IJST, Transactions of Electrical Engineering, Vol. 39, No. E2, pp 115-131
Printed in The Islamic Republic of Iran, 2015

A NEW FRAMEWORK FOR CAPACITY MARKET IN RESTRUCTURED POWER SYSTEMS*

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Abstract– In order to improve the reliability of the power system, sufficient amount of new capacity should be installed in the network. Usually generation units' payoff in an energy market is not adequate to cover their expenses. Therefore, energy only market cannot induce investors to invest in generation field. Due to energy only market inefficiency, a supplementary algorithm is suggested to cover the mentioned defect and consequently to have adequate level of generation to meet demand in peak periods. This work tries to present a new pay as bid capacity market in which consumers compete with each other in order to obtain their adequate level of subscribed capacity. In this model, consumers bid their optimum subscribed capacity level alongside their optimum capacity price to the ISO. ISO clears the market considering the proposed capacity level from the generation side and capacity bids from the demand side. Those consumers which are accepted in the market, buy their market admitted capacity levels based on their proposed capacity prices. The generation units' payoffs obtained from the proposed capacity market increase the investors' incentive to invest in new power plants which results in higher available installed capacity in the time of peak load. For more transparency, two kinds of uncertainties (short-term and long-term uncertainties) are taken in to account to model the consumers and market behavior and system is simulated over a long planning horizon and obtained results are compared with two other types of markets, Energy Only and basic Capacity Subscription. The impressive results obtained from the simulation show the efficiency of the new proposed method.

Keywords– Restructuring, capacity market, capacity subscription market, generation expansion planning

1. INTRODUCTION

Reliability in an electrical power system can be considered in two aspects: security and adequacy. Adequacy, as the main concern of this article, is the ability of an electric system to supply the aggregate electrical demand and energy requirements of their customers at all times [1]. Security, although is not in the scope of this article, can be defined as the ability of the system to withstand sudden disturbances such as electric short circuits, or the unanticipated loss of system elements such as generating units or transmission lines [1, 2].

Regarding adequacy, all the consumers usually expect to receive the electricity with high reliability and without any curtailment, not only in the time of demand fluctuations but also in the time of unexpected generation outages. Usually, generation units' payoff in an energy market is not sufficient to cover their fixed costs as well as their variable costs; therefore, energy market cannot induce investors to invest in different generation levels. On the other hand, generation capacity shortages caused by demand growth in different levels (base, medium and peak) result in low network reliability which is one of the main challenges in restructured power systems. Having capacity market along with energy market is one

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*Received by the editors November 8, 2013; Accepted November 2, 2015.
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of the best devised methods to encourage more investment in generation. Coordination between generation and demand and also avoiding sparks of spot prices in peak periods, are no doubt, the two most important advantages of capacity markets.

Different types of capacity markets such as fixed and dynamic capacity payment, capacity obligation, capacity subscription, installed capacity payment, etc, show the vast variety of studies investigated in this field. For instance, [3-5] present a comprehensive comparison of different market designs. In [6] a comparison is made between energy only and capacity obligation policies. In [7] a design is presented that avoids problems found in early capacity markets by only rewarding capacities that contribute to reliability and avoid energy market and regulatory risks. In [8] the motivations for different resource adequacy methods are explored and how each of these different polices addresses the goal of resource adequacy is discussed. [9] tries to introduce a new iterative dynamic programming for capacity subscription services to reduce peak load of substations which are suffering from capacity shortage. In [10] a model is discussed in which the capacity payment paid to a generator is proportional to its investment cost and remains constant during operation periods. In the proposed model of generation expansion in [11], uncertainties in bidding for long-term contracts are considered. [12] represents a dynamic model which is used in PJM to highlight the effect of reserve margin, LOLP, generator profits and amount of cost paid by consumers. In order to increase the incentives of generation investment, a new approach is proposed in [13] in which reliability contracts are auctioned where price and their allocation among different plants are determined in a competitive mechanism. Installed Capacity mechanism (ICAP) is reviewed in [14] considering a method of computing LOLP in which it is proved that ICAP mechanism used in US electricity markets does not necessarily provide a desirable level of reliability. [15, 16] try to show that a market based signal would ensure sufficient and optimal investment in generation and transmission and [17] represents a market mechanism for long-term transmission and generation capacity adequacy respectively. [18] tries to present a locational capacity price model to encourage investments in generation and transmission expansions. [19] presents the theoretical basis of how to apply forward capacity markets for hydrothermal systems with significant portion of hydro generation. [20] proposes a dynamic time simulation model based on system dynamics concept for long-term generation capacity investment decision in the presence of either perfect or imperfect electricity market. [21] analyzes the best structure and rules for capacity markets to ensure the smooth introduction and non-conflicting cooperation with the existing energy market. [22-23] discusses the general necessity of capacity markets and the impact of capacity markets on demand response respectively. [24] introduces the motivation for developing capacity markets with respect to the mechanism which is currently used in North America. [25] presents the application of fuzzy sets for the analysis of the capacity market requirements and coordination of capacity and energy markets.

Different capacity policies follow up different mechanisms to reach resource adequacy. For instance, in Capacity Payment (CP) policy, which is the most common type of capacity markets, amount of money is paid to those units which are available in peak periods to cover a part of their fixed costs [26]. This payment can be categorized into two types, dynamic payment and fixed payment. Capacity Obligation (CO) determines amount of capacity obligation for each load serving entity, according to its share of total demand and system reliability criteria. But new capacity obligation policy follow up a method mostly like capacity payments [3, 6]. Capacity Subscription (CS) tries to focus on demand management to overcome the lack of resource adequacy in the time of peak periods. Using this policy, it is possible to avoid sparks in spot prices by limiting consumers' electricity consumption to their subscribed capacity during peak periods. [27, 28] give a complete description of CS policy.

In this article we try to present a new approach of capacity subscription model. Due to the necessity of special hardware presence like load limit devices (Smart Meters), this model has not been widely implemented in capacity markets up to now, but it does not reduce the merit of this fascinating method.

The proposed model tries to keep all the advantages of the basic capacity subscription model [27] alongside presenting a new strategy to cover defects for better performance. For simplicity, we call the basic model of CS as old capacity subscription (old CS) and the proposed model of this study as new capacity subscription (new CS) in the figures. This study tries to reform consumers' role from a composed role in the basic capacity subscription model, into a more determinative and competitive role in the proposed model. In the proposed capacity subscription model, consumers are prioritized, not only according to their acceptance in the capacity market, but also according to their offered capacity price. In the proposed capacity subscription model, consumer's proposed capacity price and its subscribed capacity level are determined coordinately and according to consumer preference to pay for the capacity. The competitive structure of the proposed model results in more incentives for investments in new capacities which cause considerable reduction in energy prices in different load levels.

In the second section of this article, part 2.1, a quick review of the basic capacity subscription model is presented and the proposed capacity subscription model is introduced in part 2.2. Problem formulation and numerical results are discussed in sections 3 and 4, respectively. At last, a brief conclusion is expressed in section 5.

2. MATERIAL AND METHODS

a) Quick review on the basic capacity subscription model

Capacity inadequacy which leads to unexpected disconnections during peak periods basically happens as a consequence of two major reasons in traditional systems.

- Reliability is a public merchant.
- Most of consumers buy the electricity with a fixed price.

More price responsive demand gives the network operator the opportunity to limit demand in peak periods in several ways (e.g. capacity subscription model) tailored to restructured power system rules. In basic CS model, the main idea is to subscribe for a part of installed capacity by each consumer for peak periods. In fact, the amount of capacity each consumer subscribes for is based on its preference to pay for the capacity which is definitely dependent on the capacity price. At last, in peak periods, each consumer's electricity consumption will be limited to its subscribed capacity. In order to receive more reliable electricity, a consumer has to subscribe to higher level of capacity and consequently paying more money. On the other hand, those consumers who want to reduce their cost will subscribe to lower level of capacity which may result in being curtailed during peak periods.

In basic CS model, at first, all generation units offer their available capacity to the market. Considering this amount of offered capacity, ISO starts from a basic price as a capacity price. Each consumer tries to minimize its Composed Cost based on the capacity price announced by ISO.

Consumer Composed Cost in CS policy = Cost of buying capacity + Cost of Energy Not Served (ENS) (1)

Based on the above equation, if the capacity price goes up, the consumer tendency to buy capacity goes down. In fact, those consumers who are willing to receive more reliable electricity will subscribe to higher level of capacity in comparison to other consumers.

Considering the capacity price, each consumer is offerred its desired level of subscribed capacity. ISO gathers all the offers and if the summation of all requested subscribed capacities is more than the available installed capacity in the power grid, ISO increases the capacity price and repeats the procedure again. Market is cleared whenever the available installed capacity equals the total requested subscribed capacity. In this method all consumers, with different tendency to pay for capacity, buy the capacity with the same price. This is no doubt, the biggest defect of this method. In order to have more competitive capacity market, consumers should have the authority to compete on capacity price along with the amount of required subscribed capacity. The new method which is described in the following sections tries to solve the previously mentioned problem.

b) Proposed capacity subscription model

Considering the explanation in the former section, here in this part, a new model is proposed to provide more competitive capacity market. In this new model, consumer's bid contains not only its required level of *subscribed capacity* but also its desired *capacity price*. Each consumer determines its bid contains both of the previously mentioned parameters by minimizing its Composed Cost function (CC). ISO ranks all the announced bids and market is cleared when the amount of subscribed capacities equals the available installed capacity. Since this is a pay as bid capacity market, each consumer who is accepted in the market has to buy the capacity based on its offered price. The consumers with higher offered capacity prices definitely have greater chance to get accepted in the market in comparison to others.

Opposite to the basic CS model, in which all consumers have to pay same the price for the capacity, in this new proposed model consumers compete on both capacity price and required subscribed capacity. Using this model, consumers can be reasonably ranked in the time of optimal allocation of excess capacity in peak periods [27]. Since normally there is not enough time to hold another market for excess capacity, this priority list can be helpful to allocate the capacity quickly. Load shedding in the time of unexpected outages can be applied based on this priority list and system situation to minimize the economic loss. The main advantages of the proposed CS model can be counted as:

- Generation investment increases.
- Social welfare increases.
- Consumers are ranked based on a fair mechanism.
- The proposed CS model is a one-time run market. Consumers offer their capacity prices and desired subscribed capacity levels to the ISO for once and there is no need of frequent negotiations.
- New CS model is more competitive, because consumers compete with each other on their offered capacity prices as well as their desired subscribed capacity levels.
- The proposed CS market procedure is faster in terms of clearance time.
- The priority list obtained from the proposed CS model is applicable in the time of unexpected outages.
- In contrast to CP and CO models, consumers will no more argue about paying money for the services they never receive.

3. PROPOSED MODELING

Here in this section, first an attempt is made to explain the philosophy of the proposed CS model in mathematical order. Considering the point that capacity market is used beside energy market in the power system, the energy market is also modeled in order to evaluate the proposed CS model performance in generation expansion field. Different stages of calculation procedure in this study are arranged in chronological order as stated in the following block diagram (Fig. 1):

a) Proposed capacity subscription market modeling

M groups of consumers are defined by their maximum value of cut loads ($VCL\max$). $VCL\max$ presents a consumer's maximum financial loss due to being completely disconnected from the network. Therefore, when a consumer's consumption is being restricted by smart meter in peak period, its financial loss will be a proportion of its $VCL\max$ (Eq. (2)). Statistics reveal that a consumer financial loss verses its peak demand can occur with a variety of slopes. This is implemented by the term b in Eq.2.

Term b can vary from values near zero up to ∞ which results in sharp and smooth slopes of the financial loss verses peak demand diagram, respectively [3]. Here in Eq. (2), the Value of Cut Load (VCL) represents the financial loss of a consumer group based on its load level and subscribed capacity:

$$VCL(A_m, w_s) = \left({VCL\max(m)} \Big/ {1 - e^{-b.shd(m).Q_{3,k}(w_s)}} \right).(1 - e^{-b.(shd(m).Q_{3,k}(w_s) - A_m)}) \qquad (2)$$

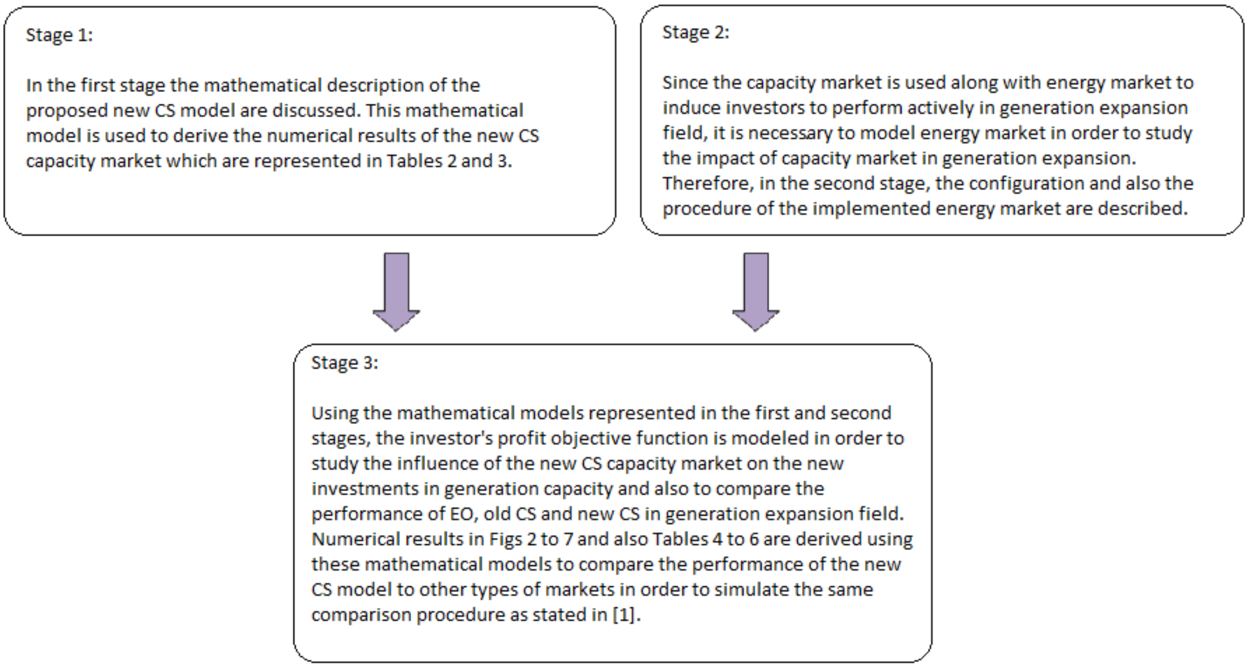


Fig. 1. Diagram of different stages of calculation procedure

Energy Not Served (ENS) (Eq. (3)) reveals the amount of imposed reduction in consumer's consumption in the time of peak period. The lower the level of subscribed capacity, the higher the level of ENS a consumer has to bear in peak demand. ENS is comparable to consumer's share of total demand and subscribed capacity as represented below:

$$ENS(m, w_s) = \max(shd(m).Q_{3,k}(w_s) - A_m, 0).ld_3 \qquad (3)$$

As stated in section 2a, Eq. (1), a consumer cost in CS model is composed of two terms, cost of buying capacity and cost of ENS. Consequently, the consumer composed cost function in the proposed CS model can be formulized as (Eq. (4)).

$$CC(m) = K_m . \underset{w_s}{E}\{VCL(A_m, m, w_s)\}.A_m + \underset{w_s}{E}\{ENS(m, w_s).VCL(A_m, m, w_s)\} \qquad (4)$$

In Eq. (4) the first term represents the cost of subscribed capacity and the second term discloses the cost of ENS. Here, it is assumed that each group tries to offer a multiple of its VCL as a capacity price which is implemented by K_m. $\underset{w_s}{E}$ is the Expected Value of each term which is calculated with respect to normal probability distribution value in predefined points. More details of $\underset{w_s}{E}$ calculation mechanism are available on [5]. Eventually, as stated in section 2a, each consumer tries to minimize its composed cost in order to reduce its expenses in capacity market. Therefore, with the help of the equation minimization above, each consumer group can determine its optimum capacity price and preferred subscribed capacity level. Consequently consumer can balance its proposed capacity price and amount of subscribed capacity in order to have minimum level of composed cost in comparison to other participants. Since each consumer wants to buy at least a part of its total demand, it has to bid a competitive price. Therefore, it has to model other consumers' Composed Costs based on the historical data of the capacity market in order to make a prediction of other consumers' capacity bids. At last, competitive capacity bid should be determined considering the prediction of other consumers' bids. Consequently, each consumer is dealing with a multi objective optimization problem which is modeled in Eq. (5) to Eq. (10).

This optimization problem is accompanied by a set of constraints which can be defined as follows:

$$\begin{cases} MinCC(1) \\ . \\ . \\ . \\ MinCC(M) \end{cases} \tag{5}$$

Subject to:

$$0 \le A_m \le shd(m).Q_{3,k} \qquad 1 \le m \le M \tag{6}$$

$$0 \le K_m \le inf \tag{7}$$

$$K_m.\underset{w_s}{E}\{VCL(A_m,w_s)\}.A_m + \underset{w_s}{E}\{ENS(m,w_s).VCL(A_m,w_s)\} < [VCL\max \tag{8}$$

$$.\underset{w_s}{E}\{shd(m).Q_{3,k}(w_s)\}] \quad 1 \le m \le M$$

$$\sum_{m=1}^{M} A_m < C_{tot} \tag{9}$$

$$\sum_{m=1}^{M} K_m.\underset{w}{E}\{VCL(A_m,m,w_s)\}.A_m \ge \text{IC} \tag{10}$$

Equation (5), as expressed in the former paragraph, states that each consumer should specify its capacity bid considering other consumers' minimum composed cost. It means that if a consumer wants to propose a competitive capacity bid, it should minimize other consumers' Composed Cost functions. To do so, it has to forecast other consumers' $VCL\max$ and peak demand using the historical data of the capacity market. Equations (6) and (7) are constraints that specify the upper and lower bands of subscribed capacity and capacity price for each group of consumers respectively. Equation (8) indicates that capacity bid should be determined in a way that the consumer group's composed cost would not violate its upper band. Basically, a consumer's maximum composed cost occurs when it has no subscribed capacity in peak period. In such situation, the consumer's maximum composed cost is equal to its $VCL\max$ multiplied by its peak demand which is shown in the right side of the nonequivalent stated in Eq. (8). Obviously, a consumer should keep its composed cost (the left side of the nonequivalent) below its maximum composed cost as shown in Eq.8. Based on Eq. (9), the sum of all subscribed capacities shouldn't exceed available capacity of the network. Eq. (10) is used in order to model the generation side in the capacity market. It should be noted that one of the main objectives of capacity market is to expedite generation expansion in the power network. As stated in section 1, capacity market participates in generation expansion by covering a part of the expenses of generation units which is not prepared thoroughly by the energy market. The term IC, in the right side of the nonequivalent in Eq. (10), addresses this concept. Consequently, the amount of money paid by the consumers to buy capacity (the left side of nonequivalent in Eq. (10)) should at least cover the IC of the generation side. In fact, Eq. (10) helps the consumer to adjust its proposed capacity price more reasonably according to the system situation. IC should be announced by ISO at the beginning of each year.

As is clear, the whole case is a multi objective optimization problem which can be simplified to a single objective optimization problem using the method below (Eq. (11)):

$$\max[(\frac{CC_{1\max}-CC_1}{CC_{1\max}-CC_{1\min}})+(\frac{CC_{2\max}-CC_2}{CC_{2\max}-CC_{2\min}})+.....+(\frac{CC_{M\max}-CC_M}{CC_{M\max}-CC_{M\min}})] \tag{11}$$

where $CC_{\max}$ and $CC_{\min}$ are the maximum and minimum value of CC function respectively. $CC_{\max}$ happens in zero subscribed capacity level for each group of consumers while $CC_{\min}$ is assumed zero for all groups. A full competitive capacity market is used to evaluate the performance of the proposed CS model.

c) Profit objective function description

Since the capacity market is used along with energy market to induce investors to perform actively in generation expansion field, it is necessary to model energy market in order to study the impact of capacity market in generation expansion.

A piecewise supply curve with two different generation technologies, base and peak, is used to model the electricity supply. The old installed generation capacity in base and peak load is assumed to have increasing marginal cost while the new installed capacity is assumed to have lower marginal cost than the existing plants.

The demand within each year is divided into three sub-periods, base, medium and peak, which differ in coefficient factor (Eq. (12)).

$$L_{\max,k}=\begin{bmatrix}L_{base,k}\\L_{medium,k}\\L_{peak,k}\end{bmatrix}=\begin{bmatrix}c_{base}\\c_{medium}\\c_{peak}\end{bmatrix}\times l_k \tag{12}$$

In order to derive an accurate model of energy market, two different types of uncertainties are taken into account. Short-term uncertainty, which shows random deviation in demand, is usually caused by temperature variations and here is modeled using a normal distribution with mean and standard deviation of 1 and 0.02 respectively. $L_{\max,k}$ in Eq. (12) depends on short-term uncertainty. Long-term uncertainty, which shows the variation in demand from year to year, is dependent on growth in a regions population and economic factors. This kind of uncertainty is modeled as a Markov chain with an expected growth of 100 MW/year, standard deviation of 200 MW/year and constant transition probability of 0.5. The fixed load l_k in Eq. (12) depends on long-term uncertainty.

As stated in the former paragraphs, demand within each year is divided into Base, Medium and Peak levels with different load durations. It is assumed that 5% of demand within each sub-period is price responsive.

Figure 2 tries to show the mechanism of energy market where energy price in different load levels is determined at the intersection of demand and supply curves.

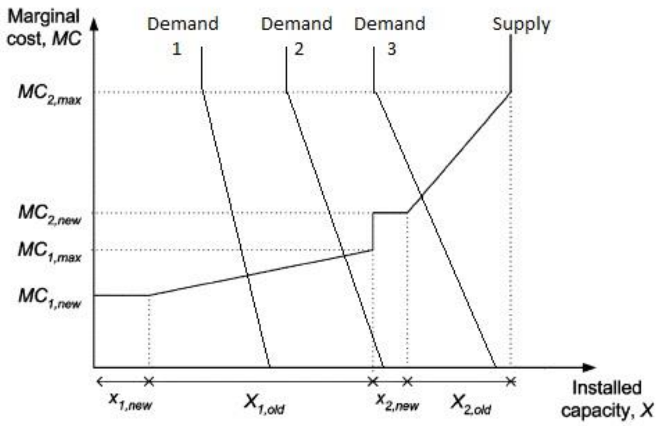


Fig. 2. Demand and supply diagram

In order to study the influence of the proposed CS capacity market on the new investments in generation capacity and also to compare the performance of EO, the basic CS and the proposed CS in generation expansion field, it is necessary to model the investors' profit objective function over a planning horizon of T years. Equation (13) states the general mathematic model of the investment optimization problem which is run by the investor to determine the appropriate time and amount of new investment in generation capacity.

$$J_0(x_0,l_0)=\max_{u_0,\ldots\mu_{T-1}}\ \underset{w_{l,k}}{E}\{\sum_{k=0}^{T-1}[(1+r)^{-k}.g_k(x_k,l_k,u_k,w_s)+(1+r)^{-T}.g_T(x_T,l_T,w_s)]\} \quad (13)$$

Payoff function $g_k(x_k,l_k,u_k,w_s)$ is made of three terms containing the payoffs obtained from capacity and energy markets plus the new installed capacity investment cost (Eqs. (14) - (16)). In Eq. (15) the annual profit obtained from the energy market is modeled by the difference between the operation revenues and costs over different generation technologies and demand sub-periods. Eq. (16) models the annual profit obtained from the capacity market over different generation technologies.

$$g_k(x_k,l_k,u_k,w_s)=g_{k,\pi cs}(x_k,l_k)+g_{k,\pi e}(x_k,l_k,u_k,w_s)-ic_k.u_k \quad (14)$$

$$g_{k,\pi e}(x_k,l_k,u_k,w_s)=\sum_{i=1}^{3}\sum_{j=1}^{2}ld_i.x_{j,new,k}.\underset{w_s}{E}\{\max[(p_{i,k}(x_k,l_k,w_s)-MC_{j,new}),0]\} \quad (15)$$

$$g_{k,\pi cs}(x_k,l_k)=CP_{k,cs}.(x_{1,new,k}+x_{2,new,k}) \quad (16)$$

Due to the fact that each accepted consumer group in the proposed CS scenario pays its own proposed price to buy capacity, the following equation is suggested to find a global capacity price to be paid to generation units considering the amount of available capacity.

$$CP_{k,newcs}=(\sum_{i=1}^{m}Dcs_{i,k}.cp_{i,k})\Big/C_{tot} \quad (17)$$

Equation (18) is used to adjust the investment cost of new technologies according to the remaining length of the planning horizon.

$$ic_{inv,k}=(1+r)^{-(l_t/2)}.ic.(\sum_{i=1}^{T-k}(1+r)^{-i})\Big/(\sum_{j=1}^{n_t}(1+r)^{-j}) \quad (18)$$

The investment problem is a multi-stage decision making problem and Stochastic Dynamic Programming (SDP) is no doubt the best solution for such kind of problems. But, due to small solution space caused by simplifications as stated in the later paragraphs and also in order to ensure obtaining the best answer possible, we preferred to test all the existing solution space.

State space is expanded by two state variables demand (l_k) and generation capacity (x_k). In order to limit the size of the state space, it is assumed that only one construction plan can be undertaken at the same time and no new expansion decision is allowed in the time of ongoing plan constructions. One can invest in either one or both base and peak technologies at the same time. For more simplification, the size of new plants in base and peak technologies are limited to 400 MW and 200 MW respectively.

A planning horizon of 10 years is taken into account to evaluate the best expansion decision of each year. The optimum answer is the one which gives maximum profit along these ten years in comparison to other options. It is also assumed that only one new plant of each technology can be constructed within the planning horizon. In order to study the investment dynamic over a longer time period, system is simulated over 30 years according to the steps explained by the flowchart shown in Fig. 3.

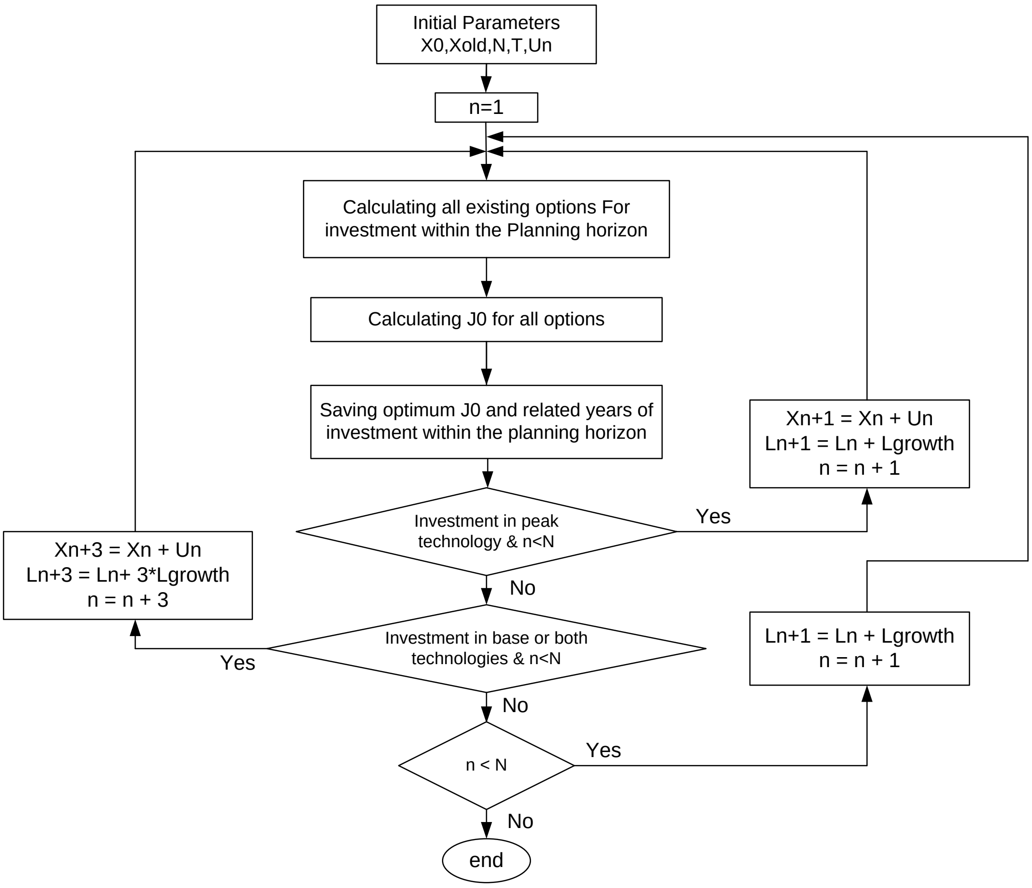


Fig. 3. Profit optimization flowchart

As shown in Fig. 3, in the first year of simulation period, the optimization algorithm calculates all the possible investment strategies including their investment year and their related J_0 over the 10 years of the planning horizon. Then, among all the possible investment strategies, the one with maximum J_0 will be selected as the optimum solution. In this way, three different possibilities may arise. First, if the optimum solution is to invest in peak technology then the algorithm will increase the installed capacity by 200 MW and the load by 100 MW and then the procedure is repeated for the year after. Second, if the optimum solution is to invest in base or both base and peak technologies, then the algorithm will increase the installed capacity by the amount of investment which is decided to be undertaken in base or both base and peak technologies, the amount of load by 300 MW, the year number by 3 and then the procedure is repeated. Third, if no new investment decision is made, then the algorithm will only increase the load by 100 MW and the procedure is repeated for the next year. The whole procedure will be continued till the year number reaches 30.

4. RESULTS

Table 1 specifies the parameters of the under study system. Three different scenarios, Energy Only with the price cap (EO), the basic Capacity Subscription (old CS) and the proposed Capacity Subscription (new CS), are simulated and analyzed. Ten groups of consumers with different $VCL\max$ ranging from 1000 ($/MWh) to 4000 ($/MWh) are defined to be used in both basic CS and proposed CS scenarios. Price cap of 170 ($/MWh) is taken into account in EO scenario and initial demand level is set equal to 9300 MW. The investment price related to (Eq. 10) is assumed equal to one third of mean value of base and peak technologies investment costs per KW as expressed in Table 1.

Table 1. Parameters of under study system

Identifier	Value	Identifier	Value
l_0	9300 (MW)	b	0.8
ld	[5760 2900 100] (hours)	$X_{newinitial}$	[0 0] (MW)
l_{growth}	100 (MW/year)	X_{old}	[10000 6000] (MW)
l_{sdv}	200 (MW/year)	MC_{new}	[16.7 30.1] ($/MWh)
$VOLL$	1700 ($/MWh)	$MC_{\max}$	[20.1 67] ($/MWh)
$Pcap$	170 ($/MWh)	ic_{new}	[2010.2 1005.1] ($/KW)
r	6 %pa.	n_t	[30 20] (years)
Ω_u	[0/400 0/200] (MW)	l_t	[3 1] (years)
N	30 (year)	T	10 (year)

Tables 2 and 3 show the output of proposed CS capacity market for two different load levels 9500 MW and 10000 MW and installed capacity of 16000 MW. As it is clear, in both tables, consumers with higher VCLmax offer higher capacity prices in comparison to those with lower VCLmax. This is the main strategy which consumers should follow up when trying to determine their capacity bids. It means, if the electricity has much more value to one consumer (consumer has higher level of VCLmax), it should try to end up with higher level of offered capacity price compared to those with lower VCLmax in order to increase its chance of being accepted in the market. As it is clear, capacity prices in Table 3 are higher than Table 2 due to increasing level of demand and constant amount of installed capacity. 825 MW (1.65×500 according to peak load definition) of load growth in peak demand results in more intense competition between consumers which leads to higher level of capacity bids. As it is clear, the variations of VCLmax and *shd* in both Tables 2 and 3 are similar to the variation of consumers' types in industrialized countries where usually, industries have higher level of share of total demand and much more off losses in the time of disconnections and curtailments.

Table 2. New CS Capacity Market Results for Load = 9500 MW

Consumer Group No.	1	2	3	4	5	6	7	8	9	10
VCLmax ($/MWh)	1065.41	1099.25	1186.70	1305.64	1447.86	1476.34	1545.02	1654.24	2620.82	3350.36
Shd	0.0195	0.0408	0.0487	0.0806	0.0910	0.1049	0.1071	0.1127	0.1321	0.2626
Bid ($/MW)	11223.71	11542.95	12074.78	13279.15	14391.39	14401.49	31181.96	31255.67	33449.99	33543.60
Subscribed Capacity (MW)	291.7	608	725.6	1200.6	1355.5	1562.5	1595.2	1678.1	1967.8	3912.4

Table 3. New CS Capacity Market Results for Load = 10000 MW

Consumer Group No.	1	2	3	4	5	6	7	8	9	10
VCLmax ($/MWh)	1065.41	1099.25	1186.70	1305.64	1447.86	1476.34	1545.02	1654.24	2620.82	3350.36
Shd	0.0195	0.0408	0.0487	0.0806	0.0910	0.1049	0.1071	0.1127	0.1321	0.2626
Bid ($/MW)	14431.68	18815.62	18954.66	31029.36	31225.36	31305.76	34325.87	34493.38	67561.68	67749.30
Subscribed Capacity (MW)	312.1	639.6	763.6	1263.1	1426.3	1644.1	1678.7	1766.3	2070.7	4116.2

Figure 4 shows the construction time of new expansion decisions of the three models. In proposed CS policy 3600 MW new generation capacity is constructed within the assumed 30 years of simulation time which is 50% greater than EO policy and 13% greater than the basic CS model (Table 4). Total new capacity of 3200 MW and 2400 MW is constructed during simulation time in the basic CS and EO policies respectively and in none of these three polices (EO, basic CS and proposed CS) no new capacity is constructed in peak technology. As Fig. 5 shows, in the proposed and basic CS models, due to the restrictions applied to consumers in the time of peak periods, demand level never exceeds the installed capacity and consequently, price of energy is limited to maximum level of 67 ($/MWh). This reduction in peak energy price is the main reason of peak generation investment incentive reduction. The same thing happens to EO scenario where price cap limitation reduces the peak energy price and consequently the amount of peak generation investments.

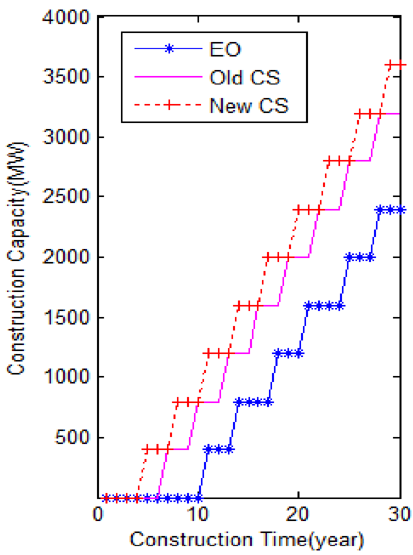
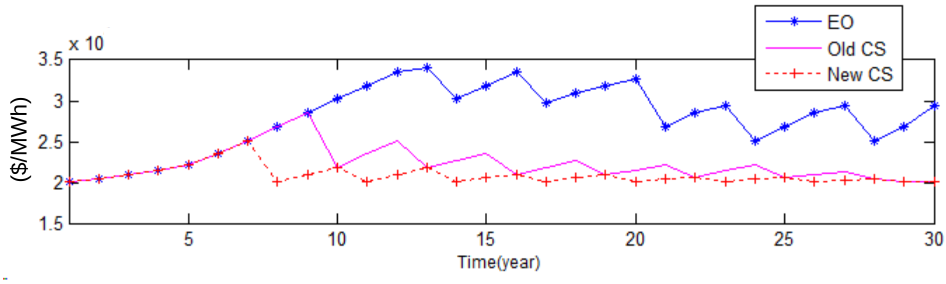


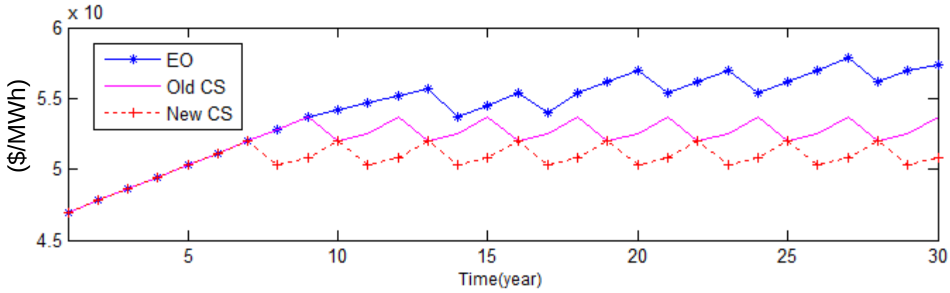
Fig. 4. Construction year of new capacities

Table 4. Commissioning year of new investigations

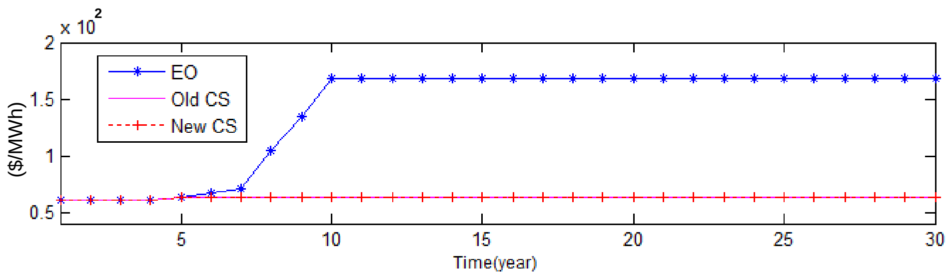
New Capacity Construction No.	EO	Old CS	New CS
1	14	10	8
2	17	13	11
3	21	16	14
4	24	19	17
5	28	22	20
6	31	25	23
7		28	26
8		31	29
9			32
$\sum capacity_{new}$ (MW)	2400	3200	3600
$\sum capacity_{total}$ (MW)	18400	19200	19600



(a)



(b)



(c)

Fig. 5. Energy price for different demand levels, a. Base Load, b. Medium Load, c. Peak Load

Figure 5 illustrates the energy price in base, medium and peak load levels. Average energy price in the proposed CS policy in base load level is 25.01% and 5.82% and in medium load level is 6.45% and 2.6% lower than EO and basic CS policies respectively. In proposed CS model, investors' higher tendency to invest in new capacities results in the first power plant construction two years earlier than the basic CS policy which leads to this amount of reduction in base energy price. As Table 5 shows, although the proposed and basic CS models have close competition in terms of average medium energy price, the proposed CS model medium energy price is still lower than the basic CS model and also has considerable difference with medium energy price in EO model.

Table 5. Energy market simulation results

Scenario	Av. Base energy price ($/MWh)	Av. Medium energy price ($ /MWh)	Av. Peak energy price ($ /MWh)	Av. Load shedding (MW)	Av. Social welfare (Million $)
EO	27.85	54.13	139.96	1882.5	2.29
Old CS	22.17	51.99	63.57	0	26.75
New CS	20.88	50.64	63.57	0	27.09

Capacity balance illustrated in Fig. 6 is a good criterion to evaluate the capacity sufficiency in the system. It expresses the proportion of demand which is not supplied to the total available installed capacity in the system [3].As the figure shows, the proposed CS model ends up with a positive capacity balance where the basic CS and EO policies capacity balances are negative at the end of a 30 year period. Due to the price cap applied in EO model which leads to lower amount new capacity investments, a great capacity insufficiency is sequenced. Higher values of capacity balance of the proposed CS model in comparison to the basic CS model confirm that the proposed model is more qualified in stimulating the investors' to invest in new generation capacities.

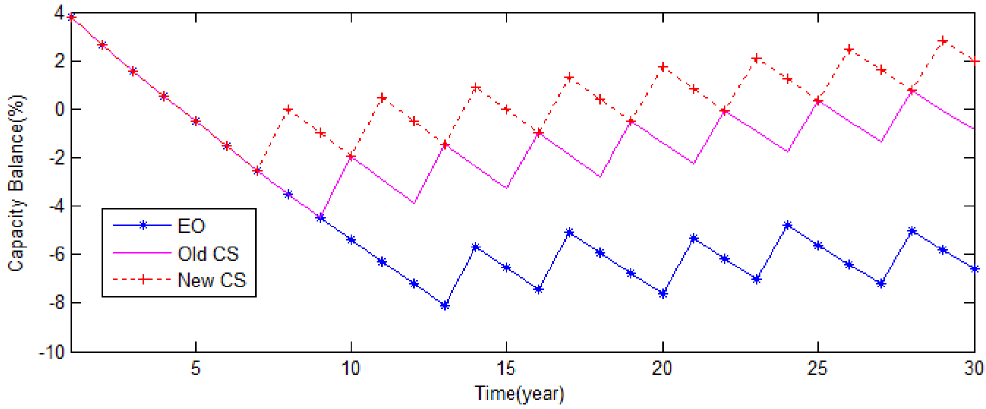


Fig. 6. Capacity balance in peak demand

Due to consumers' limitation during peak periods in both CS models, demand never exceeds the available installed capacity. Therefore, no load shedding is applied. But in EO policy average load shedding of 1882.5 MW, which is 10.23% of total installed capacity, is required to restrict demand as shown in Fig. 7.

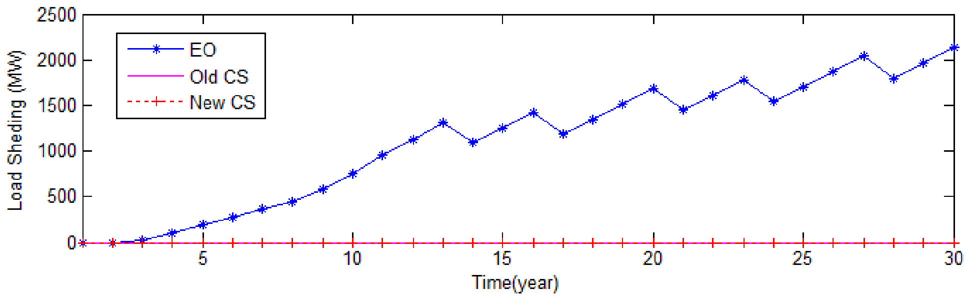


Fig. 7. Average load shedding in peak demand

As Fig. 8 shows, social welfare in proposed CS model is higher than the basic CS model which means consumers' and producers' surpluses increase due to more and sooner investments in new capacities. As expressed in Table 5, average social welfare in proposed CS model is 1.26% higher than the basic CS model and social welfare in EO policy has a small amount relative to two other policies because of applied price cap which restricts peak load energy prices.

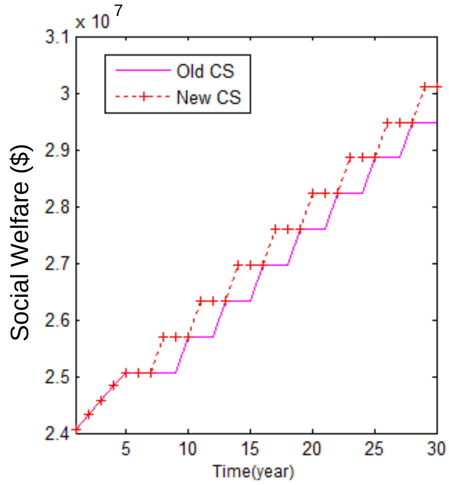


Fig. 8. Social welfare in peak demand

As explained in section 1 and 2, smart meters are able to limit each consumer's demand to its subscribed capacity level during peak periods, which means in the time of generation shortage, consumer is not completely disconnected from the system but its demand is restricted to its permitted level. Figure 9 shows that the amount of average restricted demand in proposed CS model is 31.62% lower than the basic CS model. More installed capacity resulted from more applied investments in new power plants, enables the system to cover a higher level of demand in proposed CS model during peak periods. Due to absence of subscribed capacities, priority list of consumers and smart meters in EO model, consumers' demands are not partially restricted. In fact, some of the consumers are completely disconnected from the network in the time of generation shortages (Fig. 7). These sorts of disconnections to reduce demand result in more damages, because they happen randomly and are not anticipated by the consumers.

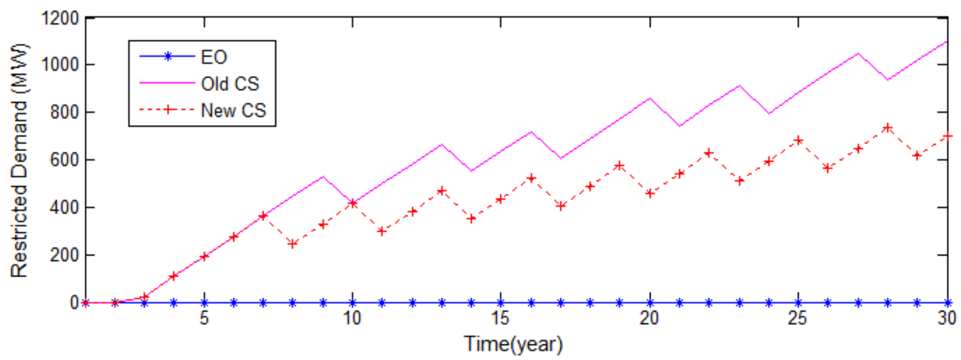


Fig. 9. Average restricted peak demand

Table 6 shows that capacity price and profit in the proposed CS model are more than the basic CS model which is the main reason of sooner and more applied investments in new capacities. More incentive in new capacity investment caused by more profit obtained by producers in the proposed CS capacity market result in higher level of installed capacity which leads to lower energy prices compared to EO model and lower level of load curtailments and higher level of social welfare compared to the basic CS model.

Table 6. Capacity market simulation results

Scenario	Technology	Construction year	Capacity price ($/MW)	Capacity profit ($)
EO	1	11	0	0
Old CS	1	7	28496.49	455943791.70
New CS	1	5	32699.51	523192224

5. CONCLUSION

A new capacity subscription model is proposed in this article where each consumer group bids a *Capacity Price* alongside its *Desired Subscribed Capacity Level* to the market. Each consumer group which is accepted in the market buys the capacity according to its offered capacity price. Numerical results obtained from the simulations show that the proposed CS market structure intensifies the competition between consumers which leads to higher level of revenues obtained by generation units. Increments in producers' income result in more investments in new generation capacities which cause considerable reduction in energy prices and increase in social welfare. Based on the numerical results, some of the more important advantages of the proposed CS model in comparison to other market types can be counted as:

- Generation investment increases.
- Social welfare increases.
- Consumers are ranked based on a fair mechanism.
- The proposed CS model is more competitive, because consumers compete with each other on their offered capacity price alongside their desired subscribed capacity level.
- The priority list obtained from the proposed CS model is applicable in the time of unexpected outages.

Therefore, considering above descriptions, the proposed CS model seems more efficient in resource adequacy field in comparison to the basic CS model.

NOMENCLATURE

VCL	value of cut load for consumer group m [$/MWh].
$shd(m).Q_{3,k}$	share of total peak demand for consumer group m [MW].
b	steepness of the VCL function [MW^{-1}].
A_m	subscribed capacity for consumer group m [MW].
$VCL\max(m)$	value of cut load for zero served load, consumer group m [$/MWh].
w_s	short-term uncertainty in demand (will be explained in Section 3.2).
ENS	energy not served for consumer group m [MWh].
ld_3	peak load duration [hours].
$\begin{bmatrix} L_{base,k} \\ L_{medium,k} \\ L_{peak,k} \end{bmatrix}$	Base, medium and peak load within each year
$\begin{bmatrix} c_{base} \\ c_{medium} \\ c_{peak} \end{bmatrix}$	Coefficient factors of different sub-period loads
l_k	Fixed load within each year
$J_0(x_0, l_0)$	maximum expected payoff within the planning horizon [Million $].

$g_k(x_k, l_k, u_k, w_s)$	payoff function, time step k [Million $].
x_k	vector of installed capacity for technologies 1 and 2, time step k [MW].
l_k	demand, time step k [MW].
u_k	investment decision for technologies 1 and 2, time step k [MW].
$w_{l,k}$	long-term uncertainty in demand level, time step k [MW].
r	real risk adjusted discount rate.
Ω_{x,l,u,w_l,w_s}	discrete feasible sets for x, l, u, w_l and w_s.
$g_{k,\pi cs}$	payoff function for capacity payments [Million $].
$g_{k,\pi e}$	payoff function for energy payments [Million $].
ic_k	vector with investment cost for new technologies 1 and 2, time step k [$/MW].
$MC_{j,new}$	operation cost, new technologies 1 and 2 [$/MWh].
$p_{i,k}$	energy price, demand level i, time step k [$/MWh].
$CP_{k,cs}$	capacity price, time step k [$/MW].
$Dcs_{i,k}$	market admitted subscribed capacity level for consumer group I, time step k [MW].
$cp_{i,k}$	consumer group i proposed capacity price [$/MW].
m	number of accepted groups of consumers in the proposed CS capacity market.
n_t	life time of technologies 1 and 2 [years].
l_t	construction lead time for technologies 1 and 2 [years].

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