https://adv-j-sci-eng.com eISSN: 2717-0705

Advanced Journal of Science and Engineering

Original Research

# Market Clearing due to the Reliability of Electricity Generation Units

**Ebadollah Amouzad Mahdiraji**[1,✉], **Mojtaba Sedghi Amiri**[2]

[1] *Department of Engineering, Sari Branch, Islamic Azad University, Sari, Iran*
[2] *Neka Power Generation Management Company, Neka, Iran*

✉ *Corresponding author*: **E.M. Amouzad**; *E-mail address*: **ebad.amouzad@gmail.com**, *ORCiD*: **0000-0003-3777-4811**.



***Received***: 15 December 2020 / ***Accepted***: 08 March 2021 / ***Published Online***: 30 March 2021

**ABSTRACT**

This paper presented a method for simultaneous clearing of energy and storage markets. The proposed method pursued two goals. The first goal was to take into account the random changes in production in the power grid, for which a random clearing model and the Monte Carlo method were used. In the second goal, the economic operation of production units and their reliability in the process of allocating the required capacity of the energy market and storage to generators, was considered. In the relevant objective function, in addition to energy supply and storage costs, non-energy delivery and storage costs were also included. The outputs of the proposed method could be used in the process of creating the necessary incentives among manufacturers. Because the more reliable the manufacturer, the more market share it would have. The efficiency of the proposed method on a sample network was evaluated and the results are presented.

**KEYWORDS** Simulation, Energy market, Storage market, Random market clearing, Unit reliability.

**CITE** Amouzad Mahdiraji E, Sedghi Amiri M. Market Clearing due to the Reliability of Electricity Generation Units. Advanced Journal of Science and Engineering. 2021;2(1):42-50.

**DOI** https://doi.org/10.22034/advjscieng21021042

**URL** https://sciengpub.com/adv-j-sci-eng/article/view/advjscieng21021042

## INTRODUCTION

In a restructured environment, energy and storage markets are managed to achieve the desired quality of energy supply to consumers. One of the important issues in this regard is the reliability of energy supply to consumers. The timely and continuous response of production units to their obligations in the electricity market plays a key role in meeting the constraint of reliability of power delivery to consumers. In a restructured environment, it is usually up to the system operator to meet the reliability constraint. The operator should divide the energy and storage system between the production units in such a way that while providing technical constraints, including reliability, the lowest operating cost is achieved. The issue of pricing and market clearing is of great importance, which has been addressed in various papers.[1-6] In general, in the electricity market clearing, two simultaneous and asynchronous clearing structures are used. Simultaneous clearing structure, used in the PJM, ISO-NI, and California electricity markets.[2-4] Energy and storage markets are cleared simultaneously.[5] A clearing with an asynchronous structure is characterized by the sequential settlement of energy and storage markets.[6] Achieving social welfare outweighs the benefits of simultaneous structure and simplicity and complexity outweigh the benefits of asynchronous structure. Various costs are included in the objective functions of the proposed methods for market clearing.[5-11] A previous work[5] provided a method for allocating storage capacity between production units according to the needs of the consumer side. Another previous work[6] suggested a way to solve the clearing problems in the asynchronous structure by adding the opportunity cost to the objective function. Probabilistic planning for the market model as a pond in a simultaneous structure was also used in an earlier work.[7] A point that is less considered in these papers is the effect of how power is distributed between units on network reliability.[12-17]

In this paper, a method for market clearing in a simultaneous structure is presented, which pursues the following two goals. First, applying the random clearing model to take into account the random nature of the operation of the power network. Second, using two new costs in the objective function to achieve greater reliability in production units. To achieve the first goal, Monte Carlo simulation was used, which resulted in different scenarios of electricity generation. As described in next section, a threshold value was used to reduce the number of scenarios during this process. Then, the clearing model was applied to the accepted scenarios. To achieve the second goal, which was to try to increase the reliability or availability of production units, two costs of non-delivery of energy and non-delivery of storage in the target function were considered in addition to energy supply and storage costs. The effect of using these two costs and minimizing them, along with the usual costs in the market, was to divide the required network capacity between units that are more reliable and less costly. In the proposed method, from the possible options for clearing the market, the option was selected leading to the lowest cost and highest reliability. This clearing method caused the production units to move to increase their reliability to gain more market share. The point to keep in mind was that although increasing the reliability of a production unit was costly, the production unit could offset these costs by having a larger market share and its bid price to participate in Keep the market at a good level.

## MATERIALS & METHODS

*Production of Scenario by Monte Carlo Method*

One advantage of the Monte Carlo method is that the number of samples required to achieve a certain level of accuracy is independent of the dimensions of the network. In the Monte Carlo process, a two-state stochastic model is used for production units. At the beginning of the simulation, it is assumed that the power grid is in a normal state. The number of units generating random numbers is created between 0 and 1, and the state of a unit is determined by comparing the value of a random number with the forced exit rate of that unit as indicated by the relationship of eq. (1).

$$\begin{gathered} U_i\left(i = 1,2,\dots,N_g\right) \\ u_i = 1(on\ state)\ if\ U_i \geq FOR_i \\ u_i = 0(off\ state)\ if\ U_i \geq FOR_i \end{gathered} \tag{1}$$

The components of eq. (1) are; *i*: Production unit counter, $U_i$: random number for unit *i*, $N_g$: number of production units, $U_i$: unit status *i*, $FOR_i$: Compulsory exit rate of unit *i*. If $u_i = 1$, it is possible for unit *i* to participate in the market. In this case, the availability of *i* unit is equal to $u_i \times (1 - FOR_i)$. If $u_i = 0$, unit *i* cannot participate in the market and its unavailability is equal to $(1 - u_i) \times FOR_i$. When this process is done for all units, a production scenario is obtained. The probability of each scenario is considered as described in eq. (2).

$$\Pr ob_s = \prod_{i=1}^{N_g}\{u_i(1 - FOR_i) + (1 - u_i)FOR_i\} \tag{2}$$

Given the myriad of production scenarios, it is necessary to use a method to keep the number of scenarios limited. In this paper, scenarios with a probability of occurrence of less than 0.002 as well as similar scenarios are omitted.[8]

*Objective Function and Costs Included*

The main goal of the papers for the market clearing is to minimize costs. In the proposed method, in addition to energy supply and storage costs, the two costs of non-delivery of energy and non-delivery of storage are also included in the objective function. These two costs can be considered as a way for manufacturers to increase the reliability of their energy and storage market commitments in practice. As a result, by optimizing the objective function in the proposed method, units with higher reliability and lower proposed cost receive more market share. According to the above explanations, the objective function in the proposed method is described by eq. (3).

$$\sum_{s=1}^{N_s} \Pr ob_s \left\{ \sum_{t=1}^{N_p} \left[ \sum_{i=1}^{N_g} \begin{pmatrix} UC(AE_{i,t}^s) \times ue_{i,t}^s + \\ UC(AR_{i,t}^s) \times ur_{i,t}^s + \\ NDEC_t^s \times NDRC_t^s \end{pmatrix} \right] \right\} \quad , \quad \begin{matrix} UC(AE_{i,t}^s) = AE_{i,t}^s \times BPE_i^s \\ UC(AR_{i,t}^s) = AR_{i,t}^s \times BPR_i^s \end{matrix} \tag{3}$$

The components of eq. (3) are; $N_S$: number of scenarios remaining after reducing the number of scenarios, $N_P$: number of hours studied, $AE_{i,t}^s$: unit i share of energy market in scenario *s*, $BPE_i^s$: bid price of unit i for energy market in scenario *s*, $AR_{i,t}^s$: unit *i* share of the stock market in scenario *s*, $BPR_i^s$: bid price of unit i for the stock market in scenario *s*, $ue_{i,t}^s$: the situation of unit *i* in the energy market at hour t in scenario *s*, $ur_{i,t}^s$: the status of unit *i* in the stock market at hour t in scenario *s*, $NDEC_t^s$: cost of non-delivery of energy per hour t in scenario *s*, $NDRC_t^s$: cost of non-delivery of stock per hour t in scenario *s*. The set of constraints includes the constraints of the production limits of the units, the constraints of the minimum on and off time of the units and the rate of increase of their power. The following section describes how to calculate non-delivery and storage costs.

*Calculation of Non-Delivery Energy and Storage Costs*

The amounts of non-delivery energy and storage costs can be calculated from eqs. (4) and (5).

$$NDEC_t^s = NDE_t^s \times NSEF_t^s \tag{4}$$
$$NDRC_t^s = NDR_t^s \times NSRF_t^s \tag{5}$$

The components of eqs. (4) and (5) are; $NDE_t^s$: the rate of non-delivery of energy per hour *t* in scenario *s*, $NSEF_t^s$: factor of non-delivery of energy per hour *t* in scenario *s*, $NDR_t^s$: the rate of non-delivery of reserves per hour *t* in scenario *s*, $NSRF_t^s$: inventory non-delivery factor at hour *t* in scenario *s*. Given that a number of units may not meet their obligations per hour, the amount of energy and reserves not delivered is calculated from eqs. (6) and (7).

$$NDE_t^s = \sum_{k=1}^{N_e^s} \left\{ \begin{matrix} \left[ FOR_k \prod_{\substack{i=1, \\ i \neq k}}^{N_e^s} (1 - FOR_i) \right] \times \\ \left[ \sum_{\substack{i=1 \\ i \neq k}}^{N_e^s} AE_{i,t}^s - AE_{k,t}^s \right] \end{matrix} \right\} + \\ \sum_{k=1}^{N_e^s} \sum_{f>k}^{N_e^s} \left\{ \begin{matrix} \left[ FOR_k FOR_f \prod_{\substack{i=1, \\ i \neq k,f}}^{N_e^s} (1 - FOR_i) \right] \times \\ \left[ \sum_{\substack{i=1 \\ i \neq k,f}}^{N_e^s} AE_{i,t}^s - (AE_{k,t}^s + AE_{k,t}^s) \right] \end{matrix} \right\} + \cdots \tag{6}$$

$$NDR_t^s = \sum_{k=1}^{N_r^s} \left\{ \begin{matrix} \left[ PF_k^{mt} \prod_{\substack{i=1, \\ i \neq k}}^{N_r^s} (1 - PF_i^{mt}) \right] \times \\ \left[ \sum_{\substack{i=1 \\ i \neq k}}^{N_r^s} AR_{i,t}^s - AR_{k,t}^s \right] \end{matrix} \right\} + \\ \sum_{k=1}^{N_r^s} \sum_{f>k}^{N_r^s} \left\{ \begin{matrix} \left[ PF_k^{mt} PF_f^{mt} \prod_{\substack{i=1, \\ i \neq k,f}}^{N_r^s} (1 - PF_i^{mt}) \right] \times \\ \left[ \sum_{\substack{i=1 \\ i \neq k,f}}^{N_r^s} AR_{i,t}^s - (AR_{k,t}^s + AR_{f,t}^s) \right] \end{matrix} \right\} + \cdots \tag{7}$$

In eqs. (6) and (7); $N_e^s$: number of production units accepted in the energy market in scenario *s*, $N_r^s$: number of production units accepted in the stock market in scenario *s*, $PF_i^{mt}$: the probability of a unit failing to respond to unit *i* within the time period *mt*. The *mt* time period means that each production unit accepted in the stock market, depending on the type of stock in question, must meet its obligations within a certain period of time. For example, this interval can be 10 min for revolving storage. It should be noted that there are differences between the existing methods to compensate for the non-delivery of energy and storage. If some production units involved in the energy market have difficulty in fulfilling their obligations, the system operator can use the following methods to compensate for this shortcoming:

- New alternative unit (with or without acceptance from the energy market) among the units that have additional capacity,
- Replacement from the reserve market if sufficient storage capacity is available to compensate for non-delivery from the energy market,
- Shut down, if the first two options cannot compensate for non-delivery.

In cases where the production units accepted in the stock market cannot fulfill their obligations, the existing compensation methods are different from the previous conditions, which can be summarized as follows:

- A new alternative unit that is not involved in the energy and storage markets and has the necessary conditions for the storage market (the required conditions are the response rate and the necessary capacity),
- Reducing the capacity of some units accepted in the energy market and moving this capacity to the reserve market. Units involved in these situations are entitled to the opportunity fee,
- Load cut.

It should be noted that the second method is used if units with sufficient response rates are not available for the stock market. In other words, units with this feature have already been accepted in the energy market. In this paper, a method is used to compensate for non-delivery that has the lowest cost and highest reliability of the units. The probability of non-delivery of energy and reserve depends on the forced exit rate of the units and the probability of failure of the unit to respond within the specified time of delivery of reserve, respectively. A fixed period of time is the period that a unit has the opportunity to convert a potentially allocated reserve into an actual reserve. This probability of non-delivery, for example, in cases where one or two units do not meet their obligations simultaneously, can be calculated by eq. (8).

$$
\begin{aligned}
Pr_k^e &= FOR_k \prod_{\substack{i=1,\\ i\neq k}}^{N_r} (1 - FOR_i) \\
Pr_{k,f}^e &= FOR_k FOR_f \prod_{\substack{i=1,\\ i\neq k,f}}^{N_e} (1 - FOR_i) \\
Pr_k^r &= PF_k \prod_{\substack{i=1,\\ i\neq k}}^{N_r} (1 - PF_i) \\
Pr_{k,f}^r &= PF_k PF_f \prod_{\substack{i=1,\\ i\neq k,f}}^{N_r} (1 - PF_i)
\end{aligned}
\tag{8}
$$

Components of eq. (8) are; $Pr_k^e$: possibility of non-delivery of *k* unit energy, $Pr_{k,f}^e$: probability of non-delivery of *k* and *f* unit energy, $Pr_k^r$: possibility of non-delivery of *k* unit reserve, $Pr_{k,f}^r$: possibility of non-delivery of *k* and *f* unit reserves. By using these relationships, it is possible to influence the distribution of the required capacity between units on their reliability. By selecting the non-delivery cases and the optimal method of compensating them, the energy non-delivery and storage factors ($NSRF_i^s$, $NSEF_i^s$) can be calculated based on the cost of the alternative method.

*Proposed Algorithm*

This section describes the proposed market clearing algorithm. First, different production scenarios are created using the Monte Carlo method, and by applying the scenario reduction method, scenarios with higher probabilities are selected. For this purpose, non-energy delivery and storage factors must be calculated. To do this, initial planning is done without the cost of non-delivery. Then, among the non-delivery cases based on eqs. (9) and (10), the cases with the highest probability of occurrence and the share of non-delivery are selected and according to the available methods for compensation, using eqs. (11) and (12) the optimal solution is selected. Based on the cost of the optimal method, non-delivery factors are calculated. Finally, the final planning is determined by the non-delivery costs. Fig. 1 shows the process view of the proposed algorithm.

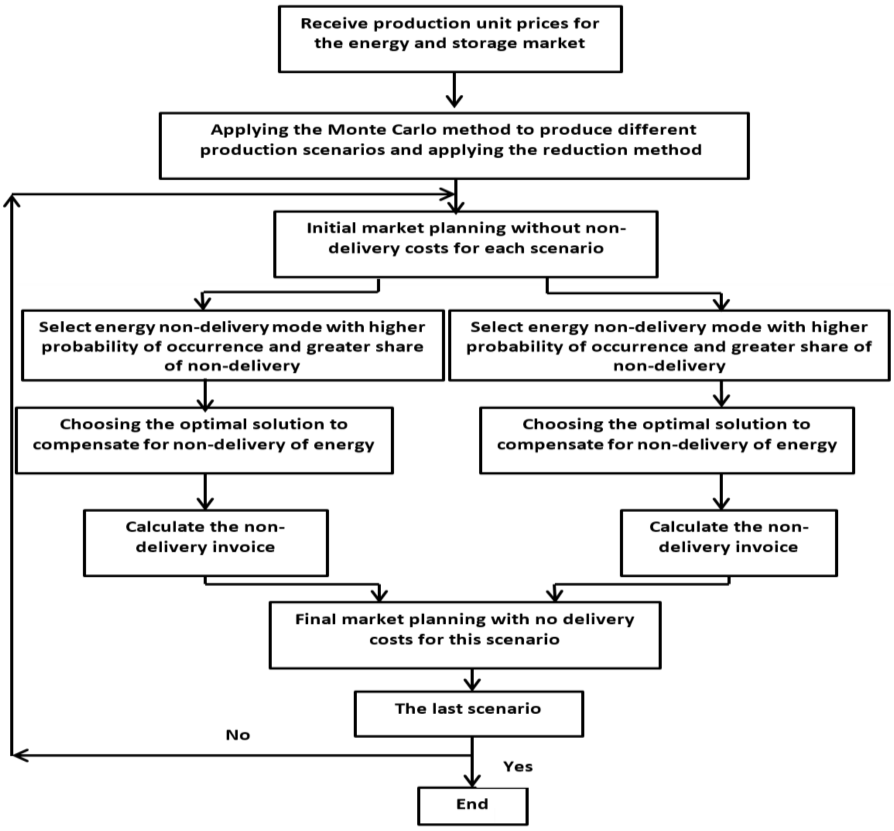


**Fig. 1:** Flowchart of the proposed algorithm.

## RESULTS & DISCUSSION

A 6-bus sample network, is used to demonstrate the efficiency of the proposed method.[6, 17] Fig. 2 shows a single line view of the network. This network has 6 generators with capacities of 17 and 520 MW. The total production capacity of the network is 1227 MW and its maximum load is 1000 MW. The bus bars of 1 to 6 are assumed to be 23, 11, 23, 21, 17, and 5% of the total load, respectively. The proposals of production units for the energy and storage market and their specifications are given in Table 1. The simulation period is 24 h, during which the network load varies from 350 to 1000 MW. The required storage amount is assumed to be equal to 10% of the network load.

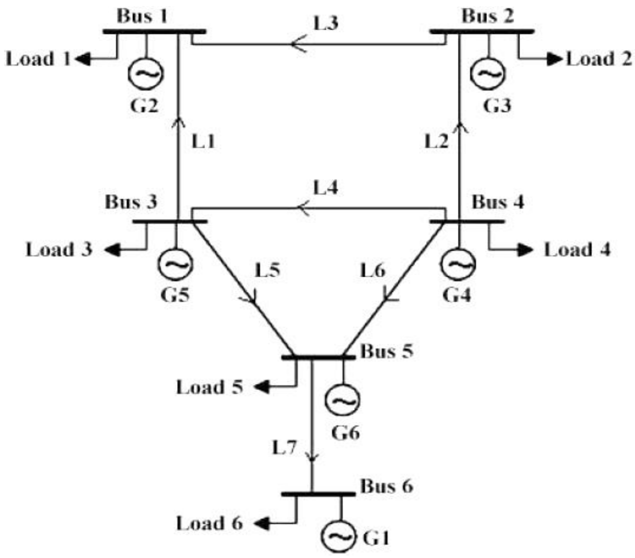


**Fig. 2:** Single-line view of a 6-bus sample network.

A program has been written in the MATLAB environment to run Monte Carlo simulations. In the output of this program, scenarios with a probability of less than 0.002 are ignored. After reducing the scenarios based on this probability threshold, the first and second order events remain, which are sufficiently accurate for the calculations. After generating the scenarios, for each scenario, a settlement program with the objective function (3) and the relevant constraints must be executed. GAMS software was used to run this optimization program. The optimization problem is modeled as Mixed-integer linear programming (MILP) and solved by Solver, CPLEX9 under GAMS.[18, 19]

**Table 1:** Information of production units.

| Production Unit | Energy Offer | | | | | | Save Offer | |
|---|---|---|---|---|---|---|---|---|
| | Interval 1 | | Interval 2 | | Interval 3 | | Interval 1 | |
| | MW | Price ($) | MW | Price ($) | MW | Price ($) | MW | Price ($) |
| 1 | 5 | 13 | 7 | 23 | 5 | 27 | 17 | 7.5 |
| 2 | 80 | 14 | 60 | 26 | 60 | 28 | 200 | 10 |
| 3 | 70 | 11 | 15 | 22 | 15 | 25 | 100 | 8.5 |
| 4 | 400 | 12 | 60 | 21 | 60 | 24 | 520 | 2 |
| 5 | 200 | 10 | 40 | 11 | 40 | 12 | 280 | 1 |
| 6 | 50 | 17 | 30 | 27 | 30 | 29 | 110 | 10 |

**Table 1 (Next Part):** Information of production units.

| Production Unit | Power Increase Rate (MW/min) | Maximum Production Capacity (MW) | The Minimum Off Time (hours) | The Minimum On Time (hours) | FOR | λ(f/yr) |
|---|---|---|---|---|---|---|
| 1 | 1 | 17 | 2 | 4 | 0.02 | 3 |
| 2 | 2 | 200 | 10 | 12 | 0.05 | 9.2 |
| 3 | 1 | 100 | 8 | 8 | 0.04 | 7.3 |
| 4 | 2 | 520 | 10 | 12 | 0.08 | 8 |
| 5 | 4 | 280 | 10 | 12 | 0.06 | 7.6 |
| 6 | 1 | 110 | 8 | 8 | 0.04 | 9.1 |

**Table 2:** Results of energy and storage market initial planning (excluding non-delivery costs).

| Hour | Load (MW) | Required Storage (MW) | Production Unit Number | Energy Market Clearing and Storage Results | | |
|---|---|---|---|---|---|---|
| | | | | Energy Share (MW) | Save Share (MW) | Total Cost (K$) |
| 1 | 600 | 60 | 1 | 3.8 | 0 | 7.2 |
| | | | 2 | 9.4 | 0 | |
| | | | 3 | 56 | 0 | |
| | | | 4 | 269.4 | 22 | |
| | | | 5 | 234 | 38 | |
| | | | 6 | 0.4 | 0 | |
| 2 | 700 | 70 | 1 | 5 | 7.6 | 8.7 |
| | | | 2 | 51.8 | 0 | |
| | | | 3 | 70 | 0 | |
| | | | 4 | 315.8 | 22 | |
| | | | 5 | 242.8 | 38 | |
| | | | 6 | 15.2 | 2.4 | |
| 3 | 800 | 80 | 1 | 5 | 7.6 | 9.8 |
| | | | 2 | 80 | 0 | |
| | | | 3 | 70 | 9.6 | |
| | | | 4 | 377.2 | 22 | |
| | | | 5 | 240 | 38 | |
| | | | 6 | 27.8 | 2.8 | |
| 4 | 900 | 90 | 1 | 9.7 | 7.3 | 17.8 |
| | | | 2 | 98.7 | 20 | |
| | | | 3 | 91.3 | 8.7 | |
| | | | 4 | 402.5 | 19.2 | |
| | | | 5 | 268.2 | 18.3 | |
| | | | 6 | 29.1 | 23.5 | |
| 5 | 1000 | 100 | 1 | 11.3 | 5.7 | 20.7 |
| | | | 2 | 163.2 | 30 | |
| | | | 3 | 91.8 | 8.2 | |
| | | | 4 | 438.6 | 20 | |
| | | | 5 | 268.7 | 11.3 | |
| | | | 6 | 26.4 | 24.8 | |

In the first step, the non-delivery factors must be calculated for each scenario. For this purpose, an initial planning is performed based on the objective function (3) without the cost of non-delivery. Table 2 shows the results of this initial planning for the energy and storage market in 5 hours. In the next step, based on the results of Table 2, the non-delivery cases are selected with the highest probability of occurrence and the highest share of non-delivery, the results of which are presented in Tables 3 and 4, respectively, for the energy and storage markets.

**Table 3:** Choose the mode between non-energy delivery modes for three load levels.

| Load (MW) | Unit | Initial Planning Energy (MW) | Initial Planning Storage (MW) | Residual Capacity (MW) | Unit with Non-Delivery | Amount of Non-Delivery (MW) | Probability Mode | Share of Total Non-Delivery | Select Mode |
|---|---|---|---|---|---|---|---|---|---|
| 800 | 1 | 5 | 7.6 | 4.4 | 1 | 5 | 0.015 | 0 | 0 |
| | 2 | 80 | 0 | 120 | 2 | 80 | 0.039 | 0.006 | 0.003 |
| | 3 | 70 | 9.6 | 20.4 | 3 | 70 | 0.03 | 0.1 | 0.002 |
| | 4 | 377.2 | 22 | 120.8 | 4 | 377.2 | 0.064 | 0.471 | 0.03 |
| | 5 | 240 | 38 | 2 | 5 | 240 | 0.047 | 0.3 | 0.004 |
| | 6 | 27.8 | 2.8 | 79.4 | 6 | 27.8 | 0.03 | 0.034 | 0.001 |
| 900 | 1 | 9.7 | 3.7 | 0 | 1 | 9.7 | 0.015 | 0.01 | 0 |
| | 2 | 98.7 | 20 | 81.3 | 2 | 98.7 | 0.039 | 0.109 | 0.004 |
| | 3 | 91.3 | 8.7 | 0 | 3 | 91.3 | 0.03 | 0.101 | 0.003 |
| | 4 | 402.5 | 19.2 | 98.3 | 4 | 402.5 | 0.064 | 0.447 | 0.028 |
| | 5 | 268.7 | 11.3 | 0 | 5 | 268.7 | 0.047 | 0.298 | 0.014 |
| | 6 | 291.1 | 23.5 | 57.4 | 6 | 29.1 | 0.03 | 0.032 | 0 |
| 1000 | 1 | 11.3 | 5.7 | 0 | 1 | 11.3 | 0.015 | 0.011 | 0 |
| | 2 | 163.2 | 30 | 6.8 | 2 | 163.2 | 0.039 | 0.163 | 0.006 |
| | 3 | 91.8 | 8.2 | 0 | 3 | 91.8 | 0.039 | 0.091 | 0.002 |
| | 4 | 438.6 | 20 | 61.04 | 4 | 438.6 | 0.064 | 0.438 | 0.028 |
| | 5 | 468.7 | 11.3 | 0 | 5 | 268.7 | 0.047 | 0.268 | 0.012 |
| | 6 | 26.4 | 24.8 | 58.8 | 6 | 26.4 | 0.03 | 0.026 | 0 |

**Table 4:** Results of final energy and storage market planning taking into account non-delivery costs.

| Hour | Network Load (MW) | Reserve Requirements (MW) | Production Unit | Energy market clearing and storage results: Energy Share (MW) | Save Share (MW) | Total Cost (K$) |
|---|---|---|---|---|---|---|
| 1 | 600 | 60 | 1 | 6 | 0 | 7.06 |
| | | | 2 | 11.4 | 0 | |
| | | | 3 | 73 | 0 | |
| | | | 4 | 269.4 | 20 | |
| | | | 5 | 240 | 40 | |
| | | | 6 | 0.2 | 0 | |
| 2 | 700 | 70 | 1 | 5.8 | 7 | 8.6 |
| | | | 2 | 43.8 | 0 | |
| | | | 3 | 78.2 | 0 | |
| | | | 4 | 323.8 | 20 | |
| | | | 5 | 240 | 40 | |
| | | | 6 | 8.4 | 3 | |
| 3 | 800 | 80 | 1 | 5 | 7 | 1 |
| | | | 2 | 80 | 0 | |
| | | | 3 | 70 | 9.2 | |
| | | | 4 | 365.2 | 20 | |
| | | | 5 | 240 | 40 | |
| | | | 6 | 39.8 | 8.3 | |
| 4 | 900 | 90 | 1 | 7.2 | 9.8 | 1.2 |
| | | | 2 | 93.3 | 20 | |
| | | | 3 | 90 | 10 | |
| | | | 4 | 399 | 18.9 | |
| | | | 5 | 258.7 | 21.3 | |
| | | | 6 | 51.8 | 10 | |
| 5 | 1000 | 100 | 1 | 7 | 10 | 1.5 |
| | | | 2 | 152 | 20 | |
| | | | 3 | 90 | 10 | |
| | | | 4 | 421 | 20 | |
| | | | 5 | 250 | 30 | |
| | | | 6 | 80 | 10 | |

Since non-delivery of energy or storage of two or more units at the same time is very unlikely, in these studies only the results of non-delivery of single units have been investigated. The lines highlighted in these tables show the probabilities of occurrence and the greater the share of non-delivery. Based on Tables 3 and 4, the non-delivery factors for 24 h are calculated, the results of which are shown in Fig. 3.

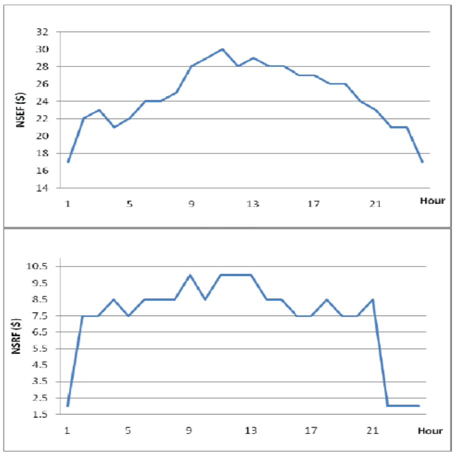


**Fig. 3:** Results of calculations of energy non-delivery and storage factors.

For example, suppose that at 1000 MW, Unit 4 fails to meet its obligations from the energy market (438.6 MW), the optimal solution to compensate for this shortcoming is to use the remaining capacity of Units 1, 2, 3, 5, and 6. But the remaining capacity of these units is only 65.6 MW and another solution is to use the storage capacity. The storage capacity can also compensate for another 80 MW (it is assumed that a unit that fails to meet its obligations from the energy market will not be able to deliver the storage capacity). As a result, load shedding is unavoidable in this case. Based on the cost of non-supply, the energy non-delivery factor, in this case, is equivalent to 30 $ per MW. In the case of the stock market, if Unit 2 fails to meet its obligations from the stock market (30 MW), the remaining capacity of Units 4 and 6 can be used for compensation, which is 2 $ and 10 $ per MW for the market, respectively. Save suggested. Due to the limited capacity of the transmission network, unit 6 is selected, in which case the non-delivery factor of the equivalent of 10 $ per MW is taken into account. After calculating the factors of non-delivery of energy and storage, the final planning can be done. At this stage, the final planning is done in the presence of non-delivery costs in the objective function (3). The results of the final planning are presented in Table 5 to observe the effect of the proposed method on the reliability of participation of production units in a situation where non-delivery costs are not in the objective function. The results showed that the proposed method could lead to a higher level of reliability.

**Table 5:** Comparison of reliability in proposed and clearing methods without taking into account non-delivery costs.

| Network Load (MW) | Reliability of Energy Mar`ket Responsiveness | | Reliability of Stock Market Responsiveness | |
|---|---|---|---|---|
| | No Cost Method of Delivery | Suggested Method | No Cost Method of Delivery | Suggested Method |
| 600 | 0.9339 | 0.9341 | 0.9996 | 0.9997 |
| 700 | 0.9342 | 0.9342 | 0.9996 | 0.9996 |
| 800 | 0.9343 | 0.9349 | 0.9996 | 0.9996 |
| 900 | 0.9353 | 0.9356 | 0.9994 | 0.9995 |
| 1000 | 0.9357 | 0.9368 | 0.9994 | 0.9995 |

## CONCLUSION

In this paper, a method for simultaneous clearing of energy and storage markets was presented, which two important features could be listed by following notes. The random nature of the participation of generating units in the electricity market was considered using the Monte Carlo method. The costs of "non-delivery of energy" and "non-delivery of reserves" were entered in the objective function. Considering these two costs caused the required capacity of the market to be allocated to units whose production was associated with lower costs and greater reliability. The results of the method implementation on the sample network showed the role of an important factor of production risk in achieving more realistic answers in solving the optimization problem. These results could be used as a tool for planning, according to the production risk, by electricity companies, the proposed method helps manufacturers to achieve a greater share of the electricity market to decide on increasing the reliability of production.

## DISCLOSURE STATEMENT

The author(s) did not report any potential conflict of interest.

## REFERENCES

1. Adebisi OI, Adejumobi IA. Development of a load management scheme for the Nigerian deregulated electricity market using regression model. IEEE PES/IAS Power Africa. 2019:682-687.
2. Scheduling operations manual. Pennsylvania - New Jersey - Maryland (PJM) Interconnection. Available at the URL: http://www.pjm.com.
3. Market operations. Independent System Operator (ISO). New England. Available at the URL: http://www.iso-ne.com.
4. CAISO 28-Jun MD02 tariff filing of clean tariff sheets and errata. Available at the URL: http://www.caiso.com.
5. Najafi M, Ehsan M, Fotuhi-Firuzabad M, Akhavein A, Afshar K. Optimal reserve capacity allocation with consideration of customer reliability requirements. Energy. 2010;35:3883-3890.
6. Banshwar A, Sharma NK, Sood YR, Shrivastava R. A sequential optimization approach for competitive procurement of energy and ancillary services. International Conference on Electrical Power and Energy Systems. 2016:498-503.
7. Aminifar F, Fotuhi-Firuzabad M, Shahidehpour M. Unit commitment with probabilistic spinning reserve and interruptible load considerations. IEEE Transactions on Power Systems. 2009;24:388-397.
8. Shi K, Chen H, Li P, Wang X, Liu Y, Sun G. Analysis of two electricity market clearing mechanisms based on co-evolution [J]. Automation of Electric Power Systems. 2019;43:68-77.
9. Huang L, Chen H. Simulation and analysis of centralized bidding market clearing method based on intelligent algorithm. IEEE Innovative Smart Grid Technologies-Asia. 2019:2963-2967.
10. Wang J, Wei Z, Yang B, Yong Y, Xue M, Sun G, Zang H, Chen S. Two-stage integrated electricity and heat market clearing with energy stations. IEEE Access. 2019;7:44928-44938.
11. Yu CW, Zhao XS, Wen FS, Chung CY, Chung TS, Huang MX. Pricing and procurement of operating reserves in competitive pool-based electricity markets. Electric Power Systems Research. 2005;73:37-43.
12. Allan RN. Reliability evaluation of power systems. Springer Science & Business Media. 2013.
13. Wu L, Shahidehpour M, Li T. Cost of reliability analysis based on stochastic unit commitment. IEEE Transactions on Power Systems. 2008;23:1364-1374.
14. Mok YL, Chung TS. Prediction of domestic, industrial and commercial interruption costs by relational approach. International Conference on Advances in Power System Control, Operation and Management.1997;450:209-215.
15. Yang D, Sun Y, Li B, Zhang X, Li P, Zhang T. Design of long-term and medium-term trading model under multi-energy coupling. IOP Conference Series: Earth and Environmental Science 2019;371:052052.
16. Bhattacharya K, Bollen MH, Daalder JE. Real time optimal interruptible tariff mechanism incorporating utility-customer interactions. IEEE Transactions on Power Systems. 2000;15:700-706.
17. Jingyi S, Xin J, Jinfeng G, Haoyong C, Ke S. Experimental analysis of equilibrium of long-term market clearing mechanism in China. IEEE Innovative Smart Grid Technologies-Asia. 2019:2986-2990.
18. Hillier FS. Introduction to operations research. Tata McGraw-Hill Education. 2012.
19. Bussieck MR, Meeraus A. General algebraic modeling system (GAMS). Modeling Languages in Mathematical Optimization 2004:137-157.

*Please visit the journal homepage:*
**https://adv-j-sci-eng.com**