OF THE PROBLEM

The model presented in this paper simulates the wind and hydro generation with two types of electricity markets. The model can sell or buy energy in the day-ahead market (DM), including a balancing market to penalize the imbalances between generation and offers/bids. The energy can also be sold in a physical bilateral contract (PBC). Moreover, a risk-hedging measure is considered in the problem, evaluating its effects.

Wind generation presents high uncertainty because it depends on wind speed, but the hydro-pump generation is known in the short term. Wind generation uncertainty can be reduced in part considering the wind and the hydro-pump power units as a single unit. This paper includes a new approach to reduce wind generation uncertainty together with a hydro-pump power unit by selling/buying the energy in the DM and also selling it through a PBC. A penalization mechanism is considered in the second stage of the problem due to the uncertainty of wind generation as presented in Section III.

The PBC allows us to compensate for part of the uncertainty in the expected profit. In this way, the PBC is defined by the energy to be satisfied and its price.

The time frame to evaluate the problem is one week, because it is the minimum time to have a PBC and to make the decisions for the DM in that time horizon.

Therefore, the problem modeled using stochastic programming has two stages:

- First stage: the decisions of the problem are made. The variables of the first stage are identified because they do not depend on the scenario index, *w*. The variables are: $b_{t,i=1}^{DA}$ and b_t^{Bil}. Thus, the model decides the power to be offered in the DM and the PBC, respectively.

- Second stage: represents all the variables that depend on the scenario index, *w*. For example, the imbalances $\Delta_{t,i=1,w}$ depend on the decisions of the first stage.

CVaR is used as a risk-hedging measure where the solution is affected by it for several values of risk aversion.

The problem has two kinds of uncertainties, internal and external. The internal uncertainty occurs with respect to the electricity market prices and the external uncertainty is related to the weather conditions that affect wind and hydro generation. Due to this, uncertainty is represented through scenarios of water inflows, market prices and imbalance market prices, and wind generation. Furthermore, several values of the main parameters of the PBC are evaluated for the problem; these parameters are the PBC price and the PBC energy limit. Other market mechanisms are not considered since the SWHPS tries to compensate for uncertainties.

The diagram of Fig. 1 depicts the main idea of the strategy: i) the energy offered and purchased in the electricity market, where sales/purchases in the DM including the balancing market penalize imbalances and ii) the energy needed for the PBC.

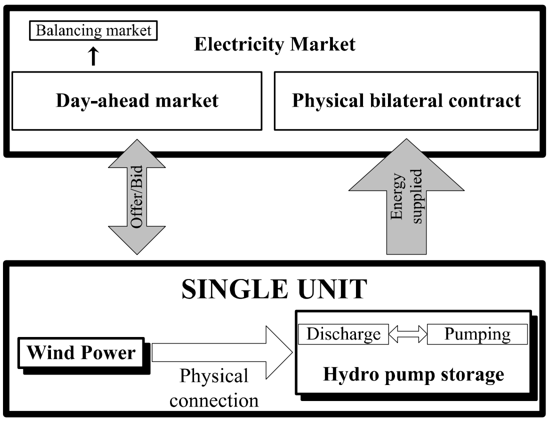

Fig. 1. Diagram of the offering strategy.

The problem is studied for several parameters of the PBC such as PBC prices and the minimum amount of energy sold in the PBC. Note that when the bilateral price is equal to zero, the problem is equivalent to operate only in the DM. The parametrization of the PBC allows knowing what could be the best strategy for the single power producer.

III. MATHEMATICAL FORMULATION

The offering strategy is modeled through stochastic programming, where the objective function maximizes the profits of offering the energy in the DM and through a PBC. The mixed integer linear model proposed is composed of the objective function and its constraints.

A. Objective Function

The objective function maximizes the profits of selling or purchasing energy in the DM and through a PBC including a measure of risk, the Conditional Value at Risk (*CVaR*). This function decides the optimal offer/bid (sale/purchase) of a wind farm and a hydro unit *i*, per period *t* for all scenarios *w*, depending on the water inflows to water reserves, DM prices, positive imbalance market prices, negative imbalance market prices, wind production, PBC price and the lower limit of the energy for the PBC. The hydro-pump power unit comprises two water reserves, defined by index *i*=1 (upper reserve) and *i*=2 (lower reserve). The hydro-pump power unit is in *i*=1, where the discharge is from *i*=1 (upper reserve) and the charge is from *i*=2 (lower reserve) as in [20]. These factors are parameters of the model. The objective function is defined as follows:

$$max \;\; (1-\beta)\cdot(PF)+\beta\cdot CVaR \qquad (1)$$

where

$$PF = I^{DA} + I^{Bil} - TC; \tag{2}$$

$$I^{DA} = \sum_{w} \rho_w \left[\sum_{t} \left(\lambda_{t,w} \cdot b^{DA}_{t,i=1} + \lambda^{+}_{t,w} \cdot \Delta^{+}_{t,i=1,w} \right) \right]; \tag{3}$$

$$I^{Bil} = \sum_{t} \lambda^{Bil} \cdot b^{Bil}_{t}; \tag{4}$$

$$\begin{aligned} TC = \sum_{w} \rho_w \Bigg[\sum_{t} \Big(& c^{H}_{i=1} \cdot (p_{t,i=1,w} + np_{t,i=1,w}) \\ & + c^{p}_{i=1} \cdot pr_{t,i=1,w} + c_{i=1} \cdot y_{t,i=1,w} \\ & + \lambda^{-}_{t,w} \cdot \Delta^{-}_{t,i=1,w} + c^{W} \cdot gw_{t,w} \Big) \Bigg]; \end{aligned} \tag{5}$$

$$CVaR = VaR - \frac{1}{1-\alpha} \sum_{w} \rho_w \cdot \eta_w. \tag{6}$$

As can be seen in (2), the profit PF is divided into two kinds of incomes: from the DM, I^{DA}, and, from the PBC, I^{Bil}. The incomes come from the DM (3), where the energy is sold in the DM and the positive imbalance, $\Delta^{+}_{t,i=1,w}$, is paid in the balancing market at a lower price, $\lambda^{+}_{t,w}$. When the energy is bought in the DM, the decision variable $b^{DA}_{t,i=1}$ is negative and variable $I^{DA}_{t,i=1,w}$ could be negative, thus this represents a cost. Also, the PBC income comes from the energy, b^{Bil}_{t}, sold in the PBC at the bilateral price, λ^{Bil} (4).

TC (5) is given by the total cost of charge and discharge of the hydro pump storage unit, start-up and shutdown hydro costs, wind generation cost, and the negative imbalance paid at the negative imbalance price.

CVaR is the mean of the generalized α-tail distribution as shown in (6).

B. Constraints

The constraints are classified into seven types: *CVaR* constraints, hydro power curve linearization constraints, hydro reservoir constraints, pumping constraints, wind-hydro interconnection constraints, energy offer constraints and imbalance constraints. The constraints are presented as follows.

1) CVaR Constraints: all profits are considered per period and scenario (7)–(9), as shown in (10).

$$I^{DA}_{t,i=1,w} = \lambda_{t,w} \cdot b^{DA}_{t,i=1} + \lambda^{+}_{t,w} \cdot \Delta^{+}_{t,i=1,w}; \tag{7}$$

$$I^{Bil}_{t} = \lambda^{Bil} \cdot b^{Bil}_{t}; \tag{8}$$

$$\begin{aligned} TC_{t,i=1,w} = {} & c^{H}_{i=1} \cdot (p_{t,i=1,w} + np_{t,i=1,w}) \\ & + c^{p}_{i=1} \cdot pr_{t,i=1,w} + c_{i=1} \cdot y_{t,i=1,w} \\ & + \lambda^{-}_{t,w} \cdot \Delta^{-}_{t,i=1,w} + c^{W} \cdot gw_{t,w}; \end{aligned} \tag{9}$$

$$PF_{t,i=1,w} = I^{DA}_{t,i=1,w} + I^{Bil}_{t} - TC_{t,i=1,w}; \tag{10}$$

Positive variable η_w is evaluated with respect to the profits per scenario, $\sum_t PF_{t,i=1,w}$ in (11), together with *VaR*, where the energy offering decisions in the DM, $b^{DA}_{t,i=1}$ and the energy sold in the PBC, b^{Bil}_{t}, change the value of *CVaR* depending on *VaR* calculated in (11) as depicted in Fig. 2.

$$-\left(\sum_{t} PF_{t,i=1,w} \right) + VaR - \eta_w \leq 0. \tag{11}$$

In [27] CVaR with a confidence level $\alpha \in]0,1[$ is defined as the mean of the generalized α-tail distribution as shown in Fig. 2.

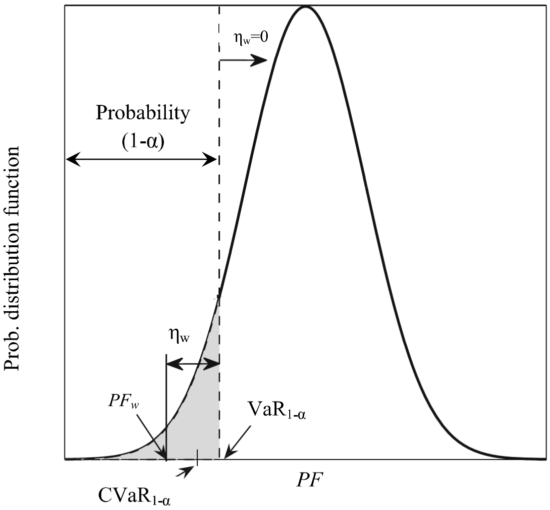

Fig. 2. Var & CVaR concepts.

2) Hydro Power Curve Linearization Constraints: The hydro power curve is linearized based on [7] and [20], where (12) is the maximum capacity in MW.

$$B0_{i=1} = porhoh_{i=1} + \sum_{i} umax_{l,i=1} \cdot rhoh_{l,i=1}. \tag{12}$$

Equation (13) is the discharge of hydro unit *i*, depending on the linearization of the hydro power curve.

$$u_{t,i=1,w} = \sum_{l} (ul_{t,i=1,w} + umin_{i=1} \cdot v_{t,i=1,w}). \tag{13}$$

The block limits of the linearized hydro power curve are given in equations (14)–(17).

$$ul_{l=1,t,i=1,w} \leq umax_{l=1,i=1} \cdot v_{t,i=1,w}; \tag{14}$$

$$ul_{l=1,t,i=1,w} \geq umax_{l=1,i=1} \cdot w_{l=1,t,i=1,w}; \tag{15}$$

$$ul_{l,i,t} \leq umax_{l,i} \cdot w_{l-1,t,i=1,w}; \tag{16}$$

$$ul_{l,i,t} \geq umax_{l,i} \cdot w_{l,t,i=1,w}. \tag{17}$$

Equations (18)–(20) decide which power curves are selected: the higher, the intermediate or the lower one, depending on the reservoir level.

$$d^{1}_{t,i,w} \geq d^{2}_{t,i,w}; \tag{18}$$

$$r_{t,i,w} \geq vc1_i \cdot (d^{1}_{t,i,w} - d^{2}_{t,i,w}) + vc2_i \cdot d^{2}_{t,i,w}; \tag{19}$$

$$\begin{aligned} r_{t,i,w} \leq {} & vc1_i \cdot (1 - d^{1}_{t,i,w}) + vc2_i \cdot (d^{1}_{t,i,w} - d^{2}_{t,i,w}) \\ & + Vmax_i \cdot d^{2}_{t,i,w}. \end{aligned} \tag{20}$$

Equations (21)–(26) decide the power production for all power curves. Variable $np_{t,i=1,w}$, is incorporated to determine the quantity of power that a hydro unit could produce to decrease the negative wind imbalance.

$$\begin{aligned} & p_{t,i=1,w} + np_{t,i=1,w} - porhol_{i=1} \cdot v_{t,i=1,w} \\ & - \sum_{l} (ul_{l,t,i=1,w} \cdot rhol_{l,i=1}) \\ & - B0_{i=1} \cdot (d^{1}_{t,i,w} + d^{2}_{t,i,w}) \leq 0; \end{aligned} \tag{21}$$

$$p_{t,i=1,w} + np_{t,i=1,w} - porhol_{i=1} \cdot v_{t,i=1,w}$$

$$- \sum_{l} (ul_{l,t,i=1,w} \cdot rhol_{l,i=1}) + B0_{i=1} \cdot (d^1_{t,i,w} + d^2_{t,i,w}) \geq 0; \quad (22)$$

$$p_{t,i=1,w} + np_{t,i=1,w} - porhom_{i=1} \cdot v_{t,i=1,w} - \sum_{l} (ul_{l,t,i=1,w} \cdot rhom_{l,i=1}) - B0_{i=1} \cdot (1 - d^1_{t,i,w} + d^2_{t,i,w}) \leq 0; \quad (23)$$

$$p_{t,i=1,w} + np_{t,i=1,w} - porhom_{i=1} \cdot v_{t,i=1,w} - \sum_{l} (ul_{l,t,i=1,w} \cdot rhom_{l,i=1}) + B0_{i=1} \cdot (1 - d^1_{t,i,w} + d^2_{t,i,w}) \geq 0; \quad (24)$$

$$p_{t,i=1,w} + np_{t,i=1,w} - porhoh_{i=1} \cdot v_{t,i=1,w} - \sum_{l} (ul_{l,t,i=1,w} \cdot rhoh_{l,i=1}) - B0_{i=1} \cdot (2 - d^1_{t,i,w} + d^2_{t,i,w}) \leq 0; \quad (25)$$

$$p_{t,i=1,w} + np_{t,i=1,w} - porhoh_{i=1} \cdot v_{t,i=1,w} - \sum_{l} (ul_{l,t,i=1,w} \cdot rhoh_{l,i=1}) + B0_{i=1} \cdot (2 - d^1_{t,i,w} + d^2_{t,i,w}) \geq 0. \quad (26)$$

Equation (27) represents the up/down hydro logic:

$$y_{t,i=1,w} - z_{t,i=1,w} = v_{t,i=1,w} - v_{t-1,i=1,w}. \quad (27)$$

Equations (28) and (29) are the maximum limits of hydro production and extra discharge for reducing the negative imbalance. Such maximum limits represent the maximum capacity. Moreover, binary variable $a_{t,i=1,w}$ can set the hydro production limit to be between the maximum capacity and zero. Meanwhile, $np_{t,i=1,w}$ variable is limited by the maximum hydro capacity minus the hydro production, being $np_{t,i=1,w}$ the maximum value when the hydro production is zero.

$$p_{t,i=1,w} \leq B0_{i=1} \cdot a_{t,i=1,w}; \quad (28)$$

$$np_{t,i=1,w} \leq B0_{i=1} \cdot a_{t,i=1,w} - p_{t,i=1,w}. \quad (29)$$

3) Hydro Reservoir Constraints: the balance of the reservoirs is modeled through (30), while (31) is the minimum reservoir needed to start the discharge of the hydro unit and (32) fixes the reservoir level at the end of the simulations. As a consequence of a time frame of 168 hours, the hydro discharges are limited. Hence, the hydro-pump power unit cannot discharge in all time frames more than 10% of the upper reserve at the beginning of the time frame.

$$r_{t,i,w} = r_{t-1,i,w} + if_{t,i,w} - cv \cdot u_{t,i,w} + cv \cdot u_{t-1,i-1,w} - cv \cdot s_{t,i,w} + cv \cdot s_{t-1,i-1,w} + cv \cdot wf_{t,i,w} - cv \cdot wf_{t,i-1,w}; \quad (30)$$

$$r_{t,i,w} \geq Vmin_i \cdot a_{t,i,w}; \quad (31)$$

$$r_{t=tp,i,w} \geq 0.9 \cdot r^{initial}_{t=0,i}. \quad (32)$$

4) Pumping Constraints: the pumping efficiency is represented in (33)–(35). Binary variable, $a_{t,i=1,w}$, is set to decide whether to generate or to pump by the hydro pump storage unit.

$$pr_{t,i=1,w} \leq (1 - a_{t,i=1,w}) \cdot ppm_{i=1}; \quad (33)$$

$$pn_{t,i=1,w} = pr_{t,i=1,w} \cdot eff; \quad (34)$$

$$wf_{t,i=1,w} = \frac{pn_{t,i=1,w}}{rhopp_{i=1}}. \quad (35)$$

5) Wind-Hydro Interconnection Constraints: equations (36)–(46) model the interconnection between the wind farm and the hydro unit. The interconnection can be used for reducing the wind energy imbalances when the energy is offered, or to buy less energy when there is a purchase of energy. Equation (36) is used when there is a energy offer.

$$\begin{gathered} if\ gw_{t,w} > b^+_{t,w} \\ ppwm_{t,i=1,w} \leq (gw_{t,w} - b^+_{t,w}) \cdot bd_{t,i=1} \\ else\ ppwm_{t,i=1,w} = 0. \end{gathered} \quad (36)$$

Equations (37)–(45) calculate the energy offering and the energy that could be pumped from the excess of wind power, reducing the positive imbalance. And in the case of a purchase, the energy from wind is used to reduce the energy bought.

$$ppw_{t,i=1,w} = -gw_{t,w} \cdot (1 - bd_{t,i=1}) + ppwm_{t,i=1,w}; \quad (37)$$

$$ppw^-_{t,i=1,w} \leq ppm_{i=1} \cdot (1 - bd_{t,i=1}); \quad (38)$$

$$ppw^+_{t,i=1,w} \leq ppm_{i=1} \cdot bd_{t,i=1}; \quad (39)$$

$$ppw^{\pm}_{t,i=1,w} = ppw^+_{t,i=1,w} - ppw^-_{t,i=1,w}; \quad (40)$$

$$ppw^{\pm}_{t,i=1,w} = ppw_{t,i=1,w}; \quad (41)$$

$$ppb_{t,i=1,w} \leq ppm_{i=1} \cdot (1 - bd_{t,i=1}) - ppw^-_{t,i=1,w}; \quad (42)$$

$$pp_{t,i=1,w} = ppw^+_{t,i=1,w} + ppw^-_{t,i=1,w} + ppb_{t,i=1,w}; \quad (43)$$

$$pp_{t,i=1,w} \leq ppm_{i=1} \cdot (1 - a_{t,i=1,w}); \quad (44)$$

$$pr_{t,i=1,w} = pp_{t,i=1,w}. \quad (45)$$

If the imbalance is negative (46), the reversible hydro power unit could produce more energy, depending on its capacity limit.

$$\begin{gathered} if\ gw_{t,w} < b^-_{t,w} \\ np_{t,i=1,w} \leq (b^-_{t,w} - gw_{t,w}) \cdot bd_{t,i=1} \\ else\ np_{t,i=1,w} = 0. \end{gathered} \quad (46)$$

6) Energy Offer Constraints: the limits of the energy that can be sold are shown in (47)–(50). Equations (51) and (52) evaluate where the energy generated is sold, to the DM or to the PBC. In addition, the offer/bid for the DM is limited in (53) and (54). The energy limits for the PBC are shown in (55) and (56). Finally, the offers in the DM and the energy sold through the PBC are evaluated in equations (57) and (58).

$$g_{t,w}^{DA} \leq Pmax \cdot bd_{t,i=1}; \tag{47}$$

$$g_{t}^{Bil} \leq Pmax \cdot bd_{t,i=1}; \tag{48}$$

$$P_{t,i=1,w}^{DA} \leq B0_{i=1} \cdot a_{t,i=1,w}; \tag{49}$$

$$P_{t,i=1}^{Bil} \leq B0_{i=1} \cdot a_{t,i=1,w}; \tag{50}$$

$$gw_{t,w} = g_{t,w}^{DA} + g_{t}^{Bil}; \tag{51}$$

$$p_{t,i=1,w} = P_{t,i=1,w}^{DA} + P_{t,i=1}^{Bil}; \tag{52}$$

$$b_{t,i=1}^{DA} \leq Pmax \cdot bd_{t,i=1} + P_{t,i=1,w}^{DA} - g_{t}^{Bil}; \tag{53}$$

$$\begin{aligned} b_{t,i=1}^{DA} &\geq 0 \cdot bd_{t,i=1} \\ &+ P_{t,i=1,w}^{DA} - ppm_{i=1} \cdot (1 - bd_{t,i=1}); \end{aligned} \tag{54}$$

$$b_{t}^{Bil} \leq UL^{Bil}; \tag{55}$$

$$b_{t}^{Bil} \geq LL^{Bil}; \tag{56}$$

$$b_{t,i=1}^{DA} + b_{t}^{Bil} \leq Pmax \cdot bd_{t,i=1} + p_{t,i=1,w}; \tag{57}$$

$$b_{t}^{Bil} = g_{t}^{Bil} + P_{t,i=1}^{Bil}. \tag{58}$$

The generators must produce all the energy sold to the PBC, so that the DM can absorb the volatility of wind power production together with the hydro pump storage unit, the DM being necessary and always used.

7) Imbalance Constraints: the limit of each kind of imbalance is fixed in (59) for a negative imbalance and in (60) for a positive imbalance.

$$0 \leq \Delta_{t,i=1,w}^{-} \leq (B0_{i=1} + Pmax) \cdot d_{t,i=1,w}; \tag{59}$$

$$0 \leq \Delta_{t,i=1,w}^{+} \leq (Pmax + ppm_{i=1}) \cdot (1 - d_{t,i=1,w}). \tag{60}$$

The excess (positive imbalance) or lack (negative imbalance) of energy is calculated in (61).

$$\begin{aligned} \Delta_{t,i=1,w} &= g_{t,w}^{DA} + P_{t,i=1,w}^{DA} + np_{t,i=1,w} \\ &- b_{t,i=1}^{DA} - ppb_{t,i=1,w} - ppw_{t,i=1,w}^{-} - ppw_{t,i=1,w}^{+}. \end{aligned} \tag{61}$$

Whether the imbalances are positive or negative is solved in (62).

$$\Delta_{t,i=1,w} = \Delta_{t,i=1,w}^{+} - \Delta_{t,i=1,w}^{-}. \tag{62}$$

IV. CASE STUDY

A. Input Data

The model is tested for a wind farm whose capacity is 50 MW and a hydro pump storage unit with a capacity of 28.62/35.77 MW of discharge/charge. The electricity market used to test the model is the Spanish electricity market [28].

The wind farm has 25 units of 2 MW situated in Navarre, Northern Spain. Two meteorological stations near the hypothetical wind farm provide wind speed data. hence, wind power is obtained through $P(v) = 0.5 \cdot c_p(v) \cdot \rho \cdot A \cdot v^3$, where v is the wind speed, $c_p(v)$ is the overall efficiency of the wind turbine as a function of wind speed, A is the area swept by the wind turbine rotor and ρ is the air density.

The hydro pump storage unit has a capacity of 28.62 MW of discharge and 35.77 MW of charge and can accumulate energy in form of potential energy with 93% of efficiency. The hydro pump storage unit is composed of two reservoirs, upper and lower. The initial reservoirs are: i) the upper reservoir $r_{t=0,1}^{initial} = 100$ Hm^3 and ii) the lower reservoir $r_{t=0,2}^{initial} = 80$ Hm^3. The case study is tested for 168 hours. The production costs [29] are €17/MWh for wind generation, €10/MWh for discharge and €2/MWh for charging the hydro pump storage unit. The confidence level α is fixed at 0.9 and $\beta \in (0, 1)$. The single unit changes its behavior with risk aversion, where the values of β are 0.1, 0.3, 0.5, 0.7 0.9.

B. Scenarios

The scenarios are combined forming a tree. The tree is formed by: i) 4 scenarios of water inflows for the 2 reservoirs, ii) 10 scenarios for market prices [28], positive imbalance market prices and negative imbalance market prices [30], and iii) 14 scenarios for wind generation, upper limit of the wind farm power offer and lower limit of the wind farm energy offer as shown in Fig. 3. The total number of scenarios studied is: 4·10·14 = 560. A scenario tree for the second stage presented in Fig. 3 is generated for each hour of the first stage.

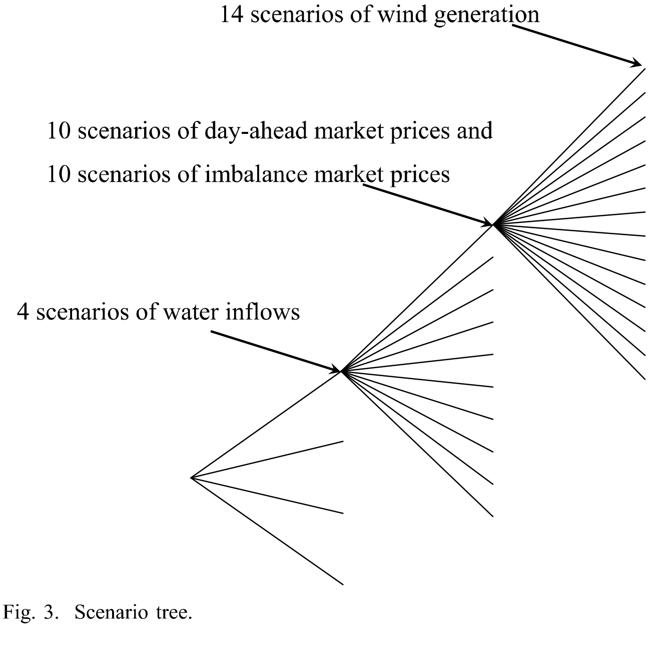

Fig. 3. Scenario tree.

Water inflow scenarios come from a Normal distribution. The market prices and imbalance market prices have been obtained using 24 Normal distributions, one per hour for January and February of 2012 and 2013, and for each price 10 samples of these distributions are selected. Wind speed scenarios have been obtained using 24 Weibull distributions, one per hour for January and February of 2013, with 14 samples of these distributions. The effect of the PBC is evaluated for different prices, λ^{Bil}, such as 0, 20, 40, 60 and €80/MWh. In addition to this, the upper limit of the energy sold, UL^{Bil}, is 78.62 MWh and the lower limit, LL^{Bil}, ranges from 0, 5 and 10 MWh per hour. As a consequence of wind uncertainty, the mathematical problem is infeasible when LL^{Bil} is higher than 10 MWh. However, if the hydro reservoirs are at the maximum capacities, this limit LL^{Bil} could be 13 MWh, but the test case is only run for the hydro reservoirs $r_{t=0,1}^{initial} = 100$ Hm^3 and $r_{t=0,2}^{initial} = 80$ Hm^3. The main input and output data needed to test the stochastic programming model are shown in Fig. 4.

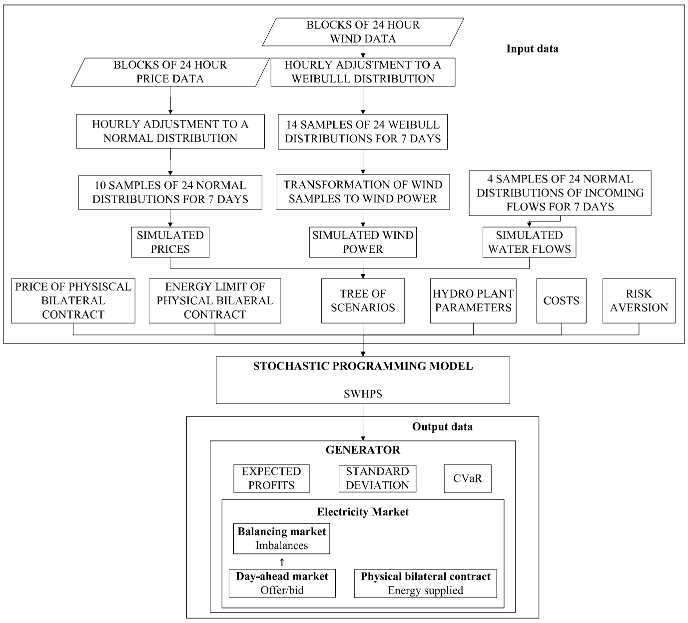

Fig. 4. Diagram of the input and output data of the simulation.

V. RESULTS

This section introduces the main results of the simulations used to evaluate the model proposed in Section III.

A. Behavior of the SWHPS for β =0.5 and λ^{Bil} =€40/MWh and €60/MWh

The main prices are shown in Fig. 5 for one scenario. The offers in the DM and the energy sold in the PBC for λ^{Bil} =€40/MWh and €60/MWh are presented in Fig. 6 and the wind generation in Fig. 7. Also, the wind imbalances are presented in Fig. 7 for λ^{Bil} =€40/MWh and €60/MWh with β =0.5 in one scenario.

The net pumping $pn_{t,i,w}$ is different from zero in only 12 out of 560 scenarios and pumping occurs at the 146th hour or the 148th hour, because the prices are lower than in previous hours and the reservoir level in hour 168 has to be 90% of the initial reservoir level. The pumped energy is 22.44 MWh at hour 146 and 17.65 MWh at hour 148. These pumping results are for λ^{Bil} =€40/MWh, LL^{Bil} =0 MWh, and β =0.5.

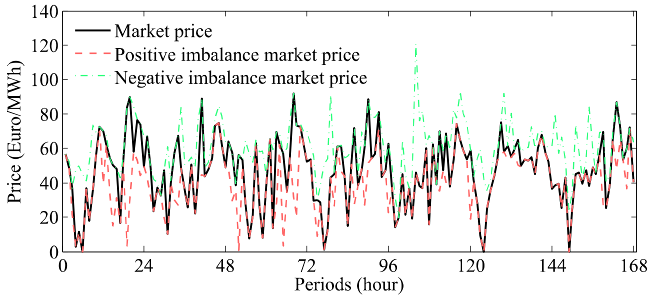

Fig. 5. Market price, positive imbalance market price and negative imbalance market price for one scenario.

The energy offered in the DM and the PBC are compared in Fig. 6. When the price of the PBC is higher than the price of the DM, $\lambda^{Bil} > \lambda_{t,w}$, the generation is sent to the PBC. Hence, for a λ^{Bil} =€60/MWh, the generator sells more energy in the PBC and reduces the offering to the DM.

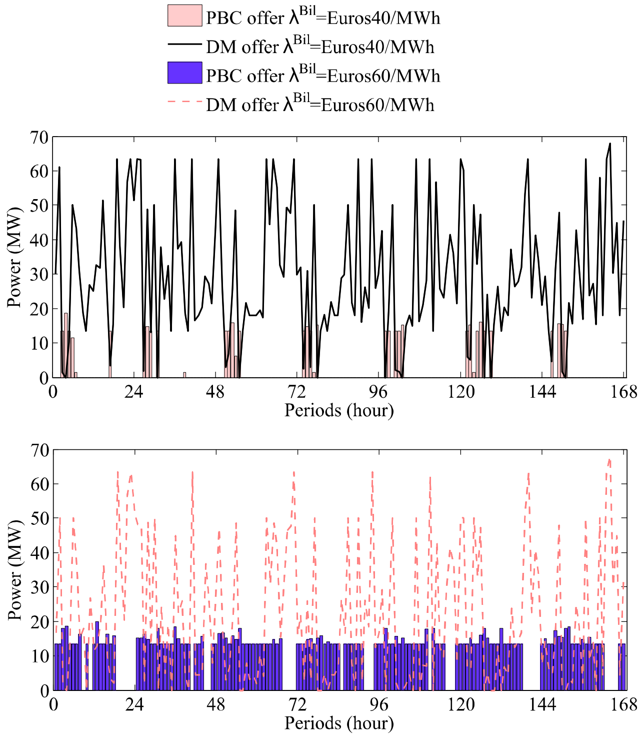

Fig. 6. Energy offered in the DM and sent to PBC for λ^{Bil} =€40/MWh, λ^{Bil} =€60/MWh, LL^{Bil} =0 MWh and β =0.5, in one scenario.

B. Risk aversion of the SWHPS

The main results are the expected profits, *CVaR*, and the standard deviation of the expected profits from the offering of the SWHPS in the DM market and the energy sold in the PBC, including imbalances, as shown in Figs. 8-12.

Higher profits imply lower *CVaRs*. λ^{Bil} has an effect on profits creating different levels of them. Every level created per λ^{Bil} includes all values of β. The SWHPS sells energy in

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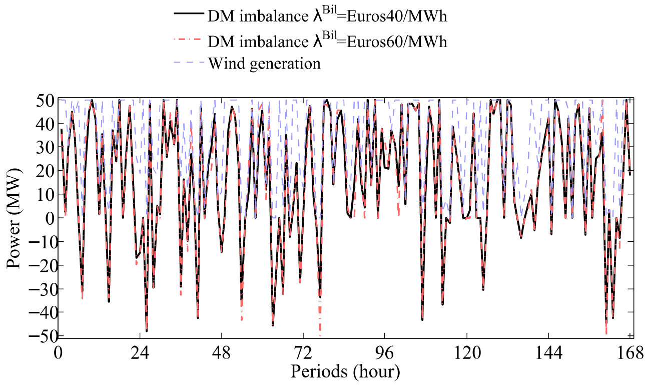

Fig. 7. Wind generation and imbalances in the DM for λ^{Bil} =€40/MWh, λ^{Bil} =€60/MWh, LL^{Bil} =0 MWh and β =0.5, in one scenario.

the PBC when λ^{Bil} >€20/MWh and LL^{Bil} is zero or higher. Also, the profits for $\lambda^{Bil} \in [20, 60]$ range from €260000 to €180000. High values of λ^{Bil} reduce the differences between profits for several values of LL^{Bil}. The difference between profits and *CVaR* for extreme β values, 0.9 and 0.1, for all the energy limits of the PBC, LL^{Bil}, are approximately €10000 for profits and *CVaR*. Also, profits vs. *CVaR* for λ^{Bil} =€80/MWh have the same values for all the energy limits of the PBC, LL^{Bil}. That effect is due to the high price of the PBC, the PBC being more profitable for the generator than the DM, hence, sending the maximum amount of energy to the PBC. The amount of energy is higher than or equal to the maximum limit, LL^{Bil} =10 MWh.

The expected profit vs. standard deviation presented in Fig. 8 shows the behavior of the profits. Higher profits mean higher standard deviations. An important issue is the influence of λ^{Bil} on the evolution of the standard deviation. For λ^{Bil} =€40/MWh, the standard deviation increases when LL^{Bil} is lower, together with having higher profits. However, when λ^{Bil} =€60/MWh, the standard deviation decreases when LL^{Bil} is lower, together with having higher profits, as a consequence of the increased participation in the PBC shown in Fig. 6.

The energy limit of the PBC affects the profits considerably, showing that the producer and the retailer could negotiate the contract for the range of PBC prices shown in Fig. 8.

In Fig. 9 it can be observed that the DM offer is reduced when the values of β increase. Fig. 10 presents the energy sold in the PBC, where the energy has not many variations with respect to the risk aversion because the PBC has no uncertainty. Then, the risk-hedging strategy does not affect the PBC to a large degree. Comparing the results for λ^{Bil}=€40/MWh and lower β values (no aversion to risk) in Fig. 10, it can be observed that the producer reduces the energy in the PBC, increasing the profits with the volatility of the DM, rising the standard deviation of the profits. When LL^{Bil} is increased, the standard deviation of the profits is reduced, where the opposite effect occurs for λ^{Bil}=€60/MWh. The previous effect for λ^{Bil}=€60/MWh is due to the higher profitability of the PBC, and, as a consequence, for lower values of β, the participation in the PBC is reduced.

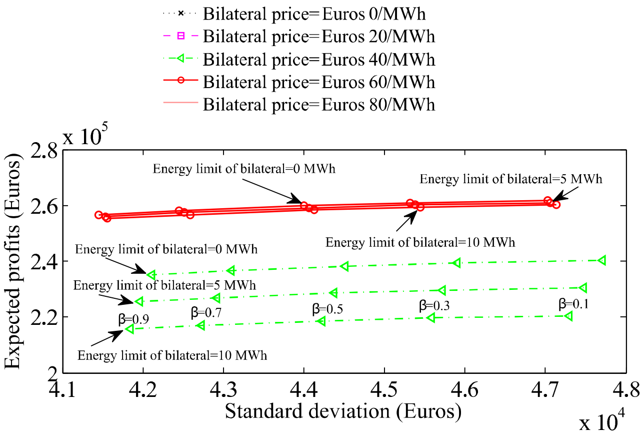

Fig. 8. Expected profits and standard deviation of the expected profits for λ^{Bil} =€40/MWh and €60/MWh, and for each LL^{Bil} and β values.

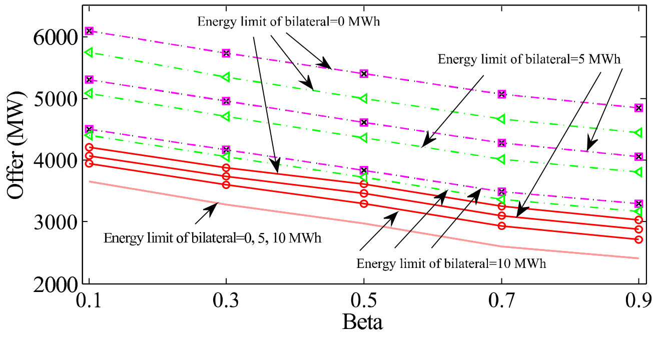

Fig. 9. DM offer for each λ^{Bil}, LL^{Bil} and β values.

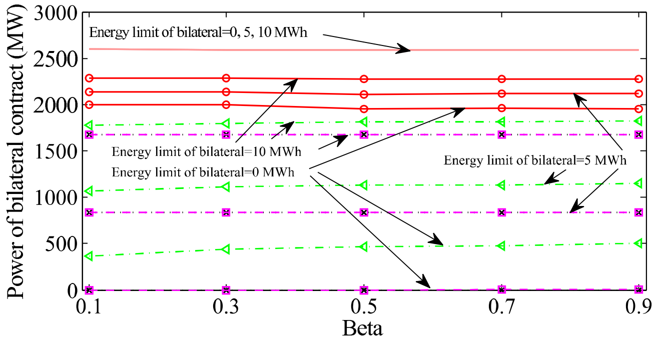

Fig. 10. Energy sold in the PBC for each λ^{Bil}, LL^{Bil} and β values.

Moreover, a risk-averse producer prefers to reduce the energy offer in the DM, reducing the volatility of its profits. So the imbalances presented in Fig. 11 and Fig. 12, are closely related to the energy offer, the possible negative imbalance being lower and the possible positive imbalance being higher for higher values of β, because the negative and positive imbalances represent costs and revenues, respectively. Hence, higher offers involve higher profits associated with higher risks (standard deviations), furthermore, a high offer increases the probability of having a negative imbalance and reduce the probability of the positive imbalance.

The model is programmed in GAMS [31] with CPLEX solver and using MATLAB [32] as interface between the model and data input/output. The simulations were made in a computer with 2 processors at 3.10 GHz and 256 GB of RAM which CPU time simulation was 4 hours.

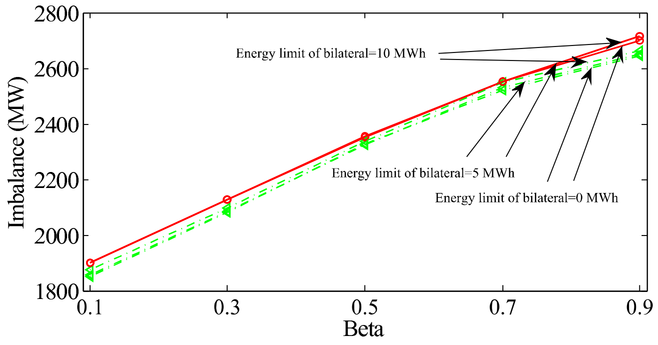

Fig. 11. Positive imbalances for λ^{Bil} =€40/MWh and €60/MWh, and for each LL^{Bil} and β values.

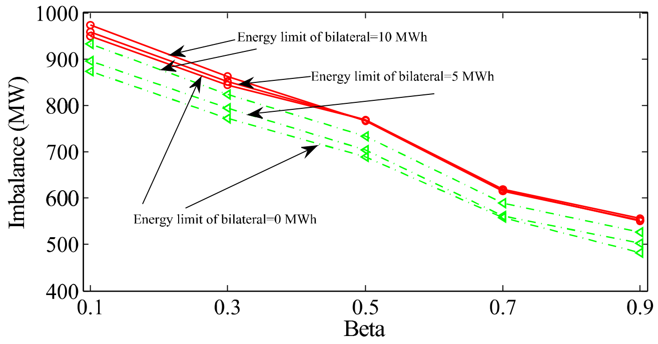

Fig. 12. Negative imbalances for λ^{Bil} =€40/MWh and €60/MWh, and for each LL^{Bil} and β values.

VI. DISCUSSION OF THE RESULTS

This section is divided into three parts to describe the main behavior regarding i) the offer in the DM, ii) the energy supplied in the PBC, and iii) the risk-hedging behavior.

A. Offering in the Day-ahead Market

The offer/bid is a decision in the model, where this variable depends on wind generation scenarios, market prices and imbalance market prices.

The offer in the DM is higher when the market price is higher than the PBC price. The offering shows different values related to the price of the PBC, as shown in Fig. 8, where the standard deviation of the profit changes having the same β value for several lower limits of the energy sold in the PBC due to the relation between the PBC and DM prices. In this way, the offer shows that, if there is more energy offered, this increases the probability of having more negative than positive imbalances and, when the offer is low, the opposite happens.

B. Energy Supplied in the Physical Bilateral Contract

The generator is able to bargain for better conditions in the PBC after looking at the results of Section V.

Hereby, the main conclusions about the PBC are related to the importance of the PBC energy limits due to the volatility of wind generation and to compensate the problem of supplying more energy (increasing the lower energy limit). The SWHPS generator increases the hydro discharge and, due to that, the PBC price should be higher, i.e., there is an extra payment as a consequence of reducing uncertainty. Furthermore, a higher PBC price reduces the risk of the profits (lower standard deviation of the profits) as shown in Fig. 8 because more energy is sold in the PBC at a constant price, decreasing the participation in the DM (see Fig. 9). However, the participation in the DM is necessary to compensate for the volatility of the generation as presented in Fig. 6.

Therefore, the SWHPS generator hopes for high prices in the bilateral contract and the specific strategy to negotiate the price of the PBC is done through the increase of the lower energy limit of the PBC.

C. Risk-hedging Behavior

The influence of risk aversion in the profit is low (Fig. 8), whose profit and standard deviation change within a small range. The energy offered in the DM affects the offering for one week by decreasing in more than 1000 MW the energy offered, as shown in Fig. 9. The reduction of the energy offered is due to the increase of the CVaR, where a higher CVaR is more likely for high values of β. A high value of the CVaR is obtained by decreasing the energy offered, i.e., a higher CVaR produces lower offers, hence, lower negative imbalances (costs) and higher positive imbalances (incomes) are likely to occur as was presented at the beginning of Section V-B and Figs. 9-12.

Another issue is risk hedging in the PBC, where the influence of risk aversion to make the decision in the PBC is very low, as shown in Fig. 10 owing to having a constant price for all periods.

VII. CONCLUSIONS

This paper has presented a new application of stochastic programming for a SWHPS unit that sells its energy in the DM and through a PBC, accounting for wind uncertainty in the short-term and considering risk aversion. The main conclusions are presented as follows:

- A higher PBC energy limit (LL^{Bil}) needs a higher PBC price (λ^{Bil}) to obtain similar profits, because the energy is forced to be sent to the PBC when DM prices are higher than the PBC price.
- A higher PBC price (λ^{Bil}) increases the standard deviation of the profits when the PBC energy limit (LL^{Bil}) is increased; whilst, for a lower λ^{Bil}, the standard deviation of the expected profits is reduced when LL^{Bil} is increased.
- The producer should negotiate with the retailer to reduce the PBC energy limit (LL^{Bil}) and increase the PBC price (λ^{Bil}), where the retailer would increase LL^{Bil} and reduce λ^{Bil}. The bargaining process about the PBC price depends on DM prices and their volatilities.

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- The demand side of the PBC party could bargain using the fact that the generator reduces the profit risk (standard deviation) with a high participation in the PBC.

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