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RESEARCH PAPER

Three-Echelon Power Supply Network Design Considering Energy Storage System to Ensure Network Sustainability

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ABSTRACT
Nowadays, the use of electrical energy storage has a significant role in flatting the load curve, peak shaving, increasing reliability and also increasing the penetration of distributed generation, reducing carbon emissions, and reducing network losses. In this article, a three-echelon power supply chain is investigated considering energy storage as a new echelon in the power supply chain. The model in this article is an integrated model of locating and capacity planning of distributed energy storage to maximize profit and reliability, which is modeled with two different approaches. The first model is modeled from the point of view of the distribution network as the owner of the energy storage and the second model is modeled from the perspective of the electricity subscribers as the owner of the energy storage. Finally, the model is solved by GAMS software and the results of sensitivity analysis are presented. According to the obtained results, the presented model is the most sensitive to the changes in demand and production, and the owners of energy storage should be sensitive to the changes in production and demand in different seasons of the year to get the maximum profit.

KEYWORDS: *Battery; Capacity planning; Location decision; Distributed energy storage; Energy storage system; Power supply chain.*

1. Introduction

The electricity supply chain, which is called the electricity distribution system, includes the power plant, transmission lines, transmission and distribution substations, distribution lines, and the final consumer. The electricity produced by the power plant is sent to distribution and transmission stations and finally consumed by customers [1]. In the electricity supply chain, the order from upstream to downstream of the chain includes suppliers of generators (generator fuel), generators as producers, transmission, distribution, and consumption. With the development of industries, the use of fossil energy is still common and replacing it with water, wind, sunlight and other renewable energies is somewhat complicated. Recently, fundamental development have been made in the electricity industry, where consumers can generate and store the energy they need [2]. The electricity supply network is a critical issue in the world economy. Recently, researchers have put more emphasis on considering economic considerations, including different pricing, in the design of the electricity supply chain [3]. With increasing concerns about environmental conditions, the use of distributed renewable energy has increased and has a significant impact on the electricity supply chain models. Consumers can be owners of distributed renewable energy equipment [4]. Achieving the goal of reducing greenhouse gas emissions requires a multi-pronged approach to decarbonize all sectors that emit greenhouse gases. Energy storage systems have emerged as a leading technology in addressing some of the challenges facing the transition to a renewable energy-based electricity

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supply chain [5]. Furthermore, energy storage devices can inject electricity into the grid during peak load as a generator and store energy during off-load as a consumer and profit from the difference in electricity prices at different hours.

In this research, in order to reduce outages and gain higher profit from the difference in electricity prices during the day and night, a new echelon is introduced in the power supply chain as its storage level. The questions that will be answered in this research:

1. What is the effect of the proposed energy storage system, as a new echelon, on managing the electricity network?
2. What are the characteristics of the candidate points in terms of installation location and energy storage capacity?

The main contributions of this research can be summarized as follows:

- Providing power supply chain from two-echelon to three-echelon
- Considering the combination of energy storage with the power supply chain in a new level offering
- Providing an integrated capacity planning and location model for energy storage in the form of ownership of energy storage with distribution network (SOEDN) and the second model which is ownership of energy storage with electricity subscribers (SOES)

The structure of this article is as follows: The next section provides the literature review and gives a brief review of the previous articles. The third section presents the proposed model and in the fourth section, the solution approach and sensitivity analysis are discussed. In the last section, the summary and conclusion are presented.

2. Literature Review

Basically, electric energy storage devices can be used in power systems for various purposes such as reducing losses, increasing reliability, improving power quality, peak shaving, etc. The battery energy storage system has advantages over conventional energy sources, including fast and stable response, adaptability, controllability, environmental friendliness, and geographical independence, which is an effective solution to the problem of global warming [6]. Energy storage devices are a flexible resource to reduce uncertainties for use in demand management, which helps to increase the safety margin of the power grid by modifying the load curve [7]. Currently, there are various technologies for electrical energy storage, including magnetic energy storage in superconductors, supercapacitor energy storage, flywheel energy storage, pumped water storage, compressed air energy storage, hydrogen-based storage systems, and energy storage in flow batteries. Each of these technologies is used for a specific purpose according to their characteristics. For example, some of them have a very short discharge time and are used to improve power quality and maintain voltage stability in transient mode. Others have a relatively long-term discharge time (several minutes or hours) that has applications such as energy management and frequency regulation [8], [9].

Various factors including privatization of electricity markets, attempts to increase system profitability, and reduce environmental concerns have drawn attention to energy storage sources. Energy storage technologies can help renewables whose output is uncontrollable to create a smooth and transportable output [8]. With the emergence of critical conditions including the spread of diseases especially covid-19 quarantine in different parts of the world, the electricity demand has changed, which has greatly affected the production and storage of energy [10]. This situation requires researchers to focus more on supply chain resilience.

Energy storage is widely used in the integration of the renewable energy production network, power transmission and distribution, distributed generation, micro-grids, and ancillary services such as frequency regulation, peak transmission, power quality improvement, quick response, etc. Yao et al. [11] evaluate the characteristics of energy storage technologies such as efficiency, capacity, life cycle, cost, and the challenges of using large-scale storage in the power system from an economic and technical point of view. Chen et al. [12] state that the connection of large-scale renewable energy sources to the power grid creates many challenges, including peak load adjustment, frequency adjustment, and renewable energy consumption of the power system, and the use of energy storage is necessary to deal with these challenges. According to [13] energy storage technology plays an important role in increasing the consumption capacity of new energy, ensuring the economic and stable performance of the power system, and improving the widespread use of renewable energy. Energy storage systems have been considered not as a replacement for old sources but as a way to make the functions of old sources better and cheaper. Moreover, Zakeri et al. [14] state that distributed energy storage is an effective solution for correcting the fluctuations of renewable energies. Rahman et al. [15] state that demand management as a control strategy can modify the load curve to shift the consumption during the peak time to the valley time in the load curve and reduce the electricity consumption during the peak load time. From the point of view of load management, energy storage devices prevent power shortages in the network by storing power during low-load hours and providing it during peak load times. From an economic point of view, energy storage systems can generate significant profit for the system by purchasing energy from the upstream network when the price of electricity is low and selling it during the hours when the price of electricity is at its highest [16].

In [17] the time of use (TOU) strategy with different prices in the peak-flat-valley times of the load curve is expressed as one of the demand management methods, and it can guide consumers to modify their consumption pattern and reach their goal of flatting the load curve. The TOU price is set by the power company for consumers with distributed energy storage equipment to optimize their discharge behavior. The benefits of the TOU strategy include delaying power grid investment, increasing consumption of renewable energy sources, and improving grid reliability [18], [19].

The average sustainable energy storage has increased drastically in recent years. Air pollution, which is mainly harmful to the environment, has led to the growth of sustainable energy sources. In other words, the adoption of sustainable energy technology can create important issues for maintaining a sustainable grid.

In [20], the evaluation of all types of batteries has been done in terms of features and capacity, and the advantages and disadvantages of each technology have been described. Finally, it has analyzed the strengths, weaknesses, opportunities, and threats of batteries in the distribution network. Furthermore, in [21], decision-makers have suggested the type of battery technology and its specifications according to the type of operation.

In [4], the problem of designing a smart electricity supply chain for a micro-grid with two decision makers including the power company and the consumer. The goal is to increase profits for the electricity company and the consumer. In [22], an off-grid micro-grid design is considered, which solves the problem of cost minimization and maximum reliability using meta-heuristic algorithms and compares the results of the two.

The final cost of the power supply chain includes all current costs of companies in the generation, transmission, distribution, purchase of electricity from outside the chain, fuel costs, electricity storage, and investment costs.

Saini and Gidwani [10] investigate a comprehensive evaluation in terms of the location and capacity of the energy storage system by determining the photovoltaic output and considering the commercial, residential, and industrial load at different times. The article aims to reduce annual energy losses, reduce backflow and overvoltage, and provide electricity during peak consumption in the distribution network. For the solution, the genetic algorithm is used to optimize the problem. In [23], distributed generation and energy storage systems have been used simultaneously to increase the reliability of the network. The objective function of the problem is to reduce unsupplied energy, lost load, load cost, and voltage fluctuation in 30 and 69 bus distribution networks. By reducing the investment cost of renewable energies and increasing their use, the amount of carbon emissions can be reduced.

Nowadays, the integration of large-sized energy storage system is desirable to achieve more reliability and efficiency for smart grids. Usually, the performance control depends on the electricity market price, for example, charge when the price of electricity is low and discharge when the price of electricity is high. The effect of the size and location of the energy storage on the market price, total production cost, energy arbitrage profit, and the total payment of the consumer has been further investigated in [24].

In [25], a three-echelon supply chain with several distribution centers (DCs), production sites, and suppliers is modeled. The problem model is in the category of facility location with capacity. In this article, two important topics are mentioned: 1) a comprehensive optimization model for the design and optimization of the production-distribution network in probabilistic environments with uncertain demand 2) a solution procedure based on the Lagrange release method and combined with the genetic algorithm to solve complex models in reasonable time is suggested.

Shankar et al. [26] present a multi-objective optimization problem of single-product four-echelon supply chain design including suppliers, manufacturing plants, DCs, and customer zones (CZ). In this research article, number and location of factories, raw materials flow from suppliers to factories, the amount of products that must be transported from factories to DCs have been considered.

Since decision-making is a critical issue in the supply chain model, Kassami et al. [27] mention that decision-making must be enough sustainable to operate appropriately in an uncertain and complex environment of the market for many years. The purpose of this paper is to model a multi-echelon supply chain problem and determine the constraints that prevent the flow from performing properly.

Khezeli et al. [28] research is focused on supply chain sustainability and resilience in which various scenarios such as environmental compatibility, product life cycle, carbon emissions, wastes, and effluents are considered.

3. Problem Description and Assumptions

With the expansion of the industry and increasing environmental concerns, the electricity industry should seek to choose suitable alternatives to fossil resources such as photovoltaic, wind, etc. renewable energies. Considering the challenges of renewable production such as uncertainty in generation, fluctuations, network voltage deviation, losses, and the use of energy storage is suggested to solve these challenges. Energy storage devices can inject electricity into the grid during peak load as a generator and store energy during low load as a consumer. In this article, a day is divided into three parts: low load, medium load, and peak load, and the energy storage is charged only during low load and discharged during peak load to create a balance between generation and consumption.

As stated in the previous section, the use of distributed energy storage improves the technical specification of the network, increases load response, and reduces demand, as well as reducing investment costs for the construction of fossil and distributed power plants. As a result, in this article, the distributed energy storage is located in the network. In this research, an integrated mixed-integer linear programming (MILP) model for capacity planning and location of the power supply chain is presented considering the energy storage as a new level of the same echelon as the distribution network to increase profit and reliability. In this research, two views of the distribution network as the owner of the energy storage and the subscribers as the owner of the energy storage have been modeled.

The first echelon of the power supply chain includes all types of generators, the second echelon includes the distribution network and energy storage in the same category, and also the third echelon includes all types of energy consumers. As shown in Figure 1, there is a two-way relationship between the distribution network and energy storage, that is, it buys electricity from the grid at certain hours and sells electricity to the grid at other times, and the only connection of the energy storage in the supply chain is with the distribution network, and there is no connection between the energy storage and electricity generators or consumers. In other words, the distribution network acts like a pool where all types of generators, including fossil and distributed generation, inject electricity into the network and consumers consume the generated electricity, as shown in Figure 2. The role of energy storage is to create a balance between generation and consumption. When the amount of generation is greater than the demand, the energy storage is placed in the role of a consumer, and when the amount of demand is greater than the generation, the energy storage is injected into the grid as a producer of electricity.

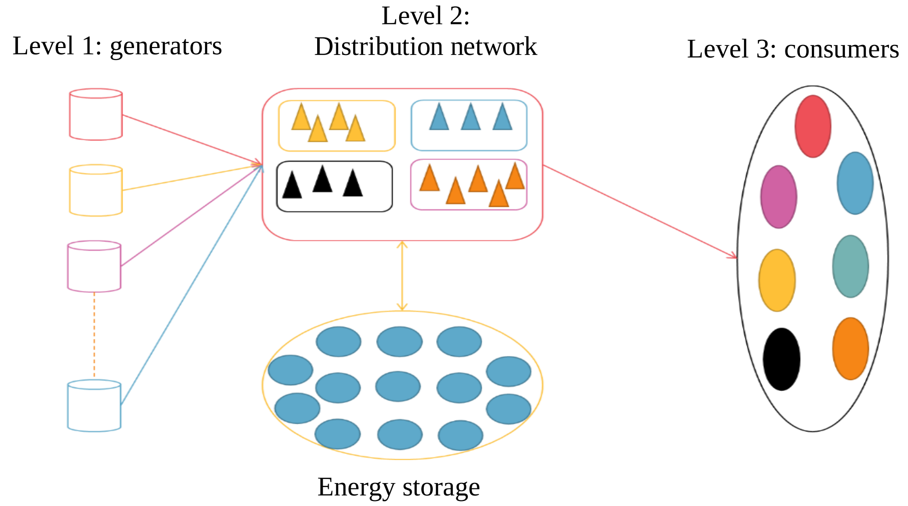

Fig. 1. Three-echelon power supply chain with energy storage

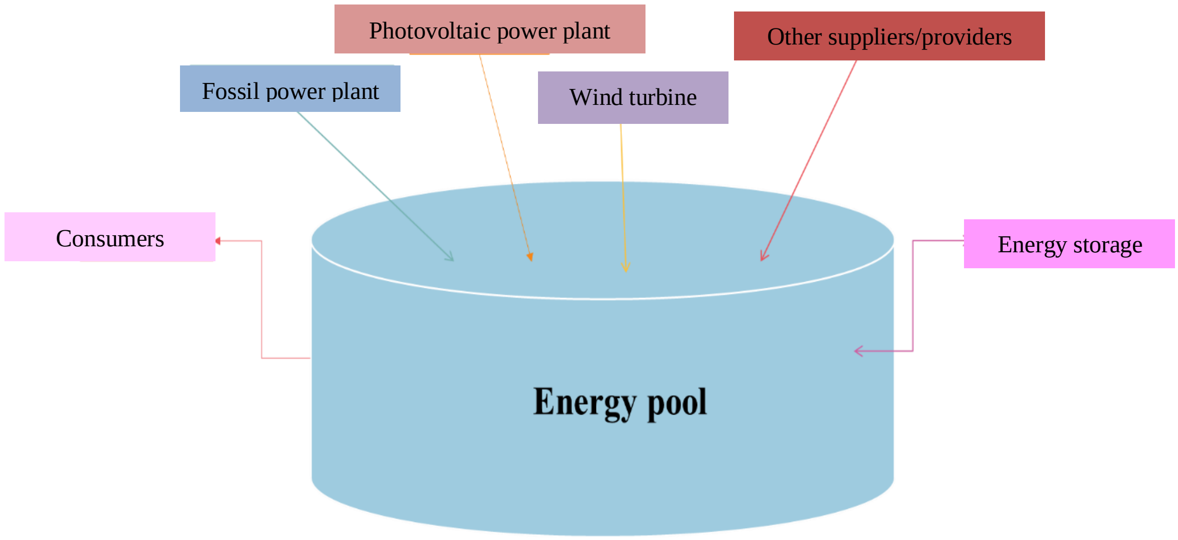

Fig. 2. Schema of the energy pool

Figure 1 shows the difference between energy storage and warehouse in the supply chain. In the supply chain, the warehouse has a relationship with both the supplier and the consumer, but the energy storage does not have this relationship, and the supplier and consumer relationship is with the distribution network. Also, transportation in the power supply chain is done by transmission and distribution lines, which is done by vehicles in the goods supply chain. In this article, two types of electricity supply chain are presented. The first model is considered from the point of view of ownership of energy storage with distribution network component (SOEDN) and the second one is ownership of energy storage with electricity subscribers (SOES). In the following, the characteristics of the first and second models will be compared.

In terms of reliability, in the first model, the amount of outages is very important and the distribution network must reduce the amount of outages to increase the reliability of the network but in the second model, since the electricity subscribers are looking for more profit and the reliability of the network is not considered for them, the amount of outage is not important.

From an environmental point of view, in the first model, it is possible to exchange carbon emissions between the distribution company and companies that request more carbon emission quotas, and in the second model, electricity subscribers can receive rewards from the distribution network for injecting carbon-free electricity into the network.

In this problem, locating the energy storage installation among the candidate points and selecting the appropriate capacity of the energy storage among the specified capacities for the selected location is considered. The objective function of the first model is profit maximization and reliability and the second model is profit maximization. The objective function of the first model includes the cost of purchasing the installation site, energy storage equipment, maintenance and repair costs, purchasing electricity from the upstream network and reselling it, receiving rewards to reduce carbon emissions and outage costs, and the second model does not include outage costs.

The assumptions of the model are as follows:

- The electricity tariff is the same for all types of consumers.
- The type of battery technology does not affect the problem.
- Energy storage devices are distributed in the grid.
- The battery should be charged and discharged once during the day.
- Each day is divided into three time periods: low load, medium load and peak load, and the prices are different in each period.
- The battery should be discharged during peak load and charged during low load
- The power supply source of the battery is considered to be the power grid, so the price of purchased electricity does not depend on the type of generator.
- The regional power company is considered as the bus.
- Each bus includes several districts.
- The price of land is different in each district.
- The grid pays rewards for injecting carbon-free electricity.

In the following, sets, decision variables, and problem parameters are defined.

3.1. Sets and model parameters

sets

i: Generators *(i=1, 2, …, I)*
l: Type of consumers *(l=1, 2, …, L)*
k: Energy storage *(k=1, 2, …, K)*
t: Number of time period per day *(t=1, 2, 3)*
m: Number of buses *(m=1, 2, …, M)*
n: Number of areas covered by each bus *(n=1, 2, …, N)*

Model parameters

P_{imt}: Production power of power plant *i* in bus *m* in period *t*
D_{lmt}: The amount of demand of type *l* subscribers in bus *m* in period *t*
cap_k: Battery capacity *k*
R: Maximum percentage of battery discharge
Cf: Battery purchase cost
Cv: Battery maintenance and operation cost
η: Battery efficiency
σ: Battery self-discharge rate
TC: Battery charging time
TD: Battery discharge time
h: Interest rate
C_{mn}: Land price in Bas m in area n
G: The area of land required to build a *1kwh* battery
A: Selling price per *kwh* of electricity during peak times/ periods
B: The purchase price of each *kwh* of electricity during low-load hours
CO: Outage cost per *kwh*
λ : Carbon emission rate *(ton/kwh)*
O: Price per ton of carbon *($/ton)*
U: The number of days of battery operation in a year
τ: The percentage of load growth per year
dN: The number of years of operation of the battery

Decision variables

X_{mnk}: Binary variable of choosing the location and capacity of energy storage

Y_{mt}: Binary variable expressing shortage in bus *m* in period *t*

Z_{mt}: Binary variable expressing the need of bus *m* in period *t* for the battery

ENS_t: Continuous variable that is outage cost in period *t*

In the next section, the modeling of the problem is discussed according to the stated assumptions and introduced parameters.

3.2. Description of the proposed mathematical models

According to the assumptions of the problem and Figure 1, as well as the two points of view that were introduced, the modeling of the problem is discussed and explained in this section. For each model, the objective function is expressed and the problem constraints are presented.

3.2.1. SOEDN model

This model is formulated from the point of view of ownership of energy storage with the distribution network. The objective function consists of incomes and operations costs. The income function of this model includes the income from buying and selling energy in different period frames and the income from the carbon emission exchange. The cost function includes the cost of building the battery location, the investment cost, the operation and maintenance of the batteries, and the outage cost.

$$f_1 = (A - B) \times \sum_{m=1}^{M} \sum_{t=1}^{T} (\sum_{l=1}^{L} (D_{lmt} - \sum_{i=1}^{I} P_{imt}) \times Z_{mt} \quad (1)$$

Equation 1 shows the income from buying and selling energy during the day and night.

$$f_2 = \lambda \times O \times \sum_{m=1}^{M} \sum_{t=1}^{T} (\sum_{l=1}^{L} D_{lmt} - \sum_{i=1}^{I} P_{imt}) \times Z_{mt} \quad (2)$$

Equation 2 shows the income from the exchange of carbon emissions. If the electricity grid uses energy storage system instead of fossil fuel and carbon emissions during peak consumption and produces electricity, it can sell its surplus carbon share to carbon-buying companies.

$$f_3 = \frac{G}{U} \times \frac{h(1+h)^{dN}}{(1+h)^{dN}-1} \times \sum_{m=1}^{M} \sum_{n=1}^{N} \sum_{k=1}^{K} C_{mn} \times cap_k \times X_{mnk} \quad (3)$$

Equation 3 shows the construction cost of all the batteries. Since the price of land in each area is different in each bus, an area with the lowest price is chosen to install the storage. If bus *m* needs to install a battery and there is a place for the installation of energy storage at the location of the distribution substation, paying this fee is waived and it is for the benefit of the electricity company.

$$f_4 = \sum_{m=1}^{M} \sum_{n=1}^{N} \sum_{k=1}^{K} ((\frac{Cf}{U} \times \frac{h(1+h)^{dN}}{(1+h)^{dN}-1} \times cap_k \times X_{mnk}) + (Cv \times \frac{cap_k}{TD} \times X_{mnk})) \quad (4)$$

Equation 4 shows the cost of investment, operation, and maintenance of batteries.

$$f_5 = Co \times \sum_{t=1}^{T} ENS_t \quad (5)$$

Equation 5 shows the cost of the blackout in the network.

Therefore, the objective function is equal to the difference of the total costs from the total income, which is equal to Equation 6.

$$max\, f = f_1 + f_2 - (f_3 + f_4 + f_5) \quad (6)$$

The model constraints are according to Equations 7 to 21.

$$(\sum_{l=1}^{L} D_{lmt} - \sum_{i=1}^{I} P_{imt}) \times Y_{mt} \geq 0. \forall m.t \quad (7)$$

Equation 7 identifies the buses in which the shortage occurred. If in bus *m* in period *t* the amount of demand exceeds the production and there is a shortage, Y_{mt} will be equal to one, otherwise, it will be zero.

$$\sum_{m=1}^{M} Y_{mt} \leq M \quad \forall m.t \quad (8)$$

Equation 8 guarantees that the shortage occurs at most as many as the number of available buses.

$$PD_{mt} = (\sum_{l=1}^{L} D_{lmt} - \sum_{i=1}^{I} P_{imt}) \times Y_{mt} \geq 0 \quad \forall m.t \quad (9)$$

Equation 9 shows the amount of energy shortage in bus *m* in period *t*.

$$PD_{mt} \times (1+\tau) \geq R \times Cap_k \times Z_{mt} \quad \forall m.t \quad \forall k = 1 \quad (10)$$

Equation 10 shows the minimum capacity of energy storage that can be installed on buses. In other words, energy storage should be installed at least to the extent of energy shortage in the target bus.

$$PD_{mt} = (\sum_{l=1}^{L} D_{lmt} - \sum_{i=1}^{I} P_{imt}) \times (1 - Y_{mt}) \geq 0 \quad \forall m.t \quad (11)$$

Equation 11 shows the amount of excess energy in bus *m* in period *t* to charge the energy storage.

$$Y_{mt} \geq Z_{mt} \quad \forall m.t \tag{12}$$

In relation 12 it is guaranteed that a bus can request energy storage when a shortage has occurred.

$$\sum_{t=1}^{T} Z_{mt} \leq 1 \quad \forall m \tag{13}$$

In relation 13, it is guaranteed that each bus can request battery discharge at most once during the day.

$$\sum_{n=1}^{N}(\sum_{l=1}^{L} D_{lmt} - \sum_{i=1}^{I} P_{imt}) \times (1+\tau) \times X_{mnk} \leq R \times Cap_k \times Z_{mt} \quad \forall m.k.t \tag{14}$$

It is stated in Equation 14 that if the shortage in bus *m* in period *t*, taking into account the load growth percentage, is greater than the minimum battery capacity that can be installed and Z_{mt} takes a value of one, the battery with capacity Cap_k to be installed in bus *m* at location *n* must be selected and thus X_{mnk} takes a value of one. The smallest battery that has a capacity equal to the demand should be selected.

$$\sum_{n=1}^{N}\sum_{k=1}^{K} X_{mnk} \leq \sum_{t=1}^{T} Z_{mt} \quad \forall m \tag{15}$$

According to Equation 15, it is possible to install energy storage in bus *m* of area *n* with a certain capacity if there is a shortage in that bus.

$$\sum_{n=1}^{N}\sum_{k=1}^{K} X_{mnk} \leq 1 \quad \forall m \tag{16}$$

According to Equation 16, at most one battery with capacity Cap_k can be installed in each bus.

$$\sum_{m=1}^{M}\sum_{n=1}^{N}\sum_{k=1}^{K} X_{mnk} \leq \mathrm{M} \tag{17}$$

Equation 17, guarantees that energy storage can be installed as many as the available buses.

$$\sum_{m=1}^{M}\sum_{n=1}^{N}\sum_{k=1}^{K} X_{mnk} = \sum_{m=1}^{M}\sum_{t=1}^{T} Z_{mt} \tag{18}$$

In Equation, it is guaranteed that batteries will be installed in the number of buses that require battery installation.

$$ENS_t = \sum_{m=1}^{M}(\sum_{l=1}^{L} D_{lmt} - \sum_{i=1}^{I} P_{imt}) \times (Y_{mt} - Z_{mt}) \quad \forall t \tag{19}$$

Equation 19, states that in a situation where the amount of demand is greater than the generation in bus *m* in period *t* and it is impossible to install a battery, some of the required load is not supplied and outage occurs in the network. This outage should be as minimal as possible.

Constraints 20 and 21 specify the status of binary and continuous variables.

$$ENS_t \geq 0 \quad \forall t. \quad PD_{mt} \geq 0 \quad \forall m.t. \quad PC_{mt} \geq 0 \quad \forall m.t \tag{20}$$

$$Z_{mt} \in \{0.1\} \quad \forall m.t. \quad Y_{mt} \in \{0.1\} \quad \forall m.t. \quad X_{mnk} \in \{0.1\} \quad \forall m.n.k \tag{21}$$

3.2.2. SOES model

This model is formulated from the point of view of ownership of energy storage with subscribers. The objective function consists of income and cost functions. The income function of this model includes the income from buying and selling energy in different time frames and the reward from injecting carbon-free electricity into the network. The cost function includes the cost of building the battery location, the cost of investment, operation, and maintenance of batteries.

$$f_1 = (A - B) \times \sum_{m=1}^{M}\sum_{t=1}^{T}(\sum_{l=1}^{L}(D_{lmt} - \sum_{i=1}^{I} P_{imt}) \times Z_{mt} \tag{22}$$

Equation 22 shows the income from buying and selling energy during the day and night.

$$f_2 = \lambda \times O \times \sum_{m=1}^{M}\sum_{t=1}^{T}(\sum_{l=1}^{L} D_{lmt} - \sum_{i=1}^{I} P_{imt}) \times Z_{mt} \tag{23}$$

Equation 23 calculates the income from injecting carbon-free electricity into the power grid. Battery owners can receive rewards from the power grid for battery discharge capacity that allows them to inject carbon-free electricity into the grid.

$$f_3 = \frac{G}{U} \times \frac{h(1+h)^{dN}}{(1+h)^{dN}-1} \times \sum_{m=1}^{M}\sum_{n=1}^{N}\sum_{k=1}^{K} C_{mn} \times cap_k \times X_{mnk} \tag{24}$$

Equation 24 shows the construction cost of all the batteries. This fee is waived if the subscribers use their residential building (if it meets the conditions for installing the energy storage) to install the energy storage.

$$f_4 = \sum_{m=1}^{M}\sum_{n=1}^{N}\sum_{k=1}^{K}((\frac{Cf}{U} \times \frac{h(1+h)^{dN}}{(1+h)^{dN}-1} \times cap_k \times X_{mnk}) + (Cv \times \frac{cap_k}{TD} \times X_{mnk})) \tag{25}$$

Equation 25 shows the cost of investment, operation, and maintenance of batteries.
Therefore, the objective function is equal to the difference between the total costs and the total income, which is equal to Equation 26:

$$\mathrm{Max}\, f = f_1 + f_2 - (f_3 + f_4) \tag{26}$$

The model constraints are according to Equations 27 to 40.

$$\left(\sum_{l=1}^{L} D_{lmt} - \sum_{i=1}^{I} P_{imt}\right) \times Y_{mt} \geq 0. \forall m.t \quad (27)$$

Equation 27, identifies the buses in which the shortage occurred. If in bus *m* in period *t* the amount of demand exceeds the generation and there is a shortage, Y_{mt} will be equal to one, otherwise, it will be zero.

$$\sum_{m=1}^{M} Y_{mt} \leq M \quad \forall m,t \quad (28)$$

Equation 28, guarantees that the shortage occurs at most as many as the number of available buses.

$$PD_{mt} = \left(\sum_{l=1}^{L} D_{lmt} - \sum_{i=1}^{I} P_{imt}\right) \times Y_{mt} \geq 0 \;\; \forall m,t \quad (29)$$

Equation 29 shows the amount of energy shortage in bus *m* in period *t*.

$$PD_{mt} \times (1+\tau) \geq R \times Cap_k \times Z_{mt} \;\; \forall m.t \;\; \forall k=1 \quad (30)$$

Equation 30 shows the minimum capacity of energy storage that can be installed on buses. In other words, energy storage should be installed at least to the extent of energy shortage in the target bus.

$$PC_{mt} = \left(\sum_{l=1}^{L} D_{lmt} - \sum_{i=1}^{I} P_{imt}\right) \times (1 - Y_{mt}) \geq 0 \quad \forall m.t \quad (31)$$

Equation 31 shows the amount of excess energy in bus *m* in period *t* to charge the energy storage.

$$Y_{mt} \geq Z_{mt} \quad \forall m.t \quad (32)$$

Equation 32 guarantees that a bus can request energy storage when a shortage has occurred.

$$\sum_{t=1}^{T} Z_{mt} \leq 1 \quad \forall m \quad (33)$$

In relation 33, it is guaranteed that each bus can request battery discharge at most once during the day.

$$\sum_{n=1}^{N}\left(\sum_{l=1}^{L} D_{lmt} - \sum_{i=1}^{I} P_{imt}\right)(1+\tau) X_{mnk} \leq R \times Cap_k \times Z_{mt} \quad \forall m.k.t \quad (34)$$

As it stated in relation 34, if the deficiency in bus *m* in period *t*, taking into account the load growth percentage, is greater than the minimum battery capacity that can be installed and Z_{mt} takes a value of one, the battery with capacity Cap_k to be installed in bus *m* at location *n* must be selected and thus X_{mnk} takes a value of one. The smallest battery that has a capacity equal to the demand should be selected.

$$\sum_{n=1}^{N}\sum_{k=1}^{K} X_{mnk} \leq \sum_{t=1}^{T} Z_{mt} \quad \forall m \quad (35)$$

According to Equation 35, it is possible to install energy storage in bus *m* of area *n* with a certain capacity if there is a shortage in that bus.

$$\sum_{n=1}^{N}\sum_{k=1}^{K} X_{mnk} \leq 1 \quad \forall m \quad (36)$$

According to Equation 36, at most one battery with capacity Cap_k can be installed in each bus.

$$\sum_{m=1}^{M}\sum_{n=1}^{N}\sum_{k=1}^{K} X_{mnk} \leq \mathrm{M} \quad (37)$$

In relation 37, it is guaranteed that energy storage can be installed regarding the available buses.

$$\sum_{m=1}^{M}\sum_{n=1}^{N}\sum_{k=1}^{K} X_{mnk} = \sum_{m=1}^{M}\sum_{t=1}^{T} Z_{mt} \quad (38)$$

In relation 38, it is guaranteed that batteries will be installed in the number of buses that require battery installation.

Constraints 39 and 40 specify the status of binary and continuous variables.

$$PD_{mt} \geq 0 \quad \forall m.t. \;\; PC_{mt} \geq 0 \quad \forall m.t \quad (39)$$

$$Z_{mt} \in \{0.1\} \quad \forall m.t. \;\; Y_{mt} \in \{0.1\} \quad \forall m.t. \;\; X_{mnk} \in \{0.1\} \quad \forall m.n.k \quad (40)$$

As a result, by developing these models, it is possible to determine the bus that needs to install energy storage, assign the right capacity of the energy storage, and the right location to it. In the next section, solving the model using GAMS software and model sensitivity analysis will be discussed.

4. Solving Approach of the Proposed Mathematical Model

This section consists of two sub-sections, which are presented in section 4-1, the model is solved using GAMS software and its results are presented. In sub-section 4-2, the sensitivity analysis of the model will be discussed considering the parameters of the problem.

4.1. Solving the model by GAMS software

Since the first and second presented models have no structural difference and differ only in terms of reliability (outage cost), therefore, to avoid repetition, the first model has been solved and tested in this section. The model provided by

GAMS software is solved and 30 examples of problems are tested for validation in a range of parameters. To select the input parameters and dimensions of designed test problems, it is critical to include a diverse range of problems including small, medium, and large-size problems. These issues have a significant impact on the relative confidence of the proposed solution method and have sufficient reliability. For this purpose, empirical observations and frameworks of the other articles have been used [25]. Table 1 shows the values of the sample problems' numerical solutions (test problem) and includes 30 different sample problems that are compared in terms of the number of selected batteries, the value of the objective function, and the problem-solving time. As can be seen from Table 1, the dimensions of problem 30 include 6,491 constraints and 20,120 binary variables. Since the t index cannot have a value other than 3 according to the assumptions of the problem, it is not included in Table 1. The meaning of continuous variable is the amount of outage, the number of which depends on the index t and is always 3.

Tab. 1. Numerical solution values of sample problems

#	sets					Continues variable	Binary variable	Number of Battery	Number of constraints	Objective function	Solving time
	i	l	m	n	k						
1	2	3	10	3	15	3	510	3	701	8482.6	2
2	2	3	10	4	20	3	860	3	851	8896.4	2
3	2	5	20	6	50	3	6,120	4	3,491	-1803.1	33
4	2	5	20	8	100	3	16,120	4	6,491	-461.4	211
5	5	2	10	2	15	3	360	6	701	2639.4	2
6	5	2	10	4	20	3	860	6	851	2707.6	2
7	5	4	20	6	50	3	6,120	17	3,491	83801.6	169
8	5	4	20	8	100	3	16,120	15	6,491	75648.8	805
9	10	3	10	2	15	3	360	10	701	251796.2	2
10	10	3	10	4	20	3	860	10	851	253362.3	3
11	10	5	20	6	50	3	6,120	19	3,491	250197.7	146
12	10	5	20	8	100	3	16,120	19	6,491	251551.2	739
13	15	3	10	2	15	3	360	9	701	116678.5	3
14	15	3	10	4	20	3	860	9	851	116876.6	5
15	15	5	20	6	50	3	6,120	18	3,491	248518.8	103
16	15	5	20	8	100	3	16,120	6	6,491	32872.9	265
17	20	3	10	2	15	3	360	2	701	8060.2	5
18	20	3	10	4	20	3	860	2	851	7858.9	3
19	20	5	20	6	50	3	6,120	20	3,491	763068.7	39
20	20	5	20	8	100	3	16,120	20	6,491	756032.0	160
21	25	3	10	2	15	3	360	1	701	2589.1	1
22	25	3	10	4	20	3	860	1	851	2546.7	2
23	25	5	20	6	50	3	6,120	20	3,491	510775.3	81
24	25	5	20	8	100	3	16,120	20	6,491	513957.7	387
25	50	3	10	2	15	3	360	1	701	2589.1	2
26	50	3	10	4	20	3	860	1	851	2614.3	2
27	50	5	20	6	50	3	6,120	20	3,491	487246.9	82
28	50	5	20	8	100	3	16,120	20	6,491	484816.6	412
29	50	10	20	10	100	3	20,120	20	6,491	966249.3	298
30	50	20	20	10	100	3	20,120	20	6,491	966249.3	300

As it is clear from Table 1, the maximum time of solving by GAMS software was 805 seconds; therefore, meta-heuristic algorithms were not used to solve the problem. In the following, the sensitivity analysis of the model to different parameters is discussed.

4.2. Sensitivity analysis

In this sub-section, problem number 11 is selected from the test problem and sensitivity analysis is done to different parameters. The model has been analyzed according to two categories of parameters. The first category is the parameters that the decision maker has no choice over, and the second category is the parameters that the decision maker has the choice to choose.

The first category includes the amount of demand and generation, which depends on the conditions and is not available to the decision-makers. The second category includes the price of land in each region, the number of days of use of energy storage, battery life, capacity of energy storage, purchase and operation cost of energy storage, and maximum discharge capacity of energy storage.

Figure 3 shows the model sensitivity analysis. As it is known, changes in the amount of demand have a direct effect and also have the greatest effect on the amount of the objective function. The second type of influence on the model is related to the amount of generation and has the opposite effect on the model. The four parameters of discharge percentage, number of days of operation, battery life, and purchase cost have almost the same slope and are equally effective but the 50% reduction in the number of days of operation and battery life compared to other situations has made a greater change.

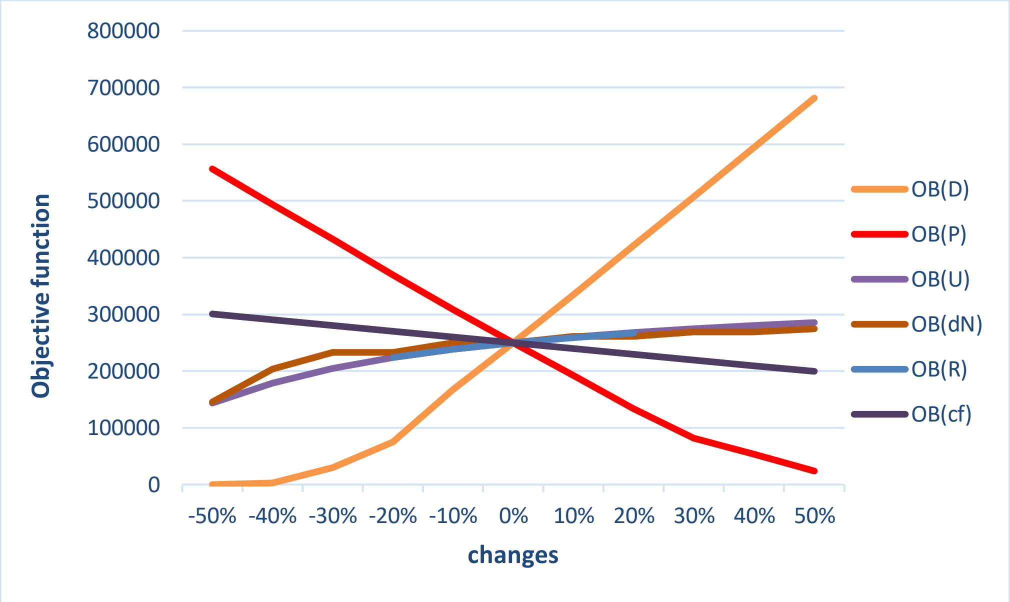

Fig. 3. Sensivity analysis

Therefore, decision-makers should be sensitive to demand changes in different seasons of the year as well as production changes to get the most profit from installing energy storage. If the amount of demand from the network increases, this demand is transferred to the energy storage system and the amount of purchases by subscribers from the upstream network decreases in hours and reduces the peak load, in addition to increasing the reliability of the network, the amount of profit from using energy storages increases.

5. Summary and Conclusion

Considering the increasing energy consumption and the lack of fossil fuels, as well as the improvement of climatic conditions, fundamental changes in the electricity supply chain should be considered. One of the reasonable solutions is the use of energy storage devices. As mentioned in the previous sections, the use of distributed energy storage as a new echelon in the electricity supply chain increases reliability and reduces outages in the network, improves the technical indicators of the network, postpones the upgrade of network equipment, reduces investment in the construction of fossil and renewable power plants, reduces air pollution and environmental risks and profitability for energy storage owners.

Considering the reviewed articles and paying less attention to the problem of capacity planning modeling and location of the electricity supply chain with the presence of energy storage, this issue has been addressed in this article.

The presented MILP model is an integrated model of capacity planning and location of a three-echelon power supply chain to maximize profit and reliability. The first echelon of the supply chain includes all types of generators, the second echelon includes the distribution network and energy storage, and the third echelon includes all types of consumers. Since the use of energy storage can be profitable for both the distribution network and electricity subscribers, in this research, two three-echelon power supply chain models have been presented, the first model is from the point of view of ownership of energy storage with the distribution network and the second model is from the point of view of ownership of energy storage with electricity subscribers. In each model, the features are stated and it is possible to use each model according to the type of investment. These two models determine the required bus to install energy storage, and then assign the right capacity of the energy storage and the right location for it.

According to the sensitivity analysis, investors can use energy storage when demand increases or when generation is lower than demand and profit from the difference between generation and demand. Decision makers can get the most profit from the energy storage system according to the sensitivity analysis performed on various parameters. so that:

- According to the changes in demand and generation in different seasons of the year, increase or decrease the capacity of energy storage to take advantage of the maximum usable capacity.
- Also, according to the parameter of battery life and the fixed cost of purchasing equipment, which depends on the type of battery, they can earn more profit by choosing the most suitable battery.
- On the other hand, by increasing the number of days of using the energy storage system, they can use the maximum capacity of the energy storage system and reduce their costs.

This work could be extended to the case of three-echelon integrated modeling of the power supply chain by considering the appropriate type of energy storage technology in each storage location. Furthermore, according to the variety of customers, pricing decisions could also be considered for future research.

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