Optimization and Technical-Economical Viability for the Integration of Renewable Energies into Pumping Stations

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Abstract.

The wind power energy, in addition to the problem related to its randomness, has the disadvantage that it needs a high electrical infrastructure. Nevertheless, if it is considered its integration with other systems, sharing part of the infrastructure, the cost of installation diminishes and its efficiency increases. In this paper it will be presented a method for studing the combination of a large pumping station for irrigation with renewable power supports, it will be explained the economical and energetic balances for evaluating the cost of the facilities, and it will be presented some results about one analysed case.

Key words

Integration of renewable energy resources, pumping stations, technical-economical viability.

1. Introduction

The 70% of the energy consumed in Spain is imported, which shows a high dependency. One of the objectives of the Spanish policy is to increase the diversification of the power sources and the participation of the renewable energies, and to foment the saving and rational use of the energy, with more robust electrical systems. Using autochthonous renewable resources, power dependency and environmental effects are reduced.

On the other hand, the electrical grid has been conceived for the transmission of energy from the great electrical power stations to the consumption places. The increasing demand of energy implies the necessity to build new generation power plants and to raise the capacity of the electrical grid; this supposes economic problems as much as environmental effects. In this topic distributed generation systems offers a solution to this problem [3,8].

The concept of distributed generation is related to a group of low power energy productors, connected to the grid, located near the consumption points, in contrast to the great power stations which are far away from consumers.

Moreover, distributed generation with integration of renewable sources contributes with technical and economical advantages, such as improvement of the voltage levels, operation and stability of the system, better quality of wave, increased grid capacity to solve pick demands, reduction of the investments to increase the power in the existing systems of generation. Indeed, in some locations the cost of electricity is prohibitive, and self-generation is the only solution [11].

It is also interesting to consider the random character of some renewable sources, which implies the necessity to integrate storage systems assuring the continuity in the electrical energy supply.

Considering all the factors previously commented, in the present paper it is shown the study of a system with the integration of wind and hydroelectric renewable sources, which incorporates a storage system, different from the classic batteries or fuel cells, which is a pumping facility with a water reservoir. This application allows the development of rural areas with wind and water resources.

In this paper an analysis for the optimization of an integrated solution is presented. This solution implies the integration of wind power and hydraulic generation system on pumping facilities. This paper is organised as follows: in point 2 the proposal system is presented, in point 3 the optimization analysis is briefly developed, a computer for automatic calculation is shown in the fourth point, and in fifth point a facility is analysed.

2. Integration of renewable energies in pumping stations

There are many proposals for the integration of renewable resources, such us wind energy, solar or bio-diesel, mainly, in order supply the electrical necessities in rural and remote areas [2, 11]. In some cases, the wind support has been applied used to supply, entirely or almost partially, the pumping energy needs. Sometimes, water is used for irrigations purposes [7, 9, 10], and others for hydroelectric production [6, 8], isolated or connected to the grid. In this paper, both solutions are combined: irrigation and hydroelectric production.

Energetic and economical optimization of these systems have been analyzed in several ways [4, 5, 6, 9], but the sizing of the facilities are not clearly explained, so the costs are not well defined. The solution proposed in this paper optimizes the size of the subsystems of the whole facility: water pumping, hydroelectric generation system and wind power system, considering the investment and operating costs, irrigation needs, and efficient use of energy.

Moreover, the proposed system can be connected to the grid or isolated. The first one can be seen in figure 1, and the second in figure 2.

If the system is connected to the grid, the wind energy is used to reduce the electric consumption from the grid. If the water reservoir is not full, wind energy is used to raise more water, ever the irrigation need is satisfied. In this way, wind power is storaged in hydroelectric form. If it is no necessary to pump water and there is enough water in the reservoir, it is used to generate hydroelectric energy.

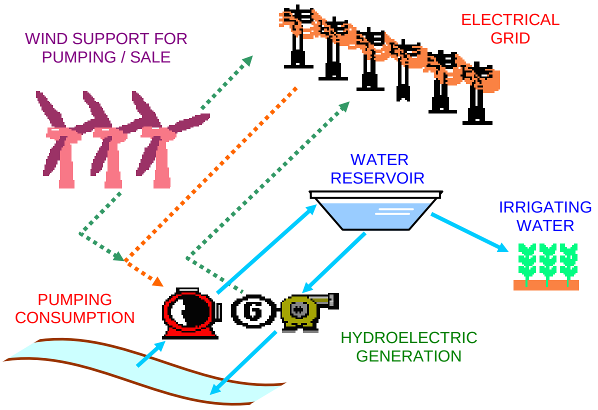


Figure 1. Scheme of the pumping with integration of renewable energies for water consumption, with grid connected consumers.

If the system works isolated, more electrical consumers can be considered, in addiction to the pumping facility. In this case, the electric demand is covered with wind turbines, hydroelectric generator, and with a diesel supply if it is necessary. And water demand is covered with wind turbines and diesel supply. As in the previous case, also the water reservoir it is use as the storing system.

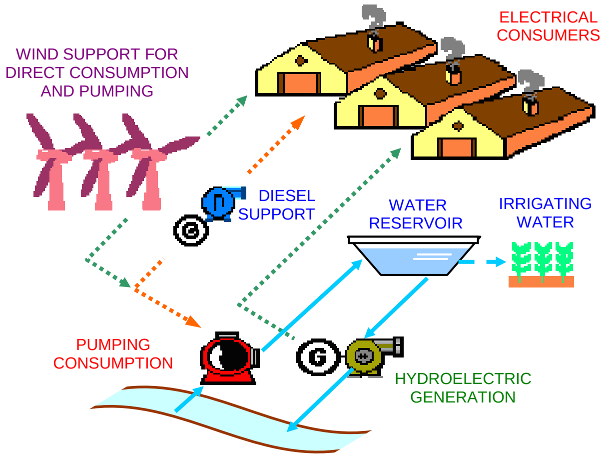


Figure 2. Scheme of the pumping with integration of renewable energies for electric supply with isolated consumers.

3. Analysis for the optimization

In this point, the optimization criterion, the operation balances, the facility dimension, investment and operation costs and the optimization method are explained.

A. Optimization criterion

Optimization of the global system is made taking into account two main aspects [1, 5, 8]: firstly, the dimension of the different elements of the system, secondly, the optimal operation of the integrated system. To do it, operation and investment cost are considered, using the NPV, IRR and PayBack methods like functions to optimize.

The optimal operation is analysed considering different decisions depending on if the system is grid connected or isolated.

In the first case, the decisions are:

- If the water reservoir is not full and there is wind energy, it is used for pumping
- When the irrigation necessities are no covered with the storied water in the reservoir, and the wind is not enough for supply the pumps, it is taken from the grid
- If is foreseen in the sort term that water stored is not enough for irrigation needs and the price of electricity is low, the water is pumped using the grid

If the system is isolated and there are other electrical consumers than the pumping station, the decisions are:

- To satisfy the electrical demand with wind and diesel
- If there is not wind are there is water enough, the electrical demand is satisfied with hydroelectric (and diesel if necessary)
- If there is more wind energy than the electrical demand of the consumers, it is used for water storage

With the application of the operational balances, the optimal operation is found for each one of the 8760 hours of a complete year. When there is grid connection, the different price of the electricity at different hours (valley: V, medium: LL o pick: P) is considered.

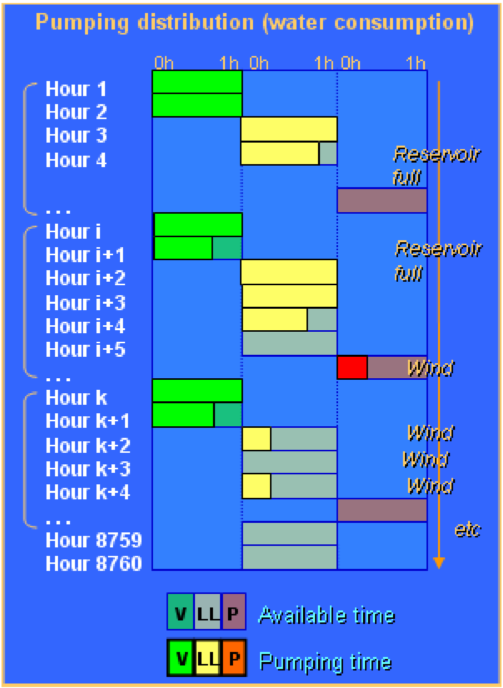


Figure 3. Example of distribution of time for pumping, in a system with grid connection

The way in which the investment and operational costs and other economic parameters have been considered it is explained in this paper.

B. *Operation balances*

The operation analisys of the integrated system implies the application of both electrical and water balances, for each hour of the studied period. In the first case, all the energetic generation must be equal to the electric demand plus the pumping consumption and the storaged energy. In the second case, the reservoir water capacity must be controled, because its level increases with the pumped water and decreases when there is water demand or hydroelectric generation.

At each generic X hour analysed, the energetic balance between demand (DEM) and generation (GEN) is as follows:

$$(\mathrm{ELECTRIC_{DEM}+PUMPING_{DEM}+PUMPING_{STORAGE}})_X=$$
$$(\mathrm{WIND_{GEN}+HYDROELECTRIC_{GEN}+DIESEL_{GEN}+GRID\ SUPPLY})_X$$

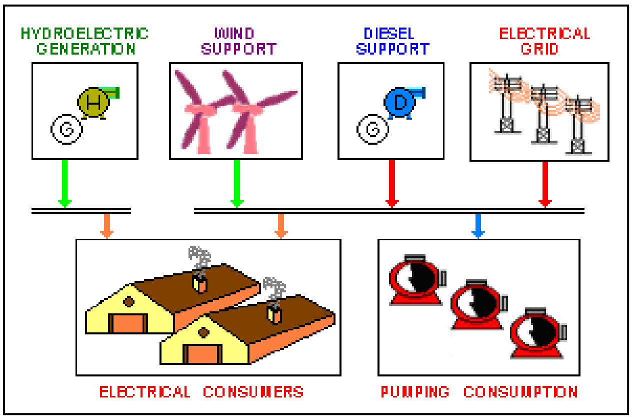


Figure 4. Energetic balance diagram.

The water balance permits the reservoir level being controlled, and at a generic X hour is the following one:

$$\mathrm{RESERVOIR\ LEVEL_X}=$$
$$\mathrm{RESERVOIR\ LEVEL_{X\text{-}1}+PUMPED\ WATER_{WIND.X}+PUMPED\ WATER_{DIESEL.X}+PUMPED\ WATER_{GRID.X}}$$
$$\mathrm{-\ DEMANDED\ WATER_X-TURBINED\ WATER_X}$$

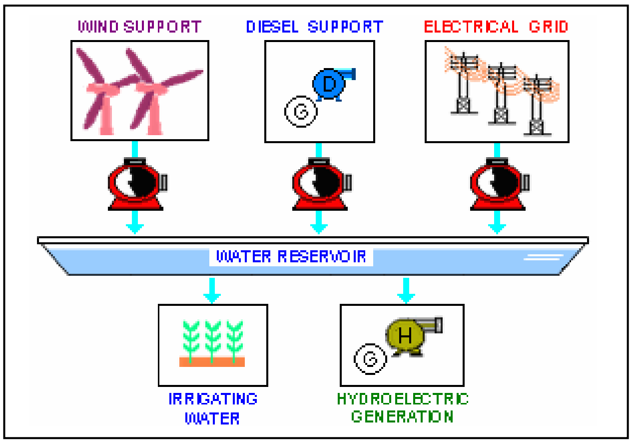


Figure 5. Water balance diagram.

In both balances the following restrictions are considered:

- There is priority for the use of the wind resource.
- Whenever wind energy exceeds the electrical demand (if isolated) and the reservoir is not full, it is used for pumping water.
- The pumps use electricity from grid or diesel generator if there is not enough water for irrigation in the reservoir
- If is foreseen that the irrigation demand exceeds the stored water, energy from the grid will be used only at valley hour
- Only water pumped with wind is subject to be used for hydroelectricity purposes.
- As the hydro-turbines use the same pipe that the pumps, hydroelectric generation only can be used when pumps are not working and there is exceed of water previously pumped with wind support
- If grid connection is possible, the system try to avoid the grid supply pumping at pick hours. To do it, water is stored at valley hours using the grid

C. *Facility dimensions and investment costs*

In the optimization process, the economic results of different dimensions from the facilities are analyzed and compared. These results depend on factors related to the consumptions and availability of renewable resources:

- The more wind turbines power, the cheaper energetic supply
- The efficiency of the pump increases with its size
- In order to take advantage of low wind, it is better to use several low power pumps than only one high power one
- The storage capacity is increased with the reservoir size
- The more hydroelectric or diesel generators power, the more generation capacity

But in all these cases, the increasing in the power efficiency face high costs of investment, so it is necessary to look for intermediate solutions so an optimization is needed.

After a previous estimation of a water reservoir size and a total pumping volume, a selection of the technical characteristics of the equipment is done. And with the pumping power and the pumping height (H_B), the necessary pumping volume (Q_B) can be calculated. And taking into account the pumping efficiency (η_B) (different in each model, which depend on the pumping height and volume) their electrical consumption ($P_{\mathrm{electric.B}}$) can be known, using the expression 1.

$$P_{electr.B}[kW]=9{,}81\cdot Q_B[m^3/s]\cdot H_B[m]/\eta_B \qquad (1)$$

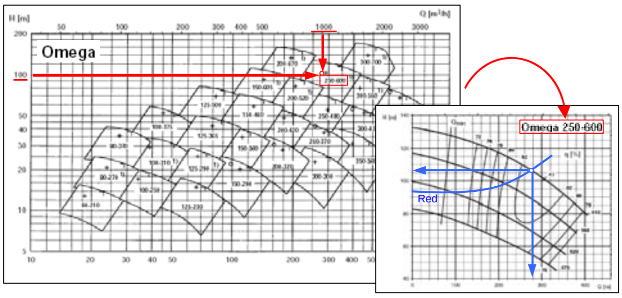


Figure 6. Example of selection and efficiency determination of a pump

The impulsion pipe diameter can be calculated by using the Manning formula, which relates the pipe size, diameter (D_{pipe}) and length (L_{pipe}), with the hydraulic losses percentage (h_f), the pumping height ($H_{geometric}$), and the pumping volume ($Q_{pumping}$), as follows:

$$D_{pipe}[m] = \left(\frac{10{,}3}{h_f[\%]/100}\right)^{1/5{,}333} \left(\frac{Q_{pumping}{}^2[m^3/s]*n^2*L_{pipe}[m]}{H_{geometric}[m]}\right)^{1/5{,}333} \quad (2)$$

The total power of the wind turbines it is determined in order to be able to supply the pumping energy. Depending on the selected wind turbine model, its behaviour is described by a specific power-wind curve. This relation between generated power and wind speed will be used for evaluating the wind resource. In order to making this evaluation, it is used the hourly mean wind speed during all the year.

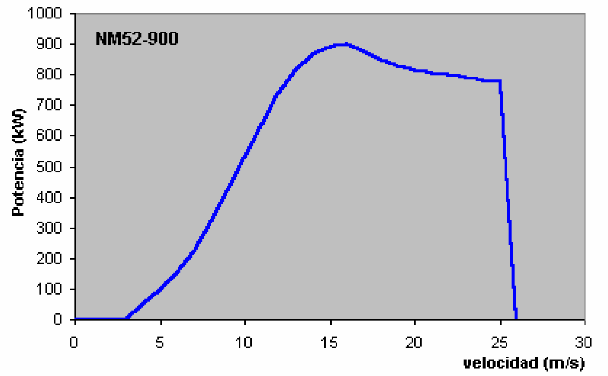


Figure 7. Example of wind curve (power-wind speed) of a wind turbine.

When the height of the wind turbine nacelle ($h_{nacelle}$) does not match with the measuring height ($h_{measured}$) of the estimated speed ($V_{measured}$), the following expression is used to calculate the wind speed for the wind turbine ($V_{nacelle}$), where h_0 is a factor which depends on the terrain roughness:

$$V_{nacelle} = V_{measured} \cdot \frac{\ln(h_{nacelle}/h_0)}{\ln(h_{measured}/h_0)} \quad (3)$$

The type of the hydraulic turbine (and consequently its efficiency, η_T), depends on the hydraulic height (H_T) and water volume (Q_T). The figure 8 shows the working zones for different types of hydro-turbines. Those factors, and the efficiency of the electric generator (η_G), allow us to evaluate the electric power supplied by the hydraulic resource, as follows.

$$P_{hidroel}[kW] = \frac{9{,}81 \cdot Q_T[m^3/s] \cdot H_T[m]}{\eta_G \cdot \eta_T} \quad (4)$$

The rated power of the diesel generator should be the necessary for supplying the pick demands of electrical consumption and water pumping necessities. This technical parameter is the result of the energetic balance between electrical demand and renewable energy resources. If isolated operation is considered, the electrical grid is replaced by a diesel generator unity.

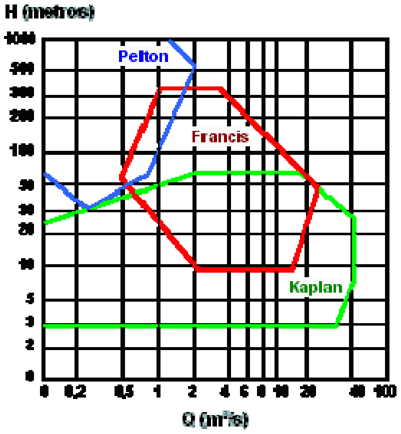


Figure 8. Working zones for types of hydroelectric turbines.

Once the technical parameters (sizes and rated powers) are known, the prices of the different elements that compose the systems are determined. These prices are in a database obtained from different commercial provider.

D. *Facility operation costs*

Once the size of the utilities is known it is possible to analyze the operation and maintenance costs. On the one hand, it is necessary to consider the maintenance of the used machinery, that is, pumps, wind, hydroelectric and diesel generators. On the other hand, it is necessary the evaluation of the operation costs generated by the energetic consumption. These last ones can be due to two alternative causes:

- The cost of the electrical energy which has been get from the grid
- The cost of the fuel which has been consumed by the diesel generator

By applying the energetic and water balances, it is possible to know how much time each machine has been working, in order to evaluate the maintenance and operation costs. So can be understood the importance of applying the balances on the most adequate way.

E. *Optimization process*

A double optimization analysis is presented, not only relating to the facilities operation, but also on the economical viability. After determining the water and electrical demands, different alternatives are analysed by considering different water reservoir sizes, different pumping and wind turbine powers.

Due to the multiple influence factors which affects to the costs, and the difficulties for their mathematical modelling, linear optimization methods have not been considered. It has been used an enumerative method for the economical optimization.

The energetic optimization is related to the efficient use of the renewable resources, by giving priority to these resources instead of to the electrical energy from the grid or from the diesel generator, such as has been explain in previous paragraphs.

The steps considered for each alternative are:

a) Technical characteristics of the facilities (sizes and rate powers) are determined, in order to evaluate the investment costs
b) Energetic and water balances are applied, taking into account the machinery efficiencies, in order to obtain operation costs
c) For each alternative, an economic viability study is applied (NPV, IRR, Pay-Back)

The different results of the viability studies are compared, and the case with the best factors is selected as the most suitable system (the optimized system).

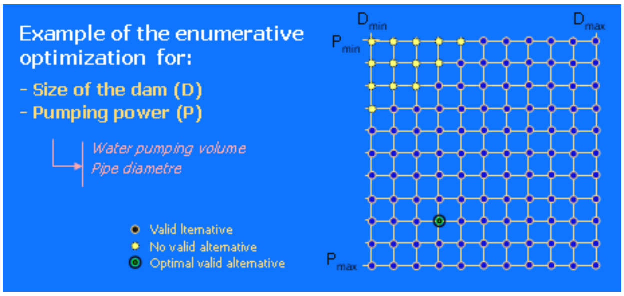


Figure 9. Example of enumerative method in the optimization of the size of the water reservoir (dam) and the pumping power.

As an example, some of the factors that must be optimized are the number of pumps and wind turbines in the facilities. The more number of the equipments, the less rate power for each one. Not only the investment cost but also the efficiency of the machines (and consequently the operating results) is going to be different, depending on the selected option. So, various numbers and models of pumps and wind turbines are analyzed.

4. Computer tool for automatic calculations

A. *General characteristics of the tool*

A computer science tool has been developed. This tool automatically searches the optimal technical and operational characteristics of the facilities, from the economic and energetic points of view previously commented.

Its name is OEBIER (Optimización de Estaciones de Bombeo con Integración de Energies Renovables), and it is a science tool very friendly to use. It includes a database with technical characteristics and prices of commercial equipment such as pumps and turbines, which allows selecting the parameters that are going to be optimized.

The renewable integration options of the OEBIER programme are different:

- Only water demand, only electrical demand, or both demands
- Only wind support, but not hydroelectric generation, or both renewable supports
- Electric net connected or isolated

B. *Previous specifications for the tool*

In order to make a complete study and optimization of a pumping system with renewable energy by using OEBIER, it is necessary to specify four groups of input data (figures 10-13):

- General specifications of the pumping necessities (monthly water demand and daily distribution of the demand, pipe length and height) and electrical demand (monthly demand and daily distribution of the demand)
- Estimated hourly wind speed, for a complete year
- Margin for the optimizable parameters (for example, maximum number of pumps, wind turbines, maximum and minimum size for the water reservoir)
- Economical factors for the viability analysis (period for amortization, interest for a loan, rate of inflation, percentage of annual increase for the prices of purchase and sale of the electricity…)

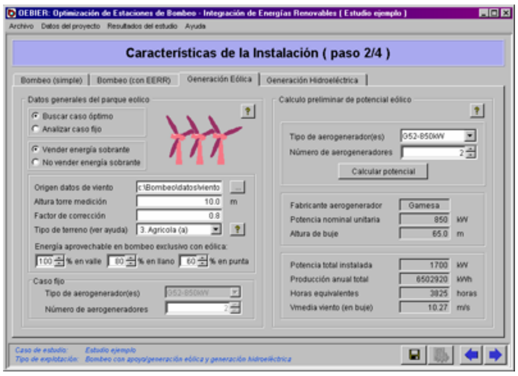
Características de la Instalación (paso 2/4)

Balsa / Potencia de bombeo (por etapa)
● Buscar caso óptimo
○ Analizar caso fijo
Caso a optimizar
Capacidad de balsa mínima 20000.0 m3
Capacidad de balsa máxima 50000.0 m3
Intervalos de cálculo (balsa) 20
Potencia de bombeo mínima 500.0 kW
Potencia de bombeo máxima 2000.0 kW
Intervalos de cálculo (bombeo) 20
Caso fijo
Capacidad de balsa m3
Potencia de bombeo kW
Caudal de bombeo m3/h

Grupo de bombeo (por etapa)
Caso a optimizar
Número mínimo de bombas 5 +1 bombas
Número máximo de bombas 10 +1 bombas
Caso fijo
Número de bombas 5 +1 bombas
Tipo de bombas Usuario
Características unitarias de bombas
Usuario
Hb m
Qb m3/h
Modelo
Rendimiento %
Pot. bombeo kW
Pot. elect kW
fdp motor
Precio €

Caso de estudio: Estudio ejemplo
Tipo de explotación: Bombeo con apoyo/generación eólica y generación hidroeléctrica

Figure 10. Configuration of technical data (1).



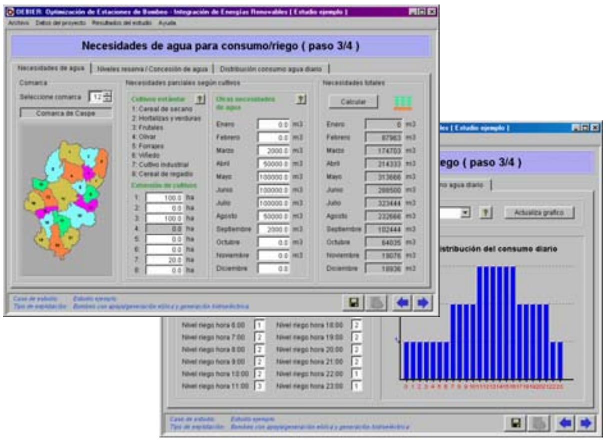
Características de la Instalación (paso 2/4)

Datos generales del parque eolico
● Buscar caso óptimo
○ Analizar caso fijo
● Vender energía sobrante
○ No vender energía sobrante
Origen datos de viento c:\Bombeo\datos\viento
Altura torre medición 10.0 m
Factor de corrección 0.8
Tipo de terreno (ver ayuda) 3. Agrícola (a)
Energía aprovechable en bombeo exclusivo con eólica:
100 % en valle 80 % en llano 60 % en punta
Caso fijo
Tipo de aerogenerador(es) G52-850kW
Número de aerogeneradores 2

Calculo preliminar de potencial eólico
Tipo de aerogenerador(es) G52-850kW
Número de aerogeneradores 2
Fabricante aerogenerador Gamesa
Potencia nominal unitaria 850 kW
Altura de buje 65.0 m
Potencia total instalada 1700 kW
Producción anual total 6502920 kWh
Horas equivalentes 3825 horas
Vmedia viento (en buje) 10.27 m/s

Caso de estudio: Estudio ejemplo
Tipo de explotación: Bombeo con apoyo/generación eólica y generación hidroeléctrica

Figure 11. Configuration of technical data (2).



Necesidades de agua para consumo/riego (paso 3/4)

Comarca
Seleccione comarca 12
Comarca de Caspe

Necesidades parciales según cultivos
Cultivos estándar
1: Cereal de secano
2: Hortalizas y verduras
3: Frutales
4: Olivar
5: Forrajes
6: Viñedo
7: Cultivo industrial
8: Cereal de regadío
Extensión de cultivos
1: 100.0 ha
2: 0.0 ha
3: 100.0 ha
4: 0.0 ha
5: 0.0 ha
6: 0.0 ha
7: 20.0 ha
8: 0.0 ha

	Otras necesidades de agua	Necesidades totales
Enero	0.0 m3	0 m3
Febrero	0.0 m3	87963 m3
Marzo	2000.0 m3	174703 m3
Abril	50000.0 m3	214333 m3
Mayo	100000.0 m3	313666 m3
Junio	100000.0 m3	288500 m3
Julio	100000.0 m3	323444 m3
Agosto	50000.0 m3	232666 m3
Septiembre	2000.0 m3	102444 m3
Octubre	0.0 m3	64035 m3
Noviembre	0.0 m3	19076 m3
Diciembre	0.0	18936 m3

Nivel riego hora 6:00 1
Nivel riego hora 7:00 2
Nivel riego hora 8:00 2
Nivel riego hora 9:00 2
Nivel riego hora 10:00 2
Nivel riego hora 11:00 3
Nivel riego hora 18:00 2
Nivel riego hora 19:00 2
Nivel riego hora 20:00 2
Nivel riego hora 21:00 2
Nivel riego hora 22:00 1
Nivel riego hora 23:00 1

Caso de estudio: Estudio ejemplo
Tipo de explotación: Bombeo con apoyo/generación eólica y generación hidroeléctrica

Figure 12. Configuration of the demands.

Parámetros Económicos (paso 4/4)

Datos generales de inversión

Origen de fondos para inversion

Recursos propios: 30 %

Recursos ajenos: 70 %

Subvenciones: 0 %

Primer año de estudio: 2003

Vida útil de instalación: 20 años

Plazo amortiz. obra civil: 15 años

Plazo amortiz. electromecan.: 10 años

Préstamo para inversion

Método amortización: Amortización cte.

Interés del préstamo: 5.0 %

Plazo de amortización: 20 años

Costes de operación anuales

Mantenimiento de instalación de bombeo: 0.003 €/kWh

Seguros para instalación de bombeo: 0.6 €/kW

Mantenimiento de instalación eólica: 0.003 €/kWh

Seguros para instalación eólica: 0.6 €/kW

Mantenimiento de instalación hidroelec.: 0.003 €/kWh

Seguros para instalación hidroelec.: 0.6 €/kW

Otros

Tasa de impuesto de sociedades: 35.0 %

Tasa de inflación anual: 1.5 %

Tasa de descuento: 5.0 %

Aumento anual precio compra electricidad: 1.5 %

Aumento anual precio venta electricidad: 1.5 %

Factor a emplear en optimizaciones: V.A.N.

Caso de estudio: Estudio ejemplo

Tipo de explotación: Bombeo con apoyo/generación eólica y generación hidroeléctrica

Figure 13. Configuration of economical data.

In order to apply the energetic and water balances, OEBIER tool implements an annual simulation algorithm. Hourly evolution of electric generation and demands (water and electricity) is considered. It is used a cumulative method, considering the available capacity of the water reservoir, describing the hourly storage variations occurring during the annual operation of the whole system.

C. Results of the optimization study

The main outputs of the analysis made by the OEBIER tool are (figure 14):

- Characteristics (dimensions of civil facility and rated powers of electromechanical equipment) of the optimized system
- Annual optimal operation strategies for each subsystem.
- Costs of investment of each part of the pumping system with renewable supports
- Costs of operation by electricity consumption, and income by sale
- Account of economical results for the optimized project
- Sensitivity of the economic rates (NPV, IRR, paybac) as opposed to variations of the investment, expenses or income, inflation, etc.

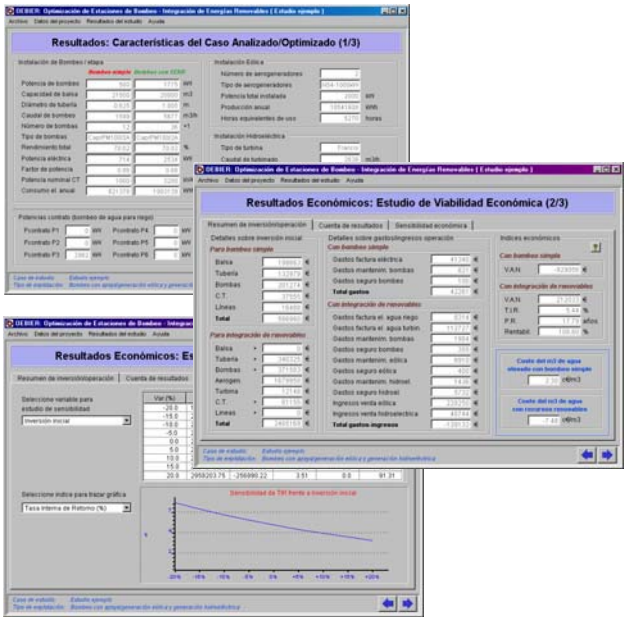


Figure 14. Results of an optimized system.

In addition to the economic results which are necessary to analyse the economic viability, application OEBIER also shows the monthly characteristics of operation in the first year of use, on consumed and generated energy, expenses and income and elevated volume of water (for consumption or hydroelectric generation).

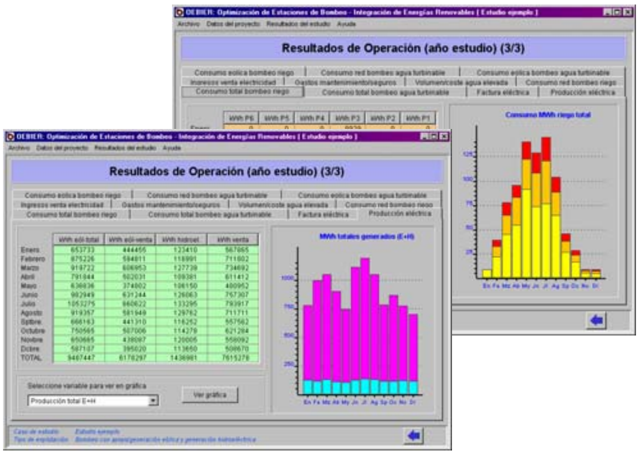


Figure 15. Results of operation for an optimized system.

5. Application

A great pumping station, in the area of Andorra (Teruel, Spain) has been analyzed in order to determine the economical viability of wind power support. (figure 16). The elevation is made in four steps, with two intermediate water extractions, three different reservoirs (dams) which accumulate the water demanded in different areas, and wind power support in all the pumping steps.

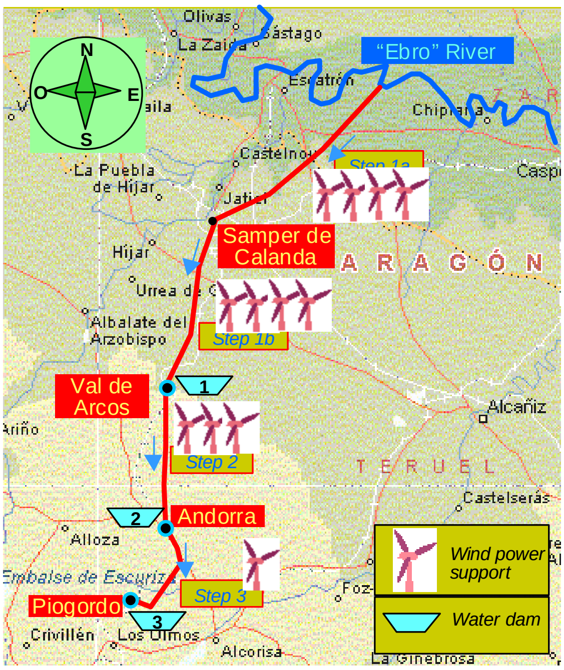


Figure 16. General map of the pumping stations

The monthly water demand is known (for irrigating, domestic and industrial use) in each zone (figure 17).

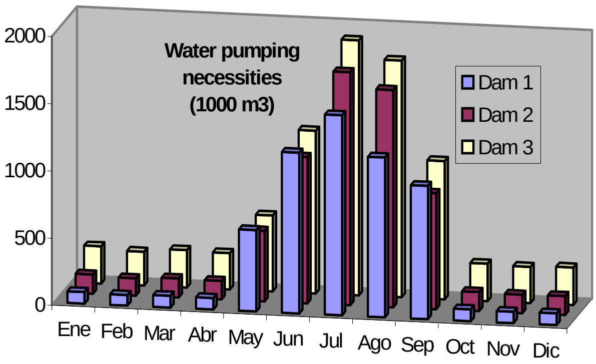


Figure 17. Water pumping necessities (10^3 m^3).

This pumping system has been initially projected with the technical characteristics shown in table I.

TABLE I. -Technical data about the pumping station.

	Step 1a	*Step 1b*	*Step 2*	*Step 3*
Pumping height	215m	230m	170m	40m
Pipe length	20,6km	13,9km	7,8km	3,8km
Pumping volume	1,91m^3/s	1,91m^3/s	1,36m^3/s	0,72m^3/s
Dam size	-	$325\cdot10^3$m^3	$195\cdot10^3$m^3	$300\cdot10^3$m^3
Wind power support	4x650kW	4x650kW	3x650kW	1x650kW

For this initial proposal, it has been considered a total efficiency of 70% in the pumping process, and a wind support with Vestas turbins (V47-650 model).

The following rates have been taken into account for the economical analysis:

Useful life:	20 years
Own / outer resources:	35% / 65%
Inflation / taxes:	1,5% / 35%
Loan rate / updating rate:	3% / 3%
Electric contract:	2.1 High Voltage (≤36kV)
Without electric energy sale	

A. *Summary of results: initial proposal*

With the use of OEBIER tool it has been analysed the viability of the pumping system, for each step, and with the technical characteristics shown in table I. In order to know the convenience of installing the wind power support, the tool makes a comparison between the cost with or without this renewable energy, as shown in table II. The consumption reductions owing to the wind support are also presented in percentages.

Figure 18 shows a comparison between the monthly energy consumption with or without wind support, for the first pumping step in the initial proposal.

Taking into account additional costs for the investment (in wind turbines), maintenance and insurance (apart from the electric annual cost shown in table II), the result related with the main economical rates are shown in table III.

TABLE II. – Consumption results for the initial proposal.

Simple pumping (without renewable wind support)			
	Step 1	*Step 2*	*Step 3*
Power consumption	38,5GWh	10,47GWh	1,36GWh
Electric cost	$2670\cdot10^3$ €	$735\cdot10^3$ €	$92{,}4\cdot10^3$ €
Water cost	12,7 c€/m^3	4,9 c€/m^3	1,12 c€/m^3
Pumping with renewable wind support			
	Step 1	*Step 2*	*Step 3*
Power consumption	29,3 GWh *(-23,82%)*	7,125GWh *(-32%)*	0,36GWh *(-73,5%)*
Electric cost	$2160\cdot10^3$ € *(-19,1%)*	$556\cdot10^3$ € *(-24,3%)*	$34{,}8\cdot10^3$ € *(-62,3%)*
Water cost	10,35 c€/m^3 *(-18,5%)*	3,74 c€/m^3 *(-23,7%)*	0,43 c€/m^3 *(-61,6%)*

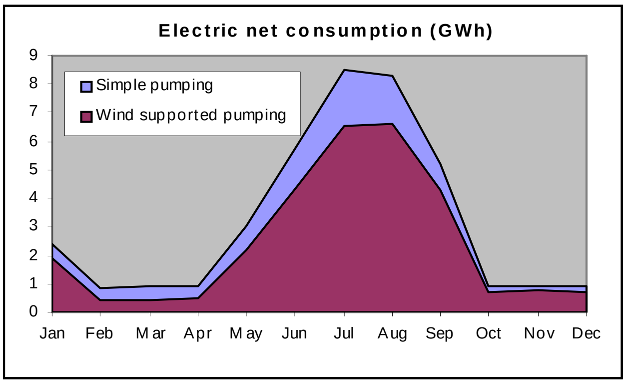


Figure 18. Consumption from the electric net (initial proposal).

TABLE III. – Economic results for the initial proposal.

Pumping with renewable wind support			
	Step 1	*Step 2*	*Step 3*
Investment	$4{,}8\cdot10^6$ €	$1{,}8\cdot10^6$ €	$0{,}6\cdot10^6$ €
Pay Back	15,22 years	16,26 years	18,66 years
N.P.V.	$1{,}35\cdot10^6$ €	$0{,}36\cdot10^6$ €	$0{,}34\cdot10^6$ €
I.R.R.	5,65 %	4,93 %	3,59 %

The annual cash flows for the calculation of the pay back, NPV and the IRR have been obtained from the saving in the electric cost of net consumption, due to the wind support.

It can be seen that the renewable support is economically convenient for all the pumping steps. Anyway, the economic viability is better in the first step than in the last one, owing to the important energetic necessities at the beginning of the pumping process (with a higher pumping height).

B. *Summary of results: optimized proposal*

With the optimization capabilities of the OEBIER tool, it has been search the technical characteristics of the pumping system, in each one of the pumping steps, in order to obtain the best economic option, with the results shown in table IV.

TABLE IV. – Technical data of the optimized pumpimg station.

	Step 1	*Step 2*	*Step 3*
Pumping volume	1,77m^3/s	1,44m^3/s	0,722m^3/s
Dam size	1365·10^{3}m^3	195·10^{3}m^3	300·10^{3}m^3
Wind power support	3x1000kW (Nordex N54)	2x1000kW (Nordex N54)	1x600kW (Nordex N43)

The most significant difference between the initial and the optimized proposal is the size of the reservoir (dam) at the end of the first pumping step. Owing to the important pumping height for the first step, it is recommended to increase it in order to reduce the electric energy consumption at pick hours. The optimized total power of the wind support is similar to the initial case.

As in the previous analysis for the initial proposal, in order to know the convenience of installing the wind power support, the tool makes a comparison between the cost with or without this renewable energy, as shown in table V.

As an example, the graphic in figure 19 shows a comparison between the monthly energy consumption with or without wind support along one complete year, for the first pumping step in the optimized proposal.

TABLE V. – Consumption results for the optimized proposal.

Optimized simple pumping (without renewable wind support)			
	Step 1	*Step 2*	*Step 3*
Power consumption	32,68GWh	8,8GWh	1,19GWh
Electric cost	2130·10^3 €	605·10^3 €	83,4·10^3 €
Water cost	10,15 c€/m^3	4,03 c€/m^3	1,01 c€/m^3
Optimized pumping with renewable wind support			
	Step 1	*Step 2*	*Step 3*
Power consumption	25,8 GWh *(-21%)*	4,65 GWh *(-47,22%)*	0,34 GWh *(-80,6%)*
Electric cost	1670·10^3 € *(-21,6%)*	386,6·10^3 € *(-36%)*	33,42·10^3 € *(-60%)*
Water cost	7,97 c€/m^3 *(-21,48%)*	2,55 c€/m^3 *(-36,7%)*	0,41 c€/m^3 *(-59,4%)*

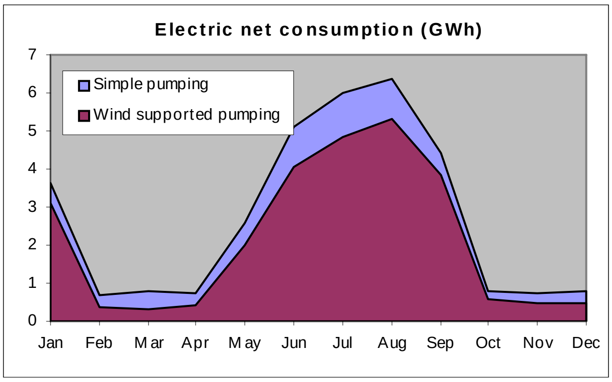


Figure 19. Consumption from the electric net (optimized proposal).

In the same way of previous case, final results are shown in table VI.

TABLE VI. – Economic results for the optimized proposal.

Pumping with renewable wind support			
	Step 1	*Step 2*	*Step 3*
Investment	2,57·10^6 €	1,71·10^6 €	0,52·10^6 €
Pay Back	8,79 years	13,14 years	18,41 years
N.P.V.	2,87·10^6 €	0,74·10^6 €	0,035·10^6 €
I.R.R.	12,3 %	7,06 %	3,71 %

It can be seen that the renewable support for this optimized system is also economically convenient for all the pumping steps. And, in comparison with the initial proposal, appears an economic improvement.

6. Conclusions

In this project, an optimization process for the integration of renewable energy in pumping stations, including optimal sizing of all the facilities and optimal operation strategies.

Thanks to some analyzed cases, it has been observed that the integration proposal is viable, depending on the specific case. As it is very difficult to generalize the results, always must be studied the case.

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