Opportunities for Energy Storage Associated to Wind Farms with Guaranteed Feed-in Tariffs in the Present French Law

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Abstract - This paper considers a wind farm with an obligation to purchase at a fixed feed-in tariff. The wind farm production must always stay below an upper limit existing for the obligation to purchase energy. An energy storage system associated to the studied wind farm allows to increase the installed capacity while maintaining the same upper limit for the wind farm production power. This operation may enhance the wind farm availability and present an added value to the project by increasing its energy sales. The net present value of the project is calculated as a function of the energy storage system characteristics and the wind farm installed capacity.

Keywords - Energy storage, wind energy, batteries, power system economics.

1 Introduction

THE European Union has adopted a directive on the promotion of electricity produced from renewable energy sources (RES) in the internal electricity market. It sets national indicative targets for future consumption of electricity produced from RES. Particularly, France has set its own national targets concerning wind energy production : to pass from 25 MW (1999) to minimum 3000 MW (2010). Economical procedures are to be implemented in order to reach the above-mentioned targets; one of the main supporting mechanisms for the RES technologies supplying energy to the grid is the “Guaranteed Feed-in Prices”; it includes the obligation to purchase energy from renewable sources at a specified price [1].

This study considers an existing wind farm in France with an installed capacity of 12 MW, the upper production limit for wind farms with obligation to purchase [2]. So as a renewable energy producer, this wind farm is provided granted outlets and prices and utilities have to purchase this electricity at a fixed price (feed-in prices).

In the present study it is supposed that wind energy producers with feed-in tariff can have wind installation beyond 12 MW while keeping their production power below this limit. Energy produced exceeding the above-mentioned limit is a non-distributed one. Installing an energy storage system (ESS) within the wind farm may be a solution to storing a part of this energy and then delivering it later to the power system when the wind farm production is less than 12 MW (fig.1).

In fact, recent developments and advances in energy storage and power electronics technologies are making the use of energy storage a potentially viable solution for modern power applications, allowing to operate the system in a more flexible, controllable manner [3].

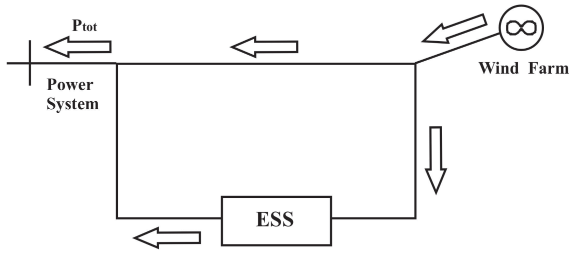

Figure 1: Energy storage installed within a farm wind

This study presents a methodology to explore the effect of increasing the wind farm availability by defining optimal characteristics and control strategy to the energy storage system installed within the wind farm.

Increasing a wind farm production capacity while maintaining the upper limit for distributed energy by installing energy storage system may present an added value to the wind energy producer.

So for each energy storage system installed and depending of its characteristics and the wind farm capacity installed the net present value (NPV) is determined. Upon this value, the economical performance of the system is evaluated.

Energy storage technologies simulated in this study are redox-flow VRB (Vanadium Redox batteries) and classical Lead-acid batteries. For the installed energy storage system, the optimal control strategy and optimal characteristics are determined in simulations in order to maximize the net present value of the project.

2 Wind farm economic model

2.1 Cost considerations

In order to establish an economical analysis, one must consider the wind farm capital, operating and maintenance costs:

- the wind farm capital cost is taken on the basis of 800$/kW [4]
- operation and maintenance costs are estimated as 1.5%/year of total capital cost [4]
- network access invoice is calculated as 0.18$ for each injected MWh [5]

The wind farm total present cost is called C_{WF} in this paper.

2.2 *Wind farm availability*

The studied wind farm has an installed capacity P_{ins}=12 MW. Its maximal production power is then Pe_{max}=P_{ins}. The wind farm availability D (hours) is defined as:

$$D = \frac{E_{an}}{Pe_{max}} \qquad (1)$$

Where E_{an} is the annually produced energy by the studied wind farm and Pe_{max}=12 MW is the maximal production power for a wind farm with the obligation to purchase.

In the present French law, during the first 5 years of the purchase contract wind energy is sold at 8.38 cents/kWh, then for the next 10 years the purchase tariff (cents/kWh) becomes a deceasing function of the wind farm availability (table 1 and fig.2) [2]. This structure is probably chosen to reach a well distributed wind energy production park between the different regions whatever was their wind level.

Table 1: Wind farm purchase tariff

D (hours)	**Tariff (first 5 years)**	**Tariff (next 10 years)**
$\leq$ 2000	8.38	8.38
2000< D < 2600	8.38	Linear interpolation
2600	8.38	5.95
2600< D < 3600	8.38	Linear interpolation
$\geq$ 3600	8.38	3.05

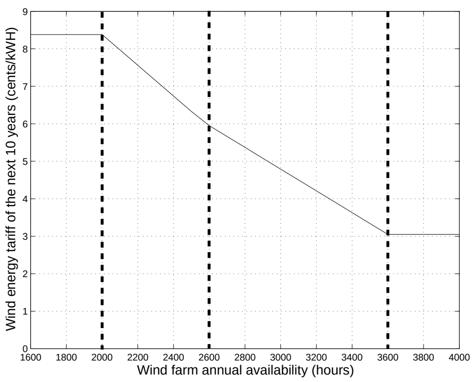

Figure 2: Wind energy tariff of the next 10 years (cents/kWh) in France as a function of the wind farm annual availability (hours)

For the wind farm studied in this paper, the annual production curve data show an availability of 2860 hours before increasing its production capacity and installing ESS; this value will define the energy purchase tariff over the 15-year contract:

$$p_0 = \begin{cases} 8.38 \text{ cents/kWh} & \text{years : 1 to 5} \\ 5.20 \text{ cents/kWh} & \text{years : 6 to 15} \end{cases}$$

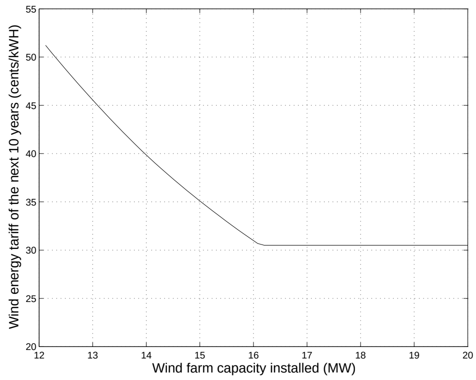

Figure 3: Wind energy tariff of the next 10 years (cents/kWh) as a function of the studied wind farm capacity (MW)

3 ESS model and control strategy

3.1 *ESS mathematical model*

The ESS state determination is crucial at each stage of the current study. Thus, the energy stored in the ESS is used as the state variable [6], the power output of the ESS can be calculated as the difference between stored energies of two consecutive stages [7]. Time stages used are all of half an hour, so all of the curves considered this study are defined with 8760(hours) $\times 2 = 17520$ values [8]. Energy stored in the storage device is expressed as:
When the ESS is charging ($P_j < 0$):

$$E_{j+1} = E_j - P_j \times \text{(1/2 hour)} \qquad (2)$$

And when the ESS is discharging ($P_j > 0$):

$$E_{j+1} = E_j - P_j/\eta \times \text{(1/2 hour)} \qquad (3)$$

Where η is the energy storage system efficiency [9].

The ESS will be functioning under $C/4$ discharge regime in order to avoid efficiency and lifespan degradation [10]; therefore the following relationship between ESS characteristics (P_{max}, W_{max}) is defined such as:

$$P_{max} = \frac{W_{max}}{4} \qquad (4)$$

3.2 *Cost considerations*

In order to establish an economical analysis, one must consider the ESS capital, operating and maintenance costs and parameters of which they depend, and energy purchase costs.

3.2.1 *ESS capital cost*

Energy storage system capital cost $C_{capital}$ is defined as a function of two main parts. One is related to the storable energy; the other depends on the peak power that the storage must deliver and is controlled by the charge/discharge control system according to the demand requirements. Therefore, the ESS capital cost will be expressed as [7], [11]:

$$C_{capital} = C_P P_{max} + C_W W_{max} \qquad (5)$$

Where P_{max} (kW) and W_{max} (kWh) are ESS power and energy capacities and their specific costs C_P ($/kW) and C_W ($/kWh).

3.2.2 ESS operating and maintenance cost

Energy storage annual operating and maintenance cost C_{OM} (equation 6) is defined as a function of two main parts: a fixed one related to the ESS rated power and a variable part depending on its annual discharged energy.

$$C_{OM} = (C_{Mf} P_{max} + C_{Mv} W_{annual}) \qquad (6)$$

Where C_{Mf} ($/kW/year) and C_{Mv} ($/kWh) are fixed and variable operating and maintenance specific costs and W_{annual} (kWh/year) is ESS annual discharged energy.

The net present value of operating and maintenance cost over the ESS lifespan is expressed as $NPV(C_{OM})$.

For studied redox-flow battery technologies, technical and economical characteristics considered in this study [12] are presented in table 2.

Table 2: Battery technical and economical data [12]

Technologies	VRB	Lead-acid
C_P **($/kW)**	426	0
C_W **($/kWh)**	100	150
C_{Mf} **($/kW/year)**	9	9
C_{Mv} **($/kWh/year)**	0	0
Efficiency %	70	85
Lifespan (yrs)	15	15
Nbr. of cycles 80%	15000	1500
Nbr. of cycles 40%	15000	4000

3.3 ESS control strategy

In addition to the fact that wind farm production power must always stay below the 12 MW obligation-to-purchase limit (French law), the wind farm operator must follow the curtailment schedule respecting the safety requirements defined by the network operator.

At each time stage i, the ESS must be controlled such as the global production of the association "ESS/wind farm" stays below a limit P_{lim} given by the curtailment schedule :

$$P_i + Pe_i \leq P_{lim_i} \qquad (7)$$

Where P_i is the ESS production power at time stage i, Pe_i the wind farm production power and P_{lim_i} the upper limit for total production power. So the ESS control strategy will be such as 4:

- to store wind energy when the production power exceeds P_{lim},
- and to discharge the stored energy with respect to the condition of inequality 7.

4 Economic assessment

The main goal of a financial proforma analysis is to define and calculate the project net present value (NPV). This NPV is determined through an economical study (proforma analysis) over the project lifespan and considering inflation and discount rates, taxes, etc.:

1. S is the net present value of total wind farm energy sales
2. $OM = S - (O\&M\ cost)$ is the operating margin
3. $OP = OM - D$ is the operating profit where D is the depreciation
4. $NP = OP - tax$ is the net profit
5. $CF = NP + D$ is the project cash flow
6. $NPV = CF - (Investment\ cost)$ is the project net present value to maximize

The depreciation ratio α and the tax rate k are defined as:

$$\alpha = \frac{D}{C_{capital}} \qquad (8)$$

$$k = \frac{tax}{OP} \qquad (9)$$

Considering α and k definitions, a detailed expression of NPV can now be written as:

- before installing energy storage system:

$$\begin{aligned} NPV_0 &= (1-k)OM_0 - (1-\alpha k)C_{inv0} \\ &= (1-k)OM_0 - (1-\alpha k)C_{WF0} \end{aligned} \qquad (10)$$

- after increasing the wind farm production capacity and installing energy storage system:

$$\begin{aligned} NPV &= (1-k)OM - (1-\alpha k)C_{inv} \\ &= (1-k)OM - (1-\alpha k)(C_{WF} + C_{capital}) \end{aligned} \qquad (11)$$

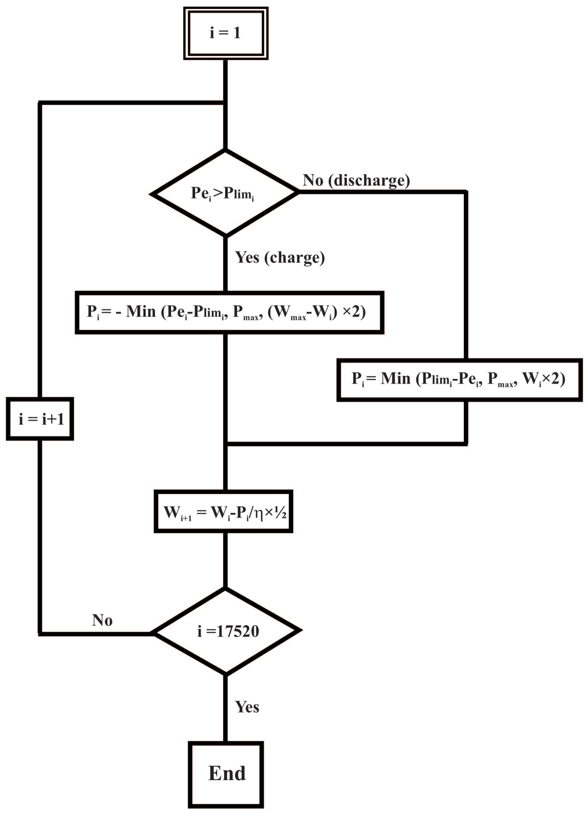

Figure 4: Energy storage system control strategy

5 Simulations

This study starts with an existing wind farm in France of 12 MW production capacity. Gradually, the wind farm capacity is increased and a corresponding ESS is installed within the wind farm (fig.1). The project financial lifespan is 15 years; therefore, simulations in this study consider replacements of storage elements with less than 15 years lifespan.

A one-week ESS (example : 6MW/24MWh VRB system) production curve is shown in fig.5.

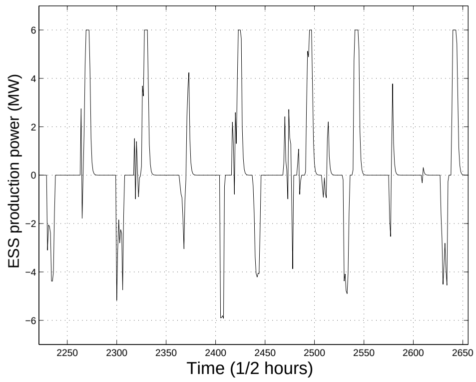

Figure 5: Example of ESS one-week production curve

Fig.6 shows the corresponding wind farm production curve before and after installing VRB energy storage system.

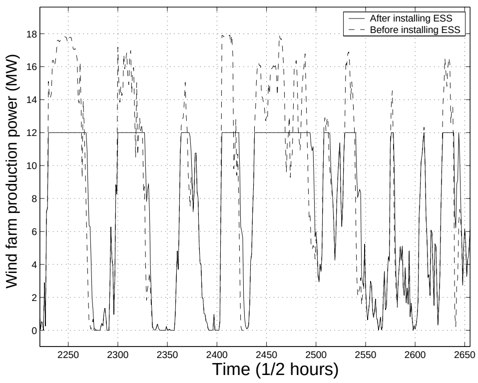

Figure 6: Wind farm production curve before and after installing ESS

The following sections present results obtained by simulating energy storage technologies (section 1) associated to the studied wind farm.

5.1 VRB battery installation

Technico-economical data concerning VRB batteries are taken from table 2. Simulations give the following results:

- the wind farm annual availability in fig.7,

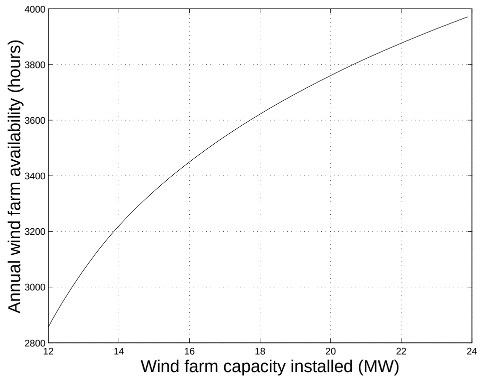

Figure 7: Annual availability for the wind farm with VRB batteries

- the investment costs of ESS and the wind farm additional capacity in fig.8,

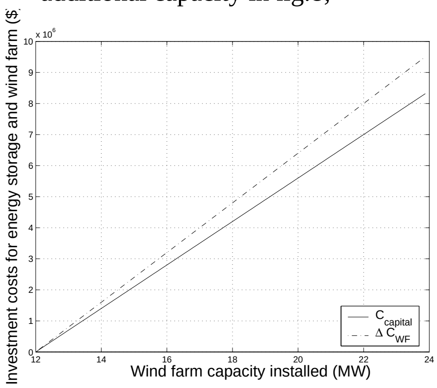

Figure 8: Investment costs with VRB batteries

5.2 Lead-acid battery installation

Technico-economical data concerning lead-acid batteries are taken from table 2. Simulations give the following results :

- the wind farm annual availability in fig.9,

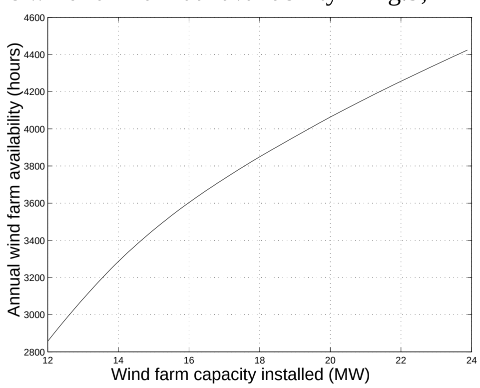

Figure 9: Annual availability for the wind farm with lead-acid batteries

- the investment costs of ESS and the wind farm additional capacity in fig.10,

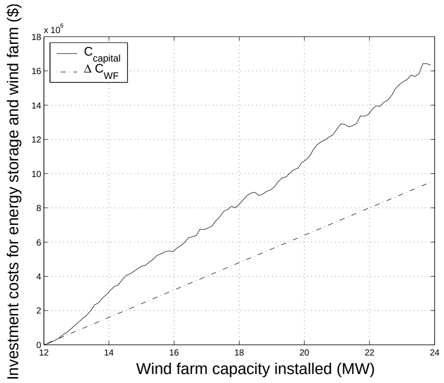

Figure 10: Investment costs with lead-acid batteries

6 Result analysis

By increasing the production capacity installed of the farm wind and associating to it an adapted ESS, fig.7 and fig.9 show the increase of the annual availability D reaching higher values with lead-acid batteries than VRB. This is due to the higher efficiency of lead-acid technology (85%) instead of 70% for VRB with higher stored energy losses.

Replacements of the lead-acid battery system due to its low lifespan cause an increase of its investment cost over the study period. For this reason the project net present value decrease much faster than with VRB system.

Moreover, with both technologies the project net present value is lower than it was before installing any storage system.

7 Conclusions

The goal of this study is to show that there are potential applications for energy storage in guaranteed feed-in tariff situations, especially for increasing the wind energy sales in the project. This possibility is analyzed by a comparative method to evaluate economical performances of two energy storage technologies.

Considering the obtained results, no benefit can be made by increasing the wind farm production capacity beyond 12 MW and installing energy storage systems within it in the present situation:

- The wind energy tariff decreasing along with the increase of the wind farm availability is the main cause for the project non-profitability.

- The heavy investment to be made in reinforcing the wind farm and installing the energy storage system is much higher than the increase in the wind farm sales. All those drawbacks are mainly due to the high values of specific costs for the wind farm and the energy storage system.

In the near future with progressive steps done in research and development for energy storage technologies and wind energy production techniques, storage prices are expected to decrease due to massive production of those systems with high scale installations. This fact would probably cause a positive effect on installing storage systems within wind farms.

Moreover, in other countries where different wind energy tariffs are considered this study using new data for storage elements and other juridical frames defining wind energy tariffs may give positive results and prove the profitability of installing energy storage systems within wind farms with guaranteed feed-in tariffs .

8 Acknowledgement

This paper describes work carried out in the context of ENERGIE project at SUPELEC thanks to the supporting collaboration of "Electricity of France" http://www.supelec.fr/ecole/eei/energie

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