

Article

Optimal Insertion of Energy Storage Systems Considering the Economic Dispatch and the Minimization of Energy Not Supplied

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Abstract: This study presents an optimal insertion model for battery storage systems in the nodes of an electrical transmission network. The proposed model is developed through mixed integer linear programming applied to the calculation of DC power flows, considering restrictions given by the characteristics of the network and by the parameters of the generation units. The proposal's main objective is to reduce the costs of operation and non-supplied energy produced, due to needing to meet the demand fully or partially. As a case study to evaluate the proposed methodology, the IEEE 24-bar test system is used. In this base case, electrical generators that depend on different primary energy resources are modeled: hydraulic, thermal, photovoltaic, and wind, in addition to potential electrical energy storage systems. These storage systems are assigned as possible analysis scenarios through the proposed optimization technique. The study is carried out in a time horizon of 24 h per day, according to a standard demand curve. With the incorporation of optimally selected storage systems in their capacity and location, it is possible to minimize dependence on the use of fossil fuels. In addition, considerable savings are obtained by reducing generation costs, and the stability of the energy supply is guaranteed. This novel proposal presents a methodology that covers all the variables of this problem, thus guaranteeing an authentic and precise study in terms of optimization. The results obtained highlight and demonstrate the benefits of stability, continuous attention to demand, reduction in dependence on exhaustible and polluting sources, and cost reduction.



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1. Introduction

The electricity system has the task of proposing strategies to guarantee its operation and fulfill its mission of covering the current and future energy demand, which is growing rapidly, in line with global economic and technological development. The electricity market has been opened to new efficient technologies being applied, to strengthen electricity production using clean, non-polluting energy sources and energy storage systems. This has encouraged the interest in conducting this research [1].

The capacity of power system equipment must correspond to the energy needs of consumers. This postulate corresponds to the balance between the generation and consumption of electrical energy. It constitutes a challenge for electrical systems in operation in real-time, since the demand is presented as a dynamic hourly consumption with high uncertainty, which threatens the system's adaptability. Considering this scenario, it is worth highlighting the importance of the new technologies mentioned above, to find alternative sources and means to accumulate energy, since they support the network and makes the system dynamic [2,3].

In this circumstance, the energy supply agents must have an adequate response in their operation and the correct planning for the load supply. Thus, according to [4], the

energy produced must exceed by an estimated 20% percent the energy demanded by users, to maintain a balance.

The transfer of electrical energy in most power systems is instantaneous to the load, which increases the level of risk in operation due to the occurrence of faults, causing the loss of continuity in the delivery of the electrical supply [5]. Due to this inefficiency, the dynamic nature of consumption, and the instability of the different energy sources they use, new energy storage strategies are crucial to support the system, because of their reliable structure, security, and economic benefits. They also open the door for other generating units to achieve greater efficiency and decrease losses in energy transport activity [6–8]. The ESS (energy storage system) strengthens the operation of the electricity system and provides opportunities for the entry of alternative generations, mostly from renewable energy sources. This way, the system can expand its capacity to meet the demand [9].

Different types of energy storage require schemes that efficiently manage the energy received for its conservation and subsequent delivery, executing optimal and safe work. Various means harness the available resource, such as energy from electrochemical and thermal effects, potential and kinetic energy, or electromagnetic energy [10]. These multiple solutions have their limitations, based on the portion of the energy they can take for storage, the on-site installation of the systems, and the likelihood of continuous operation. These requirements are met mainly by systems of electrochemical origin due to the robust, flexible, and constant development of their technology, especially batteries, with their diverse chemical composition (Pb, Ion, Li, Cd–Ni, S–Na, etc.). Therefore, their applicability to the electrical grid can be highlighted because they are economically profitable, reliable, high-performance, flexible, and high capacity [11,12]. Battery storage is a primary response mechanism in delivering energy to the grid, and its operation is extended for long periods. It is worth highlighting the composition of lead–acid batteries which, due to their robust design, are the most widely implemented large-scale ESS in the electrical system [13].

The transcendental function of energy storage systems, for the present case of batteries, which is the most used EES when operating power systems, is to find a balance between the participating parts of the system, precisely, the productive amount, with several solutions that demand electric service. In addition, their role is to dampen the fluctuations coming from conventional and non-conventional energy sources and provide stability to the network [14]. Therefore, it is relevant to perform an analysis focused on the impact of the penetration of battery storage energy systems, or BESS, to plan and operate the power system and thus be able to access the benefits in the stages of the system, starting with the decrease in losses and readjustment of power flows, which decongests the network and postpones the overall growth of the system, improving voltage levels and reliability [15].

Considering the advantages of the BESS, there have been works such as [16,17] that, using mixed integer programming, have designed an optimal network integrated with BESS. The authors of [17] optimally integrate these systems, with renewable energy-reducing costs as an objective function, as does [18]. Still, this work locates the storage systems based on the dimension of the transformers, and [19] incorporates the BESS into the network but reduces losses.

Based on the literature review, it is possible to define aspects that highlight the contribution of this modeling in comparison with previous work [20–22]. This proposal is defined by a mixed integer linear type programming, that considers constraints and technical characteristics of the system and battery storage, DC power flows, and costs (operating, energy not supplied, and storage charge and discharge costs). This study guarantees a complete solution, with consideration of multiple variables. Thus, with the purpose of implementing a methodology that allows the optimal adaptation of the BESS to the electrical system, considering their location, choice, and commissioning in conjunction with the networks, a new generation dispatch model is introduced that, based on technical and economic characteristics, allows locating and sizing the BESS in the network, taking into account constraints, to achieve the objective of minimizing costs, also considering the prices that involve the unserved energy. The model formulation uses linear flow equations and

operating cost variables, to include in the storage dispatch by batteries that are optimally attached to the transmission lines, to meet the supply of consumer demand [23].

In this sense, the model proposed for the optimal location of battery storage systems, considering the economic dispatch and the energy not supplied, provides the following improvements in the electrical power system:

- Reduce operating costs due to the state of charge of the batteries as a storage medium.
- Plan possible expansions in the electrical transmission system by redirecting power flows, through the contribution of energy storage systems.
- Increase firmness in delivering non-conventional renewable energy whose resource is intermittent.
- Minimize the income from the dispatch of thermoelectric generation in hours when the energy cost is high, and prioritize the entry of energy storage systems.
- Mitigate the effect of the emission of polluting gases by reducing plants that demand fossil fuel resources, replacing them with clean energy storage and generation through renewable energies.

2. Materials and Methods

Analysis of Battery Storage in the Electric Grid

BESS is a technology of chemical origin, considered the most common and mature technology used for energy storage. The charging process occurs by sensing electrical power and storing it in sets of cells that, by electrochemistry, create a flow of electrons that can return electricity to its output, reversing the process so that it is now a discharge process [24]. The work of these systems makes electrical grids flexible because they optimize fuel requirements, making them less harmful to the environment. They are highly responsive to load changes, which cushions demand fluctuations and give greater openness to the generation's entry from distributed and renewable resources. Therefore, batteries, in general, are a tool used to improve the quality of energy; they contribute to, or complement, generation and support for transmission and distribution networks [25].

It is possible to detail the most relevant functions of storage in electrical systems [26]:

Generation

Storage is an energy backup used during peak hours, and in cases of contingencies occurring in the generation units, and for black start [27]. BESS is a form of frequency control during critical and normal generation operations and controls the portions of power transfer to other regions.

Transmission Networks

The BESS helps to defer network growth and manage the existing structure concerning congestion, provides stability, and regulates the voltage at the nodes reached by the lines [28–30].

Alternative energy sources

Storage is a complement to adhere a more significant portion of clean generation to the electrical system, where batteries configure energy by fast charging and discharging in operation for more extended periods as required. Due to the energy reserve, demand forecasts are accurate at correcting errors in delivering demand through renewable energies. In addition, it generates decongestion and a reduction in oscillations by sources and charge [31].

Other energy services

With storage, it is possible to manage energy, acting in the face of fluctuations, to improve its quality and reliability.

Some technologies have been recognized among the different means of battery storage, because they have been tested and used over the years, for example, lead–acid batteries. Others, such as flux, nickel cadmium, and lithium-ion, are also available but could be improved for their applicability to the energy market. New technologies are being developed daily to improve efficiency, cost, and flexibility of use, such as fuel cells [32]. The storage mechanisms mentioned above are approximately 60 to 95 percent efficient [22], providing

significant benefits throughout the energy chain. The main objective of integrating BESS into electricity grids is to contribute to demand supply, as an economically and technically strategic backup supply source.

It should be noted that the costs corresponding to the operation of the generators, transportation activities, and maintenance, up to the point of supply, must be well managed or optimally minimized by the system operators and planners, since the consumers must pay these costs. Therefore, an adequate cost calculation is reflected and evidenced in the tariff of the service, and such service must comply with the due requirements of quality, safety, and reliability. Deficiencies or lack of energy supply in the system result in a cost for energy not supplied that, in competitive markets, must be assumed by the responsible party, or that is justified in the tariff. This concept is related to the energy storage activity because it represents an adequate backup for the electric grid in terms of possible lack of energy supply or unserved energy, which can be reduced by integrating ESS [33,34].

When energy resources are optimized, it is necessary to consider the use of energy that, in specific processes or stages of generation, is produced in excess, and that can be used as a reserve to cover the load directly or indirectly when required, to obtain an energy balance. This can be achieved with storage systems [35].

The disadvantages of BESS are that, their implementation can lead to high investment costs, and their adaptation to the power system requires planning for their optimal integration according to the objectives at technical and economic levels. The choice of the appropriate storage technology depends on the performance indicators of each storage system, because although each technology has the same objective, the design has different particularities depending on its energy origins, such as efficiency, lifetime, self-discharge, and deep discharge rate, capacity, power, and energy density with their specific and nominal values, as well as implementation costs depending on the cost of energy [10,36].

Sizing and optimal location of BESS

The insertion of storage systems is challenging for the electrical grid, so the ideal location and capacity must be considered, to minimize costs and losses and improve voltage and power quality, to avoid contradictory results affecting system stability and cost benefit [14,37].

This first analysis of the BESS involves an optimization problem, because it is not profitable to place these systems in all the busbars of the network, due to their large extension and because their size cannot be exceeded, due to the costs involved in the implementation [38]. To achieve a scenario adapted to the needs of the system, it is necessary to model the power system electrically and economically with storage, to find the proper sizing and management of the facilities, including the possibility of the entry of renewable and distributed generation and its subsequent integration into the electricity market [39]. For this reason, for storage modeling, in this case, the BESS, an electrical model is initially used, where the location and/or energy capacity is calculated based on restrictive operating limits, so that the incorporation of batteries is reliable and safe, and then the financial details are analyzed.

Strategic generation unit with BESS

The economical operation is the next challenge for the inclusion of BESS in the generation dispatch, where the generation units and BESS available to supply electricity to the system demand are configured. The objective of this dispatch problem is to minimize the cost function, considering the cost of the energy not supplied, so the model must consider the equipment restrictions. For the current case, in order to locate the battery storage, capacity limits, power charge, and discharge states, and a selection variable for the BESS input are presented; if the network is considered, flow limits for the lines are included; and for generation, power limits, start and stop ramps, power balances in the nodes, among others, depending on how detailed the study or its objective [40].

The electrical or technical combination with the economic one leads to the application of tools to solve optimization problems that jointly determine the sizing and location of the units, as well as the operation in the electricity sector markets [41]. Optimization algorithms

allow different operating strategies to be evaluated, but from the mathematical perspective, for general dispatch that includes BESS along with consideration of the power grid, the modeling of the operating state may be [42]:

- (1) Non-linear for the AC flow equations and a mixed integer for the selection and investment decision variables.
- (2) Linear by the DC flow equations and mixed integer by the selection and investment decision variables [43].

Methodology for optimal placement of BESS by applying linear load flows.

The electrical and market characteristics corresponding to the system structure must be included in the mathematical formulation of the model to be solved by optimization, to locate the energy storage systems considering power flows.

The programming optimization model, which in this case is mixed integer linear, contemplates objectives and restrictions represented by a set of equations and inequalities that identify parameters and limit the values that the variables involved can have. The characterization that represents the model is detailed below.

Objective function: minimizing total operating costs.

This corresponds to the function to be optimized, of which the minimum value will be found; this objective function is the cost function, considering that it is subject to certain restrictions.

$$FO = \text{Minimize} \rightarrow \text{Total_Cost} \quad (1)$$

The constitution of the objective cost function for the model is in three segments, as follows:

$$\text{Total_Cost} = \text{cost}_1 + \text{cost}_2 + \text{cost}_3 \quad (2)$$

Generation cost of conventional and non-conventional energy sources.

This cost is determined by the product between the variable cost of production and the hourly power dispatched by this generator.

$$\text{cost}_1 = \sum_t \sum_{u \in GC \cup GNC} C_{gu} \cdot G_{u,t} \quad (3)$$

Cost of energy not delivered or not served.

This cost is calculated as the product between the cost of unsupplied energy regulated in each electrical system and the hourly power that was not supplied.

$$\text{cost}_2 = \sum_t \sum_i Y_{ens} \cdot DNS_{i,t} \quad (4)$$

The cost associated with the charging and discharging process of batteries as storage systems. In the case of charging the storage system, the cost is an incremental value. It is determined by the product between the absorbed hourly power of the system and the cost of the electrical energy consumed in that hour. While in the case of the discharge, it is considered a reduction in the total cost, since the storage system delivers energy on an hourly basis, whose valuation is made with the cost of electrical energy at that moment.

$$\text{cost}_3 = \sum_t \sum_i P_C B_{i,t} \cdot \varphi_C - P_D B_{i,t} \cdot \sigma_D \quad (5)$$

where

u	Generation plants
GC	Conventional generation (thermal and hydro)
GNC	Non-conventional generation (wind and solar)
t	Time horizon temporal of analysis
i	Bar or network connection nodes
C_{gu}	The unit cost of generation per generating plant

$G_{u,t}$	Power of each generating plant per hour
Y_{ens}	Unserved energy cost per unit
$DNS_{i,t}$	Load not served per bar in each hour
$P_{CB_{i,t}}$	Battery charging power per bar per hour
$P_{DB_{i,t}}$	Battery discharge power per bar per hour
φ_C	Valued price of the charge
σ_D	Valued price of the discharge

Restrictions

The restrictions that delimit the objective function are related to the generation units, the network, storage, and demand:

Restriction limiting the power delivery capacity of generators.

This restriction guarantees that the generation units' hourly power to be dispatched is within the established technical limits.

$$Cg_u^{min} \leq Cg_{u,t} \leq Cg_u^{max} \quad (6)$$

$$Cg_u^{min} \leq \frac{Cg_{u,t}}{RE_{u,t}} \leq Cg_u^{max} \quad (7)$$

where

Cg_u^{min}	The minimum power of each generator
Cg_u^{max}	Maximum power of each generator
$RE_{u,t}$	Resource occurrence per generator per hour

Hourly power to be delivered and absorbed per generator.

This corresponds to the start and stop ramp, which is a special feature of thermal and hydraulic generators. Technically, this restriction guarantees that the generator does not make an excessive mechanical effort to increase or reduce its power delivered from one hour to another.

$$G_{u,t+1} - G_{u,t} \leq RA_u^+ \forall u \in EC \quad (8)$$

$$G_{u,t-1} - G_{u,t} \leq RP_u^- \forall u \in EC \quad (9)$$

where

RA_u^+	Start ramp for power delivery per generator per hour
RP_u^-	Stop ramp from absorbing energy per generator per hour.

Energy per block usable in a defined period for hydroelectric sources (hydrological model of the system).

This restriction applies to hydroelectric generators, since a dispatch plan considers a limited amount of energy to be used. For this reason, the proposed mathematical formulation guarantees that the energy limit is not exceeded, considering the hourly power dispatched and the plant factor of this type of generator.

$$\sum_{u \in hyd} \sum_t G_{u,t} \leq P \cdot fp \cdot \sum_{u \in hyd} Cg_u^{max} \quad (10)$$

where

P	One-day analysis period (24 h)
fp	Capacity utilization factor of each generator

Restriction of active power balance at busbars.

This restriction allows that, for each node of the modeled system, the Kirchhoff node law (LCK) applied to the power flow is fulfilled. For this case, the generation delivered, the unsupplied power, the loading and unloading of the storage system, and the DC power flow are modeled.

$$\sum_{\substack{u \in GC \wedge GNC \\ u \in t}} G_{u,t} + DNS_{i,t} - D_{i,t} + P_{DB_{i,t}} - P_{CB_{i,t}} = \sum_j b_{i,j} (\delta_{i,t} - \delta_{j,t}) \quad (11)$$

where

$D_{i,t}$	Demand located in the bar, i corresponding to a respective hour
$b_{i,j}$	Susceptance of the line between the bars i and j
$\delta_{i,t} \delta_{j,t}$	The angle of i or j end bar as a function of time

The restriction that limits the capacity of power flow that circulates through transmission lines (chargeability).

This inequality guarantees that the DC power flow that circulates through each of the links does not exceed the thermal limit established based on the physical constitution of the conductor.

$$-LT_{i,j}^{max} \leq b_{i,j}(\delta_{i,t} - \delta_{j,t}) \quad (12)$$

$$b_{i,j}(\delta_{i,t} - \delta_{j,t}) \leq LT_{i,j}^{max} \quad (13)$$

where

$LT_{i,j}^{max}$	Active power limit for energy transfer through transmission lines
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The parameter that models the state of charge of the BESS

This allows us to assess the optimal performance of the batteries in a study period, which helps to preserve their useful life. In this context, the state of charge is evaluated considering the initial state of the storage system and its loading and unloading based on the efficiency of these two processes.

$$EC_{i,t} = EC_{ini} \quad i, t \quad + EC \quad i, t - 1 \quad + P_C B_{i,t} \cdot \mu_{CBESS} - \frac{P_D B_{i,t}}{\mu_{DBESS}} \quad (14)$$

$t = 1 \quad t \geq 1$

where

$EC_{i,t}$	BESS state of charge per bar per hour
$EC_{ini} \quad i, t$	The initial state of charge of each BESS per bar per hour
$t = 1$	
μ_{CBESS}	BESS charge efficiency
μ_{DBESS}	BESS discharge efficiency

The restriction that limits the state of charge and the charge and discharge power of the BESS.

To select and locate the BESS, it is necessary to include a decision variable within the restrictions that characterize the physical scheme of the BESS. In this context, the state of charge is evaluated, considering the initial state of the storage system and its unloading and charging based on its efficiency in these two processes.

$$EC_{i,t} \geq C_{\%min} + EC_i^{max} \cdot \beta_i \quad (15)$$

$$EC_{i,t} \leq EC_i^{max} \cdot \beta_i \quad (16)$$

$$EC_{i,t=24} = EC_{\%min} \cdot EC_i^{max} \cdot \beta_i \quad (17)$$

$$P_D B_{i,t} \geq 0 \quad (18)$$

$$P_D B_{i,t} \leq D_{i\%max}^{max} \quad (19)$$

$$P_C B_{i,t} \geq 0 \quad (20)$$

$$P_C B_{i,t} \leq C_{i\%max}^{max} \quad (21)$$

where

EC_i^{max}	Maximum BESS state of charge
$D_{\%max}$	Maximum percentage discharge of the BESS
$C_{\%min}$	Maximum percentage charge of the BESS
$EC_{\%min}$	Minimum percentage of the state of charge
β_i	Decision variable for choosing the BESS

Restriction to determine the number of BESS to be implemented.

This formulation allows a certain number of storage systems to be incorporated into the electrical grid, considering the restrictions imposed by intermittent resources.

$$\sum_i \beta_i \leq n_{BESS} \quad (22)$$

where:

n_{BESS}

Total BESS units to be incorporated

Solution process of the optimization problem.

Through the formulation of the model, the costs related to generation, unserved energy, and BESS are minimized, to determine the optimal location of the battery storage systems to be incorporated into the electric grid. The algorithm for the location of the BESS is shown in Table 1.

Considering the proposed pseudocode and the optimization model, the corresponding flow chart is shown in Figure 1.

Table 1. Pseudocode.

Optimal placement of storage systems using DC power flows.	
Step 1:	Absorption of technical data of the power system
Step 2	Establishment of the components associated with the generation and transportation networks, as well as the factors related to the potential storage systems to be incorporated
	<ul style="list-style-type: none"> – Generation costs and technical factors – Hourly demand – Cost of energy not served – Energy resource occurrence – Network characteristics – Study time horizon – State of charge and discharge (maximum and initial) – Percentage charge and discharge – Minimum percentage of the state of charge
Step 3	Determination of variables Continuous: $G_{u,t}$ $DNS_{i,t}$ $P_C B_{i,t}$ $P_D B_{i,t}$ $\delta_{i,t}$ $\delta_{j,t}$ Binary : β_i , n_{BESS}
Step 4	Optimization model formulation
	FO Minimize total operating costs, including the fees of energy that is not supplied to demand. Restrictions <ul style="list-style-type: none"> – Limitation of power delivery capacity of generators – Hourly delivery of power and generation absorption – Energy per block usable in a period – Balance of active power at the busbars – Capacity limit of the power flow through the networks – Parameter that models the state of charge of the BESS – Restriction that limits the state of charge and the BESS charging and discharging power – BESS location decision – Number of BESS
Step 5	Implementation and solution of case studies
Step 6	Studies of the responses were obtained.
Step 7	End

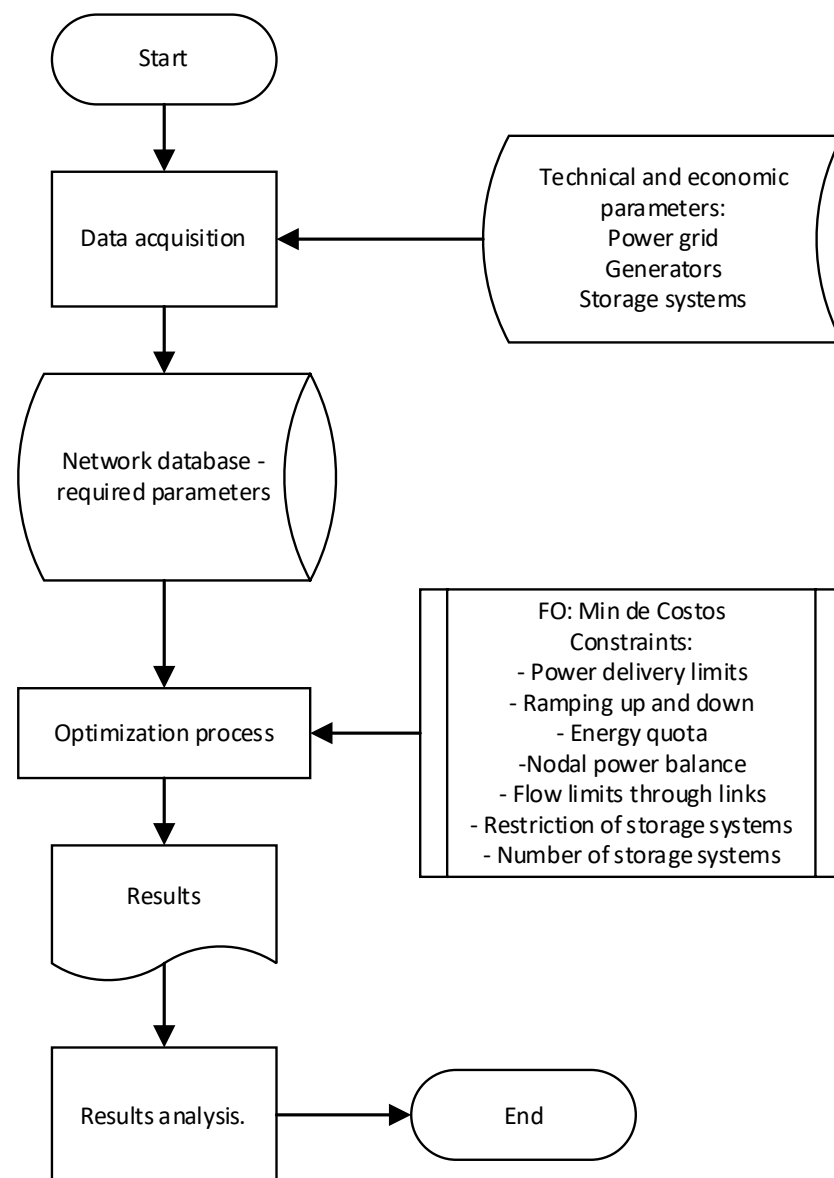


Figure 1. Flowchart.

Study Cases

The formulated modeling, based on mixed integer linear programming, is analyzed and evaluated in two cases applied to the IEEE 24-bus system.

- (1) This first study is considered the base case, and it analyzes power dispatch, the charge flows of the lines, and the resulting costs without batteries as a means of storage. The demand–supply is evaluated at the energy level, and from the electrical point of view, the resulting variables are evaluated when demand is at its maximum.
- (2) For this study, the optimization model incorporating the BESS is applied, and the power dispatch, the charge flows of the lines, and resulting costs are also analyzed. The energy and electrical level evaluation is similar to the base case, but the effects of storage systems are also considered.

With the approach of these two case studies, it is possible to verify the benefits of the optimal location of storage systems, which are reflected in technical and economic factors.

The applied IEEE model system is presented in Figure 2, and the parameters characterizing the conventional and non-conventional generators are shown in Tables 2 and 3 [44,45]. The plant factor required by the hydroelectric generators is 0.75, considering medium hydrology; this value generates a total daily energy of 6.3 TWh for these plants [46–48].

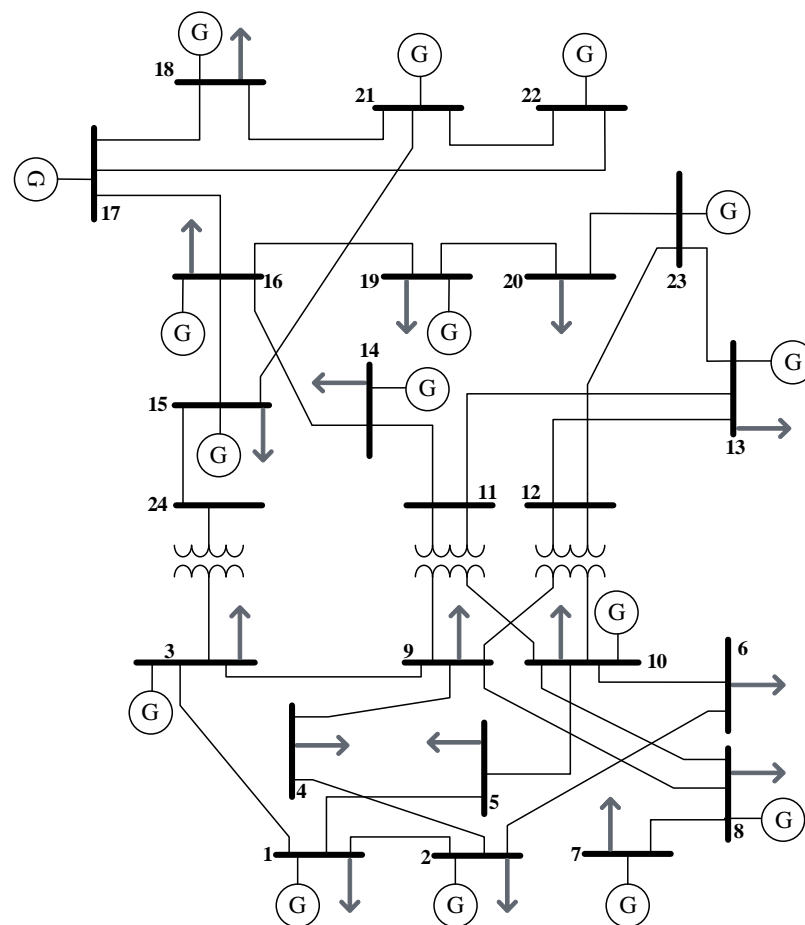


Figure 2. IEEE 24-bar diagram [44].

Table 2. Technical parameters of conventional generation sources.

	Type	Bus	Cg_u^{max} (MW)	Cg_u^{min} (MW)	RA_u^+ (MWh)	RP_u^- (MWh)	Cg_u (\$/MWh)
u1	T	18	300	100	120	66.63	55.341
u2	T	21	300	100	65	36.12	56.321
u3	T	1	122	31	36	20.00	127.714
u4	T	2	122	31	65	36.18	127.714
u5	T	15	105	52	50	27.76	156.800
u6	T	16	105	32	65	36.12	98.510
u7	T	23	110	20	45	25.01	98.510
u8	T	23	200	10	32	12.00	98.872
u9	T	7	200	75	45	14.00	196.686
u10	T	13	600	120	18	26.99	49.911
u11	T	15	60	10	32	47.96	254.908
u12	T	22	200	0	32	48.10	73.500
u13	H	14	210	0	32	8.00	35.280
u14	H	3	100	0	32	44.12	22.540
u15	H	10	40	0	32	48.00	41.160

Table 3. Parameters of non-conventional generation sources.

Type	Bus	$C_{g_u}^{max}$ (MW)	$C_{g_u}^{min}$ (MW)	C_{g_u} (USD/MWh)
E1	8	150	0	43
E2	19	100	0	
E3	21	80	0	
FV1	17	90	0	38
FV2	23	70	0	

The application of the model for the first case considers the energy resource as the basis for the power dispatch problem. The occurrence of this resource for non-conventional sources is shown in Table 4 [49,50].

Table 4. Renewable generation energy resource.

	E	FV		E	FV
t1	10.2%	0.0%	t13	85.5%	100.0%
t2	12.2%	0.0%	t14	92.6%	99.7%
t3	13.2%	0.0%	t15	94.6%	81.4%
t4	24.4%	0.0%	t16	90.5%	50.9%
t5	33.6%	0.0%	t17	76.3%	30.5%
t6	50.9%	10.2%	t18	68.2%	20.3%
t7	61.0%	14.2%	t19	63.1%	0.0%
t8	52.9%	30.3%	t20	54.9%	0.0%
t9	44.8%	53.6%	t21	57.0%	0.0%
t10	48.8%	76.3%	t22	52.9%	0.0%
t11	68.2%	86.5%	t23	45.8%	0.0%
t12	73.3%	98.7%	t24	32.6%	0.0%

For the modeling of the thermal and hydraulic generation units, the technical and economic characteristics shown in Table 2 have been considered.

The technical and economic characteristics presented in Table 2 have been considered for modeling the thermal and hydraulic generation units.

For modeling the extractable generation units, it is essential to have the percentage amount that the primary resource is available based on the hours of the day. This aspect is detailed in Table 4.

For transmission networks, specific data on busbars and lines are required. These data are shown in Tables 5 and 6 [44].

Table 5. Characteristics of the bars.

Bar	Dem_i (MW)	Bar	Dem_i (MW)
1	108	13	265
2	97	14	194
3	180	15	317
4	74	16	100
5	71	17	0
6	136	18	333
7	125	19	181
8	171	20	128
9	175	21	0
10	195	22	0
11	0	23	0
12	0	24	0

The charges located in each bar have a dynamic behavior over time [49], and for the analysis, a charge curve is created, using percentages that are tabulated in Table 7. The accumulated curve is shown in Figure 3 [44].

Table 6. Characteristics of the lines.

Bar i	Bar j	X (pu)	Limit (MVA)
1	2	0.0139	175
1	3	0.2112	175
1	5	0.0845	175
2	4	0.1267	175
2	6	0.192	175
3	9	0.119	175
3	24	0.0839	400
4	9	0.1037	175
5	10	0.0883	175
6	10	0.0605	175
7	8	0.0614	175
8	9	0.1651	175
8	10	0.1651	175
9	11	0.0839	400
9	12	0.0839	400
10	11	0.0839	400
10	12	0.0839	400
11	13	0.0476	500
11	14	0.0418	500
12	13	0.0476	500
12	23	0.0966	500
13	23	0.0865	500
14	16	0.0389	500
15	16	0.0173	500
15	21	0.0245	1000
15	24	0.0519	500
16	17	0.0259	500
16	19	0.0231	500
17	18	0.0144	500
17	22	0.1053	500
18	21	0.013	1000
19	20	0.0198	1000
20	23	0.0108	1000
21	22	0.0678	500

Table 7. System charge behavior.

h	Dem _i (%)	h	Dem _i (%)
t1	49.00	t13	78.40
t2	50.96	t14	79.38
t3	49.98	t15	86.36
t4	49.00	t16	92.14
t5	49.98	t17	98.08
t6	54.88	t18	100.00
t7	63.70	t19	96.04
t8	68.60	t20	90.28
t9	70.56	t21	82.36
t10	69.58	t22	73.50
t11	72.52	t23	68.60
t12	77.42	t24	53.90

BESS to be incorporated are shown in Table 8, and the proposed parameters are shown in Table 9. [51,52]:

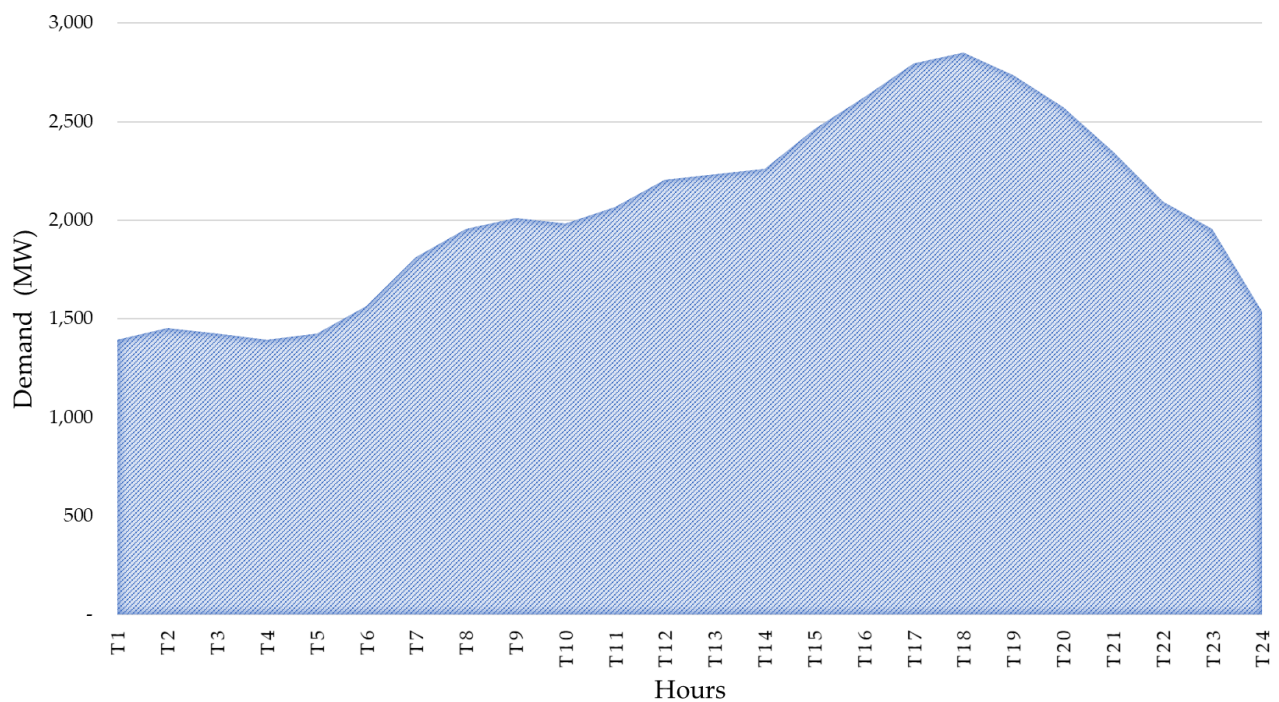


Figure 3. The accumulated curve of hourly charge.

Table 8. Data of potential BESS.

	Bar	EC_i^{max}
BESS 1	19	100
BESS 2	21	80
BESS 3	8	150
BESS 4	17	90
BESS 5	23	70

Table 9. Parameters for BESS.

EC_i^0	$0.2 \cdot EC_i^{max}$
$EC_{\%min}$	20%
μc_{BESS}	95%
μd_{BESS}	90%

3. Results

Based on the formulation and application of the optimization model in the cases presented, and considering the necessary parameters detailed in the previous section, an economic, technical, and energy evaluation can be carried out.

i. Base Case: IEEE 24-bus system without BESS

This initial case energetically evaluates the generation dispatch in 24 h, according to the chosen technologies, as shown in Figure 4. This figure shows that the available generation sources supply the hourly demand, with thermal generation being predominant and, to a lesser extent, the energy produced by the renewable sources of hydraulic, photovoltaic, and wind energy. It should be noted that there is no shortage.

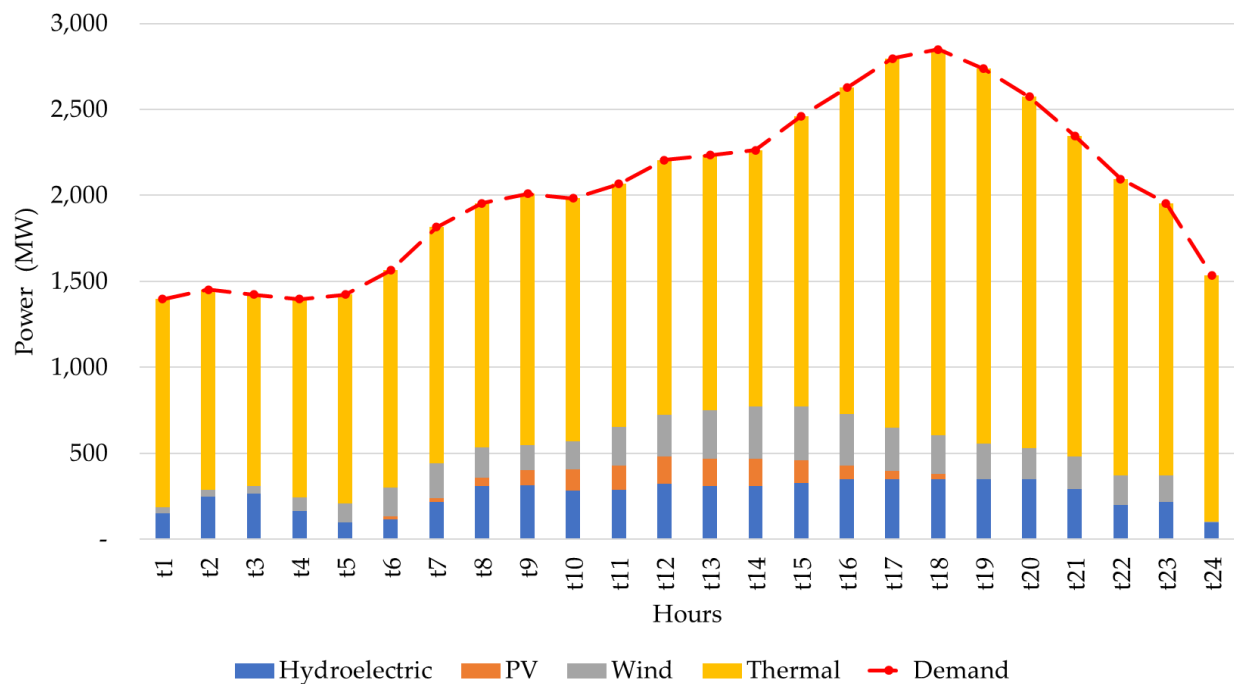


Figure 4. Time dispatch with the generation technologies involved.

The energy delivery and the respective costs for each technology are shown in detail in Table 10. Based on the results obtained, it can be observed that a portion equivalent to 76% corresponds to the energy produced by thermal sources, and the remaining amount to the rest of the generators. In this case, wind energy contributes 8.6%, that amounts to 4208.36 MWh. In contrast, hydraulic energy corresponds to 12.8%, with an energy of 6300 MWh, and finally, photovoltaic energy contributes 2.6%, whose energy corresponds to 1204.24 MWh.

Table 10. Energy dispatch by technology.

Technology	Bar	Energy (MWH)	Total (MWH)	Cost (USD)	Total (USD)
Hydro	bar 3	2400.00	6300.00	54,096.00	193,326.54
	bar 10	278.66		11,469.81	
	bar 14	3621.34		127,760.7	
FV	bar 17	677.39	1204.24	25,740.63	45,761.12
	bar 23	526.86		20,020.49	
Wind	bar 8	1912.35	4208.36	82,231.05	180,959.48
	bar 19	1274.90		54,820.70	
	bar 21	1021.11		43,907.73	
Thermal	bar 1	968.00	37,456.17	123,627.1	2,810,098.78
	bar 2	968.00		123,627.1	
	bar 7	1961.10		385,720.9	
	bar 13	14,361.5		716,795.4	
	bar 15	1647.00		281,795.5	
	bar 16	1204.63		118,668.3	
	bar 18	6578.02		364,034.2	
	bar 21	5285.95		297,709.8	
	bar 22	1760.00		129,360.0	
	bar 23	2722.00		268,760.3	
Total			49,168.77		3,230,145.9

These dispatch values can be represented through costs in Figure 5, where the most significant economic portion (87%) is associated with thermal generation, and the remainder with other technologies (hydro 6% and solar/wind 7%). It is observed that the total cost at the operational level corresponds to USD 3,230,145.9. By the unit values of energy sales prices by technology, it is concluded that photovoltaic energy is the least expensive, and its value amounts to USD 45,761.12.

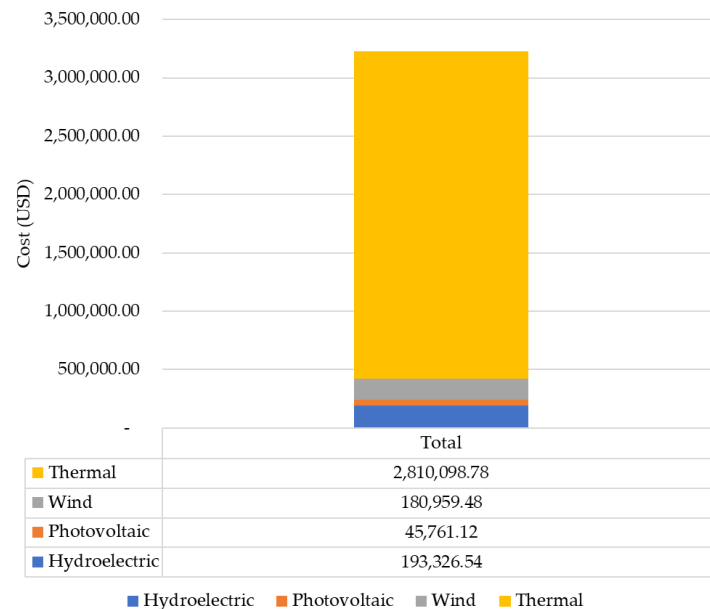


Figure 5. Dispatch costs segmented by generation type.

For an electrical analysis, the charge values are considered for supply when the demand is maximum. In this way, it is possible to determine the amount of production of the generation units in the dispatch. The results of the dispatch are presented in Table 11. In this period, the demand increases to 2850.00 MW, of which 2242.38 MW are supplied by thermal generation, leaving the rest to extractable energy.

Table 11. Power dispatched by technology.

Technology	Bar	Power (MW)	Total (MW)
Hydro	bar 3	100.00	350.00
	bar 10	40.00	
	bar 14	210.00	
FV	bar 17	18.32	32.56
	bar 23	14.25	
Wind	bar 8	102.30	225.06
	bar 19	68.20	
	bar 21	54.56	
Thermal	bar 1	87.00	2242.38
	bar 2	87.00	
	bar 7	138.38	
	bar 13	600.00	
	bar 15	115.00	
	bar 16	105.00	
	bar 18	300.00	
	bar 21	300.00	
	bar 22	200.00	
	bar 23	310.00	
Total			2850.00

On the other hand, Table 12 shows the flow of power transferred in the links; from this result, it is concluded that none exceeded the established thermal limit, and it is guaranteed that there is no excessive chargeability in the links.

Table 12. Charge flow through the lines of the IEEE 24 busbar system.

Bar			Bar		
I	j	Flow (MW)	I	j	Flow (MW)
1	2	19.15	13	12	188.12
1	5	8.92	14	11	139.00
2	6	12.81	15	24	146.82
3	1	49.07	16	14	123.00
3	9	17.75	16	15	10.88
4	2	3.66	16	19	73.06
7	8	13.38	17	16	201.94
9	4	77.66	18	17	88.76
9	8	38.33	20	19	39.74
10	5	62.08	21	15	337.94
10	6	123.19	21	18	121.76
10	8	16.99	22	17	94.86
11	9	138.77	22	21	105.14
11	10	180.78	23	12	122.84
12	9	134.48	23	13	33.66
12	10	176.48	23	20	167.74
13	11	180.55	24	3	146.82

Given the results shown for the maximum demand, Figure 6 shows a single-line diagram of the modeled system, in which the results of both the generation dispatch and the flows through the links have been incorporated, validating that each node complies with the nodal balance associated with Kirchhoff's node law (LCK).

ii. *Optimal location of the BESS in the IEEE 24-bar systems*

Firstly, the result of selecting the incorporation of the energy storage systems is shown. For the present formulated model, the characterization of the batteries for their optimal location has been considered. Table 13 indicates the BESS that are selected to be located in the corresponding bars.

Table 13. Potential Bess data.

Bar	Optimal BESS
8	✓
17	✓
19	✓

With the optimal selection of the BESS, the same evaluation can be performed on the economic, technical, and energy levels. Therefore, it is possible to represent graphically (Figure 6) the generation dispatch for the energy configuration in an hourly period, where it is visualized how the storage influences the energy production. Figure 7 shows the energy delivery by the different production technologies, with thermal generation having the most significant weight in the energy supply, and the influence of the BESS on the dispatch is observed.

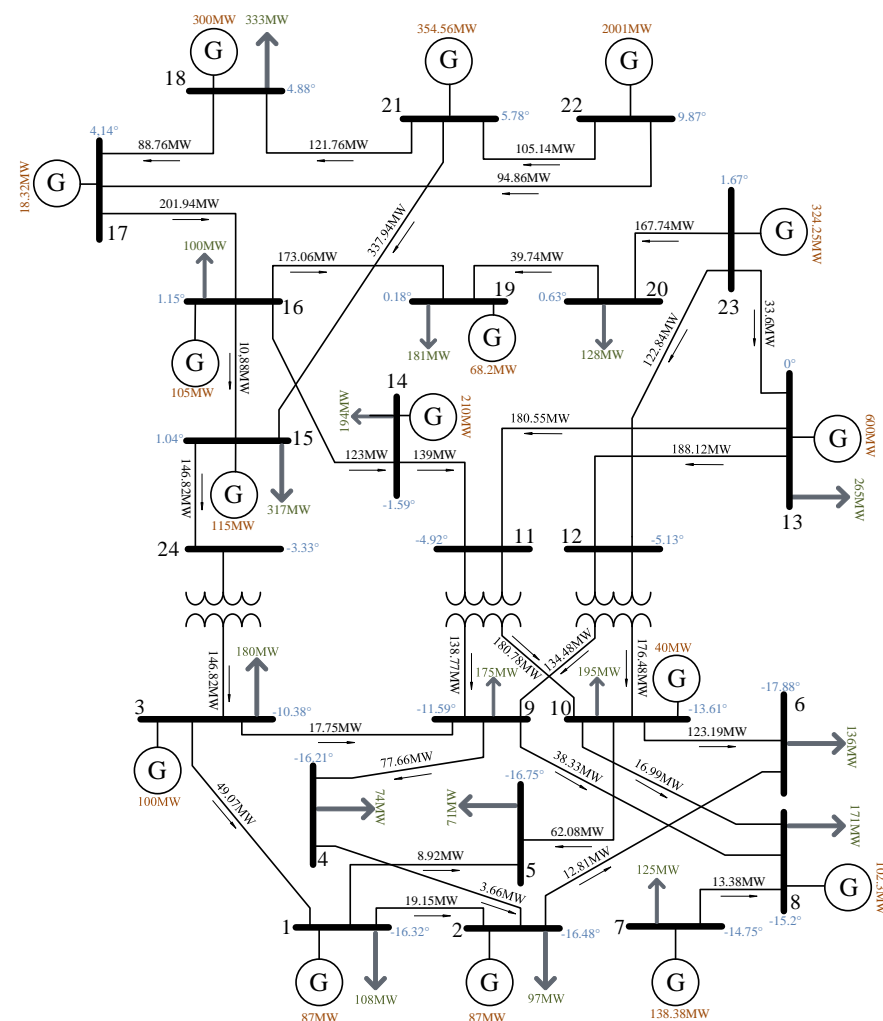


Figure 6. The single-line diagram at maximum demand for the base study.

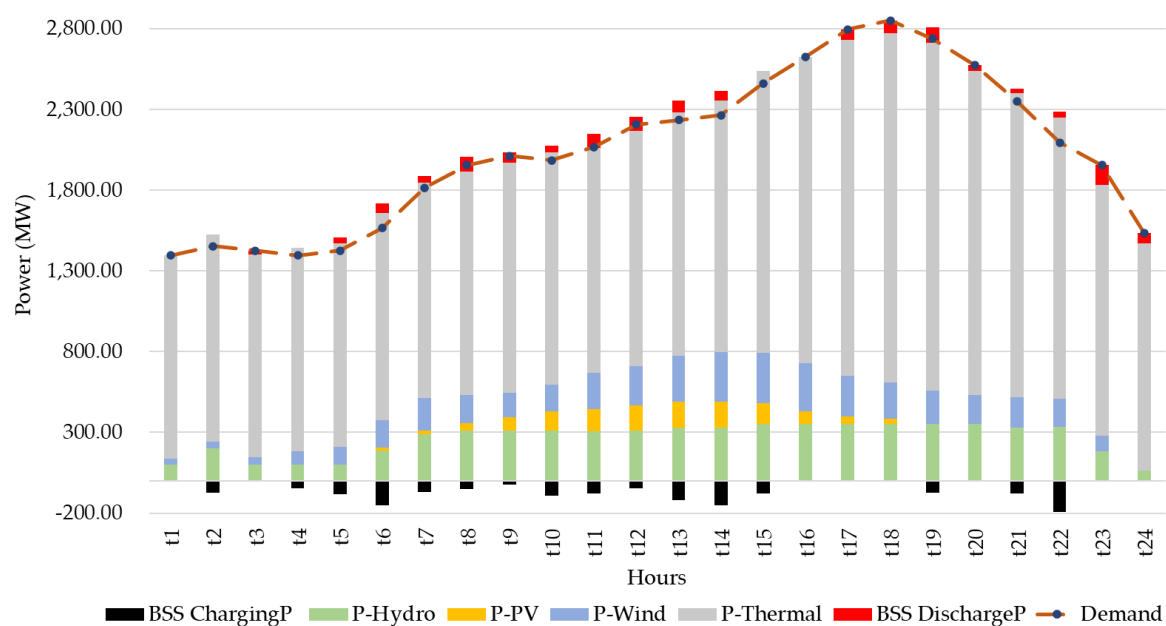


Figure 7. Hourly dispatch based on generation technologies and battery storage systems.

Table 14 shows the dispatch results concerning total energy production and per type of generation and storage technology, and includes the respective costs per technology together with storage. Based on the results obtained, it is observed that the portion equivalent to 76.7% corresponds to the energy produced by thermal sources, and the remaining 23.3% (hydro 12.8%) by the rest of the generators, considering that the BESSs deliver a total of 2.5% of the energy to the electric system.

Table 14. Energy dispatch per generation and storage technology.

Technology	Bar	Energy (MWH)	Total (MWH)	Cost (USD)	Total (USD)
BESS charge	bar 8	−583.16	−1402.15	−127,097.1	−305,593.91
	bar 17	−448.00		−97,639.96	
	bar 19	−370.99		−80,856.82	
BESS discharge	bar 8	498.60	1198.84	13,144.38	31,604.51
	bar 17	383.04		10,097.92	
	bar 19	317.20		8362.21	
Hydro	bar 3	2331.33	6300.00	52,548.18	194,611.58
	bar 10	348.42		14,341.05	
	bar 14	3620.25		127,722.3	
FV	bar 17	677.39	1204.24	25,740.63	45,761.12
	bar 23	526.86		20,020.49	
Wind	bar 8	1912.35	4151.61	82,231.05	178,519.23
	bar 19	1255.98		54,007.14	
	bar 21	983.28		42,281.04	
Thermal	bar 1	968.00	37,716.23	123,627.1	2,796,531.85
	bar 2	968.00		123,627.1	
	bar 7	1837.10		361,331.8	
	bar 13	14,337.0		715,574.0	
	bar 15	1614.00		276,621.1	
	bar 16	1206.00		118,803.1	
	bar 18	7049.85		390,145.9	
	bar 21	5388.30		303,474.5	
	bar 22	1820.79		133,827.7	
	bar 23	2527.19		249,499.4	
Total			49,168.77		2,941,434.38

These dispatch values can be represented by the costs shown in Figure 8, where the most significant economic portion (95.1%) is associated with thermal generation, and the remainder to other technologies (14.2%). Still, storage systems stand out, because they represent 1.1% of the total cost when the loading process occurs, while the unloading process generates a considerable saving of 10.4%.

Due to the implementation of storage, it is essential to present the behavior of the variables corresponding to the charging and discharging power, and the state of charge produced during dispatch. These are shown in Figures 9–11. In the case of the BESS located at bus 8, it is observed that there is a delivered energy of 498.6 MWh, maintaining the state of charge between a minimum value of 30 MW and a maximum value of 150 MW.

Likewise, for the BESS located in bar 17, it is observed that there is an energy delivered of 383.04 MWh, maintaining the state of charge between a minimum value of 18 MW and a maximum value of 90 MW.

Finally, for the BESS located in bar 19, it is observed that there is an energy delivered of 317.20 MWh, maintaining the state of charge between a minimum value of 20 MW and a maximum value of 100 MW.

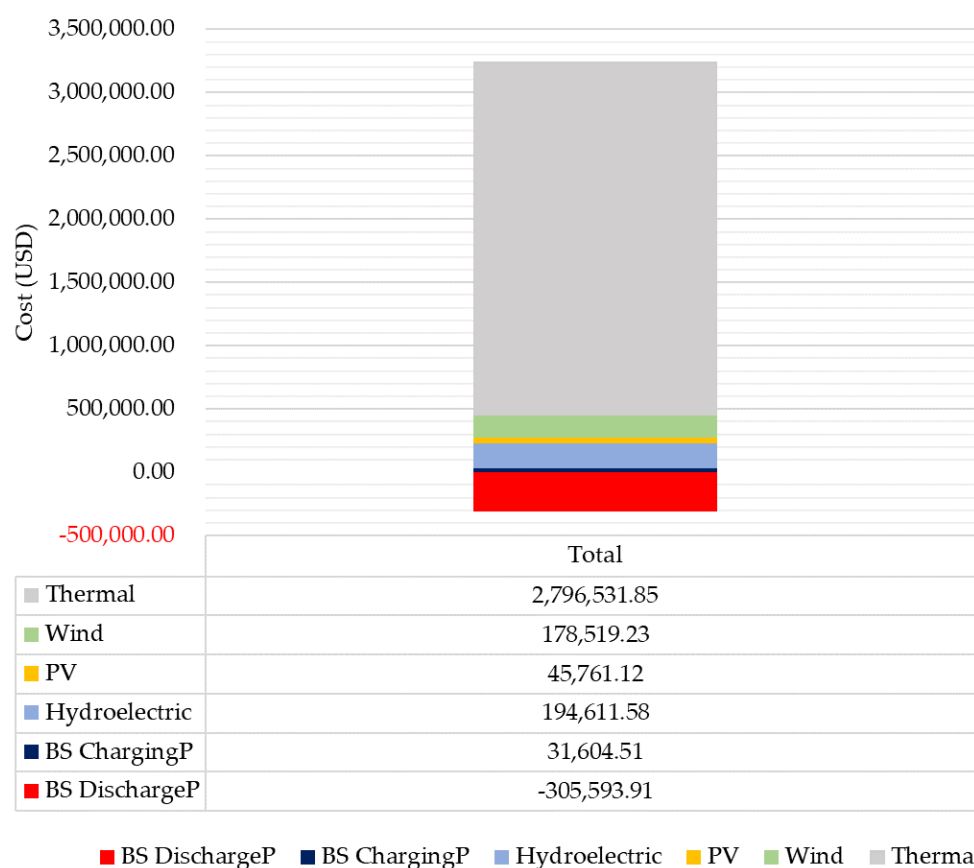


Figure 8. Dispatch costs by type, of generation and storage.

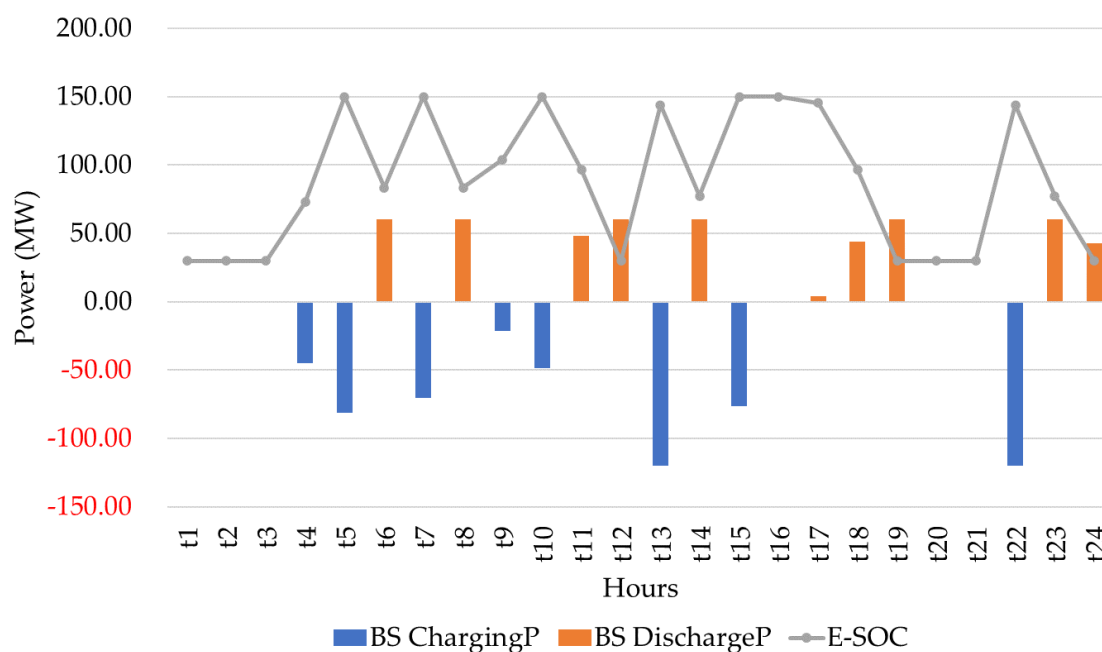


Figure 9. BESS in bar 8.

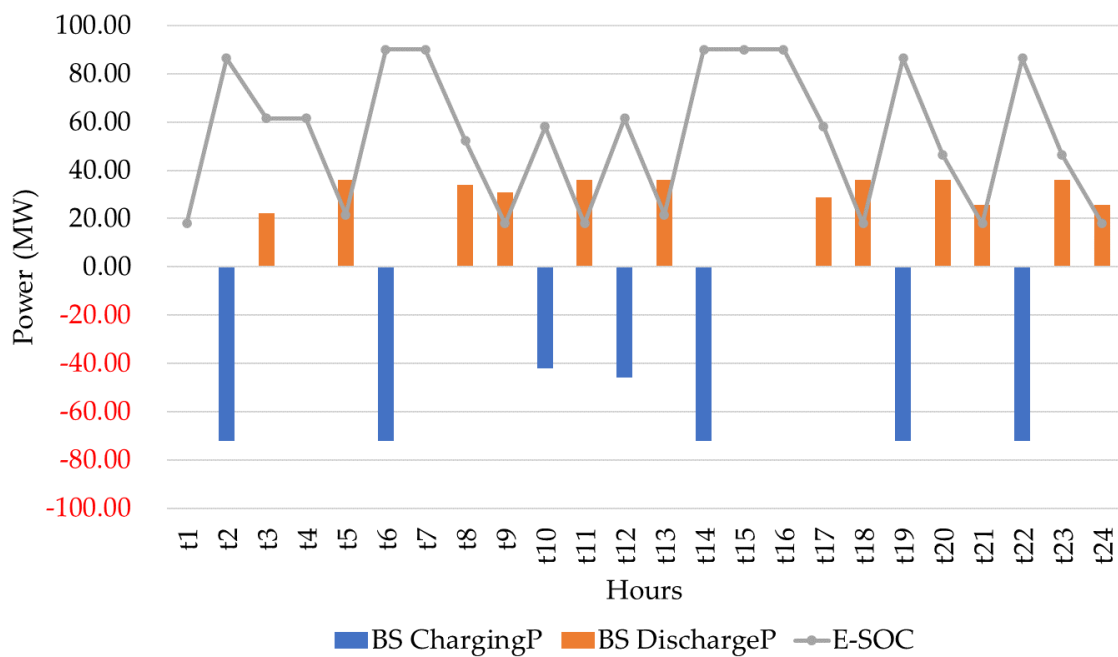


Figure 10. BESS in bar 17.

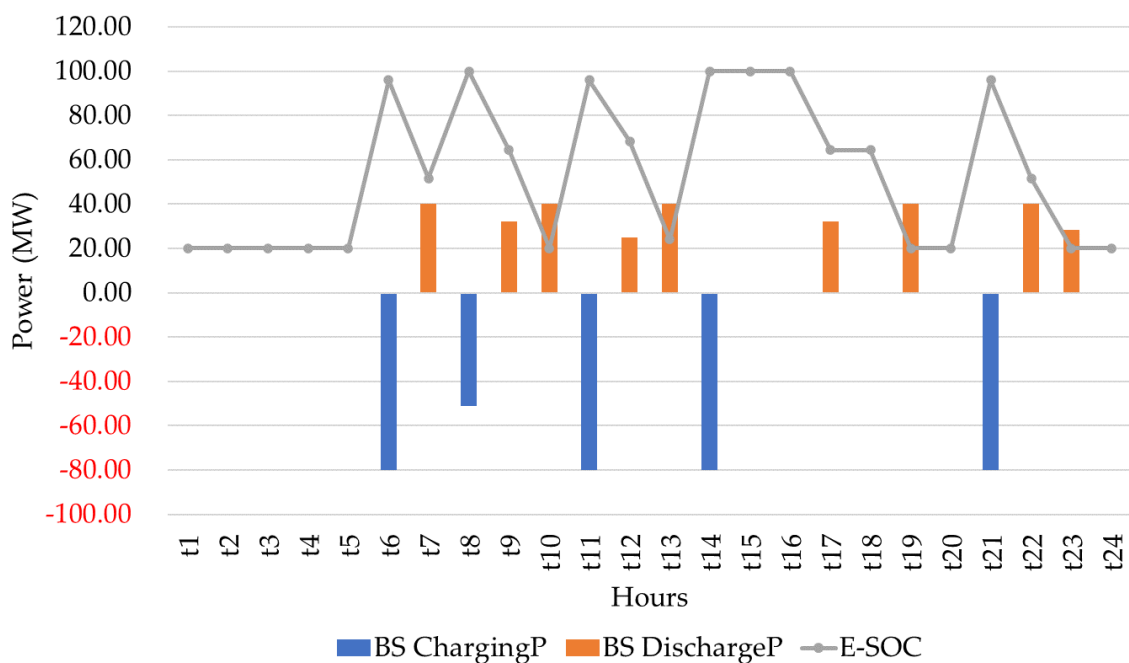


Figure 11. BESS in bar 19.

As in the base case, and as a final part of the study, an electrical analysis is performed where the load values are considered for their supply when the demand is maximum. Thus, it is possible to determine the amount of production of the generation units in the dispatch, particularly considering the ESS. The results are shown in Table 15. For the analyzed demand, it is obtained that the BESS located in buses 8 and 17 contributed 79.76 MW. Additionally, the electricity production with the most significant contribution continues to be thermal generation, with a contribution of 2162.62 MW, which is less than the base case but continues to manifest itself.

Table 15. Power dispatched by technology with storage.

Technology	Bar	Power (MW)	Total (MW)
BESS Charge	bar 8	43.76	79.76
	bar 17	36.00	
Hydro	bar 3	100.00	350.00
	bar 10	40.00	
	bar 14	210.00	
FV	bar 17	18.32	32.56
	bar 23	14.25	
Wind	bar 8	102.30	225.06
	bar 19	68.20	
	bar 21	54.56	
Thermal	bar 1	87.00	2162.62
	bar 2	87.00	
	bar 7	75.00	
	bar 13	600.00	
	bar 15	104.00	
	bar 16	105.00	
	bar 18	300.00	
	bar 21	300.00	
	bar 22	200.00	
	bar 23	304.62	
Total			2850.00

The power flow through the transmission lines is presented in Table 16. From this result, it can be evidenced that there is a redirection of the power flow, but it is also confirmed that the chargeability level, and the thermal limit for each link, are not exceeded.

Table 16. Charge flow through the lines of the IEEE 24 busbar system with storage.

Bar			Bar		
i	j	Flow (MW)	i	j	Flow (MW)
1	2	19.89	13	12	190.65
1	5	9.73	14	11	148.35
2	6	13.32	15	24	151.66
3	1	50.62	16	14	132.35
3	9	21.04	16	15	13.52
4	2	3.43	16	19	83.86
7	8	50.00	17	16	224.73
9	4	77.43	18	17	77.36
9	8	48.37	20	19	28.94
10	5	61.27	21	15	351.14
10	6	122.68	21	18	110.36
10	8	26.57	22	17	93.06
11	9	142.84	22	21	106.94
11	10	185.73	23	12	126.06
12	9	136.91	23	13	35.86
12	10	179.80	23	20	156.94
13	11	180.21	24	3	151.66

Finally, the results obtained and tabulated above are presented in a one-line diagram of the electrical system, shown in the Figure 12.

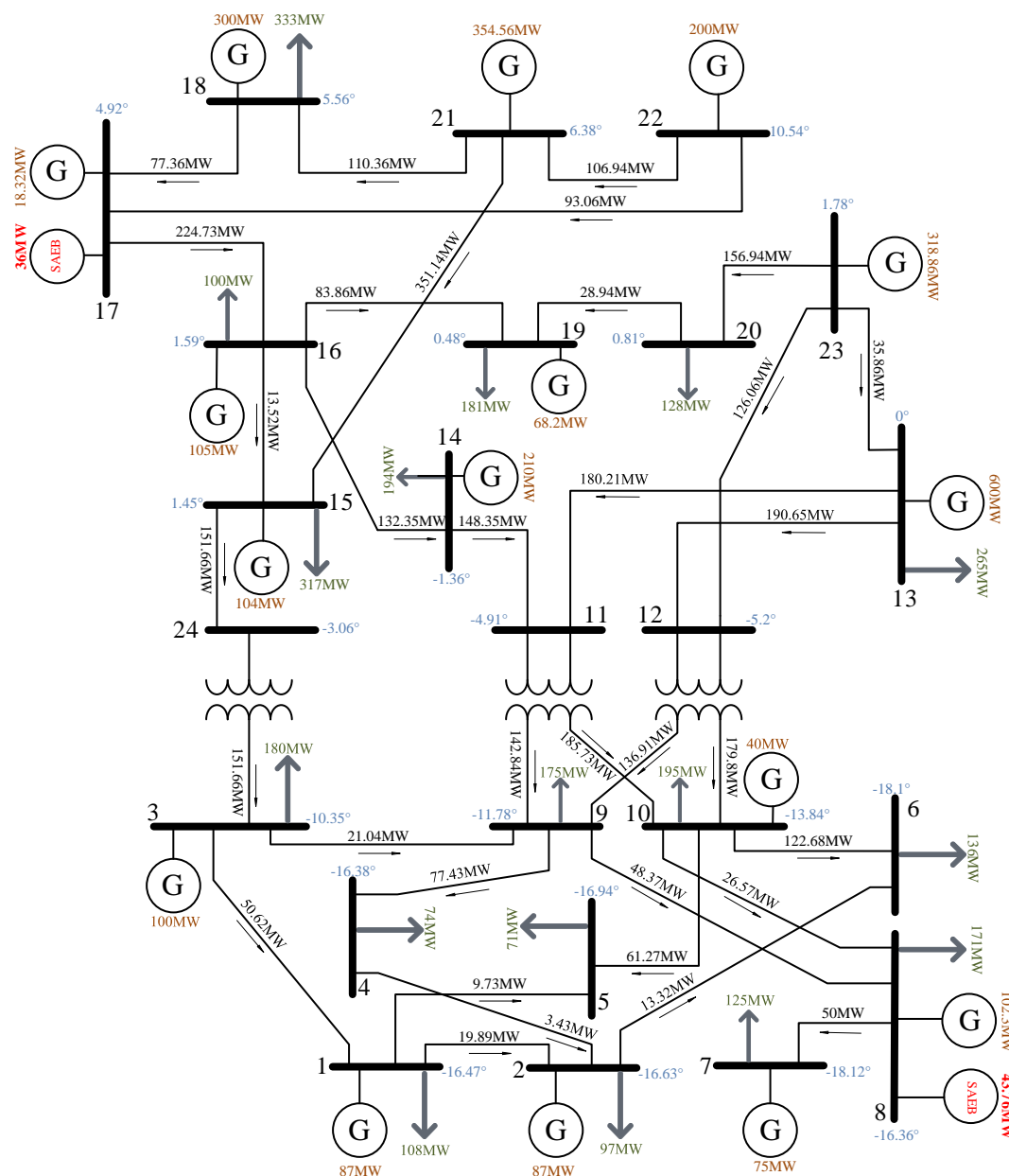


Figure 12. The single-line diagram in maximum demand with storage systems.

From the analysis, it is indicated that by including the storage systems, the generation dispatch is affected, with the thermal generation being the one that increases by 260 MWh, since it has enough resource. Under this context, the stored energy, which amounts to 1198.84 MWh, is delivered to the system, causing a cost reduction that results in a daily saving of USD 288,711.54, which amounts to approximately 105 million dollars per year.

In order to qualitatively compare the results obtained here to the works mentioned as being the state of the art, it can be pointed out that the mathematical model developed herein allows establishing of the location of storage systems in electrical networks taking into account the dynamics of the system over time, using DC power flows, which, compared to the study carried out in [15], allows modeling transmission networks and not distribution networks, which allows an advantage for the electricity market at the wholesale level, to undertake technical and economic analysis.

Likewise, the proposed model is analyzing the storage systems individually and not necessarily tied to an intermittent generation, as modeled by the study in [16], thus the model establishes the optimal location of the storage systems to reduce operating costs,

without these systems being necessarily tied to the generation sources. When comparing the research in [17] with the proposed model, the advantage of simplifying the complex modeling of the transformers is obtained, without leaving aside the limits of transferability or loadability of the elements.

On the other hand, the research developed corresponds to a mathematical model of classical optimization, and its robustness surpasses the heuristic models, such as the optimization algorithm under uncertainty, described in [18]. Given the above, the model provides advantages and contributions for storage systems to be evaluated and analyzed at the level of transmission networks, and to promote new studies at the market and dispatch level.

Among the main advantages of the proposed study are that the modeling of the network is simplified by the use of DC power flows, in addition to allowing a steady state analysis for each period of time during the 24 h of the day, evaluating the cost of energy not supplied and the optimal location of the storage systems, for which the variables involved are linked in time, i.e., the restrictions are inter-hourly, thus ensuring the operability of the generators and storage systems throughout the analysis period; one of the important advantages, is that the modeling takes into account the variability of renewable resources, which allows interaction with the loading and unloading with the storage systems entering the system, to reduce costs.

Finally, despite the advantages, the model can be adjusted in order to minimize the disadvantages, among them we can point out that the model does not consider the interaction of reactive power flows and its link with voltage levels at the nodes, which is achieved with the incorporation of AC power flows. In addition, thermal generators can be modeled in greater detail, including maximum start and stop times. For its part, the group of generators modeled can be evaluated with power reserve constraints to sudden load variations.

4. Discussion

This paper presents a novel and complete analysis of the optimal insertion of energy storage systems, considering power flows and non-supplied energy. With the optimal injection of electrical energy from the energy storage systems, it was possible to improve the voltage profiles and reduce the network's chargeability, at the minimum energy dispatch cost. In this study, most energy sources and technologies were included, making the analysis more complete and more complex. The results show the possible energy injection scenarios, and the incidence comparisons, in the variables considered with the power flow.

5. Conclusions

The high penetration of intermittent renewable sources has modified the operational performance of electrical systems. Thus, to compensate for the variation in energy production from these new intermittent sources, energy storage systems have been implemented as a very efficient solution. Energy storage systems, in addition to providing a certain degree of energy stability, guarantee the continuity of electrical service. In addition, the optimal insertion of storage systems allows for minimizing the operating cost, by displacing expensive generation, and also improves voltage levels, by operating as distributed generation.

Considering the above, the proposed mathematical model makes it possible to determine the optimal insertion of storage systems in an electrical power system, by applying DC power flows and evaluating the energy not supplied, in a standard load curve. The proposed model allows for finding the optimal location to install energy storage systems, improving the voltage profile, and significantly reducing operating and generation costs. In addition, the reallocation of the economic dispatch is achieved, displacing expensive generation, and attention to demand is guaranteed as a reliability indicator. From the results obtained in the proposed case study, an economic saving of millions of dollars can be verified, for the concept of insertion with the optimal location of energy storage. In future work, it is proposed to study joint expansion, with distribution networks incorporating

distributed generation and storage systems. Research should be done on remuneration mechanisms, considering energy delivery by energy storage systems. The energy reserves for primary control in electrical systems could also be evaluated, considering the stability of the frequency.

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