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Smart self-scheduling of Gencos with thermal and energy storage units under price uncertainty

Alireza Soroudi

***Abstract*—This paper provides a self scheduling tool for price taker Gencos. This methodology is based on Robust Optimization (RO) to deal with the uncertainties of market price values in the day-ahead electricity pool market. The Genco is assumed to be the entity who decides about the operating schedules of its thermal units and Compressed Air Energy Storage (CAES) units. The benefits of Genco brought by smart grid technology and energy storage systems are investigated in this work. The applicability of the proposed method is analyzed through different scenarios.**

***Index Terms*—Robust optimization, price taker Genco, thermal scheduling, uncertainty modeling, smart grids.**

NOMENCLATURE

Parameters

λ_t^a	Actual value of electricity price in time t
Γ	Budget of uncertainty
η_g	Generation efficiency of CAES
t	Hour index
$\lambda_t^{\max}$	Maximum value of electricity price in time t
$\lambda_t^{\min}$	Minimum value of electricity price in time t
$V_r^{\min}$	Minimum releasable air of CAES translated in to MW
$V_r^{\max}$	Maximum releasable air of CAES translated in to MW
$V_s^{\min}$	Minimum storage air in CAES translated into MW
$V_s^{\max}$	Maximum storage air in CAES translated into MW
DT_i	Minimum down time of i-th thermal unit
UT_i	Minimum up time of i-th thermal unit
$P_i^{\max\,/\,\min}$	Maximum/minimum power output of i-th thermal unit
$E^c_{\max}$	Maximum stored energy in CAES (MWh)
$E^c_{\min}$	Minimum stored energy in CAES (MWh)
$C_i(P_{i,t})$	Operating cost of thermal unit $P_{i,t}$ (\$)
λ_t^p	Predicted value of electricity price in time t
a_i, b_i, c_i	Quadratic cost coefficients of thermal unit i.
STC_i	Start-up cost of unit i
SDC_i	Shut-down cost of unit i
SU_i	Start-up limit of unit i (MW)
SD_i	Shut-down limit of unit i (MW)
η_s	Storage efficiency of CAES
UR_i, DR_i	Up/Down ramp rate of i-th thermal unit (MW/h)

Variables

U_t^g, U_t^s	Binary variables that describe the operational status (generation/storage)of the CAES units.
$Y_{i,t}, Z_{i,t}$	Binary variables that describe the start-up/shut-down status of the thermal unit i in time t.
β, ξ_t	Dual variables of robust optimization
$P_{i,t}$	Generated power of thermal unit i in time t (MW)
P_t^c	Generated or stored power of CAES in hour t (MW)
$\tau_{i,t}$	Number of hours unit i has been on/off at the end of hour t
$U_{i,t}^{th}$	On/off state of unit i in time t
$V_{r,t}$	Released air of CAES in time t
E_t^c	Stored energy in CAES in time t (MWh)
$V_{s,t}$	Stored air into CAES in time t
U_t^g	State of energy generation for CAES in time t
U_t^s	State of energy storage for CAES in time t
TC	Total operating cost of thermal units (\$)
PT_t	Total generated power of the Genco in time t (MW)
$\tilde{\lambda}_t$	Uncertain value of electricity price in time t

I. INTRODUCTION

A. Motivation and Approach

There are different players in a day-ahead pool market such as consumers, retailers, ISO and generating companies. The electricity price is determined based on the offering strategies of Genco entities [1], bidding strategies of consumers and finally the technical condition of the electric network. The benefits of Genco (which is inherently a profit maximizer entity) basically depend on these values and determine the operating schedule for it. In competitive electricity markets, power suppliers are required to submit to the market operator their bid quantities and prices, usually one day before real-time operation. On the other hand, the values of electricity prices during the upcoming day are uncertain parameters. The only decision variables of a price taker Genco are the operating schedules of the generating units it owns. In this context, the self scheduling problem of a price taker Genco is defined as the optimal scheduling strategies of Genco's generating assets in favor of profit maximization while the values of electricity prices are unknown. The main problem is handling the uncertainties of price values. There are some mathematical and physical tools to reduce the impact of ambiguity about price quantities. The physical tools are smart grid technology and energy storage systems. The mathematical tools for handling the uncertainties can be categorized into some basic groups such as : stochastic modeling tools, Fuzzy arithmetic, Information Gap decision theory (IGDT) [2], [3] and robust optimization. Among these tools, the robust optimization and IGDT approach need no special knowledge about the probability distribution function or membership function of uncertain parameter under study. A shortcoming with IGDT method is that it is too conservative and

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the degree of conservativeness cannot be controlled by the decision maker. An efficient procedure is needed to combine these physical and mathematical tools to achieve an optimal self scheduling solution. This is the inspiration of this work.

B. Literature Review

1) Self scheduling problem: Different studies have already tackled the self scheduling problem. In [4], the self scheduling of a hydro based Genco is analyzed with an emphasize on various technical constraints of hydro units. The concept of risk minimization along with profit maximization is the inspiration of many self scheduling researches [5], [6]. A fuzzy approach for benefit maximizing while the demand, reserve services, market prices, and probability that reserves are called and generated are uncertain quantities [7].

2) Smart grid paradigm: The context of a smart network can enhance the self scheduling procedure for Genco. It can provide useful information about the accepted prices of the price maker Gencos playing in pool market. This would decrease the uncertainty level of price values for Genco and can lead to a better outcome. This is mainly because the Genco can modify its actions as the time goes on by being informed about the price values on hourly basis as shown in Fig.1.

3) Energy storage systems: The energy storage units are mainly used to insure the reliable and satisfactory operation of the power systems at presence of renewable energy technologies [8]. One of efficient methods used for energy storage is Compressed Air Energy Storage (CAES) units [**?**]. In a CAES, the air is compressed and stored in some large reservoirs and released when needed to drive a gas turbine generator [9]. The successful utilization of CAES units has been reported in regulating wind power variation and increasing wind energy integration [10], voltage stability [11] and reliability improvement in distribution networks [12] and Security-constrained unit commitment with wind generation [13].

4) Robust optimization: The robust optimization was first proposed by Soyster [14]. The shortcoming associated with formulation proposed in [14] is that it's too conservative. In [15], Bertsimas proposed a method for solving robust optimization with an adjustable degree of conservativeness using a so called "budget of uncertainty", i.e. Γ, parameter. Suppose an optimization problem in the following form:

$$\max_{\bar{X}} F(\bar{X}, \bar{D}) \quad (1)$$

$$\text{Subject to } \bar{H}(\bar{X}, \bar{D}) \le \bar{0}$$

where $\bar{X}$ and $\bar{D}$ are decision variables and input data of the problem. The $\bar{D}$ vector is subject to uncertainty. The robust optimization method is defined as optimizing F with all possible realizations of uncertain data $\bar{D}$ [16]. The applications of robust optimization are reported in the literature in various areas such as: contingency-constrained unit commitment [17], offering Strategy [18], integration of plug-in hybrid electric vehicles (PHEVs) in to the electric networks [19]. The contributions of this research are summarized as follows:

- A robust optimization technique is proposed for dealing with electricity price uncertainty without any PDF or membership function available.
- The impact of using smart grid technology on Genco's benefits is investigated.
- The use of air compressed energy storage is analyzed.

The remaining of the paper is organized as follows: the problem formulation is described in section II, the proposed method is presented in section III. Simulation results are given in section IV and finally, the paper is concluded in section V.

II. PROBLEM FORMULATION

A. Uncertainty modeling of electricity price

Different methods are proposed in the literature for modeling the uncertainties of electricity price values like: probabilistic [20]–[22] or fuzzy methodologies [7]. In all these methods a probability density function or membership function is required for describing the nature of uncertainty but in case of severe uncertainty no such data is available for Genco. In this work, it is assumed that the electricity price values belong to an uncertainty set without any specific information about the probability distribution function of them. The electricity price λ_t is assumed to be as follows [23]:

$$\lambda_t^{\min} \le \tilde{\lambda}_t \le \lambda_t^{\max} \quad (2)$$

B. Total cost of energy production

The operating cost of thermal units is defined as [24], [25]:

$$TC = \sum_{i,t} \left[U_{i,t}^{th} * C_i(P_{i,t}) + STC_i * Y_{i,t} + SDC_i * Z_{i,t}\right] \quad (3)$$

$$C_i(P_{i,t}) = a_i(P_{i,t})^2 + b_i P_{i,t} + c_i \quad (4)$$

C. Thermal unit constraints [26]

1) Generation limits of units

$$U_{i,t}^{th} * P_i^{\min} \le P_{i,t} \le U_{i,t}^{th} * P_i^{max} \quad (5)$$

2) Ramp up/down constraints The output of thermal generator units can be different in t and $t+1$ but this decrease/increase should remain within certain limits for technical reasons as follows:

$$P_{i,t} \ge P_i^{min} * U_{i,t}^{th} \quad (6)$$

$$P_{i,t} \ge P_{i,t-1} * U_{i,t}^{th} - RD_i * U_{i,t}^{th} \quad (7)$$

$$P_{i,t} \le (P_i^{max}[U_{i,t}^{th} - Z_{i,t+1}] * Z_{i,t+1} * SD_i) * U_{i,t}^{th} \quad (8)$$

$$P_{i,t} \le (P_{i,t-1} + RU_i * U_{i,t-1}^{th} + Y_{i,t} * SU_i) * U_{i,t}^{th} \quad (9)$$

3) On/off states

$$Y_{i,t} - Z_{i,t} = U_{i,t}^{th} - U_{i,t-1}^{th} \quad (10)$$

$$Y_{i,t} + Z_{i,t} \le 1 \quad (11)$$

4) Minimum up/down time

$$[\tau_{i,t-1} + DT_i][U_{i,t}^{th} - U_{i,t-1}^{th}] \le 0 \quad (12)$$

$$[\tau_{i,t-1} - UT_i][U_{i,t-1}^{th} - U_{i,t}^{th}] \ge 0 \quad (13)$$

D. *Compressed Air Energy Storage unit constraints*

The technical constraints of CAES are described as follows [13]:

- The CAES unit in time t is either in storing, generating or idle mode. This is modeled as follows:
$$U_t^s + U_t^g \le 1 \tag{14}$$
When U_t^s / U_t^g is 1 then the CAES is operating in storing/generating mode. If U_t^s & U_t^g are 0 then the CAES is operating in idle mode.
- The released/stored air in CAES in time t should be within its operating limits as:
$$U_t^g * V_r^{\min} \le V_{r,t} \le U_t^g * V_r^{\max} \tag{15}$$
$$U_t^s * V_s^{\min} \le V_{s,t} \le U_t^s * V_s^{\max} \tag{16}$$
- The total stored air in CAES in time t depends on the capacity of CAES and also the storing/releasing volume of air in the previous hours.
$$E_t^c = E_{t-1}^c + V_{s,t} * \eta_s - V_{r,t}/\eta_g \tag{17}$$
$$E_{\min}^c \le E_t^c \le E_{\max}^c \tag{18}$$
- The generated/stored power of CAES depends on the released/stored air in CAES and also the efficiency of the system for energy conversion as follows:
$$P_t^c = V_{r,t} - V_{s,t} \tag{19}$$

E. *Objective function*

The objective function of Genco is maximizing its profit which is defined as the sold energy in the market minus the operating costs, as follows:

$$PT_t = \sum_c P_t^c + \sum_i P_{i,t} \tag{20}$$
$$OF = \sum_t PT_t * \tilde{\lambda}_t - TC \tag{21}$$

The Genco should choose the best strategy for storing/selling its energy in the pool market. Since the values of electricity prices are subject to uncertainty then an efficient tool is needed to deal with them. This tool is described in section III.

III. PROPOSED ROBUST OPTIMIZATION APPROACH

A. *Concept of robust optimization*

Consider a linear version of (1) as follows:

$$\max_{\bar{X}} \bar{Q}^T \bar{X} \tag{22}$$
$$\text{Subject to } A\bar{X} \le \bar{B}$$

where $\bar{Q}$ is the uncertain coefficient of decision vector $\bar{X}$ and the $\bar{Q}^T$ is the transposed vector of Q. The decision maker just knows some basic information about the values of $\bar{Q}$. $U(Q)$ is a set describing all possible outcomes of $\bar{Q}$ as :

$$\bar{Q} \in U(\bar{Q}) = \left\{\forall q_t | q_t^{\min} \le q_t \le q_t^{\max}\right\} \tag{23}$$

where q_t are the components of Q and $q_t^{\min}$, $q_t^{\max}$ define the lower and upper bound boundaries for q_t, respectively. Assuming that the uncertainty set is symmetrical then it is reasonable to consider the $\frac{Q_{\min}+Q_{\max}}{2}$ as the predicted value of $\bar{Q}$ and call it $\bar{Q}^p$. The robust counterpart of (22) is defined as follows:

$$\max_{\bar{X}} z \tag{24}$$
$$z \le {\bar{Q}^p}^T \bar{X} - \max_{w_t} w_t * [Q^p - Q_{min}] \tag{25}$$
$$\sum_t w_t \le \Gamma \tag{26}$$
$$A\bar{X} \le \bar{B} \tag{27}$$

Based on the method proposed in [27] the equations (24) to (27) are transformed as follows:

$$\max_{\bar{X},\beta,\xi_t} \sum_t q_t^p |x_t| - \Gamma\beta - \sum_t \xi_t \tag{28}$$
$$\beta, \xi_t \ge 0 \tag{29}$$
$$\beta + \xi_t \ge |x_t| \frac{Q_t^{\max} - Q_t^{\min}}{2} \tag{30}$$
$$A\bar{X} \le \bar{B} \tag{31}$$

It is interpreted as follows: there are N_t uncertain coefficients (q_t). The decision maker can be very optimistic about predicted values of q_t which is called q_t^p or too pessimistic about them (all values of q_i become $q_t^{\min}$). The formulation provided in (28) enables the decision maker to regulate the degree of conservativeness from being too optimistic ($\Gamma = 0$) to too pessimistic ($\Gamma = 100\%$). Actually the value of Γ states that how percent of the prediction is allowed to be false.

B. *Self scheduling in smart grid paradigm*

In this paradigm, the GenCo is allowed to re-schedule its generation during the day (intra-day rescheduling) while this rescheduling is not allowed in some electricity markets. The robust counterpart of optimization problem defined in (21) is described as follows:

$$\max_{PT_t,\beta,\xi_t} \sum_{t=1}^{24} \lambda_t^p * PT_t - \Gamma\beta - \sum_{t=1}^{24} \xi_t - TC \tag{32}$$
$$\beta, \xi_t \ge 0 \tag{33}$$
$$\beta + \xi_t \ge PT_t \frac{\lambda_t^{\max} - \lambda_t^{\min}}{2} \tag{34}$$
$$(3) \to (20)$$

As it is clear in (32) the decision variables of Genco are the operating schedule of its thermal and CAES units from $t = 1$ to $t = 24$. In this case, just one optimization is performed while the price values are uncertain from $t = 1$ to $t = 24$. The number of decision variables is as follows: $2 * N_i * (24)$ for thermal units (generating schedule +on/off state for each unit)+ $4 * N_c * (24)$ for CAES units (generating/storage schedule + storing/generating state for each unit) + 1 for β + (24) for ξ_t which would be equal to $(2 * N_i + 4 * N_c + 1) * (24) + 1$. The parameters N_c,N_i are the number of CAES and thermal units, respectively.

C. *Self scheduling in Non-smart grid paradigm*

If the Genco uses the smart grid facility (as depicted in Fig.1) then it will be informed about the actual market clearing price until time $t = h$. In hour h, one optimization is done to find the operating schedule of units in the remaining hours of the day ($t = h$ to $t = 24$). The price values of time $t = h$ is equal to $\lambda^a_{t=h}$ while $\tilde{\lambda}_{t=h+1:24}$ are uncertain. The number of decision variables in time $t = h$ is as follows: $2 * N_i * (24 - h + 1)$ for thermal units + $4 * N_c * (24 - h + 1)$ for CAES units + 1 for β + $(24 - h + 1)$ for ξ_t which would be equal to $(2 * N_i + 4 * N_c + 1) * (24 - h + 1) + 1$. It should be noted that the value of Γ for a given percent of uncertainty is not necessarily the same in smart grid (SG) and non-smart grid (NSG) paradigms. The actual Γ value (not in percent) is always equal to $\Gamma(\%) * 24$ for NSG while in SG the actual value of Γ changes with time. As mentioned before, just one optimization is performed for the day-ahead self-scheduling program in NSG. In contrast, in SG for every upcoming hour one optimization is performed (24 optimizations in total). The actual value of Γ is different in each hour since the number of uncertain price values reduces as the time goes on. For example, in $t = h$ the actual value of Γ is $\Gamma(\%) * (24 - h)$. This is because only the prices of $(24 - h)$ hours are still uncertain in SG.

The problem formulation for smart grid case in time $t = h$ is as follows:

$$\max_{PT_t, \beta, \xi_t, t \geq h} OF \tag{35}$$

$$OF = \lambda^a_h * PT_h + \sum_{t=h+1}^{24} \lambda^p_t * PT_t - \Gamma\beta - \sum_{t=h}^{24} \xi_t - TC$$

$$\beta, \xi_t \geq 0 \tag{36}$$

$$\beta + \xi_t \geq PT_t \frac{\lambda^{\max}_t - \lambda^{\min}_t}{2} \tag{37}$$

$$(3) \rightarrow (20)$$

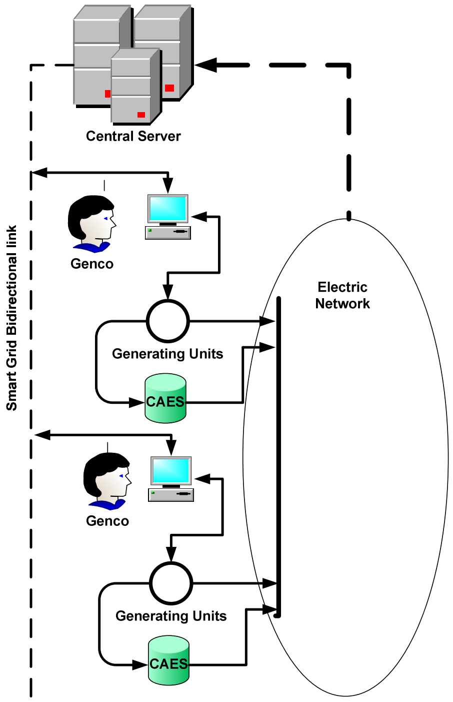

Fig. 1. The concept of smart grid

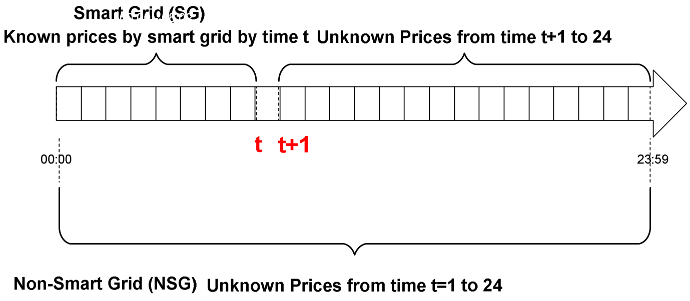

Fig. 2. The impact of using smart grid on the uncertainty that Genco should handle

IV. SIMULATION RESULTS

The proposed approach is implemented in GAMS [28] environment solved by DICOPT solver running on an Intel®Core$^{\text{TM}}$2 Duo Processor T5300 (1.73 GHz) PC with 1 GB RAM. It is applied to a 11-units system [29] as described in Table I. The values of electricity prices for the upcoming day are given in Table III [23].

TABLE I
THE CHARACTERISTICS OF THERMAL POWER GENERATORS

i	a_i	b_i	c_i	RU_i	RD_i	$P_i^{\min}$	$P_i^{\max}$
1	0.01	13	130	30	30	5	30
2	0.01	12	120	30	30	5	30
3	0.01	8	80	500	500	150	500
4	0.01	9	90	300	300	100	300
5	0.01	11	110	100	100	25	100
6	0.01	8.5	85	300	300	100	300
	UT_i	DT_i	$S0_i$	STC_i	SDC_i	SU_i	SD_i
1	1	1	2	40	40	24	6
2	1	1	2	40	40	24	6
3	10	10	11	440	440	400	180
4	10	10	11	110	110	240	120
5	5	5	6	50	50	80	30
6	8	8	9	100	100	240	120

TABLE II
THE CHARACTERISTICS OF CAES

Parameter	Dimension	value
η_g		0.95
η_s		0.95
$V_r^{\min}$	MW	2
$V_r^{\max}$	MW	250
$V_s^{\min}$	MW	0
$V_s^{\max}$	MW	150
$E^c_{\min}$	MWh	5
$E^c_{\max}$	MWh	500

In this work, for getting closer to reality, it is assumed that the Genco can only participate a portion of its capacity in pool market. This might be due to internal demand supply requirements, technical constraints for power injection into the grid, fuel limitations, emission allowance or bilateral contracts as follows:

$$\sum_{i,t} P_{i,t} \leq \eta * 24 * \sum_i P_i^{\max} \tag{38}$$

In this study, the value of η is assumed to be 80%. Imposing this constraint would make the self scheduling problem of Genco more challenging because it should have a robust strategy to sell its limited resources of energy in the market.

TABLE III

THE ACTUAL AND PREDICTED INTERVAL FOR PRICE VALUES ($)

Hour	λ_t^a	$\lambda_t^{\min}$	$\lambda_t^{\max}$
t_1	44.80	39.00	52.44
t_2	41.03	33.36	49.90
t_3	36.10	27.64	44.94
t_4	33.00	24.05	41.25
t_5	33.00	22.59	39.81
t_6	36.46	23.25	41.77
t_7	43.01	27.73	50.41
t_8	47.05	30.77	56.29
t_9	46.06	30.75	56.51
t_{10}	45.51	31.53	58.11
t_{11}	46.06	32.61	60.21
t_{12}	44.50	32.06	59.26
t_{13}	45.61	32.83	60.73
t_{14}	45.42	32.47	60.09
t_{15}	39.28	31.58	58.46
t_{16}	41.16	32.41	59.99
t_{17}	42.01	32.38	59.96
t_{18}	43.00	32.28	59.78
t_{19}	41.16	31.65	58.61
t_{20}	41.63	30.74	56.92
t_{21}	42.00	29.67	54.95
t_{22}	41.16	29.29	54.25
t_{23}	41.87	30.18	55.88
t_{24}	36.81	28.83	53.41

A. *Case-I: Robust decision making without CAES*

In this case, the Genco tries to sell its energy in pool market without using CAES. Two self scheduling scenarios are analyzed with and without smart grid facility. The Genco should be careful about its total generated energy till hour t. This is mainly due to (38) which limits the total available energy of the Genco. If the price value in hour t is high then the Genco is persuaded to produce and sell its generated power regardless of the price values in the upcoming hours. Since the total available energy is limited and no energy storage device is available then in case the remaining hours of the day experience higher price values, it would reduce the total benefits of the Genco. The total benefits of Genco ($) with different budgets of uncertainty in SG and NSG without CAES are described in Table V. In both SG and NSG cases the benefits of Genco decreases with the increase of Γ and for all values of Γ, in SG is higher than NSG because in SG there are more information available about price values. There is an exception in $\Gamma = 0$ that the benefits of Genco in NSG is higher than SG. This is explained as follows: in SG mode, for t_1 the value of price is known and is equal to λ_t^a but in NSG, the predicted value of price is assumed to be $\frac{\lambda_t^{\max}+\lambda_t^{\min}}{2}$. Since the simulation data shows that $\lambda_{t_1}^a \leq \frac{\lambda_{t_1}^{\max}+\lambda_{t_1}^{\min}}{2}$ this explains why the benefits of Genco is higher in NSG in $\Gamma = 0$. The power schedule of Genco's unit with $\Gamma = 10\%$ in SG and NSG without CAES are given in Table IV.

Imposing the (38) obliges the Genco to use only some of its units in the pool market.

B. *Case-II: Robust decision making with CAES*

In this case the Genco uses the benefits of CAES and tries to maximize its benefits by storing energy in low price hours and selling it in high price periods. The operating schedules with different budgets of uncertainties in SG and NSG are given in Table VIII,IX, respectively.

The total benefits of Genco ($) with different budgets of uncertainty in Smart Grid (SG) and non-Smart Grid (NSG) with CAES are given in Table VII.

TABLE V

THE TOTAL BENEFITS OF GENCO ($) WITH DIFFERENT BUDGETS OF UNCERTAINTY IN SMART GRID (SG) AND NON-SMART GRID (NSG) WITHOUT CAES

Γ (%)	SG	NSG
0	723756.51	758417.74
10	725393.37	714655.61
20	727667.20	676479.76
30	725682.96	639900.63
40	723186.04	604252.20
50	718448.83	569785.31
60	711508.03	536928.58
70	705418.32	506222.84
80	701552.96	480489.31
90	699311.05	458921.10
100	699175.98	447572.19

TABLE VII

THE TOTAL BENEFITS OF GENCO ($) WITH DIFFERENT BUDGETS OF UNCERTAINTY IN SMART GRID (SG) AND NON-SMART GRID (NSG) WITH CAES

Γ (%)	SG	NSG
0	724008.35	760638.82
10	725696.87	715560.12
20	727791.05	676809.10
30	725722.67	639900.63
40	723186.04	604252.20
50	718448.83	569785.31
60	711508.03	536928.58
70	705418.32	506222.84
80	701552.96	480489.31
90	699311.05	458921.10
100	699125.98	448144.27

The marginal benefits of Genco due to use of CAES ($) versus the budget of uncertainty Γ are depicted in Fig.3. This shows how using the CAES may affect the benefits of Genco in SG and NSG modes. In both cases, the marginal benefit is a positive number but differs in different values of Γ as well as the operating paradigm (SG/NSG). For example, in SG and $\Gamma = 100\%$ the marginal benefit is equal to 250981.71$ for just one day. This would be around 691608324.49$ in a year which may justify being equipped with CAES or any other energy storage utilities for Genco.

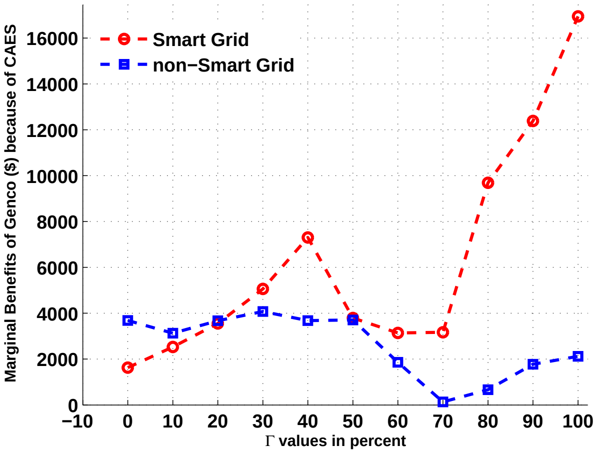

Fig. 3. The marginal benefits of Genco due to use of CAES ($) versus the budgets of uncertainty Γ

Since the efficiency of energy conversion in CAES whether it is working in storage or generation mode is not ideal then there are always energy loss in this process. The power schedule of Genco's unit with $\Gamma = 10\%$ in SG and NSG without CAES are given in Table X.

TABLE IV

THE POWER SCHEDULE OF GENCO WITH $\Gamma = 10\%$ IN SMART GRID (SG) AND NON-SMART GRID (NSG) WITHOUT CAES

Time	SG						NSG					
	$P_{1,t}$	$P_{2,t}$	$P_{3,t}$	$P_{4,t}$	$P_{5,t}$	$P_{6,t}$	$P_{1,t}$	$P_{2,t}$	$P_{3,t}$	$P_{4,t}$	$P_{5,t}$	$P_{6,t}$
t_1	30.0	30.0	500.0	300.0	100.0	300.0	30.0	30.0	500.0	300.0	100.0	300.0
t_2	21.0	21.0	325.0	140.0	25.0	140.0	30.0	21.0	395.0	220.0	55.0	220.0
t_3	5.0	5.0	150.0	100.0	25.0	100.0	6.0	5.0	150.0	100.0	25.0	100.0
t_4			150.0	100.0	25.0	100.0			150.0	100.0	25.0	100.0
t_5	5.0	5.0	150.0	100.0	25.0	100.0	5.0	5.0	150.0	100.0	25.0	100.0
t_6			150.0	100.0	25.0	100.0			150.0	100.0	25.0	100.0
t_7	24.0	24.0	500.0	300.0	100.0	300.0	24.0	5.0	290.0	100.0	25.0	100.0
t_8	30.0	30.0	500.0	300.0	100.0	300.0	30.0	30.0	500.0	300.0	100.0	300.0
t_9	30.0	30.0	500.0	300.0	100.0	300.0	30.0	30.0	465.0	290.0	100.0	290.0
t_{10}	30.0	30.0	500.0	300.0	100.0	300.0	30.0	30.0	500.0	300.0	100.0	300.0
t_{11}	30.0	30.0	500.0	300.0	100.0	300.0	30.0	30.0	447.5	280.0	100.0	279.3
t_{12}	30.0	30.0	500.0	300.0	100.0	300.0	30.0	30.0	438.8	260.0	88.8	260.0
t_{13}	30.0	30.0	500.0	300.0	100.0	300.0	30.0	30.0	465.4	290.4	100.0	300.0
t_{14}	30.0	30.0	500.0	300.0	100.0	300.0	30.0	30.0	447.5	270.0	98.3	270.0
t_{15}	11.0	11.0	307.5	140.0	25.0	140.0	30.0	30.0	500.0	300.0	100.0	300.0
t_{16}	30.0	30.0	360.0	190.0	70.0	190.0	30.0	30.0	432.7	260.0	88.8	260.0
t_{17}	30.0	30.0	377.5	210.0	100.0	210.0	30.0	30.0	447.5	263.0	96.3	260.7
t_{18}	30.0	30.0	500.0	300.0	100.0	300.0	30.0	30.0	447.5	270.0	99.5	270.0
t_{19}	30.0	30.0	396.4	260.0	100.0	260.0	30.0	30.0	465.0	285.9	100.0	280.0
t_{20}	30.0	30.0	447.5	290.0	100.0	290.0	30.0	30.0	450.6	280.0	100.0	280.0
t_{21}	30.0	30.0	482.5	300.0	100.0	300.0	30.0	30.0	465.0	280.7	100.0	280.0
t_{22}	30.0	30.0	430.0	270.0	100.0	270.0	30.0	30.0	412.5	240.0	70.0	240.0
t_{23}	30.0	30.0	461.1	300.0	100.0	300.0	6.0	30.0	447.5	270.0	98.4	270.0
t_{24}	30.0	30.0	412.5	260.0	100.0	260.0	25.0	30.0	482.5	300.0	100.0	300.0

TABLE VI

THE TOTAL GENERATED POWER OF GENCO (MW) WITH DIFFERENT BUDGETS OF UNCERTAINTY IN SMART GRID (SG) AND NON-SMART GRID (NSG) WITHOUT CAES

	NSG											—SG										
$\Gamma(\%)$	0	10	20	30	40	50	60	70	80	90	100	0	10	20	30	40	50	60	70	80	90	100
t_1	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0
t_2	797.3	944.7	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1187.5	1242.5	1260.0	559.5	672.0	1033.8	1242.5	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0
t_3	386.0	386.0	473.5	662.0	895.8	1225.0	1260.0	1260.0	1172.2	908.7	587.0	385.0	385.0	456.0	567.0	784.5	1110.0	1260.0	1260.0	1260.0	1260.0	1260.0
t_4	375.0	375.0	375.0	392.5	462.5	712.5	1023.8	1215.4	1225.5	950.0	392.5	375.0	375.0	375.0	392.6	462.5	623.5	898.8	1150.0	1242.5	1260.0	1260.0
t_5	385.0	385.0	385.0	385.0	385.0	470.0	597.5	773.5	913.7	843.7	385.0	385.0	385.0	385.0	385.0	420.0	462.5	692.5	902.8	1105.0	1242.5	1260.0
t_6	375.0	375.0	375.0	375.0	427.5	597.5	895.0	1130.0	993.5	770.1	375.0	375.0	375.0	427.5	480.0	612.5	859.3	1092.5	1225.0	1260.0	1260.0	1260.0
t_7	474.0	558.7	850.2	1193.0	1248.0	1260.0	1260.0	1106.9	917.3	711.1	729.3	1248.0	1248.0	1248.0	1248.0	1248.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0
t_8	1205.0	1260.0	1252.2	1212.6	1185.6	1130.6	1076.6	935.4	1035.0	1130.0	1225.0	1242.5	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0
t_9	1072.5	1205.0	1260.0	1239.2	1211.6	1155.4	1100.2	955.9	940.0	1035.0	1130.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0
t_{10}	1187.5	1260.0	1208.2	1170.0	1144.0	1091.0	1038.8	902.6	940.0	1035.0	1130.0	1257.5	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0
t_{11}	1260.0	1156.1	1062.9	1029.3	1006.4	959.8	975.0	1187.5	1229.2	1260.0	1260.0	1242.5	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0
t_{12}	1260.0	1097.4	1008.9	977.0	955.3	911.0	867.4	875.0	997.5	1092.5	1187.5	1205.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0
t_{13}	1260.0	1204.6	1107.5	1072.5	1048.6	1000.0	952.2	975.0	1072.5	1187.5	1242.5	1242.5	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0
t_{14}	1260.0	1135.3	1043.8	1010.8	988.3	942.5	897.4	1031.3	1130.0	1216.4	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0
t_{15}	1257.5	1260.0	1260.0	1260.0	1236.0	1178.7	1122.3	1130.0	1203.0	1242.5	1260.0	597.0	634.5	801.3	1055.0	1190.0	1225.0	1260.0	1260.0	1260.0	1260.0	1260.0
t_{16}	1260.0	1091.4	1003.4	971.7	950.1	906.0	862.7	1027.5	1130.0	1207.5	1242.5	852.5	870.0	1020.0	1163.8	1211.7	1242.5	1260.0	1260.0	1260.0	1260.0	1260.0
t_{17}	1260.0	1117.1	1027.1	994.6	972.5	927.4	883.0	1030.9	1130.0	1207.5	1260.0	920.0	957.5	1023.8	1132.5	1207.5	1225.0	1242.5	1260.0	1247.5	1260.0	1260.0
t_{18}	1260.0	1136.5	1044.9	1011.9	989.4	943.5	898.4	955.0	1072.5	1150.0	1240.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1199.2	1214.8	1260.0	1260.0
t_{19}	1260.0	1227.0	1128.1	1092.4	1068.1	1018.6	969.9	842.7	957.5	1055.0	1150.0	1035.0	1076.4	1092.5	1132.5	1172.5	1172.5	875.0	989.6	1205.2	1142.5	1125.0
t_{20}	1260.0	1183.4	1088.1	1053.6	1030.2	982.4	935.5	812.8	764.5	929.5	1072.5	1207.5	1187.5	1207.5	1190.0	1172.5	794.7	704.2	710.4	387.0	387.0	387.0
t_{21}	1110.0	1186.6	1091.0	1056.5	1033.0	985.1	938.0	815.0	675.4	637.5	817.5	1260.0	1242.5	1222.5	1190.0	836.0	749.1	690.2	375.0	150.0		
t_{22}	882.5	1026.3	1167.0	1130.1	1104.9	1053.7	1003.3	871.8	722.4	560.0	737.5	1242.5	1130.0	1017.5	768.4	674.6	547.1	250.1				
t_{23}	979.8	1123.5	1229.5	1190.6	1164.1	1110.2	1057.1	918.5	761.1	722.5	925.8	1260.0	1221.1	969.8	504.6	439.7	279.9	100.0				
t_{24}	1105.0	1237.5	1230.6	1191.6	1165.1	1111.1	1058.0	919.3	761.8	837.5	1062.5	1260.0	1092.5	572.0	400.0	160.0	40.0					

C. *Computational performance analysis*

The computational performance of the proposed algorithm is analyzed in this section. The CPU time usage (in seconds) for both SG and NSG paradigms are given in Table XI. In NSG case, since the decision making procedure is performed off-line then the computational burden is not of great concern. The maximum time in this framework is 45.887 seconds in $\Gamma = 50\%$. On the other hand, in SG case the maximum CPU time is 37.811 seconds in $\Gamma = 60\%$ in time t_1. In this paradigm (SG), usually the computation time is maximum in t_1 because the number of decision variables are maximum in this case.

V. CONCLUSION

A short term self-scheduling method based on robust optimization technique is proposed as a powerful decision making tool for Genco. The proposed model considers the impacts of price uncertainties, smart grid facility and compressed air energy storage units on Genco's benefits. The proposed method is applied to a system to demonstrate its effectiveness. Future work may be extended with modeling the renewable energies and other uncertain parameters affecting the Genco's benefits.

TABLE XI

THE COMPUTATIONAL BURDEN IN CPU TIME (S) FOR DIFFERENT BUDGETS OF UNCERTAINTY IN SMART GRID (SG) AND NON-SMART GRID (NSG) WITH CAES

		Γ values in (%)										
Paradigm	Time	0	10	20	30	40	50	60	70	80	90	100
NSG	$t_1 \rightarrow t_{24}$	1.473	2.411	2.890	7.022	14.888	45.887	15.178	12.848	6.336	4.940	3.714
SG	t_1	1.493	2.452	3.143	6.159	12.977	20.492	37.811	25.642	8.613	4.794	4.954
	t_2	0.444	0.832	1.553	2.052	1.849	2.767	1.849	2.084	2.190	1.777	1.400
	t_3	0.499	0.723	1.385	1.640	1.568	2.223	1.660	1.974	1.611	1.422	1.426
	t_4	0.433	1.007	1.171	1.339	1.558	1.891	1.893	1.817	1.612	1.948	1.088
	t_5	0.532	0.979	1.129	1.450	1.358	1.490	1.756	1.485	1.761	1.786	1.147
	t_6	0.569	0.583	0.525	0.580	0.539	1.408	1.650	1.592	1.685	1.662	1.402
	t_7	0.180	0.164	0.280	0.469	0.601	1.102	1.968	1.372	1.323	1.190	1.488
	t_8	0.190	0.293	0.203	0.525	0.394	1.221	1.488	1.407	1.179	1.133	1.504
	t_9	0.202	0.293	0.293	0.438	0.582	1.107	1.251	1.057	1.205	1.016	1.287
	t_{10}	0.178	0.273	0.218	0.556	0.550	1.034	1.071	0.970	0.934	1.033	1.028
	t_{11}	0.182	0.315	0.214	0.389	0.495	0.759	0.792	0.817	1.066	0.832	0.709
	t_{12}	0.198	0.324	0.203	0.380	0.507	0.599	0.851	0.814	0.710	0.675	0.805
	t_{13}	0.203	0.217	0.220	0.259	0.395	0.583	0.556	0.618	0.619	0.589	0.584
	t_{14}	0.176	0.216	0.093	0.212	0.373	0.493	0.558	0.492	0.472	0.410	0.538
	t_{15}	0.184	0.090	0.191	0.201	0.201	0.356	0.398	0.322	0.333	0.353	0.400
	t_{16}	0.182	0.083	0.072	0.204	0.188	0.324	0.297	0.199	0.287	0.222	0.306
	t_{17}	0.157	0.067	0.205	0.175	0.117	0.208	0.181	0.092	0.187	0.203	0.218
	t_{18}	0.081	0.059	0.082	0.070	0.074	0.193	0.209	0.156	0.104	0.101	0.202
	t_{19}	0.075	0.100	0.059	0.056	0.071	0.077	0.080	0.080	0.103	0.077	0.079
	t_{20}	0.074	0.063	0.062	0.061	0.064	0.084	0.074	0.072	0.065	0.077	0.071
	t_{21}	0.069	0.066	0.082	0.066	0.057	0.076	0.085	0.081	0.085	0.066	0.061
	t_{22}	0.067	0.078	0.061	0.083	0.082	0.080	0.078	0.042	0.068	0.065	0.061
	t_{23}	0.062	0.080	0.081	0.083	0.085	0.069	0.063	0.065	0.082	0.083	0.060
	t_{24}	0.062	0.046	0.050	0.043	0.042	0.084	0.058	0.061	0.076	0.067	0.081

REFERENCES

[1] B. Mohammadi-Ivatloo, H. Zareipour, M. Ehsan, and N. Amjady, "Economic impact of price forecasting inaccuracies on self-scheduling of generation

TABLE VIII

THE OPERATING SCHEDULE WITH DIFFERENT BUDGETS OF UNCERTAINTY IN SMART GRID (SG)

Γ(%)	Parameter	t_1	t_2	t_3	t_4	t_5	t_6	t_7	t_8	t_9	t_{10}	t_{11}	t_{12}	t_{13}	t_{14}	t_{15}	t_{16}	t_{17}	t_{18}	t_{19}	t_{20}	t_{21}	t_{22}	t_{23}	t_{24}
0	E_t^c	5.0	5.0	5.0	147.5	290.0	395.0	395.0	395.0	395.0	395.0	395.0	395.0	395.0	200.0	200.0	200.0	200.0	139.7	139.7	72.4	38.7	21.8	13.4	9.2
	$V_{s,t}^c$				150.0	150.0	110.5																		
	$V_{r,t}^c$														185.3				57.3		64.0	32.0	16.0	8.0	4.0
	$P_{I,t}$	1260.0	559.5	385.0	375.0	385.0	375.0	1248.0	1242.5	1260.0	1257.5	1242.5	1205.0	1242.5	1260.0	597.0	852.5	920.0	1260.0	1035.0	1207.5	1260.0	1242.5	1260.0	1260.0
	PT_t	1260.0	559.5	385.0	225.0	235.0	264.5	1248.0	1242.5	1260.0	1257.5	1242.5	1205.0	1242.5	1445.3	597.0	852.5	920.0	1317.3	1035.0	1271.5	1292.0	1258.5	1268.0	1264.0
10	E_t^c	5.0	5.0	5.0	72.5	215.0	215.0	110.0	57.5	31.3	18.1	11.6	9.2	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1
	$V_{s,t}^c$				71.1	150.0																			
	$V_{r,t}^c$							99.8	49.9	24.9	12.5	6.2	2.2	2.0											
	$P_{I,t}$	1260.0	672.0	385.0	375.0	385.0	375.0	1248.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	634.5	870.0	957.5	1260.0	1076.4	1187.5	1242.5	1130.0	1221.1	1092.5
	PT_t	1260.0	672.0	385.0	303.9	235.0	375.0	1347.8	1309.9	1284.9	1272.5	1266.2	1262.2	1262.0	1260.0	634.5	870.0	957.5	1260.0	1076.4	1187.5	1242.5	1130.0	1221.1	1092.5
20	E_t^c	5.0	5.0	5.0	5.0	147.5	147.5	76.3	40.6	22.8	13.9	11.3	9.2	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1	7.1
	$V_{s,t}^c$					150.0																			
	$V_{r,t}^c$							67.7	33.8	16.9	8.5	2.5	2.0	2.0											
	$P_{I,t}$	1260.0	967.0	455.0	375.0	385.0	427.5	1248.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	804.2	1023.8	1023.8	1260.0	1092.5	1207.5	1225.0	1017.5	997.5	602.8
	PT_t	1260.0	967.0	455.0	375.0	235.0	427.5	1315.7	1293.8	1276.9	1268.5	1262.5	1262.0	1262.0	1260.0	804.2	1023.8	1023.8	1260.0	1092.5	1207.5	1225.0	1017.5	997.5	602.8
30	E_t^c	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
	$P_{I,t}$	1260.0	1225.0	567.0	392.5	385.0	480.0	1248.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1055.0	1164.0	1147.5	1260.0	1132.5	1190.0	1190.0	770.9	504.6	400.0
	PT_t	1260.0	1225.0	567.0	392.5	385.0	480.0	1248.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1055.0	1164.0	1147.5	1260.0	1132.5	1190.0	1190.0	770.9	504.6	400.0
40	E_t^c	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
	$P_{I,t}$	1260.0	1260.0	784.5	462.5	420.0	612.5	1248.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1190.0	1211.7	1207.5	1260.0	1172.5	1172.5	836.0	674.6	439.7	160.0
	PT_t	1260.0	1260.0	784.5	462.5	420.0	612.5	1248.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1190.0	1211.7	1207.5	1260.0	1172.5	1172.5	836.0	674.6	439.7	160.0
50	E_t^c	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
	$P_{I,t}$	1260.0	1260.0	1110.0	623.5	462.5	859.3	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1225.0	1242.5	1225.0	1260.0	1172.5	794.7	749.1	547.1	279.9	40.0
	PT_t	1260.0	1260.0	1110.0	623.5	462.5	859.3	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1225.0	1242.5	1225.0	1260.0	1172.5	794.7	749.1	547.1	279.9	40.0
60	E_t^c	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
	$P_{I,t}$	1260.0	1260.0	1260.0	898.8	692.5	1092.5	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1242.5	1260.0	875.0	704.2	690.2	250.1	100.0	
	PT_t	1260.0	1260.0	1260.0	898.8	692.5	1092.5	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1242.5	1260.0	875.0	704.2	690.2	250.1	100.0	
70	E_t^c	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
	$P_{I,t}$	1260.0	1260.0	1260.0	1150.0	902.8	1225.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1199.2	989.6	710.4	375.0			
	PT_t	1260.0	1260.0	1260.0	1150.0	902.8	1225.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1199.2	989.6	710.4	375.0			
80	E_t^c	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
	$P_{I,t}$	1260.0	1260.0	1260.0	1242.5	1105.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1247.5	1214.8	1205.2	387.0	150.0			
	PT_t	1260.0	1260.0	1260.0	1242.5	1105.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1247.5	1214.8	1205.2	387.0	150.0			
90	E_t^c	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
	$P_{I,t}$	1260.0	1260.0	1260.0	1260.0	1242.5	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1142.5	387.0				
	PT_t	1260.0	1260.0	1260.0	1260.0	1242.5	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1142.5	387.0				
100	E_t^c	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
	$P_{I,t}$	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1125.0	387.0				
	PT_t	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1260.0	1125.0	387.0				

TABLE IX

THE OPERATING SCHEDULE WITH DIFFERENT BUDGETS OF UNCERTAINTY IN NON-SMART GRID (NSG)

Γ(%)	Parameter	t_1	t_2	t_3	t_4	t_5	t_6	t_7	t_8	t_9	t_{10}	t_{11}	t_{12}	t_{13}	t_{14}	t_{15}	t_{16}	t_{17}	t_{18}	t_{19}	t_{20}	t_{21}	t_{22}	t_{23}	t_{24}
0	$P_{I,t}$	1260.0	797.3	386.0	375.0	385.0	375.0	474.0	1205.0	1072.5	1187.5	1260.0	1260.0	1260.0	1260.0	1257.5	1260.0	1260.0	1260.0	1260.0	1260.0	1110.0	882.5	979.8	1105.0
	$V_{r,t}^c$											185.3			57.3		64.0	32.0	16.0	8.0	4.0	2.0			
	$V_{s,t}^c$				150.0	150.0	110.5																		
	E_t^c	5.0	5.0	5.0	147.5	290.0	395.0	395.0	395.0	395.0	395.0	200.0	200.0	200.0	139.7	139.7	72.4	38.7	21.8	13.4	9.2	7.1	7.1	7.1	7.1
	PT_t	1260.0	797.3	386.0	225.0	235.0	264.5	474.0	1205.0	1072.5	1187.5	1445.3	1260.0	1260.0	1317.3	1257.5	1324.0	1292.0	1276.0	1268.0	1264.0	1112.0	882.5	979.8	1105.0
10	$P_{I,t}$	1260.0	941.0	386.0	375.0	385.0	375.0	544.0	1260.0	1205.0	1260.0	1166.8	1107.5	1215.7	1145.8	1260.0	1101.5	1127.4	1147.0	1190.9	1170.6	1185.7	1022.5	1121.9	1237.5
	$V_{r,t}^c$								114.5		66.3					94.8				47.4	23.7	11.9	3.9	4.0	2.0
	$V_{s,t}^c$				150.0	150.0	110.5																		
	E_t^c	5.0	5.0	5.0	147.5	290.0	395.0	395.0	274.5	274.5	204.7	204.7	204.7	204.7	204.7	104.8	104.8	104.8	104.8	54.9	30.0	17.5	13.4	9.2	7.1
	PT_t	1260.0	941.0	386.0	225.0	235.0	264.5	544.0	1374.5	1205.0	1326.3	1166.8	1107.5	1215.7	1145.8	1354.8	1101.5	1127.4	1147.0	1238.3	1194.4	1197.6	1026.4	1125.9	1239.5
20	$P_{I,t}$	1260.0	1242.5	456.0	375.0	385.0	375.0	801.5	1242.5	1242.5	1221.7	1074.8	1020.2	1119.9	1055.4	1260.0	1014.6	1038.5	1056.6	1110.7	1088.2	1101.1	1172.0	1236.0	1242.3
	$V_{r,t}^c$								23.6	51.4						59.9				30.0	12.0	2.0	8.0	4.0	2.0
	$V_{s,t}^c$					150.0	65.9																		
	E_t^c	5.0	5.0	5.0	5.0	147.5	210.1	210.1	185.2	131.1	131.1	131.1	131.1	131.1	131.1	68.1	68.1	68.1	68.1	36.5	23.9	21.8	13.4	9.2	7.1
	PT_t	1260.0	1242.5	456.0	375.0	235.0	309.1	801.5	1266.1	1293.9	1221.7	1074.8	1020.2	1119.9	1055.4	1319.9	1014.6	1038.5	1056.6	1140.7	1100.2	1103.1	1180.0	1240.0	1244.3
30	$P_{I,t}$	1260.0	1260.0	662.0	392.5	385.0	375.0	1193.0	1212.6	1239.2	1170.0	1029.3	977.0	1072.5	1010.8	1260.0	971.7	994.6	1011.9	1092.4	1053.6	1056.5	1130.1	1190.6	1191.6
	E_t^c	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
	PT_t	1260.0	1260.0	662.0	392.5	385.0	375.0	1193.0	1212.6	1239.2	1170.0	1029.3	977.0	1072.5	1010.8	1260.0	971.7	994.6	1011.9	1092.4	1053.6	1056.5	1130.1	1190.6	1191.6
40	$P_{I,t}$	1260.0	1260.0	895.8	462.5	385.0	427.5	1248.0	1185.6	1211.6	1144.0	1006.4	955.3	1048.6	988.3	1236.0	950.1	972.5	989.4	1068.1	1030.2	1033.0	1104.9	1164.1	1165.1
	E_t^c	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
	PT_t	1260.0	1260.0	895.8	462.5	385.0	427.5	1248.0	1185.6	1211.6	1144.0	1006.4	955.3	1048.6	988.3	1236.0	950.1	972.5	989.4	1068.1	1030.2	1033.0	1104.9	1164.1	1165.1
50	$P_{I,t}$	1260.0	1260.0	1225.0	712.5	470.0	597.5	1260.0	1130.6	1155.4	1091.0	959.8	911.0	1000.0	942.5	1178.7	906.0	927.4	943.5	1018.6	982.4	985.1	1053.7	1110.2	1111.1
	E_t^c	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
	PT_t	1260.0	1260.0	1225.0	712.5	470.0	597.5	1260.0	1130.6	1155.4	1091.0	959.8	911.0	1000.0	942.5	1178.7	906.0	927.4	943.5	1018.6	982.4	985.1	1053.7	1110.2	1111.1
60	$P_{I,t}$	1260.0	1260.0	1260.0	1023.8	597.5	895.0	1260.0	1076.6	1100.2	1038.8	975.0	867.4	952.2	897.4	1122.3	862.7	883.0	898.4	969.9	935.5	938.0	1003.3	1057.1	1058.0
	E_t^c	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
	PT_t	1260.0	1260.0	1260.0	1023.8	597.5	895.0	1260.0	1076.6	1100.2	1038.8	975.0	867.4	952.2	897.4	1122.3	862.7	883.0	898.4	969.9	935.5	938.0	1003.3	1057.1	1058.0
70	$P_{I,t}$	1260.0	1260.0	1260.0	1215.4	773.5	1130.0	1106.9	935.4	955.9	902.6	1187.5	875.0	975.0	1031.3	1130.0	1027.5	1030.9	955.0	842.7	812.8	815.0	871.8	918.5	919.3
	E_t^c	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
	PT_t	1260.0	1260.0	1260.0	1215.4	773.5	1130.0	1106.9	935.4	955.9	902.6	1187.5	875.0	975.0	1031.3	1130.0	1027.5	1030.9	955.0	842.7	812.8	815.0	871.8	918.5	919.3
80	$P_{I,t}$	1260.0	1187.5	1172.2	1225.5	913.8	993.5	917.3	1035.0	940.0	940.0	1229.2	997.5	1072.5	1130.0	1203.0	1130.0	1130.0	1072.5	957.5	764.5	675.4	722.4	761.1	761.8
	E_t^c	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
	PT_t	1260.0	1187.5	1172.2	1225.5	913.8	993.5	917.3	1035.0	940.0	940.0	1229.2	997.5	1072.5	1130.0	1203.0	1130.0	1130.0	1072.5	957.5	764.5	675.4	722.4	761.1	761.8
90	$P_{I,t}$	1260.0	1242.5	908.7	950.0	843.7	770.1	711.1	1130.0	1035.0	1035.0	1260.0	1092.5	1187.5	1216.4	1242.5	1207.5	1207.5	1150.0	1055.0	929.5	637.5	560.0	722.5	837.5
	E_t^c	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
	PT_t	1260.0	1242.5	908.7	950.0	843.7	770.1	711.1	1130.0	1035.0	1035.0	1260.0	1092.5	1187.5	1216.4	1242.5	1207.5	1207.5	1150.0	1055.0	929.5	637.5	560.0	722.5	837.5
100	$P_{I,t}$	1260.0	1260.0	587.0	392.5	385.0	375.0	729.3	1225.0	1130.0	1130.0	1260.0	1187.5	1242.5	1260.0	1260.0	1242.5	1260.0	1240.0	1150.0	1072.5	817.5	737.5	925.8	1062.5
	$V_{r,t}^c$											135.4				67.7	33.8	16.9	8.5	2.5	2.0				2.0
	$V_{s,t}^c$					150.0	150.0																		
	E_t^c	5.0	5.0	5.0	5.0	147.5	290.0	290.0	290.0	290.0	290.0	147.5	147.5	147.5	147.5	76.3	40.6	22.8	13.9	11.3	9.2	9.2	9.2	9.2	7.1
	PT_t	1260.0	1260.0	587.0	392.5	235.0	225.0	729.3	1225.0	1130.0	1130.0	1395.4	1187.5	1242.5	1260.0	1327.7	1276.3	1276.9	1248.5	1152.5	1074.5	817.5	737.5	925.8	1064.5

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TABLE X

THE POWER SCHEDULE OF GENCO WITH $\Gamma = 10\%$ IN SMART GRID (SG) AND NON-SMART GRID (NSG) WITH CAES

Time	SG						NSG					
	$P_{1,t}$	$P_{2,t}$	$P_{3,t}$	$P_{4,t}$	$P_{5,t}$	$P_{6,t}$	$P_{1,t}$	$P_{2,t}$	$P_{3,t}$	$P_{4,t}$	$P_{5,t}$	$P_{6,t}$
t_1	30.0	30.0	500.0	300.0	100.0	300.0	30.0	30.0	500.0	300.0	100.0	300.0
t_2	21.0	21.0	325.0	140.0	25.0	140.0	30.0	21.0	395.0	220.0	55.0	220.0
t_3	5.0	5.0	150.0	100.0	25.0	100.0	6.0	5.0	150.0	100.0	25.0	100.0
t_4			150.0	100.0	25.0	100.0			150.0	100.0	25.0	100.0
t_5	5.0	5.0	150.0	100.0	25.0	100.0	5.0	5.0	150.0	100.0	25.0	100.0
t_6			150.0	100.0	25.0	100.0			150.0	100.0	25.0	100.0
t_7	24.0	24.0	500.0	300.0	100.0	300.0	24.0	5.0	290.0	100.0	25.0	100.0
t_8	30.0	30.0	500.0	300.0	100.0	300.0	30.0	30.0	500.0	300.0	100.0	300.0
t_9	30.0	30.0	500.0	300.0	100.0	300.0	30.0	30.0	465.0	290.0	100.0	290.0
t_{10}	30.0	30.0	500.0	300.0	100.0	300.0	30.0	30.0	500.0	300.0	100.0	300.0
t_{11}	30.0	30.0	500.0	300.0	100.0	300.0	30.0	30.0	447.5	280.0	100.0	279.3
t_{12}	30.0	30.0	500.0	300.0	100.0	300.0	30.0	30.0	438.8	260.0	88.8	260.0
t_{13}	30.0	30.0	500.0	300.0	100.0	300.0	30.0	30.0	465.4	290.4	100.0	300.0
t_{14}	30.0	30.0	500.0	300.0	100.0	300.0	30.0	30.0	447.5	270.0	98.3	270.0
t_{15}	11.0	11.0	307.5	140.0	25.0	140.0	30.0	30.0	500.0	300.0	100.0	300.0
t_{16}	30.0	30.0	360.0	190.0	70.0	190.0	30.0	30.0	432.7	260.0	88.8	260.0
t_{17}	30.0	30.0	377.5	210.0	100.0	210.0	30.0	30.0	447.5	263.0	96.3	260.7
t_{18}	30.0	30.0	500.0	300.0	100.0	300.0	30.0	30.0	447.5	270.0	99.5	270.0
t_{19}	30.0	30.0	396.4	260.0	100.0	260.0	30.0	30.0	465.0	285.9	100.0	280.0
t_{20}	30.0	30.0	447.5	290.0	100.0	290.0	30.0	30.0	450.6	280.0	100.0	280.0
t_{21}	30.0	30.0	482.5	300.0	100.0	300.0	30.0	30.0	465.0	280.7	100.0	280.0
t_{22}	30.0	30.0	430.0	270.0	100.0	270.0	30.0	30.0	412.5	240.0	70.0	240.0
t_{23}	30.0	30.0	461.1	300.0	100.0	300.0	6.0	30.0	447.5	270.0	98.4	270.0
t_{24}	30.0	30.0	412.5	260.0	100.0	260.0	25.0	30.0	482.5	300.0	100.0	300.0

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