

# Energy System Planning Considering Renewables and Pumped-storage Power Plants

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**Abstract**—Renewables will play an important role in the generation for the next decades, but the great problem they face is the intermittency of the natural resource availability, mainly when considering solar and wind generation. In this context, the pumped-storage finds a great opportunity. Its operation consists of two mains mechanisms: to pump water to be stored in an upper reservoir when there is surplus of energy in the system, and to generate as a regular power plant, with the stored water, when there is a lack of energy in the system. This paper presents an introductory with a revision of the world consumption and capacity of 2030 considering the parcel of renewables, and a simulation of several possibilities of the energy mix in various Scenarios. The simulations consider mainly the contribution of pumped-storage hydro. The possible arrangements of construction pumped-storage hydro, costs, and a mathematical model of linear optimization using pumped-storage are analyzed and presented. The developed method is applied to several Scenarios and the conclusions are obtained from that.

**Index Terms**—System planning, pumped-storage, renewable energy.

## I. INTRODUCTION

IN possible future scenarios, renewable generation will become more important and will have a big share in the generation mix, helping to reduce the emissions caused by coal and gas generation and to reduce the amount of CO<sub>2</sub> in the atmosphere. Therefore, renewable use seems to be a non-return path. Table I shows the world mix and the installed capacity, for some years ago and expected for 2030 [1].

The greatest problem of renewable generation is the intermittency. Even in the hydro based power generation there is intermittency. The flow of water's regime is not constant, and in the past, reservoirs were built to regulate the flow.

The same idea is used nowadays for all scales of power generation and electrical and non-electrical batteries of different magnitudes have been used to regulate the intermittency of renewable resources [2-4], and generating when there is an energy deficit.

Manuscript received September 11, 2017; revised September 29, and October 9, 2017; accepted November 20, 2017.

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TABLE I. WORLD CONSUMPTION AND CAPACITY OF ELECTRICITY [4].

	Electricity generation (TWh)				Growth (% p.a.)		Change vs. RS (%)	
	1990	2004	2015	2030	2004-2015	2004-2030	2015	2030
<b>Total generation</b>	11 731	17 408	23 682	29 835	2.8	2.1	-4.6	-11.6
Coal	4 478	6 917	9 751	10 914	3.2	1.8	-8.1	-25.8
Oil	1 313	1 161	1 154	869	-0.1	-1.1	-3.4	-7.6
Gas	1 613	3 412	4 730	6 170	3.0	2.3	-9.6	-20.8
Nuclear	2 013	2 740	3 268	4 106	1.6	1.6	5.1	24.3
Hydro	2 148	2 809	3 738	4 903	2.6	2.2	1.5	3.2
Renewables (excluding hydro)	166	369	1 041	2 872	9.9	8.2	5.5	26.8
<i>Biomass and waste</i>	125	227	455	983	6.5	5.8	8.0	22.2
<i>Wind</i>	4	82	449	1 440	16.7	11.6	3.8	27.3
<i>Geothermal</i>	36	56	100	185	5.5	4.7	0.3	6.3
<i>Solar</i>	1	4	34	238	21.0	16.8	12.8	67.8
<i>Tide and wave</i>	1	1	2	25	11.3	15.8	24.3	117.2

	Capacity (GW)			Growth (% p.a.)		Change vs. RS (%)	
	2004	2015	2030	2004-2015	2004-2030	2015	2030
<b>Total capacity</b>	4 054	5 418	7 104	2.7	2.2	-4.1	-9.8
Coal	1 235	1 664	1 885	2.7	1.6	-8.9	-26.5
Oil	453	466	336	0.3	-1.1	-3.0	-11.2
Gas	1 055	1 491	2 059	3.2	2.6	-7.0	-16.6
Nuclear	364	412	519	1.1	1.4	5.3	24.7
Hydro	851	1 100	1 431	2.4	2.0	1.9	4.2
<i>of which pumped storage</i>	79	79	79	0.0	0.0	-	-
Renewables (excluding hydro)	96	285	874	10.4	8.9	5.3	29.6
<i>Biomass and waste</i>	36	74	158	6.7	5.8	7.9	22.0
<i>Wind</i>	48	174	538	12.5	9.8	3.7	25.3
<i>Geothermal</i>	8	15	26	5.4	4.6	0.3	6.0
<i>Solar</i>	4	22	145	17.7	15.2	12.9	65.6
<i>Tide and wave</i>	0	0	7	6.0	13.3	23.7	116.9

The pumped-storage plant (PSP) plays a very special role in a power system full of renewables, storing excess energy. In fact, there is a great intermittence in the energy input. Solar and wind varies a lot depending on environmental issues. Therefore, the PSP sends water to an upper reservoir, storing energy when its price is low, and acts as a conventional hydro power plant generating energy at a higher price, balancing the system and making it a profitable resource for the system operation [5].

This paper presents the role of pumped hydro, mainly for its characteristics of storing a great amount of energy. The basics of pumped hydro is presented, their cost, and a mathematical model of linear optimization is presented in order to simulate the energy mix in the fore coming years.

## II. PUMPED STORAGE BASICS

Storage is considered the essential partner to wind and solar generation, making renewable power dispatchable, reliable, and efficient, spreading its application to a wide coverage. What is new is not the idea of storage, but the need for a different magnitude of it to accommodate an intermittent power supply in order to balance the energy over a cycle of storage and generation.

PSP have an upper water reservoir, which can be either natural or artificially created, and a lower reservoir that can be a lower basin or a river. In case electricity is required, water

flows from top to bottom, driving a turbine-generator set, and electricity is delivered through a transformer to the grid. In case of electricity in excess, motor drives a pump which sends the water from the lower reservoir to the upper reservoir and potential energy is stored [5].

In the pump mode the electric machine act as a motor and the speed of the unit is varied in accordance to the amount of water wanted to be stored per time. When the power plant acts as a conventional hydro power plant, the electrical machine works as a generator connected through a compatible element to a fixed frequency grid.

PSP can also have an upper reservoir with a natural input; therefore hydro is renewable power generation and energy storage in one plant. Depending on stored volume the pumped hydro can be classified among daily, weekly, monthly and yearly regulation.

The basic equation of the generated power is

$$P = \rho g Q \Delta h \eta \tag{1}$$

Where  $P$  is the generated power (kW),  $\rho$  is the water density ( $\text{kg/m}^3$ ),  $g$  is the local gravity constant ( $\text{m/s}^2$ ),  $Q$  is the water flow ( $\text{m}^3/\text{s}$ ),  $\Delta h$  is the height difference, and  $\eta$  is the overall efficiency of power conversion (p.u).

The available consolidate technologies of bulk energy storage that are suitable for the operation with and integration of large scale new renewables are the compressed air storage and the pumped storage. PSP exists in some different arrangement sets of machines: binary reversible machine sets, (pump-turbine motor-generator); ternary systems (consist of separate hydraulic machines installed on the same axis of the motor-generator); or even quaternary systems (in which the pump-motor set is completely separated from the turbine-generator set).

One of the state-of-art arrays is the ternary system, it consists of a motor-generator and separates turbine (typically Francis or Pelton) from the pump set. As two separate hydraulic machines, the rotation direction of the motor-generator can be the same while pumping or generating energy, reducing the mechanical stress on the axis and the unit can change from one mode to other more often, up to 200 times in a day. For the switching between turbine and pump operation, a clutch operable at standstill, a starting turbine or a synchronizing torque converter can be used. A scheme of this array is showed in Fig. 1.

Other concept of array for a pumped storage scheme that is largely installed is the binary system and consists of a motor-generator and a reversible pump-turbine that works either as pump-motor or as a turbine-generator depending on the direction of rotation, this scheme can be seen in Fig. 2. With a wide range of specific speeds, pump-turbines can be installed at sites with heads from less than 50 to more than 800 m, and with unit capacities ranging from less than 10 to over 500 MW.

If the system is assebled using an asynchronous motor-generator the rotational speed of the pump turbine can be varied, thus, the pump capacity can be adjusted to use the currently available amount of energy, which allows the project of more compact power houses, implying in savings on equipment and civil costs.

Pump storage is localized in the system as bulk storage, often near generation on the grid.

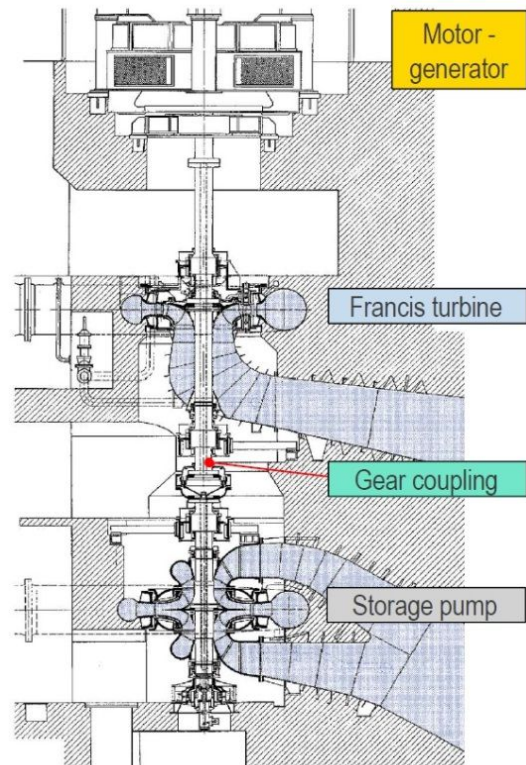


Fig. 1. Ternary group of Salto del Pintado PSP [6].

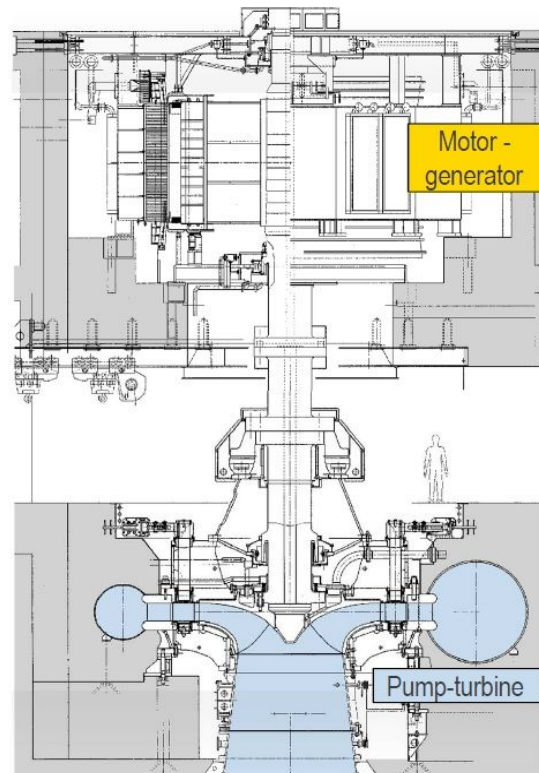


Fig. 2. Binary group of Goldisthal PSP [6].

This design allows for more compact power houses implying in savings on equipment and civil costs. Pump Storage is located in the system as bulk storage, often near generation on the grid.

### III. METHODOLOGY

It was considered that in an ideal electric system all the generated energy must be consumed instantly, or that each instantaneous demand for electric energy must have an equivalent instantaneous generation, once the system is not provided with ancillary services of batteries and the losses in transmission lines are not considered. The utilized mix of sources to provide power for the electric load consists of nuclear plants, hydro power, coal, gas peaking, wind farms and solar farms. The equations below show the approach adopted to solve the optimized dispatch problem.

$$P_t = D_t \quad (2)$$

$$P_t = \sum_{\substack{i \in I \\ t \in T}} p_{it} \quad (3)$$

Where  $P_t$  is generated power in instant of time  $t$ ,  $p_{it}$  is the generated power by each considered source at instant of time  $t$ .  $I$  is the set of power sources, i.e., nuclear, hydro, coal, gas peaking, wind, and solar; and  $T$  is the set of time intervals.

The best solution to meet the demand is related to the mix of generation sources that gives the lowest energy price, taking into account the availability and the variable price in US\$/MWh of each power supply that can be dispatched. In order to achieve the minimum cost of operation for the system, an optimization problem was solved using linear programming. The method consists in achieving the lowest cost to attend demand, mixing the different sources of power. The balance is made considering different prices for the available sources: nuclear, coal, gas peaking, hydro, wind and solar. The objective function of the optimization is shown above; its parameters were subjected to linear equalities and linear inequalities constraints.

$$D_t = \sum_{\substack{i \in I \\ t \in T}} x_i p_{it} \quad (4)$$

One of the simulation's objective was to test if a pumped storage can maximize the share of new renewables, wind and solar, as this source compete with the other sources. This would avoid wind and solar generation curtailments in periods of low demand, and minimize the dispatch of coal and nuclear plants as well as the run of gas peaking machines.

TABLE II. LEVELIZED COSTS OF ENERGY [6].

Power Source	US\$/MWh		
	Min	Max	Average
Solar utility scale	49	61	55
Solar rooftop	78	135	106.5
Wind onshore	32	62	47
Wind offshore	118	118	118
CSP	119	182	150.5
Biomass	77	110	93.5

Gas peaking	165	217	191
Nuclear	97	136	116.5
Coal	60	143	101.5
Hydro	40	77	58.5
Pumped Storage	188	274	231

Once the inputs of the natural resources are made to estimate how much energy is available from new renewables, it is possible to estimate the renewable energy cut to scale out a bulk storage capacity to enhance the operation of the system.

### IV. ADOPTED SCENARIOS

The formulation was applied to three different mixes of sources called Scenarios 1, 2 and 3. Scenario 1 comprehends a hydro based system projected to the 2030 horizon. Scenario 2 is a thermo-based system projected to the 2027 horizon. Scenario 3 is an all renewables system planned to the 2050 horizon. The share of each source in the mix is scaled in installed power. The figures below show the electrical mix of sources for each given Scenario.

In the Scenario 1, the pitched in Fig. 3, the hydro power plants are considered run of river and therefore do not have storage capacity for regularization of the generation. The affluent natural energy is of a dry period, when the flow of water is 45% of the maximum of the average historical series of flows in ten years. It also takes in consideration a share of 16% of new renewables in the mix. The scenario 1 is shown in Fig. 3.

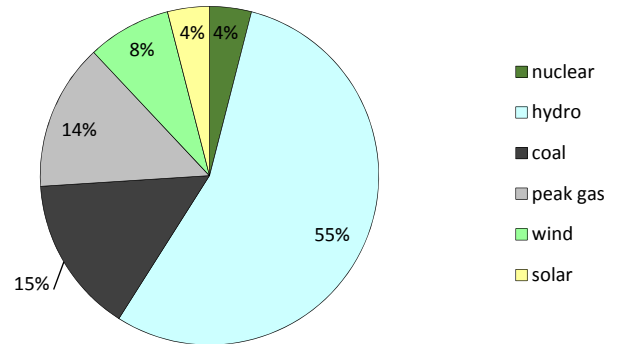


Fig. 3. Mix in a hydro-based PES.

In Scenario 2 it is proposed a change from a thermo-based energy mix of sources to a more renewable one, through the insertion of new renewables: wind and solar. These mixes were evaluated using the optimization model in order to achieve the best combination of sources. The price of energy for each source was set in according with the reference values in Table II and the best economically dispatch, in according with the simulation, indicates rather if there is lack or surplus of renewable energy, with the objective to increase the share of new renewables throughout the use of pumped storage. Such change on the mix can be observed comparing the Fig. 4 with the Fig. 5.

In the Scenario 3, depicted in Fig. 6, the mix power generation sources are solar photovoltaic, wind onshore, concentrated solar power and biomass. The total installed capacity accounts for 154 GW and as its nature for

intermittency, is natural to predict that energy storage shall be indispensable for the operation and meeting the load.

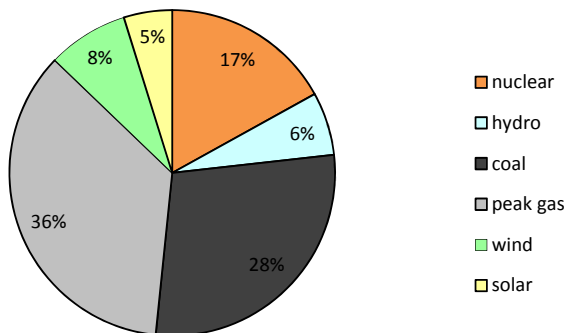


Fig. 4. Mix in a thermo-based PES.

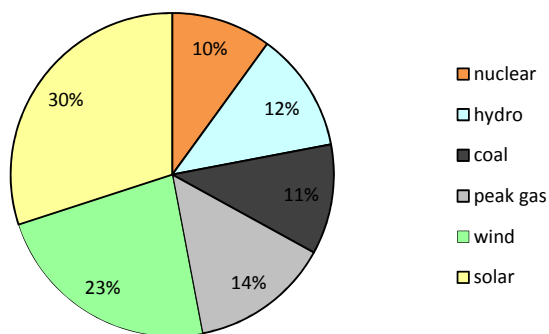


Fig. 5. Mix in an all renewable PES.

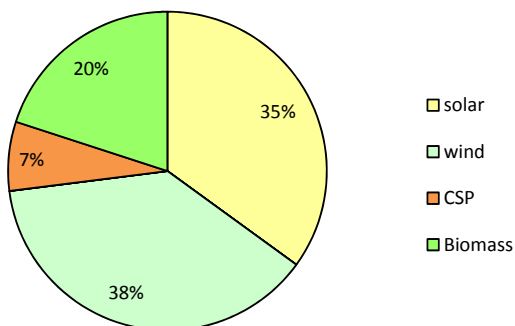


Fig. 6. Mix in an all renewable PES.

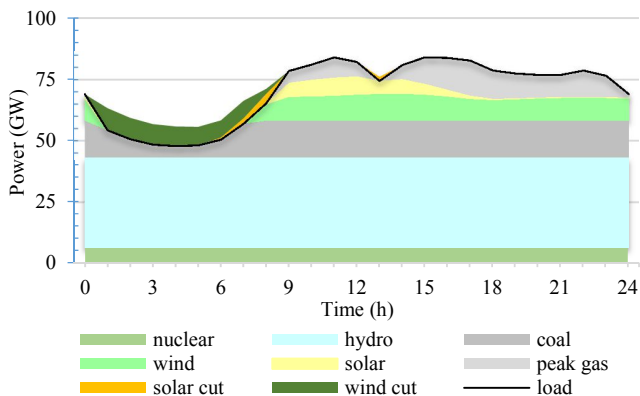


Fig. 6. Optimized dispatch for Scenario 1, mix of sources without PSP.

The end costs of energy per source used to ponder the level of usage of each installed capacity are shown in the Table III [6]; these values were extracted from the Lazard's report of December 2016.

TABLE III. PRICES CONSIDERED IN SCENARIO 1

Power Source	US\$/MWh	Capacity Factor
Nuclear	97	0.95
Hydro	40	0.60
Coal	60	0.65
Wind	62	0.60
Solar	55	0.32
Gas peaking	191	0.95
PSP	188	-

The report brings a range of values from minimum to maximum real prices from different plants all over the United States. For the calculations, mainly the average value of each source was considered.

### V. SIMULATION AND RESULTS

The results for the simulations of the given Scenarios above are shown on the frames below. The Figs. 6 and 7 presents the accomplishments for the Scenario 1. For that simulation the nuclear energy availability was considered inflexible due to operational characteristics of the system and the other sources are varying with the market prices of the energy for each one. With those given conditions, the optimum dispatch for the system results in a wind and solar energy cut in the period of lower demand.

If the PSP is introduced into the mix's mix of sources the renewable energy becomes useful, pumping water and storing potential energy for later use. During the peak hours the energy is re-leased into the power electric system and contributes to attend the peak demand, avoiding the dis-patch of expensive gas peaking, as it appears in Fig. 8, making use of clean energy and resulting on a lower operational cost in US\$/MWh, as appears in Table IV.

TABLE IV. RESULTS OF SCENARIO 1

Scenario 1	Without PSP	With PSP
Renewable energy cut (GWh)	59.9	2.9
Operation cost (US\$/MWh)	70.3	65.4
Installed Capacity (GW)	136	141

In Scenario 2, if it is considered that the power sources are competing in the market and are dis-patched for their price from the lowest to the highest, the surplus of renewable energy is available only when there is the renewable resource available and the price operation of such a renewable power plant is higher than the price of thermal sources such as coal and gas. Fig. 9 presents the results of the linear optimization for the mix presented in Fig. 4. In this case wind energy is more expensive than coal energy, as shown in table. This must be considered that nuclear power plants are inflexible, the result is a wind power cut in the period of low demand. The prices considered in Scenario 2 are presented in Table V. Table VI presents the results of Scenario 2, nuclear inflexible.

On the other hand if the nuclear plants are flexible to vary with the market prices and if the wind energy is cheaper than

coal energy, the optimization model results in the total absorption of renewable energy that is available in the system and no storage is needed to compensate and accumulate the surplus for further use, once the coal plants will run as a backup when the source is not available. The prices are the same and the results are presented in Table VII.

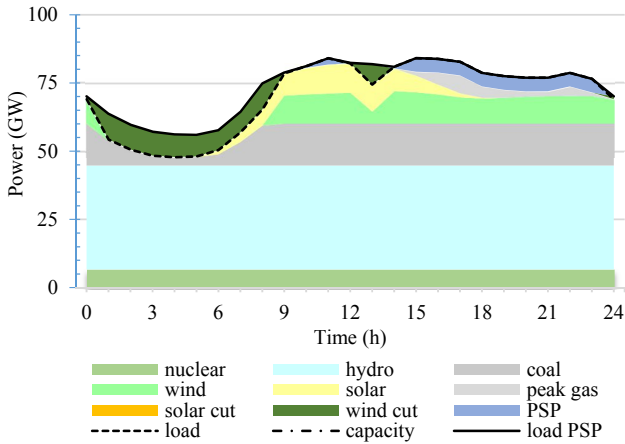


Fig. 7. Optimized dispatch for Scenario 1, mix of sources with PSP.

Considering an increase in renewables for the 2027 year, as shown in Fig. 5, the problem indicates the best dispatch to meet the load as in Fig. 10. In order to achieve this solution the thermal nuclear and coal plants were considered inflexible because of power security. This it is possible to maximize and scale up the pumped storage for bigger energy absorption during days when the natural affluent energy is plenty.

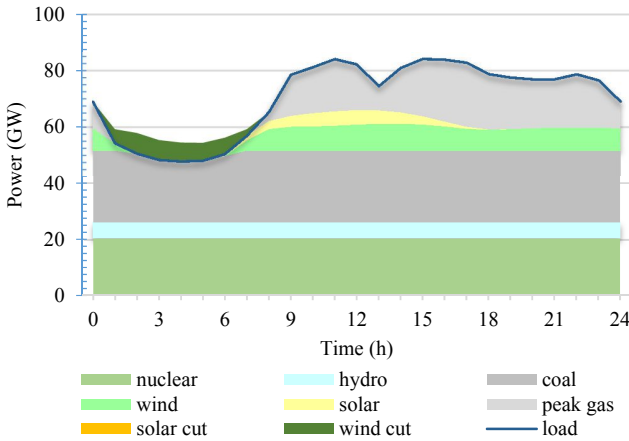


Fig. 8. Optimized dispatch for Scenario 2 with nuclear inflexibility.

TABLE V. PRICES CONSIDERED IN SCENARIO 2

Power Source	US\$/MWh	Capacity Factor
Nuclear	97	0.95
Hydro	58.5	0.60
Coal	60	0.65
Wind	62	0.60
Solar	49	0.32
Gas peaking	191	0.95
PSP	-	-

TABLE VI. RESULTS OF SCENARIO 2 – NUCLEAR INFLEXIBLE

Scenario 2	Without PSP
Renewable energy cut (GWh)	43.6
Operation cost (US\$/MWh)	90.0
Installed capacity (GW)	136

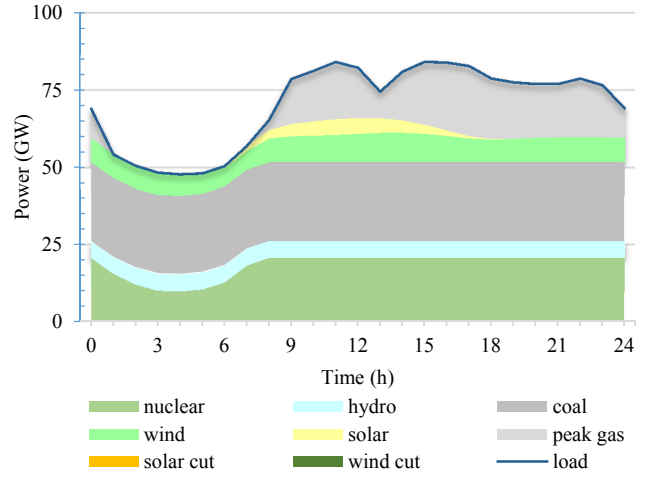


Fig. 10. Optimized dispatch for Scenario 2 with nuclear flexibility.

The share of each source in the mix is scaled in installed power. The following figures show the mix for each given Scenario. Figure 12 shows the optimized dispatch for Scenario 2 with increase of renewables running on nuclear and coal inflexibility and with PSP. The problem solving was applied to three different source mix named as Scenarios 1, 2 and 3. Scenario 1 comprehends a hydro based system projected to the 2030 horizon. Scenario 2 is a thermo-based system projected to the 2027 horizon. Scenario 3 is an all renewables system planned to the 2050 horizon.

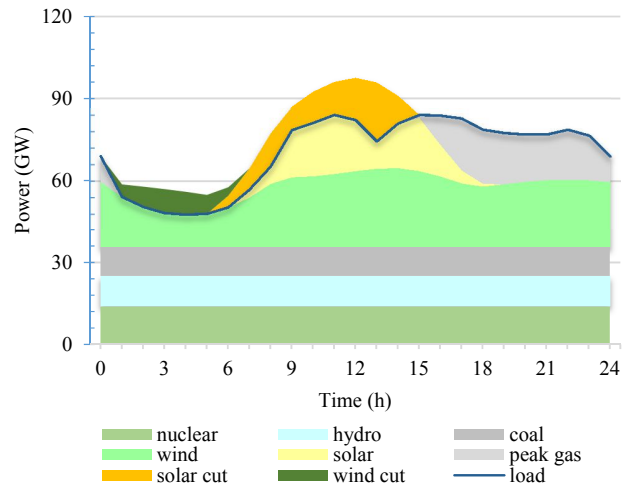


Fig. 11. Optimized dispatch for Scenario 2 with increase of renewables running on nuclear and coal inflexibility.

The model also considered energy storage using PSP. Table VIII shows the considered proces for nuclear flexible. While Table IX presents the main results obtained for Scenario 2

considering nuclear generation inflexible. In the all renewable Scenario, there is surplus of energy during the first hours of the day, including the period when the demand is highest. In the least hours of the day the generation coming from the available sources do not have enough installed capacity to meet the electric load, as it is shown in Fig. 13.

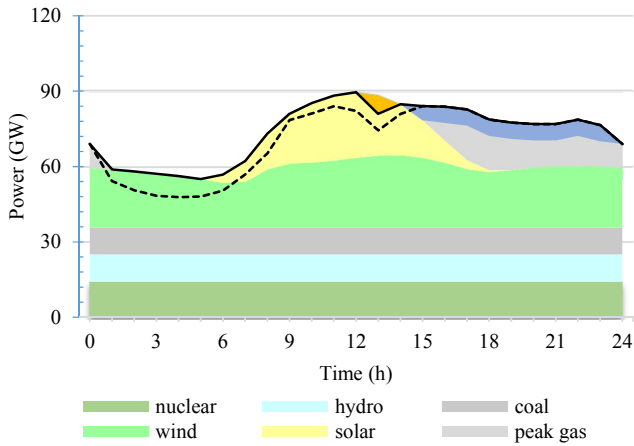


Fig. 12. Optimized dispatch for Scenario 2 with increase of renewables running on nuclear and coal inflexibility and with PSP.

TABLE VII – RESULTS IN SCENARIO 2 – NUCLEAR FLEXIBLE

Scenario 2	Without PSP
Renewable energy cut (GWh)	0.0
Operation cost (US\$/MWh)	88.5
Installed capacity (GW)	136

TABLE VIII. PRICES CONSIDERED IN SCENARIO 2

Power Source	US\$/MWh	Capacity Factor
Nuclear	97	0.95
Hydro	40	0.60
Coal	60	0.65
Wind	32	0.60
Solar	49	0.32
Gas peaking	191	0.95
PSP	188	-

TABLE IX. RESULTS OF SCENARIO 2 – NUCLEAR INFLEXIBLE

Scenario 2	Without PSP	With PSP
Renewable energy cut (GWh)	89.5	3.75
Operation cost (US\$/MWh)	66.1	64.9
Installed capacity (GW)	150	156.5

TABLE X. PRICES CONSIDERED IN SCENARIO 3

Power Source	US\$/MWh	Capacity Factor
CSP	119	0.50
Biomass	77	0.80
Wind	32	0.60
Solar	49	0.32
Gas peaking	191	0.95
PSP	188	-

When the system operates with storage capacity the extra amount of energy can be stored as water’s potential energy. A fraction of this energy is lost due to the plant’s machines performance. The efficiency adopted for the overall losses in the system, including the processes of pumping and generating was 0.87. The prices and simulation results for Scenario 3 are presented in Tables X and XI respectively.

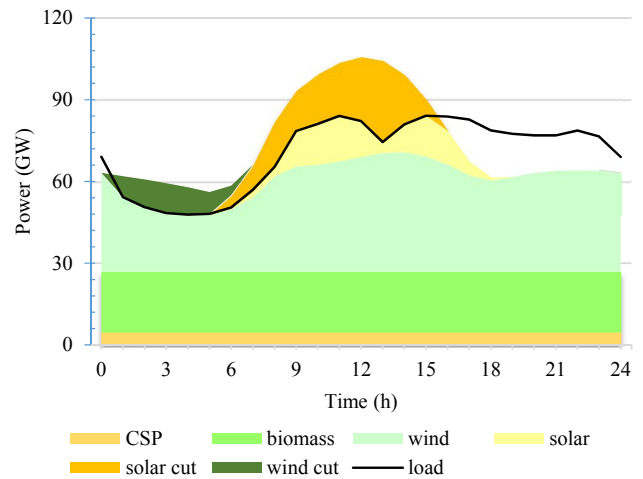


Fig. 13. Optimized dispatch for the all-renewable PES without storage system

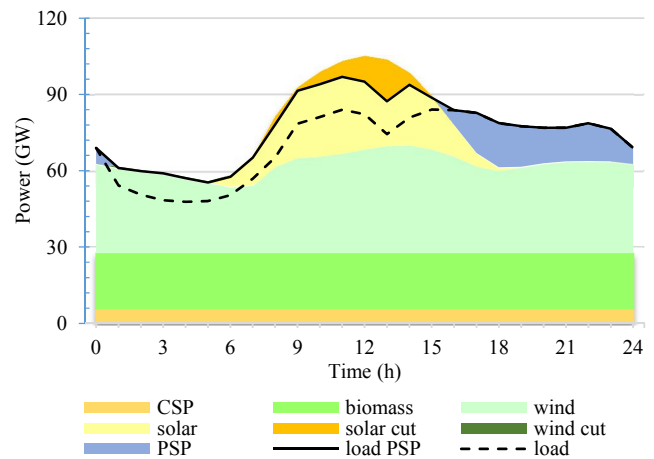


Fig. 14. Optimized dispatch for the all-renewable PES operating with a PSP

TABLE XI. RESULTS OF SCENARIO 3

Scenario 3	Without PSP	With PSP
Renewable energy cut (GWh)	190.7	27.5
Operation cost (US\$/MWh)	63.0*	60.3
Installed capacity (GW)	154	154

As can be seen in Fig. 14, the installed capacity of PSP meets the demand in the least hours of the day using the extra energy from the first hours of the day. This is like saving sun and wind for later hours, when those resources are not fully available for the operation.

## VI. CONCLUSIONS

The purpose of the simulations was to test if the insertion of a PSP in the power electric system could result in operational gains for an optimal dispatch of the available sources in the system. The model was fed with data of two typical power systems in Scenarios 1 and 2, and with a possible future system data of only renewables, for Scenario 3.

It was observed in all the simulations that the average operational cost of the systems decreased in US\$/MWh when there was renewable energy replacing coal and nuclear plants and decreased even more when there was a PSP storing cheap off-peak energy, often renewable energy, for peak use, replacing gas.

The base for the cheaper cost of operation provided by Lazard's indicate the price for the energy generated on renewable plants are getting cheaper and cheaper every year and becoming more attractive than nuclear, coal and gas. Another reason for the cheaper price is due to the system operating with a pumped storage system, the basic rule of profit: buying cheap and selling more expensive. It takes the power system to an economic better point of operation, even more when the pumped energy comes from renewables, for example, because they do not pay the fuel to run.

Comparing the gain caused by the PSP operation into the developed Scenarios is possible to quantify that in Scenario 1 the operation is 7% cheaper with PSP when accumulating extra wind energy. In Scenario 2, analyzing the increase on renewables, the cost of operation is 2% less with PSP than without, and in Scenario 3 besides being 4.3% cheaper to operate the system with PSP, the storage use is mandatory in order to achieve the load demand on an all-renewable sources mix. When developing this work it was observed that other benefits that pumped storage can bring to the system operation as a provider of ancillary services were not considered.

Further development is possible to be made to quantify the overnight costs of implementation for these structures and to calculate the total economic viability using monetary mechanisms, like green bonds for not generating from CO2 emitter sources and avoided costs of fuel to run thermal plants once renewables run on free fuel.

This work showed a bit of what is already written in literature and of what is becoming reality in some parts of the world: batteries play an indispensable role in the change from operating the electric generation with carbon based sources to a more or total renewable based sources system. Accomplishing the goal of going renewable is really very feasible, once the technologies needed are all available in the market.

Finally, since techniques make it possible to be installed and is supposed to exist free market competition beyond the sources, two of the most important attitudes to be taken in order to achieve renewable and clean energy goals are the policy making and the programs of implementation.

## VII. ACKNOWLEDGMENTS

The authors would like to thank FAPEMIG, CAPES, and CNPq for the continued support in conducting research.

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