Optimal design of isolated network systems operated by renewable energies with mixed-integer optimization algorithms

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Abstract

In this article, a method to solve isolated rural networks facilities supported by renewable energies by mixed-integer linear programming is described.
The algorithm is applied on a specific location and includes renewable energy sources like windpower, hydroelectric and biomass, electrical loads from populations and irrigation needs, as well as a storage system based on a pumping-turbinate unit.

Key words

Integration of Renewable Energy Sources (RES), mixed-integer programming, pumped-storage units, isolated networks.

1. Introduction

The study of planning networks by linear programming or mixed-integer linear programming techniques has been well known for years [1, 2, 3]. However, a very few set of articles are referred to the study of the system like isolated one with a high participation of renewable energies, mainly due to its randomness problems.

It is for that reason that, in order to be able to reach a high level of participation of RES in isolated systems, besides an aceptable level of reliability, it is necessary a storage system of high power and energy. Nowadays, these standards of requirements are only supported by pumped-storage systems and fuel cells.

The integration of fuel cells in isolated networks with RES, has been studied extensively [8, 9, 10]. However, optimization of pumped-storage systems in stationary state has been barely referred. Most of them are based on hybrid systems studies, including some kind of renewable energy with high randomness like wind or solar sources [4, 5, 6], but in papers only the transient analysis is showed. The optimal size and location for stationary state have not been proved, neither the integration of irrigation pumping system with a turbine unit operated by RES.
In addition, in many cases, the pumping facility is already installed, so the true cost of a turbine unit is reduced considerably.

The aim of the project is to show a mathematical tool that can be feasible in order to solve isolated networks based on renewable energies, keeping in mind all the restrictions that this kind of sources can introduce in our problem.

2. Description of the problem

In order to verify the algorithms showed in the following section, these ones have been applied to a real location in the North of Spain, constituted by seven rural villages with 6 935 inhabitants.
The objective function to minimize in our problem is the daily cost of the integrated system of generation-storage-distribution, where the investment and operation costs of each element are considered.
In order to fit the problem into reality, each day has been divided in 8 equal periods (of 3 hours each one). Thus, the sources and the loads have been modelled in these 8 periods.

A. Description of the electrical loads

From population data, and considering the amount of each type of consumption (domestic, industrial and services), we get the load curves of each village, that will be displayed in 8 periods, in order to obtain a better level of reality.

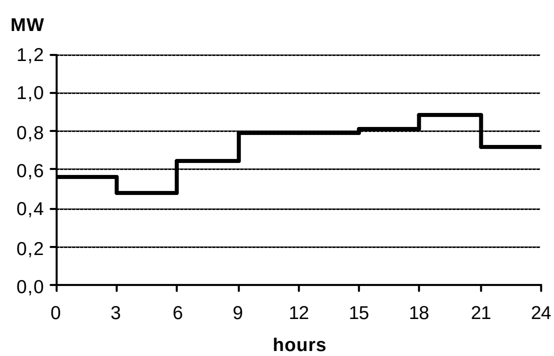

Fig. 1.- Example of load curve for a village (Almuniente)

B. Description of irrigation loads

A pumping system has been designed in a location of the region. It consists of a pumping unit, a pipe of impulsion and a regulation pool. The length of the pipe is 2 km approximately, and the height available from the pool, about 83 m. With this pool, it is wanted to extend the irrigated land to a greater number of hectares, with the consequent improvement of agricultural profits.

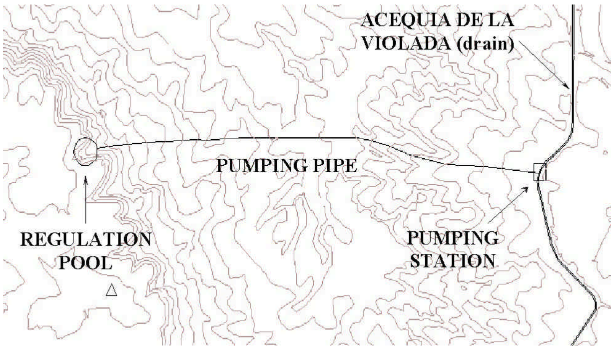

Fig. 2.- General view of the pumping station

Irrigation needs of the region have been estimated by local authorities in 6 210 m^3/ha·year, distributed in 1 000 ha of *cynara cardunculus* (thistle) and 1 000 ha of traditional crops.
Thistle and traditional crops are very well complemented, since one of them is a winter crop and the other is a summer crop. This way, the irrigation needs are uniform along the year, and the pumping system has a maximum advantage.

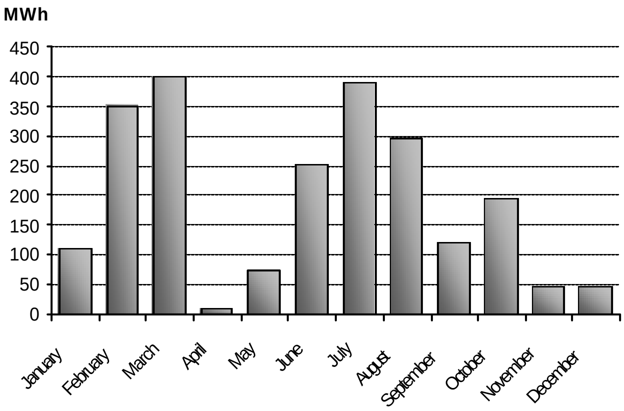

Fig. 3.- Irrigation needs along the year

If we divide the day in 8 periods and make the irrigation in four of them (within the diurnal hours), the power load on the network system can be observed in Fig. 4:

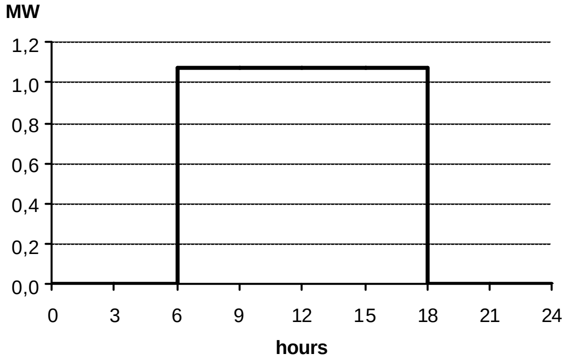

Fig. 4.- Power load of the pumping system for irrigation

C. Localization of the Renewable Energy Sources

1) Biomass power plant:

For the optimal location of the biomass unit, it is necessary to consider the amount of biomass energy that can be obtained in each village of the region. It would be considered that the optimal location of the biomass power station would be the one that minimizes the transport costs. These costs depend on the amount of biomass transported and the distance to the power plant.

Fig. 5.- Optimal location of biomass unit

2) Wind Farms

Viability of a location in wind energy usually is determined by means of geographical studies of the wind resource (W/m^2).
In our case, we have a series of measures made during a year in a location of the region. The extrapolation of the results to the whole area has been made by means of a wind analysis program called WASP, obtaining Fig. 6. In this figure, we have selected the five better locations that would be susceptible of a wind farm installation, in order to incorporate them to our model.

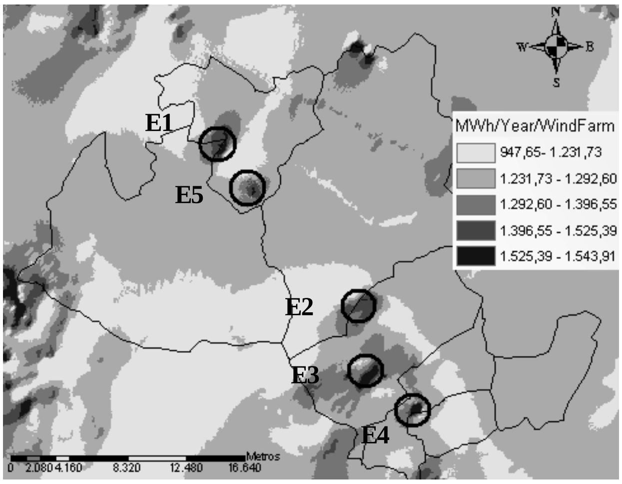

Fig. 6.- Optimal location of Wind Farms

3) Hydroelectric Generation:

For the hydroelectric generation, we have considered two existent installations in the region:

"C.H. La Sotonera" – H1 = 7 200 kW
"C.H. Marracos" – H2 = 5 000 kW

We will take these values like maximum limits for our mathematical model.

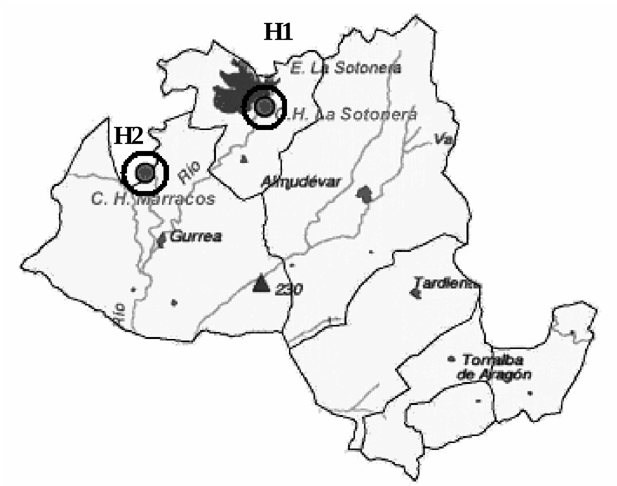

Fig. 7.- Hydroelectric units in the study region

3. Mathematical Model

The mathematical technique applied to this problem has been linear mixed-integer programming. This technique is based in the minimization of an objective function (costs function usually), whose variables are fixed to some restrictions that model the real problem.

The main advantage of mixed-integer model versus classic linear programming is that we can separate investment cost from operation cost by means of integer variables (e.g. binary variables like built/not built)

A. General Cost Function

$$\min\left(\sum_{i\in\Omega_{bio}} f_{bio,i} + \sum_{i\in\Omega_{hyd}} f_{hyd,i} + \sum_{i\in\Omega_{wind}} f_{wind,i} + \ldots \sum_{i\in\Omega_{sto}} f_{sto,i} + \sum_{i\in\Omega_{line}} f_{line,i}\right) \quad (1)$$

$f_{bio,i}$, Cost of biomass unit *i*, with O_{bio} the set of biomass facilities. Eq. (2)
$f_{hyd,i}$, Cost of hydroelectric unit *i*, with O_{hyd} the set of hydroelectric facilities. Eq. (5)
$f_{wind,i}$, Cost of wind farm unit *i*, with O_{hyd} the set of windfarms. Eq. (9)
$f_{sto,i}$, Cost of storage unit *i*, with O_{sto} the set of storage facilities. Eq. (12)
$f_{line,i}$, Cost of power line *i*, with O_{line} the set of power lines of our problem. Eq. (23)

B. Specific Cost Functions and Restrictions

1) Biomass unit

A biomass unit entails some investment costs, which are function of the total installed power and some operation costs, which depend on the energy generated at each period, therefore, the equation will be:

$$f_{bio} = P_{bio}\cdot K_{bio\_inv} + \sum_{t=1\div 8}\left(P_{bio_t}\cdot t\right)\cdot K_{bio\_op} \quad (2)$$

with,

P_{bio_t} , Power of biomass unit on period *t*, [MW]
K_{bio_inv} , Investment cost biomass unit, [€/MW·day]
K_{bio_op} , Operation costs biomass unit, [€ / MWh]
t , Period time (3 hours)

The final installed power of biomass will be the maximum power reached in one of the periods:

$$P_{bio} = \max\left\{P_{bio_t}\right\} \quad \text{for} \quad t = 1\div 8 \quad (3)$$

Biomass restrictions: Eq. (4)

The **power** of the biomass unit in a location cannot surpass the power that the fuel availability allows:

$$P_{bio} \le P_{bio,\max} \qquad (4)$$

2) Hydroelectric unit

Hydroelectric unit entails some investment costs, which are function of total installed power and some operation costs, which depend on the energy generated at each period. Although these operation costs are reduced, we cannot refuse them, since they are necessary for a good optimization of the whole system. In addition, most of the RES of the problem have low and very similar costs of operation.

$$f_{hyd} = P_{hyd} \cdot K_{hyd\_inv} + \sum_{t=1\div 8} \left(P_{hyd_t} \cdot t \right) \cdot K_{hyd\_op} \qquad (5)$$

with:

P_{hyd_t} , Power of hydro unit on period t, [MW]

K_{hyd_inv} , Investment cost hydro unit, [€/MW · day]

K_{hyd_op} , Operation costs hydro unit, [€ / MWh]

t , Period time (3 hours)

The final hydroelectric installed power will be the maximum power reached in one of the periods:

$$P_{hyd} = \max\left\{ P_{hyd_t} \right\} \qquad for\ \ t = 1 \div 8 \qquad (6)$$

Hydroelectric restrictions: Eqs. (7), (8)

The **energy** generated by a power station cannot exceed the available one due to hydrological characteristics of the site (volume of dam, annual flow…). We can describe it like:

$$\frac{E_{hydmonth}}{31\ days} \ge \sum_{t=1\div 8} \left(P_{hyd_t} \cdot t \right) \qquad (7)$$

with $E_{hydmonth}$ the energy generated by the hydroelectric unit in the most unfavourable month of an average hydrological year.

Another kind of restriction is due to the **power**. For a determined location, the power installed depends completely on the characteristics of the site (its height and flow)

$$P_{hyd} \le P_{hyd,\max} \qquad (8)$$

3) Wind Power Support

For wind farms, we optimize the cost of investment of the total power:

$$f_{wind} = P_{wind} \cdot K_{wind\_inv} \qquad (9)$$

with:

P_{wind} , Power of wind farm, [MW]

K_{wind_inv} , Investment cost of wind farm, [€/MW·day]

Wind farm restrictions: Eqs. (10), (11)

This kind of energy source, displays a clear restriction, its randomness. This problem can be modelled trough two restrictions:

First of all, an **energy and power** restriction. The real power that a wind farm can offers us at each moment is going to depend on a certain wind factor. This wind factor shows us which part of real installed power (P_{wind}) can be useful at every moment ($P_{wind,\ t}$) , and it is extracted from wind measurements made during two years on a site in the region.

$$P_{wind_t} = F_{use_t} \cdot P_{wind} \qquad (10)$$

The second restriction is centred about the **randomness** of wind power resource. In order to prevent periods without availability of wind power resource, the rest of facilities of the system (biomass, hydro, storage and power lines) must be designed so that they can supply any kind of problem a total loss of wind resource. This restriction affects to the minimum limits of the elements:

$$\begin{array}{ll} P_{bio} \ge P_{bio,\min} & P_{sto} \ge P_{sto,\min} \\ P_{hyd} \ge P_{hyd,\min} & P_{tur} \ge P_{tur,\min} \\ P_{line} \ge P_{line,\min} & P_{pump} \ge P_{pump,\min} \end{array} \qquad (11)$$

where P_{sto} , P_{tur} y P_{pump} are described in chapter 4)

4) Storage system

As we say previously, the system has a regulation pool for irrigation needs and as storage of big amount of electricity. Consts can be represented as:

$$f_{sto} = f_{dam} + f_{tur} + f_{pump} \qquad (12)$$

f_{dam} , Cost of regulation pool.

f_{tur} , Cost of the turbine unit.

f_{pump} , Cost of pumping system.

Regulation pool

$$f_{dam} = V_{dam} \cdot K_{dam} \quad (13)$$

with:

V_{dam} , Final volume of regulation dam, [m^3]

K_{dam}, Investment cost of regulation dam, [€ / m^3 · day]

The final volume of the regulation pool will be the maximum volume obtained in one of the periods and without any kind of restriction.

$$P_{dam} = \max\left\{P_{dam_t}\right\} \quad for \quad t = 1 \div 8 \quad (14)$$

Turbine unit

$$f_{tur} = P_{tur} \cdot K_{tur\_inv} + \sum_{t=1 \div 8} \left(P_{tur_t} \cdot t\right) \cdot K_{tur\_op} \quad (15)$$

with:

P_{tur} , Power of the turbine unit, [MW]

K_{tur_inv} , Investment cost of the turbine, [€/MW·day]

K_{tur_op} , Operational costs of the turbine, [€/MWh]

And the installed power will be the maximum power obtained in one of the periods:

$$P_{tur} = \max\left\{P_{tur_t}\right\} \quad for \quad t = 1 \div 8 \quad (16)$$

Pumping System

$$f_{pump} = P_{pump} \cdot K_{pump\_inv} + \sum_{t=1 \div 8} \left(P_{pump_t} \cdot t\right) \cdot K_{pump\_op} \quad (17)$$

with:

P_{pump} , Power of pumping system installed, [MW]

K_{pump_inv} , Investment cost of pumping, [€ / MW · day]

K_{pump_op} , Operational costs of pumping, [€ / MWh]

Like in the previous cases, the installed power will be the maximum power obtained in one of the periods:

$$P_{pump} = \max\left\{P_{pump_t}\right\} \quad for \quad t = 1 \div 8 \quad (18)$$

Storage system restrictions: Eqs. (19), (20), (21), (22)

The general restriction that rules the **operation** of the regulation pool is the following one:

$$V_{dam,t} = V_{dam,t-1} + L_{pump-tur} - L_{irrigation} \ [\text{m}^3] \quad (19)$$

with:

$V_{dam,t}$, Water reserve on period *t*, [m^3]

$V_{dam,t-1}$, Water reserve on period *t-1*, [m^3]

$L_{pump-tur}$, Energy exchange with pumping-turbine system, defined as:

$$L_{pump-tur} = \frac{\left(P_{pump} \cdot h_{pump} - \dfrac{P_{tur}}{h_{tur}}\right) \cdot t}{1000 \cdot 9.81 \cdot H}, \ [\text{m}^3] \quad (20)$$

$L_{irrigation}$, Necessary energy for irrigation, [m^3]

Another restriction is due to the existing **pipe** between the pumping station and the pool, since only can be used by one of the systems at any time.

$$P_{sto} = P_{pump_t} y_{pump_t} + P_{tur_t} y_{tur_t} \quad for \ t = 1 \div 8 \quad (21)$$

(y_{pump_t}, y_{tur_t}), integer binary variables (0/1), that show if a period is operated by the pumping system or by the turbine unit. Thus, they have the following restriction:

$$y_1 + y_2 \leq 1 \quad (22)$$

5) Power lines

For the design of lines we are going to consider variable and fixed costs.

Fixed costs depend on the installed power of each kind of line, and we can choose between two types of wires (1 and 2 in Fig. 8).

For variable costs, we can make lineal the electrical losses in a single linear section, as it is showed in the following figure:

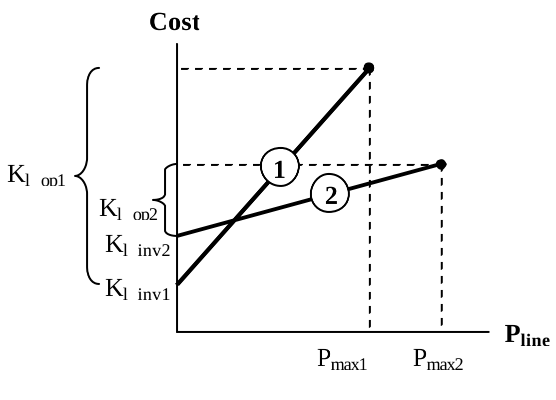

Fig. 8.- Linearization of investment and operation costs of power lines

From this graph, would be obtained the needed equations in order to model the lines (mixed-integer models). For a given period (*t*) and a line, the equation of costs is:

$$f_{line} = K_{l\_inv1} \cdot y_1 + K_{l\_inv2} \cdot y_2 + \ldots$$
$$K_{l\_op1} \cdot b_1 + K_{l\_op2} \cdot b_2 \qquad (23)$$

with:

(y_1, y_2) , Integer binary variables 0/1 that indicates if a line is built or not.

(b_1, b_2) , Auxiliary variables of the model, continuous type (0÷1), representing the percentage of power "Eq.(27)" or cost "Eq.(23)" respect to each one of both types of lines.

(K_{l_inv1}, K_{l_inv2}) , Investment costs of each type of line, [€/period]

(K_{l_op1}, K_{l_op2}) , Operation costs of each type of line, [€/period]

Fixed to the following restrictions:

$$y_1 + y_2 \le 1 \qquad (24)$$

$$b_1 \le y_1 \qquad (25)$$

$$b_2 \le y_2 \qquad (26)$$

$$P_{line} = b_1 \cdot P_{\max 1} + b_2 \cdot P_{\max 2} \qquad (27)$$

The final restriction forces the power line to be between zero and maximum power of each line.

C. Other restrictions

Obviously, since it is a resolution of some kind of power flow, the basic restriction that that the system has to fulfil will be the **power balance** at any bus. The equation for a given bus and period would be:

$$\sum P_{ren} + \sum P_{sto} + \sum P_{line} - \sum L = 0 \qquad (28)$$

with:

P_{ren} , RES power connected to the bus, [MW]

L , Load connected to the bus, [MW]

4. Case results

Two studies on the same network and conditions were carried out, one without a turbine unit system and another with the turbine system, with the purpose of being able to compare the economical advantages or disadvantages, that this kind of energy would introduce in the system. The obtained results were the following ones:

A. Case without a turbine unit

In this case, storage bus only has the pumping system, the impulsion pipe and the regulation pool in order to cover the irrigation needs.

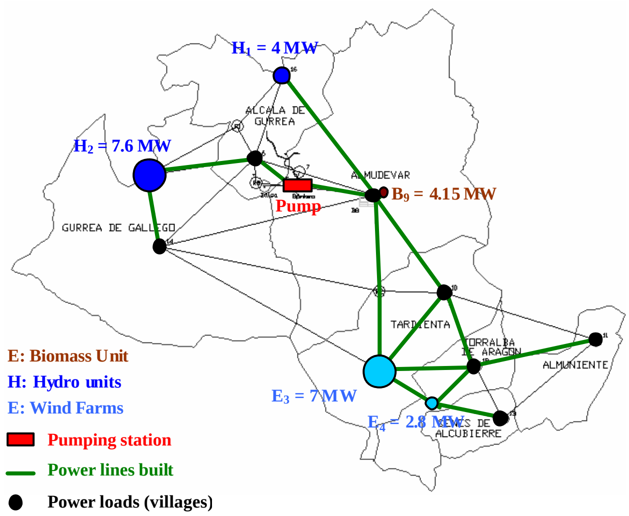

Fig. 9.- Result of system without a turbine unit

Numerical results obtained for each element of the system is showed below:

TABLE I.- Results of case without a turbine

Wind Farm bus 1	0 kW
Wind Farm bus 2	0 kW
Wind Farm bus 3	7 039 kW
Wind Farm bus 4	2 825 kW
Wind Farm bus 5	0 kW
Hydroelectric bus 15 (2)	7 660 kW
Hydroelectric bus 16 (1)	4 000 kW
Biomass bus 9	4 168 kW

Turbine unit	0 kW
Pumping system	994 kW
Regulation pool	37 642 m^3

And the diary cost of this case is:

$$f = 4369 €/day$$

TABLE II.- Distribution of pumping and turbine periods, and evolution of water reserve in regulation pool

	PERIODS							
Total loads of the system (MW)	4.86	4.86	14.59	9.71	**19.45**	14.59	9.73	4.86
$P_{turbination}$ (MW)	0.00	0.00	0.00	0.00	**2.26**	0.00	0.00	0.00
$P_{pumping}$ (MW)	-1.53	-1.53	-1.53	-1.53	**0.00**	-1.53	-1.53	-1.53
Vol. in pool (m^3)	43 502	57 836	55 920	54 004	**2 416**	500	14 834	29 168

B. *Case with a turbine unit*

In this case, storage bus has the pumping system, the impulsion pipe, the regulation pool and the turbine unit.

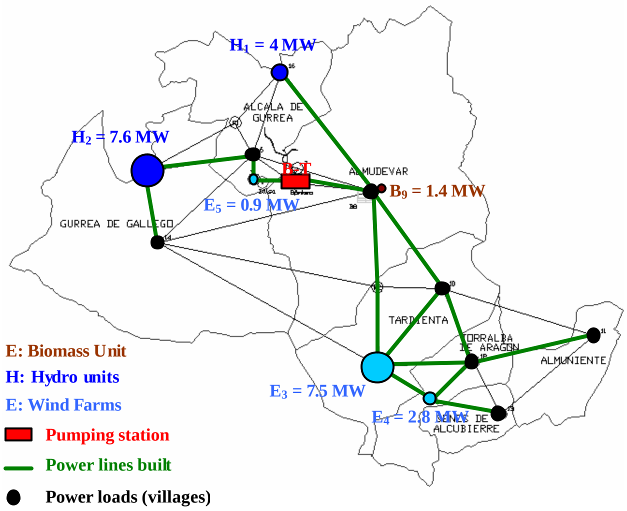

Fig. 10.- Result of system with a turbine unit

The results obtained in each period by pumping-turbine system are in TABLE II. We can see like the pumping system stores energy in water form during several periods to turbinate them latterly, in periods of high power demand.

This system generates a great saving, since in the previous case, to take care of this peak of demand, it was necessary to build 3 MW more for the biomass plant, much more expensive that a turbine connected in the pumping station that already exists.

In addition, we can see that in this case, we have obtained a wind farm in bus nº5 (900 kW). This is because now, that energy is more easily usable, since it is possible to be stored without problems in water form near the generation site.

Numerical results obtained for each element of the system is showed below:

TABLE III.- Results of case with a turbine unit.

Wind Farm bus 1	0 kW
Wind Farm bus 2	0 kW
Wind Farm bus 3	7 495 kW
Wind Farm bus 4	2 825 kW
Wind Farm bus 5	901 kW
Hydroelectric bus 15	7 660 kW
Hydroelectric bus 16	4 000 kW
Biomass bus 9	1 405 kW
Turbine unit	2 264 kW
Pumping system	1 534 kW
Regulation pool	57 835 m^3

And the diary cost of this case is:

$$f = 4285€/day$$

It represents that this system is a 2% cheaper that previous one.

5. Conclusions and main contributions

- We can observe that when we introduce investment and operation costs over the power lines, the graph of the system tends to be radial, avoiding redundant ways.
- Hydroelectric energy is the most useful one, because we obtain in each facility the maximum capacity available. This is due to the good incomes that has the hydroelectric resource, still more when its production is elevated as it is in our case.
- The storage system (pumping and turbine unit) makes a great contribution. It makes the load demand more lineal for the rest of suppliers, with 2 MW of extra power for worse periods. This allows reducing the dimensions of the rest of generators, mainly the biomass. In addition, it allows taking advantage of the nearest RES, because its storage is more easily.

Acknowledgment

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