Generation Expansion Planning in a Pool Based Electricity Market, using Game Theory and Genetic Algorithm

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Abstract—**Restructuring has changed purpose of generation expansion planning (GEP) from being cost-minimization to profit-maximization. In this paper, we introduce a new formulation for objective function of generating companies (GENCOs) GEP problem in pool electricity market which includes the revenues of energy and capacity reserve markets and costs of fuel, investment, O&M, outage and emission tax. Moreover, in order to solve GEP problem with above objective function, an algorithm are introduced that use game theory and genetic algorithm for market modeling and optimization of GENCOs objective functions, respectively. To calculate the generation levels of generating units and long-term market price, we have used the traditional probabilistic production costing (PPC) which is modified to be used in competitive electricity market.**

Keywords-generation expansion planning; pool electricity market; game theory; genetic algorithm;

I. NOMENCLATURE

B_i : Expected profit of i-th GENCO, [$]
T : Number of periods (years)
$R_{i,t}$: Revenues, [$]
$I_{i,t}$: Capital costs, [$]
$F_{i,t}$: Fuel costs, [$]
$M_{i,t}$: Operation and maintenance (O&M) costs, [$]
$O_{i,t}$: Outage costs, [$]
$T_{i,t}$: Emission tax, [$]
k : Rank of generating units
$\pi_{k,n}^t$: Energy price in n-th iteration of game, [$/MWh]
$e_{k,i}^t$: Energy generated by k-th units, [MWh]
$\pi_{r,n}^t$: Reserve price in n-th iteration of game, [$/MW]
$r_{k,i}^t$: Capacity reservation decision of k-th units, [MW]
q_k : Forced outage rate (FOR) of k-th units
ρ_k : Availability rate of k-th units
T_h : Number of hours in each planning period
$ELDC$: Equivalent load duration curve
$C_{e,k,i}^t$: Capacity of k-th units committed in energy market
MC_k : Marginal cost of k-th units, [$/MWh]
T_k : Participation time of k-th units in energy market
$D(\pi)$: Total demand as a function of price, [MW]
A : Slope of demand function
B : Demand at zero price
D_{base} : Forecasted demand, [MW]
π_{base} : Base price of energy market, [$/MWh]
ε : Demand elasticity factor
ρ_{sys} : Average availability rate of system
C^t : Total installed capacity in system, [MW]
q^t : Average customer outage cost, [$/MWh]
$U_{k,i}^t$: Expansion decision of k-th units, [MW]
$C_{inv,k}^t$: Unitary construction cost of k-th units, [$/MW]
fc_k^t : Unitary fuel cost of k-th units, [$/MWh]
UF_k^t : Unitary fixed O&M cost of k-th units, [$/MW]
UV_k^t : Unitary variable O&M cost of k-th units, [$/MWh]
$C_{k,i}^t$: Available capacity of k-th units, [MW]
π_o^t : Unitary outage cost (equal with RTP), [$/MWh]
TR^t : Unitary rate of emission tax, [$/kg]
$EM_{k,i}^t$: Emission of k-th units, [kg]
Lim_i^t : Limitation of investment, [$]
$N_{k,i}^t$: Number of new added k-th units
α : Fuel mix ratio
$U_{p,j}^t$: Aggregated capacity of new peak type units, [MW]
$U_{b,i}^t$: Aggregated capacity of new base type units, [MW]
$r_{\min}^t$: Minimum reserve margin
$r_{\max}^t$: Maximum reserve margin
G : Number of GENCOs
$LOLP^t$: Loss of load probability index
$EENS^t$: Expected energy not supply index, [GWh]

It should be noted that i and t in the above symbols indicate related i-th GENCO and t-th year, respectively.

II. INTRODUCTION

Generation expansion planning (GEP), is a large-scale, nonlinear, discrete, dynamic and highly constrained optimization problem that determines which generating units should be constructed and when should be committed online over the planning horizon in such a way that installed capacity meet forecasted demand [1-4]. The sites locations and other factors related to transmission network are commonly analyzed separately and after a size for expansion has been decided [5].

In traditional monopolistic framework, generation expansion activities has been performed by a vertically integrated utility and in order to meet long-term reliability criteria. The objective of monopolistic GEP problem, has been the minimization of the expected sum of yearly discounted costs which incorporate construction costs, operating costs, salvage value, and so on [6]. However, constraints such as reserve margin, fuel mix, reliability criteria and environmental limitations, must be considered [7]. Various models for traditional GEP, were developed to fulfill the minimum cost through several optimization algorithms [2, 3] and probabilistic production costing (PPC) [8].

In recent years, power generation industry in many countries has undergone restructuring from being a state monopoly to deregulated liberalized markets. One cause for restructuring is the belief that electricity generation no longer possesses properties of a natural monopoly due to technologically driven decreases in efficient plant sizes. Diminishment of scale of economies in generation has broken the utility industry into generation firms who compete among each other to sell power, which is transmitted by a monopoly high-voltage transmission system to independent distribution firms and local customers [9].

These changes affect long-term expansion planning, as investment decisions are now taken by private investors leading to a more reduced level of centralized coordination [10].

The other changes which restructuring has been made in GEP process, Include [1,9,10]:

- Change of the purpose from cost-minimization to profit-maximization
- Considering the demand effect on the electricity prices (introduction of Demand Response)
- Appearance of strategic interaction and gaming among firms involved in the GEP process
- The shortening of planning horizons due to the elimination of traditional guaranteed return on investment
- Considering the incomplete information structure of the market. This is usually handled by using the game theory.

GEP methods in the restructured power system depend on the model of electricity market (i.e. primary market or pool market). In primary competitive model, several independent power producers (IPP) sell their power only to the utility, but in the pool competitive model, each private generating company (GENCO) would compete with other GENCOs for profit maximization [11].

Unlike traditional approaches, competitive GEP is very complex due to the conflicts among generating companies [12].

Essentially, the competitive GEP problem in the pool electricity market, can be modeled as non-cooperative game in which GENCOs make decision about their capacity expansion to maximize their expected profit from future markets and competing with other GENCOs [13]. Profit function can be defined as the difference between revenues earned and costs incurred from providing electric service. Usually revenues are based on energy market payments and costs are based on capital and operating costs [5, 6, 10, 11, 12, 13].

In this paper, we analyze the generation expansion planning in the pool markets. We introduce a new formulation for the objective function of GEP problem in a pool market. Each GENCO uses genetic algorithm (GA) to optimizes his own objective function of GEP problem, dynamically for all years of planning.

Afterwards, GENCOs submit their plans to the regulatory body called as Independent System Operator (ISO) [12]. one of the objectives of ISO is stabilizing market through coordination between GENCOs by providing long-term market information to them, which can prevent extreme over/under investments in the electricity market [6,12]. ISO clears the market and determines energy and reserve market prices. Prices and other necessary information for planning are transmitted to each GENCO, separately. The ISO is also responsible for considering reliability constraints, reserve margin and national security [11].

In this paper, we use Cournot game for modeling the incomplete structure of the pool electricity market. Players are private power generation companies. Vector of players' decisions for which no player changes its plan after an entire round of optimization is called a Cournot equilibrium. Solution algorithm of GEP game iterates until such an equilibrium is found [1].

III. FORMULATION OF GEP IN POOL MARKET

In the pool electricity market, the goal of each GENCO in GEP is maximizing expected profit from future markets and competing with other GENCOs. Therefore, the GEP problem for the i-th GENCO can be written as (1) in which revenues consist of energy and capacity reserve markets payments and costs include capital costs, fuel costs, operation and maintenance costs, outage costs and emission tax.

$$Max\ B_i = \sum_{t=1}^{T} \left(\overline{R}_{i,t} - \left[\overline{I}_{i,t} + \overline{F}_{i,t} + \overline{M}_{i,t} + \overline{O}_{i,t} + \overline{T}_{i,t} \right] \right) \quad (1)$$

The bar over the symbols show discounted values to a reference date at a given discount rate. We have used linear depreciation method to calculate cash flow for the investment plans. The total profit of the i-th GENCO is the summation of profits in all years of planning horizon. Consequently, the profit optimization problem of each GENCO becomes a dynamic problem. This means that decision variables in each year are considered in subsequent years.

A. *Revenues*

Equation (2), represents expected revenues of i-th GENCO from the future energy and capacity reserve markets.

$$R_{i,t} = \sum_{k=1}^{N} \left(\pi_{k,n}^{t} \cdot e_{k,i}^{t} + \pi_{r,n}^{t} \cdot r_{k,i}^{t} \right) \tag{2}$$

We assumed that each GENCO bids equal to its generation marginal costs in energy market. Moreover, all accepted bids receive the same compensation rate; namely, the highest bid price to clear the market.

B. *Price and energy calculation*

To calculate each GENCO long-term profits, we need to forecast the market price and energy of the generating units. Although the production amount of each unit can be calculated in a similar way which is done in a monopoly power structure, but it is more difficult to forecast prices. Electricity Price is dependent on the other variables such as demand, elasticity, fuel prices, strategic behavior of the GENCOs and so on.

To calculate the energy produced by each unit, we use the probabilistic production costing (PPC). In other words, the energy of each unit is calculated by integration of equivalent load duration curve (ELDC). The energy produced by the generating units of the i-th GENCO is displayed in Fig. 1.

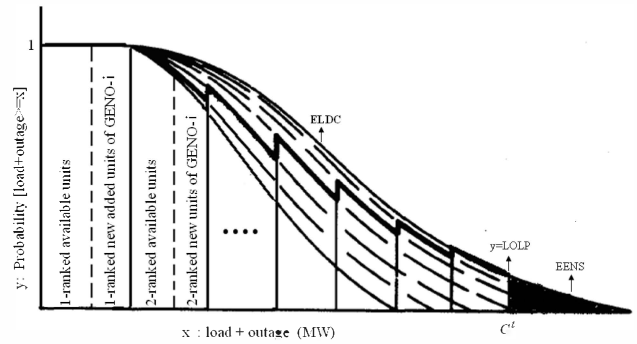

Fig. 1. Calculation of energy produced by units of i-th GENCO

At first, we establish the priority order list of generating units based on their marginal cost. Then the amount of energy produced by the k-th units of the i-th GENCO is calculated using the following equation.

$$e_{k,i}^{t} = \rho_k \cdot T_h \cdot \int_{C_{e,1}^{t}+\ldots+C_{e,k,i-1}^{t}}^{C_{e,1}^{t}+\ldots+C_{e,k,i}^{t}} ELDC_{(k-1)}^{t}(x)dx \tag{3}$$

Now, we consider outage effect of these units on load duration curve, as follows:

$$f_k^t(x) = \rho_k \cdot f_{(k-1)}^t(x) + q_k \cdot f_{(k-1)}^t(x - c_k) \tag{4}$$

c_k is capacity of k-th ranked units and f is LDC function.

For energy market price calculating, first, we obtained base price using traditional Unit Commitment (UC) and then final price is calculated by means of (6), considering elasticity of the demand. All units are assumed to sell their produced energy in market clearing price (MCP), which equal to marginal cost of the most expensive units that clears the market. Consequently, the average market price for the k-th ranked generating units is calculated as follows:

$$\pi_{base,k} = \left(\frac{(MC_N \cdot T_N) + \ldots + (MC_k \cdot (T_k - T_{k+1}))}{T_k} \right) \tag{5}$$

After calculating the base market price, the final market price is calculated as fallow:

$$D(\pi) = -A \cdot \pi + B \tag{6}$$

$$A = \varepsilon \cdot \frac{D_{base}}{\pi_{base}} \tag{7}$$

$$B = D_{base} \cdot (1 + \varepsilon) \tag{8}$$

To achieve to the market equilibrium point, supply (total available capacity) should be equal to the total demand. So with replacing total available capacity, instead of $D(\pi)$ in (6), the final market price will be calculated. Electricity prices are affected by all generating companies and all companies are correlated with each other by the prices.

Another source of revenue for GENCOs is payments related to the capacity reserve market (capacity payments). A GENCO may earn revenue by withholding some capacity from participation in the energy market in order to participate in the capacity reserve market. The value of service (VOS) reliability technique is applied in our model to establish a market price for reserve [1].

$$\pi_{r,n}^{t} = T_h \cdot \rho_{sys} \cdot ELDC^t(C^t).q^t \tag{9}$$

C. *Costs*

The costs are include construction costs, fuel costs, operation and maintenance (O&M) costs, outage costs and emission taxes that are formulated in (10) to (14); respectively.

$$I_{i,t} = \sum_{k=1}^{N} \left(U_{k,i}^{t} \cdot \overline{C}_{inv,k}^{t} \right) \tag{10}$$

$$F_{i,t} = \sum_{k=1}^{N} \left(fc_k^t \cdot e_{k,i}^t \right) \tag{11}$$

$$M_{i,t} = \sum_{k=1}^{N} \left(UF_k^t \cdot C_{k,i}^t + UV_k^t \cdot e_{k,i}^t \right) \tag{12}$$

$$O_{i,t} = \sum_{k=1}^{N} \left(\pi_o^t \cdot q_k \cdot e_{k,i}^t \right) \quad (13)$$

$$T_{i,t} = \sum_{k=1}^{N_T} \left(TR^t \cdot EM_{k,i}^t \right) \quad (14)$$

The bar used in (10) indicates that construction costs were calculated after subtracting salvage value. In this paper, the taxes on SO2 and NOx emissions have been inserted in the cost structure.

D. Constraints of GEP problem in pool market

Equations (15) to (21), represent constraints of the competitive GEP problem in the pool Electricity market.

$$C_{k,i}^t = C_{k,i}^{t-1} + U_{k,i}^t \quad (15)$$

$$I_{i,t} \le Lim_i^t \quad (16)$$

$$N_{k,\min}^t \le N_{k,i}^t \le N_{k,\max}^t \quad (17)$$

$$\sum_{k=1}^{N} U_{k,i}^t \le U_{\max}^t \quad (18)$$

$$\sum_{t=1}^{T} \sum_{j=1}^{N_p} U_{p,j}^t \ge \alpha \times \sum_{t=1}^{T} \sum_{i=1}^{N_b} U_{b,i}^t \quad (19)$$

$$(1 + r_{\min}^t) \times L_t \le \sum_{i=1}^{G} \sum_{k=1}^{N} C_{k,i}^t \le (1 + r_{\max}^t) \times L_t \quad (20)$$

$$\begin{aligned} LOLP^t &\le LOLP_{\max}^t \\ EENS^t &\le ENS_{\max}^t \end{aligned} \quad (21)$$

Equation (15) represents the capacity balance constraint. This means that total available capacity in each year should be equal to the sum of the existing capacity in last year and new added capacity in that year. Constraints (16) to (18) are called investment limitation, construction limitation and capacity limitation, respectively. These constraints are related to GENCOs characteristics. Constraint (15) represents the financial limitations of each GENCO. ISO imposes (16) to all the GENCOs in order to fulfill the system constraints, and constraint (17) is considered to control the market power.

Inequalities (19) to (21) represent the fuel mix constraint, reserve margin constraint and reliability constraint, respectively. These constraints that ensure the long-term stability of the market are related to the ISO. If any of the above constraints did not satisfy, ISO can modify the constraints of GENCOs to fulfill these constraints.

IV. SOLUTION ALGORITHM

Game Theory (GT) is one of the methods of modeling of oligopoly markets. This theory analyzes how two or more players choose their strategies that affect each player simultaneously. A sample game, consist of a set of players, a set of possible strategies for each of the players, and a set of rules [4].

In this paper, GT and particularly the Cournot game model has been used for modeling the interaction between GENCOs. Common characteristics of Carnot games are include [1]:

- Competition occurs only in quantities.
- Product is non-storable.
- Product is homogeneous.
- Market Price is determined by the auction.
- No entry occurs during the game.
- Players decide simultaneously.

There are many similarities between Cournot model and the nature of the competitive electricity markets. In competitive GEP, GENCOs must decide on how much capacity that they need to expand. Generated energies are non-storable. In addition, in the pool electricity markets, prices are determined from auctions and within each auction, products are homogeneous. Competition is inducing shorter Planning horizons, consequently probability of overlooking a new player in GEP game is high. Also, our model assumes simultaneous decision-making among GENCOs, in order to give no player a first mover advantage.

In this paper, to solve competitive GEP game in the pool electricity market, an algorithm with two programming levels is used. At the lower level, genetic algorithm (GA) finds the best solution of each player for investment decisions. Each player uses GA to maximize its objective function (profit), taking into account the latest expansion decisions of competitors, while assuming that they do not intend to modify their latest GEP which were announced by the ISO. At the higher level, the algorithm searches for a Cournot equilibrium solution for the overall game.

Fig. 2 displays solution algorithm of the competitive GEP game in a pool electricity market. GEP game process can be summarized in three stages.

In the first stage, ISO forecasts the load and energy price and determines the capacity reserve price, and announces to all the players. Afterwards, each GENCO forms his own initial expansion plan, using genetic algorithm, individually.

In the second stage, plans of GENCOs which include expansion and capacity reserve decisions are reported to ISO, and ISO announces the received information to all the GENCOs. Afterwards, ISO evaluates the system constraints. If the GEP results satisfy these constraints, ISO will accept the results of GEP. Otherwise, these results will be discarded and the ISO will modify GENCOs constraints. This means that the ISO will place new construction and capacity constraints for the GENCOs.

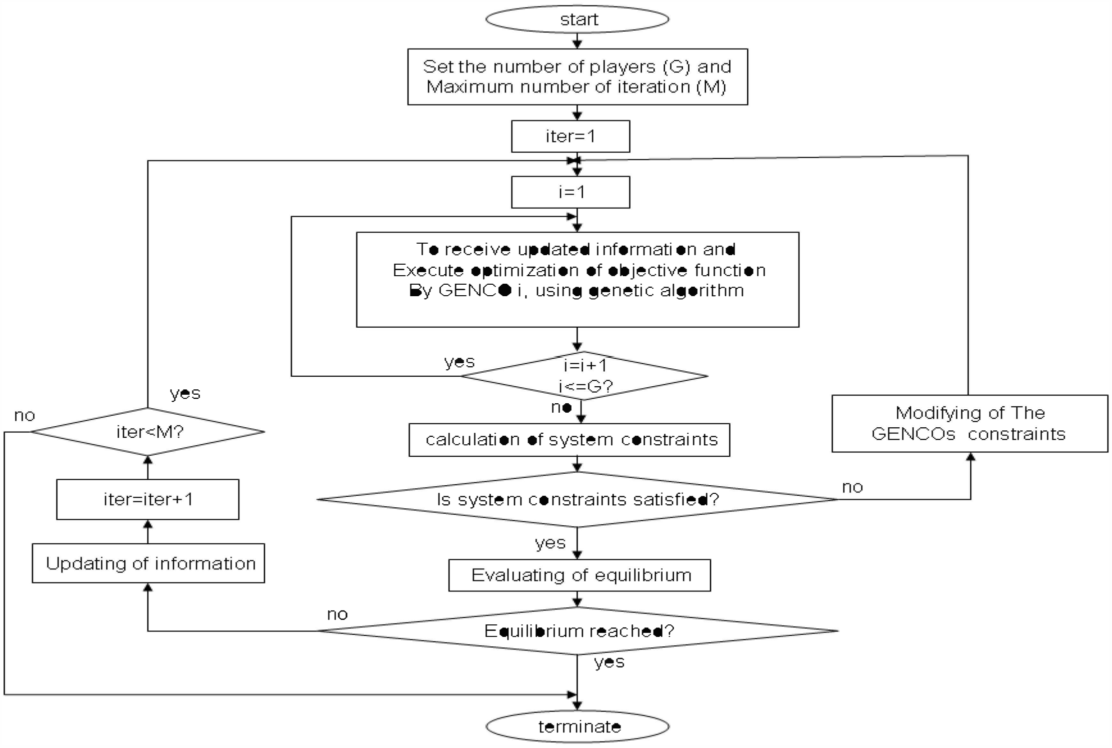

Fig. 2. Solution algorithm of competitive GEP game

In the third stage, each GENCO runs a new GEP, taking into account all other GENCOs updated plans, and resends its results to the ISO. This stage iterates until no player alters its expansion plan for one entire round. In this situation, if all the system constraints are satisfied, then the game will be successfully terminated at the Cournot equilibrium.

V. CASE STUDY

We investigate a case study in a 5 years planning horizon and on a system which consists of three GENCOs. Forecasted peak loads are listed in Table I, and technical and economical characteristics of existing generating units and candidates for expansion units are listed in Table II. These characteristics have been extracted from test system of WASP software and modified. GENCO-1, has two VNUC units and two VCOA units, GENCO-2 has one VNUC unit, two VCOA units and two V-GT units and GENCO-3 has two V-LG units, two VOIL units, two V-GT units and two V-CC units.

For each GENCO, construction limitation of one unit over a year for every type of generating unit is considered. Fuel mix limitation is such that each GENCO can not have more than three nuclear units and fuel mix ratio is 10%. The minimum and maximum reserve margins are 15% and 50%, respectively. The maximum of LOLP and EENS are considered as 1% and 30 GWh, respectively. Unitary rate of emission tax has been selected 0.05 $/kg for both of SO_2 and NOx emissions.

Table III to Table V illustrate the GEP results of GENCOs. The total GEP results of system, and reliability and reserve margin (RM) indices are listed in Table VI. The equilibrium point of GEP game is obtained at the ninth iteration of Cournot game.

The capacity expansion of base type units is mostly due to revenues of energy market and the capacity expansion of peak type units is mostly due to revenues of the capacity reserve market.

For comparison, least-cost GEP results are listed in Table VII, which are resulting of WASP software run on the proposed test system. Comparison of the results shows greater capacity expansion and system reliability under competition than under monopolistic expansion planning.

VI. CONCLUSION

Generation expansion planning in the pool electricity markets focuses on maximizing of long-term profits of private generating companies. In a competitive structure, capacity expansions are driven by expectations regarding the behavior of future prices and by the return on new investments. In this paper, we have introduced a new formulation for competitive GEP, and an algorithm consisting of genetic algorithm and Cournot game model has been used to solve it. Finally, the results of executing proposed model on the test system are presented. The results show that in a pool based electricity market, our proposed method has more generation expansion and leads to better reliability indices, comparing to GEP results in a monopoly structure.

TABLE I. FORECASTED PEAK LOAD

year	2014	2015	2016	2017	2018
Peak (MW)	6000	6333	6725	7109	7496

TABLE II. TECHNICAL AND ECONOMICAL CHARACTERISTICS OF UNITS

	VNUC	**VCOA**	**V-LG**	**VOIL**	**V-GT**	**V-CC**
Capacity (MW)	600	550	300	150	50	100
Capital cost ($/KW)	700	550	400	300	200	250
Fuel cost (c/Mkcal)	196	364	322	642	600	1000
O&M V.cost ($/MWh)	0.5	2	2	1.5	1.5	3
O&M F.cost ($/KW-M)	3.5	2.9	2.7	2.5	2.3	2.3
FOR (%)	6	8	13	5	2	3
Heat value (kcal/kg)	-	6000	1800	10000	10000	11000
SO_2emission (% wt fuel)	0	1	2.5	1	0.5	0
NOxemission (% wt fuel)	0	2	1	3	0.5	0.5

TABLE III. GEP RESULTS FOR GENCO-1

Year	**VNUC**	**VCOA**	**V-LG**	**VOIL**	**V-GT**	**V-CC**
2014	1	0	0	0	0	0
2015	0	0	0	0	1	0
2016	0	0	0	0	1	1
2017	0	0	0	1	0	1
2018	0	0	0	0	0	1
total	1	0	0	1	2	3
Profit(K$)	628100					

TABLE IV. GEP RESULTS FOR GENCO-2

Year	**VNUC**	**VCOA**	**V-LG**	**VOIL**	**V-GT**	**V-CC**
2014	1	0	0	0	0	0
2015	0	0	0	0	0	1
2016	0	0	0	0	1	0
2017	0	0	0	1	0	1
2018	0	0	0	0	0	1
Total	1	0	0	1	1	3
Profit (K$)	316900					

TABLE V. GEP RESULTS FOR GENCO-3

Year	**VNUC**	**VCOA**	**V-LG**	**VOIL**	**V-GT**	**V-CC**
2014	1	0	0	0	0	1
2015	1	0	0	0	0	0
2016	0	0	0	0	0	0
2017	0	0	0	0	0	0
2018	1	0	0	0	0	0
total	3	0	0	0	0	1
Profit (K$)	158400					

TABLE VI. TOTAL GEP AND RELIABILITY AND RM RESULTS

	2014	**2015**	**2016**	**2017**	**2018**
Expansion(MW)	1900	750	200	500	800
LOLP (%)	0.7787	0.3272	0.6222	0.4550	0.1998
EENS (GWh)	20.5	7.4	16.3	11.1	4.1
RM (%)	20	25.5	20.4	21.7	26

TABLE VII. MONOPOLISTIC GEP RESULTS

	2014	**2015**	**2016**	**2017**	**2018**
Expansion(MW)	1800	350	450	350	450
LOLP (%)	0.8944	0.8870	0.8110	0.9160	0.8387
EENS (GWh)	23.2	22.9	20.5	23.3	20.8
RM (%)	18.3	17.6	17.4	16	16

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