Impact of Renewable Energy Availability on Load Serving Entity's Sale Price and Procurement Decisions

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Abstract-**Intermittent and uncertain generation characteristics of renewable energy sources (RES) impacts decision-making problem of load serving entity (LSE). LSE makes procurement and dynamic sale price decisions well in advance to maximize its profit. It procures energy from available RES generation along with wholesale electricity market (WEM) and bilateral contracts. WEM market price uncertainty introduces volatility in procurement cost that makes LSE's profit risky. Therefore, LSE determines a trade-off between profit and risk. In this perspective, this paper put forwards an exposition of energy procurement strategy and dynamic sale price setting for RES penetration, with consideration of WEM price uncertainty. LSE's risk aversion is modeled by mean-variance technique, to obtain the trade-off between profit and risk. Case study is conducted to highlight impact of RES availability on LSE's sale price and procurement decisions. Simulation results show that during RES generation availability, LSE offers lower sale prices and would result in consumer demand shift within these hours. This strategy would enhance RES utilization.**

***Index Terms*— Dynamic sale prices, Profit, LSE, Risk, Mean-variance.**

NOMENCLATURE

A. Index and Sets

g, G	Index and set for thermal-generating units.
i, I	Index and set for bilateral contracts.
t, T	Index and set for time.

B. Constants and Parameters

a, b, c	Cost coefficients of thermal-generating units.
C_g^{sd}	Shut down cost of g^{th} thermal-generating unit [\$].
C_g^{su}	Start-up cost of g^{th} thermal-generating unit [\$].
D_t	Consumer forecasted demand at hour t [MWh].
$P_{i,t}^{min}$, $P_{i,t}^{max}$	Minimum and maximum procurement limit of i^{th} bilateral contract at hour t [MW].
P_g^{min}, P_g^{max}	Minimum and maximum capacity of g^{th} thermal-generating unit [MW].
R_g^u, R_g^d	Ramp up and ramp down limits of g^{th} thermal-generating unit [MW/h].
T_g^U, T_g^D	Up and down time of g^{th} thermal-generating unit [h].
β	Factor denoting risk-averse behavior of LSE.
ε_t	Price elasticity of consumer demand at hour t.
$\lambda_{i,t}^B$	Price of i^{th} bilateral contract at hour t [\$/MWh].
λ_t^{nsale}	Nominal sale price at hour t [\$/MWh].
λ_t^{WEM}	WEM market prices at hour t [\$/MWh].

C. Functions

$C_{g,t}$	Electricity generation cost from g^{th} thermal-generating unit at hour t.
C_t^G	Total electricity generation cost from all thermal generating units at hour t.
C_t^B	Bilateral contracts cost at hour t.
C_t^{WEM}	WEM procurement cost at hour t.

D. Decision Variables

$c_{g,t}^{sd}$	g^{th} thermal-generating unit shut down cost at hour t [\$].
$c_{g,t}^{su}$	g^{th} thermal-generating unit start up cost at hour t [\$].
D_t^{act}	Price responsive demand at hour t [MWh].
$P_{i,t}^B$	Power procurement from i^{th} bilateral contract at hour t [MW].
$P_{g,t}$	Energy procurement from g^{th} thermal-generating unit at hour t [MWh].
P_t^{WEM}	Power procurement from WEM at hour t [MW].
$X_{g,t-1}^{ON}$, $X_{g,t-1}^{OFF}$	Represents g^{th} thermal-generating unit ON/OFF (0/1) state at hour $t-1$.
λ_t^{sale}	Offered sale prices at hour t [\$/MWh].

E. Binary Variables

$w_{g,t}$	Binary variable indicates ON or OFF (0 or 1) status of g^{th} thermal-generating unit at hour

t .

$\delta_{i,t}$ Variable (0,1), 1 represents that i^{th} bilateral contract at hour t is exercised.

I. Introduction

LOAD serving entity (LSE) mainly procures electricity from wholesale electricity market (WEM) and sells to consumers. It determines procurement and sale price decisions aiming to maximize its profit. However, these decisions are influenced by wholesale price uncertainty and consumer price responsive behavior [1]-[2]. In addition to this, renewable energy (RE) integration in LSE's procurement would considerably influence sale prices and procurement decisions due to its non-dispatchability and availability characteristics.

LSE sells electricity to consumers at fixed or dynamic sale prices. Dynamic sale prices reflect time-varying cost of supply and have numerous advantages over fixed pricing [3]. Such sale prices provide an opportunity to consumers to minimizes energy bill, by modifying their demand profile in response to offered sale prices [3]-[4]. This modified demand profile can maximize LSE's profit if procurement decisions are revised accordingly. Therefore, dynamics sale prices such as time-of-use (ToU) and real-time-price (RTP) determination is getting attraction from research community. As consumers are price responsive, they may decide electricity demand based on their willingness to purchase. This willingness to purchase is considered through 24 different price quota curves (PQC) in dynamic sale price determination problem [5]. Each quota of a PQC indicates quantity to be sold for a given price [6]. Consumer flexible demand is considered in sale price determination process to optimize dynamic sale prices further [7]. Investigation indicates some consumers are more sensitive to change in offered sale price. Price responsiveness to change in sale prices and corresponding change in demand can be represented by price elasticity of demand. This elasticity of demand is used to determine dynamics of dynamic sale prices [8]-[9]. Dynamic sale prices can be set with an aim to modify procurement decisions to reduce LSE's procurement cost and, eventually, this maximizes its profit [10]. This implies that dynamic sale prices and procurement decisions should be determined simultaneously.

LSE may procure electricity from multiple sources to minimize procurement cost [2]. Therefore, in addition to WEM, LSE procures a quantum of electricity through bilateral contracts and available self-generation facility. As WEM prices are varying and uncertain, poses risk to LSE. This risk may incur financial losses to LSE. Therefore, this risk needs to be minimized, while LSE makes optimal procurement decisions to maximize profit. WEM price risk is modeled using mean-variance, conditional value at risk or information gap decision theory based approaches [9], and [11]-[12]. Investigation indicates risk is minimized at the cost of reducing profit. Hence, LSE determines a trade-off between profit and risk.

LSE can use renewable energy (RE) based sources as one of the procurement options to increase its profit [13]. However, intermittency and uncertainty of RE need to be addressed while optimal decisions are determined for LSE. RE from multiple sources such as wind and solar are considered in LSE's sale price determination problem [13]. As focus of work is to model and compare fixed, time-of-use and real-time-prices, comprehensive investigation highlighting impact of renewable energy sources (RES) on sale prices and procurement strategy are neglected. In the presence of significant RE, dynamic sale prices are determined without considering impact of WEM prices [14]. Recent work has investigated LSE's decision-making with and without RE consideration [15]. However, major emphasis is given on energy availability from solar, whereas impact of energy availability from wind on sale prices and procurement decision is neglected. A comprehensive investigation on LSE's decision-making with wind and solar as individually and simultaneously is yet to be done.

In this paper, optimal dynamic sale prices and procurement decisions are determined to maximize LSE's profit considering RES availability. WEM, bilateral contracts, and self-generation are considered as procurement option. Both thermal and RE based generation such as solar and wind are considered as part of self-generation facilities. WEM price uncertainty is modeled using mean-variance approach. Solar and wind profile are considered in aggregated form, which avoids its uncertainty modeling. Price sensitive consumers are considered, and their price responsiveness to change in sale prices are considered by its price elasticity of demand. A case study is conducted to illustrate the impact of solar and wind availability on dynamic sale prices and procurement decisions. Simulations are carried out to investigate the effectiveness of the proposed model for different sub-cases. Impact of risk-averse nature of LSE on procurement strategy, dynamic prices, and eventually overall LSE's profit are highlighted.

II. Problem Description

This work considers LSE's profit maximization problem for medium-term planning. LSE tries to maximize its profit by increasing gap between revenue earned from selling electricity to consumers and procurement cost incurred from procurement through various options. Price sensitive consumers are considered. Therefore their demand is considered as elastic in response to offered sale prices. Considering consumer behavior, LSE makes simultaneous decisions for i) electricity to be procured (from WEM, bilateral contracts, and self-generation) ii) optimal dynamic sale prices to maximize LSE's profit.

In considered problem, RES such as solar and wind is considered as one of the major sources in addition to WEM, bilateral contract, and thermal-generation for procurement. As LSE makes decisions well ahead of real-time, WEM prices are unknown to LSE. Hence, LSE experiences WEM price volatility risk, which needs to be minimized, to maximize its profit. Therefore, LSE has multiple objectives. Profit maximization and WEM price risk minimization objectives are modeled by mean-variance approach, to determine tradeoff between profit and WEM price-risk. Electricity generation from solar and wind is considered in aggregated form. This consideration helps to avoid uncertainty modeling of solar and wind sources.

III. Problem Formulation

LSE's problem is formulated to maximize profit and minimize risk, as per mean-variance approach. Difference between generated revenue and procurement cost are considered to model LSE's profit.

A. Procurement Cost

LSE procurement cost is determined by summing electricity cost incurred from bilateral contracts, self-generating units, and WEM. At hour *t*, total procurement cost C_t^{tot} is

$$C_t^{tot} = C_t^B + C_t^{SG} + C_t^{WEM} \tag{1}$$

1) Bilateral Contracts

LSE procures a part of electricity directly from generating companies through bilateral contracts. These contracts are signed at a mutually determined price $\lambda_{i,t}^B$. B number of contracts is assumed to be available on time t. Electricity cost incurred at hour t from bilateral contracts is

$$C_t^B = \sum_{i \in I} P_{i,t}^B \lambda_{i,t}^B \tag{2}$$

Constraint (3) poses minimum and maximum limits on bilateral contracts procurement.

$$P_i^{min}.\delta_{i,t} \le P_{i,t}^B \le P_i^{max}.\delta_{i,t} \tag{3}$$

2) Self-Generation

LSE uses thermal generating units and RES based solar photovoltaic (PV) and wind as self-generation facility, as one of the procurement options. The total generation cost from self-generation is sum of the cost incurred from thermal generating units C_t^{TG} and RES C_t^{RE} .

$$C_t^{SG} = C_t^{TG} + C_t^{RE} \tag{4}$$

Generation cost $C_{g,t}$ to procure $P_{g,t}$ electricity from g^{th} thermal generating units at hour t is obtained by (5). This cost is subject to constraints (6) to (14).

$$C_{g,t} = c.w_{g,t} + b.P_{g,t} + a.(P_{g,t})^2 + c_{g,t}^{su} + c_{g,t}^{sd} \tag{5}$$

$$c_{g,t}^{su} \ge C_g^{su}(w_{g,t} - w_{g,t-1}) \qquad \forall g, \forall t \tag{6}$$

$$c_{g,t}^{sd} \ge C_g^{sd}(w_{g,t-1} - w_{g,t}) \qquad \forall g, \forall t \tag{7}$$

$$P_{g,t} - P_{g,t-1} \le R_g^u.w_{g,t} \qquad \forall g, \forall t \tag{8}$$

$$P_{g,t-1} - P_{g,t} \le R_g^d.w_{g,t-1} \qquad \forall g, \forall t \tag{9}$$

$$[X_{g,t-1}^{ON} - T_g^U].[w_{g,t} - w_{g,t-1}] \ge 0 \quad \forall g, \forall t \tag{10}$$

$$[X_{g,t-1}^{OFF} - T_g^D].[w_{g,t-1} - w_{g,t}] \ge 0 \quad \forall g, \forall t \tag{11}$$

$$P_g^{min}.w_{g,t} \le P_{g,t} \le P_g^{max}.w_{g,t} \qquad \forall g, \forall t \tag{12}$$

$$c_{g,t}^{su}, c_{g,t}^{sd}, P_{g,t} \ge 0 \qquad \forall g, \forall t \tag{13}$$

$$w_{g,t} \in [0,1] \qquad \forall g, \forall t \tag{14}$$

Start up and shut down cost of thermal-generating units are determined by (6) and (7). Constraints (8) and (9) decide limits of ramping up and ramping down. Minimum up time and minimum down time are considered by constraints (10) and (11), respectively. Constraint (12) decides minimum and maximum generation limits. (13) and (14) indicates non-negativity and variable declaration constraints, respectively. The total generation cost from thermal generating units are given by

$$C_t^{TG} = \sum_g C_{g,t} \tag{15}$$

LSE procures energy from PV and Wind. Total procurement cost from RE is determined by summing the cost incurred for procuring available generation from solar and wind, as shown in (16). λ_t^{PV} and λ_t^W are priced at which available energy from PV and wind are procured, respectively. As energy from RES is considered in aggregated form, it avoids its uncertainty modeling.

$$C_t^{RE} = P_t^{PV} \lambda_t^{PV} + P_t^W \lambda_t^W \tag{16}$$

3) Wholesale Electricity Market

LSE procures certain quantum of electricity from WEM. Future prices of WEM are uncertain. Therefore, forecasted or expected WEM prices are considered. Expected cost of energy procurement from WEM at t is

$$C_t^{WEM} = P_t^{WEM} \lambda_t^{WEM} \tag{17}$$

$$P_t^{WEM} \ge 0 \tag{18}$$

$$D_t^{act} = P_t^{WEM} + \sum_{i \in I} P_t^B + \sum_g P_{g,t} + P_t^{PV} + P_t^W \tag{19}$$

Here, selling of electricity in WEM is restricted by imposing constraint (18). Energy balance constraint (19) is required to ensure that electricity procured from considered sources is equal to consumer demand at each hour. D_t^{act} represents consumer's revised demand obtained in response to offered sale prices from (21).

B. Revenue

LSE sells energy to consumers at price λ_t^{sale} that generates revenue. Revenue generated at each hour t is

$$R_t = D_t^{act} \lambda_t^{sale} \tag{20}$$

Relationship between demand and sale price is considered using a linear function [8]. In (19), per unit change in demand, from its initial value D_t , is equal to a proportional change in sale price from its nominal value, based on price elasticity of demand. Here, price elasticity of demand ε_t indicates consumer's price responsiveness to change in sale prices. Change in demand to change in sale prices exhibit a negative relationship. Therefore, increase in sale prices decreases demand.

$$D_t^{act} = D_t(1 + \varepsilon_t \frac{\lambda_t^{sale} - \lambda_t^{nsale}}{\lambda_t^{nsale}}) \tag{21}$$

$$(1 - \lambda_t^{min})\lambda_t^{nsale} \le \lambda_t^{sale} \le (1 + \lambda_t^{max})\lambda_t^{nsale} \tag{22}$$

Nominal sale prices at each hour are considered equal to the flat rate of electricity. Flat rate can be determined by taking an average of WEM prices over 24 hours. Constraint (22) ensures that sale prices cannot go below and above a certain percentage of the nominal sale price so that LSE could achieve a reasonable profit. λ_t^{min} and λ_t^{max} in (22) are a value in percentage, decided by LSE. However, maximum sale prices cannot go beyond price caps imposed by the regulatory authority. Constraint (23) ensures that total demand before and after shifting remains the same.

$$\sum_t D_t^{act} = \sum_t D_t \tag{23}$$

C. Uncertainty Consideration and Modelling

Volatility of WEM prices makes procurement cost uncertain. This is considered as a risk to LSE and needs to be minimized during decision-making. Volatility of procurement cost is modeled through variance. Considering that procurement costs from bilateral contract and self-generation are fixed, their variances would be zero, and hence volatility of cost from WEM procurement is modeled as

$$var_t^{WEM} = (P_t^{WEM})^2.var(\lambda_t^{WEM}) \tag{24}$$

For this analysis, historical WEM prices have been used to calculate its expected values and variances. In the proposed model, WEM price forecast obtained from established forecasting models can also be used. This could improve the results; however, the present work contributes by improved decision-making model.

D. Objective Function

LSE's overall objective consists of expected profit maximization and minimization of risk associated with WEM procurement. LSE calculates tradeoff between profit and risk. These objectives are combined using risk weighing factor β. Value of β depends on risk-averse behavior of LSE. This can vary from 0 to a higher value. $\beta = 0$ indicates LSE's profit maximization concern, without considering any risk, i.e., risk-neutral behavior. Higher values of β indicates LSE's risk-averse behavior. The multi-objective function of LSE is given as

$$Max\ Obj = \sum_t Prof_t - \beta \sum_t var_t^{WEM} \tag{25}$$

In (25), LSE's expected profit Prof_t is obtained by determining difference between revenue generated (20) and procurement cost (1) as shown in (26). var_t^{WEM} signifies risk (24).

$$Prof_t = R_t - C_t^{tot} \tag{26}$$

Multi-objective function (25) is maximized subject to bilateral contract constraints, thermal-generating unit, WEM, energy balance, sale price, and demand constraint. Here, revised consumer demand, sale price, and quantum of electricity procurement from considered sources are variables to be determined.

IV. Case Study and Results

A case study is considered to illustrate the proposed model for an LSE. Six sub-cases are formed to analyzed impact of solar (PV) and wind availability on LSE's decision variables. The PV or wind procurement is considered in terms of percentage of total LSE's demand. These cases are as follows.

Case-1: This case considers PV in addition to WEM, bilateral contracts, and thermal-generation. Total procurement from PV is 15% of total LSE's demand.

Case-2: Case-1 is modified by changing procurement of PV. Procurement from PV is changed from 15 to 20% of total LSE's demand.

Case-3: This case considers wind in addition to WEM, bilateral contracts, and thermal-generation. Total procurement from wind is 15% of total LSE's demand.

Case-4: Case-3 is modified by changing procurement of wind. Procurement from wind is changed from 15 to 20% of total LSE's demand.

Case-5: This case considers both PV and wind in addition to WEM, bilateral contracts, and thermal-generation. Procurement from both PV and wind is 15% of total LSE's demand, i.e., 15% from PV and 15% from wind.

Case-6: Case-5 is modified by changing procurement from both PV and wind. Procurement is changed from 15 to 20% of total LSE's demand, i.e., 20% from PV and 20% from wind.

A. Data

In this work, historical WEM prices from PJM electricity market is considered [16]. The LSE decides dynamic sale prices and procurement for medium-term planning. Bilateral contracts are procured at 34$/MWh. Minimum and maximum limits of 30 MW and 350 MW are considered on bilateral contracts, respectively. One thermal-generating unit is considered. Its specifications are shown in Table I. Considered energy generation profile from PV and wind based self-generation for various cases is shown in Fig. 1. These profiles are obtained from [17]. Energy from PV and Wind are procured at 28$/MWh.

TABLE I
Thermal-Generating Unit Data

Quantity	Value
Power Rating	130 MW
Min. Output Power	20 MW
Ramping Limit Up	80 MW/h
Ramping Limit Down	80 MW/h
Cost of Quadratic Term	0.03$/(MW)^{2}h
Cost of Linear Term	28 $/MWh
No-Load Cost	400$/h
Start Up Cost	200$
Shut Down Cost	100 $
Min. Up and Down Time	1h

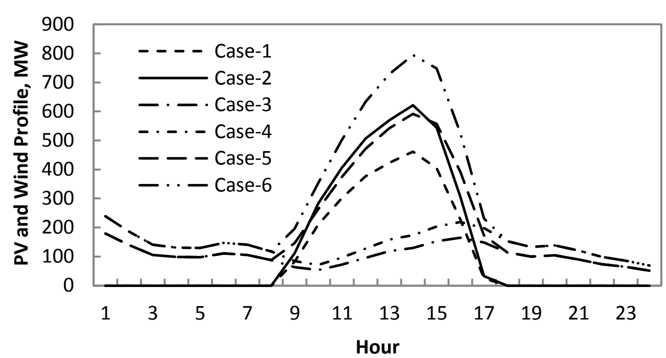


Fig. 1. Considered PV and Wind profile.

This work considers one type of consumer class. This class is obtained by clubbing consumers having similar characteristics. Consumer price responsiveness is considered through its price elasticity of demand. It is considered equal to -0.4 [18]. Considered demand profile is depicted in Fig. 2. Nominal price is considered equal to flat rate. Flat rate tariff is determined by taking an average of WEM prices. The value of flat rate is found equal to 35 $/MWh. To keep dynamic sale prices in a reasonable limit, a price range cap is assumed that LSE can vary sale prices up to 18% of the flat rate.

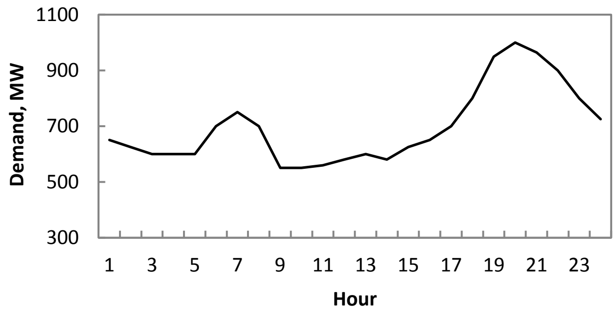


Fig. 2. Demand Profile.

B. Statistical Calculation

Expected values of WEM prices for each hour are calculated as mean of corresponding historical data, over the entire planning period. Historical WEM prices and an average of expected WEM price are used to determine standard deviation of WEM price. Calculated expected WEM prices, and its standard deviation is shown in Fig. 3.

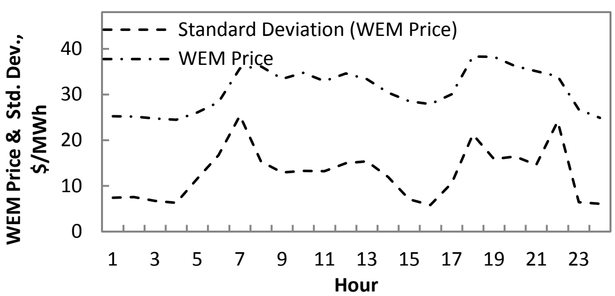


Fig. 3. WEM prices, and standard deviation of WEM Prices.

C. Simulations

Simulations are carried out to solve (25), subject to relevant constraints for different values of β. These simulations are repeated for six cases. The problem is MINLP in nature, and it has been solved using SBB and CONOPT3 solvers under GAMS® [19]. SBB solver provides MINLP solutions. This works with NLP sub-solver. It provides MIP solution to NLP sub-solver by utilizing standard Branch and Bound algorithm. Solutions obtained by SBB are utilized by CONOPT solver to solve NLP sub-problem. CONOPT uses generalized reduced gradient algorithm to solve the problem [20]. This simulation is performed on an Intel i5 system having a processor speed of 3.20 GHz and installed memory of 4GB.

D. Results

Results obtained for six cases are shown in Figs. 4 to 11. Dynamic sale prices, demand, and procurement from different options for six cases are analyzed and presented. Further, LSE's risk-neutral and risk-averse behavior for these cases are investigated.

1) Dynamic Sale Prices and Demand

Dynamic sale prices generally follow WEM price pattern (Figs. 4). Due to high sale prices, consumer tends to shift their demand from periods with high sale prices to periods with low sale prices, based on its price elasticity of demand (Fig. 5). This shift in demand is primarily governed by LSE's profit maximization.

Obtained dynamic sale prices for PV and wind indicates that electricity availability from PV and wind at each hour influences setting of dynamic sale prices. Due to a substantial difference in energy availability at each hour from PV and wind, dynamic sale prices vary (Fig. 4 and 6). It is worth to note that energy from PV is available for certain hour of day and energy from wind is available though-out day (Fig.1). For Case-1 and Case-3, revised consumer demand for offered dynamic sale prices are shown in Fig. 5a and 7a.

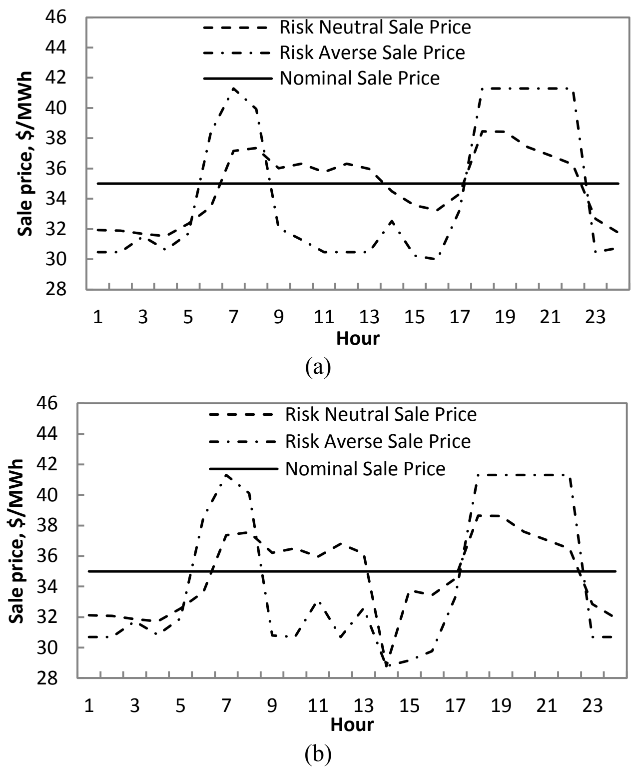
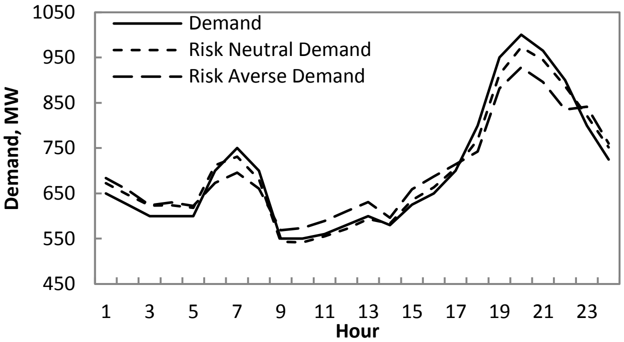


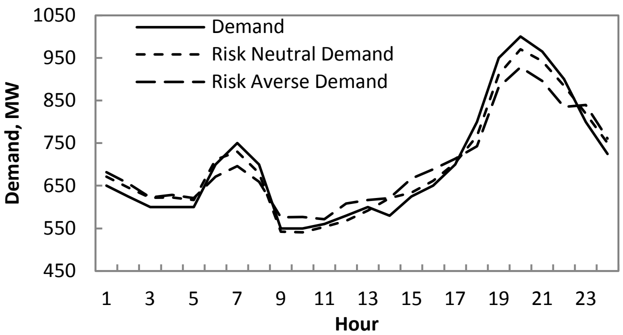
Fig. 4. Dynamic sale prices for (a). Case-1 and (b) Case-2.

As procurement from PV is increased (Case-2), sale price is lower at certain hours of PV availability to fully utilize electricity from PV (Fig. 4b). A low value of sale prices increases consumer demand to these hours. For e.g., at hour 14, sale price decreases and corresponding demand increases (Fig. 4b and 5b). Dynamic sale prices and revised consumer demand for Case-3 and Case-4 is shown in Figs. 6 and 7, respectively. For the same percentage of increase in procurement through wind energy, no significant change in sale prices are observed. This happens because procurement through wind energy is increased at each hour. In contrast to this, in the case of PV, energy is available to certain hours, and increase in procurement to these hours significantly lowering sale prices into these hours.

Dynamic sale price and revised consumer demand obtained for Case-5 and Case-6 are shown in Fig. 8 and 9, respectively. As in these cases, LSE procures from both PV and wind, difference in sale prices as compared to other cases can be observed. Sale prices are modified to utilize available PV and wind energy completely. For Case-6, analysis indicates that available energy through PV and wind cannot be completely utilized, though lowest possible sale prices are offered (Fig. 8b). This happens because energy availability in certain hours is comparatively higher than demand in those hours. Also, it is

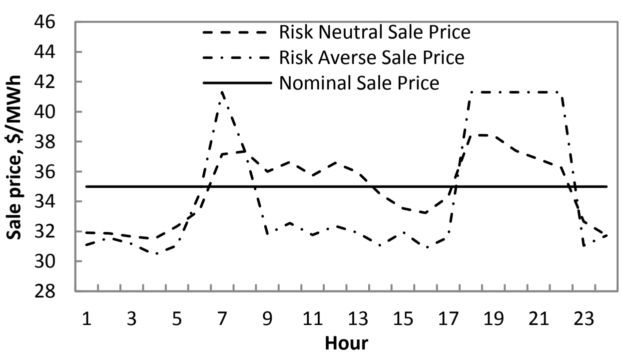


(a)



(b)

Fig. 5. LSE demand for (a). Case-1 and (b) Case-2.



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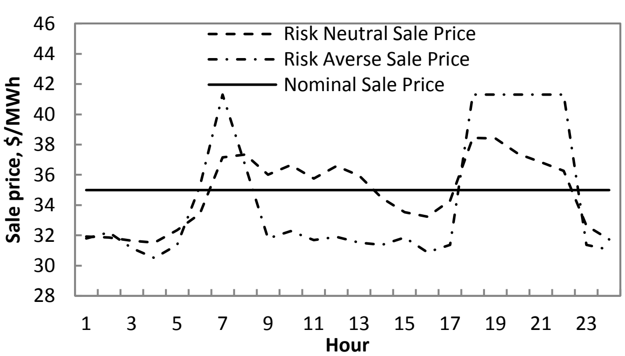
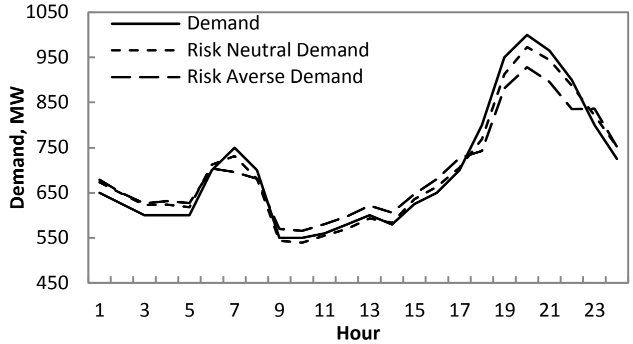
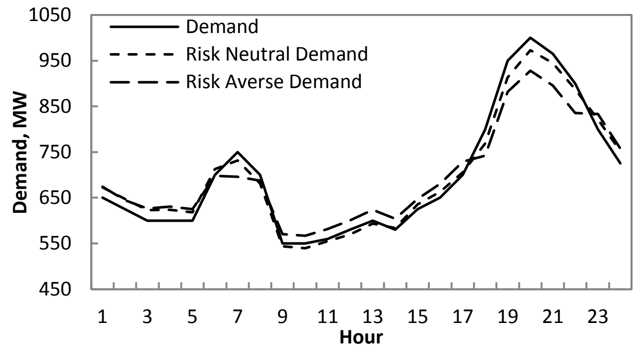


(b)

Fig. 6.Dynamic sale prices for (a). Case-3 and (b) Case-4

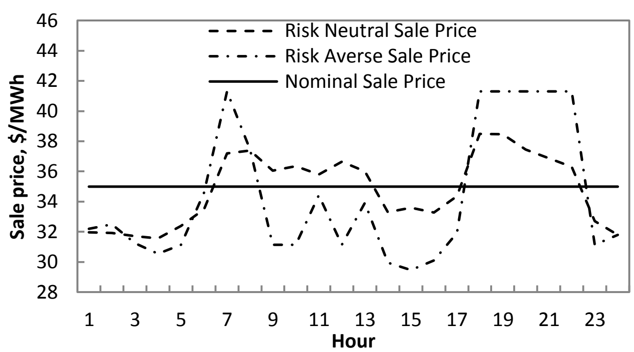


(a)

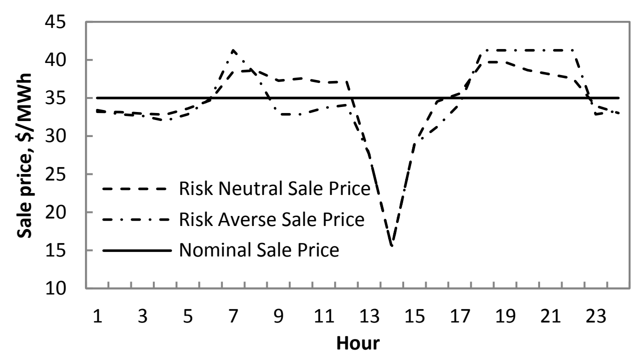


(b)

Fig. 7. LSE demand for (a). Case-3 and (b) Case-4.



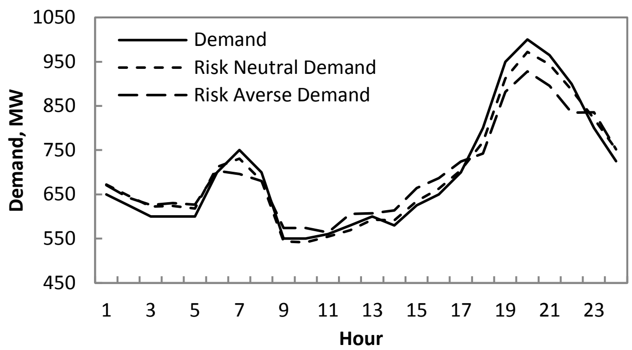
(a)



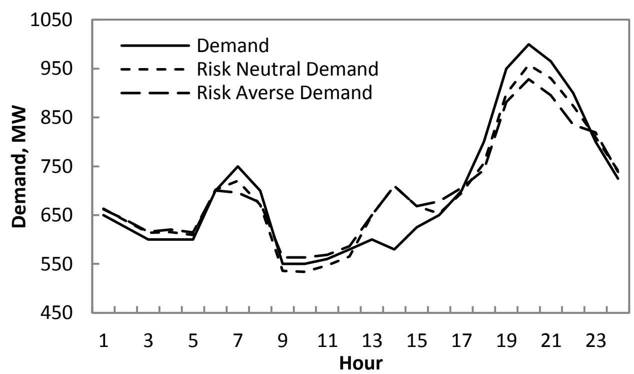
(b)

Fig. 8. Dynamic sale prices for (a). Case-5, and (b) Case-6.

not possible to match available energy and demand as consumers have fixed elasticity of demand. Therefore, a part of energy is curtailed through PV and wind in certain hours. It is found that only 18% of energy from PV and wind is utilized and remaining 2% is curtailed.



(a)



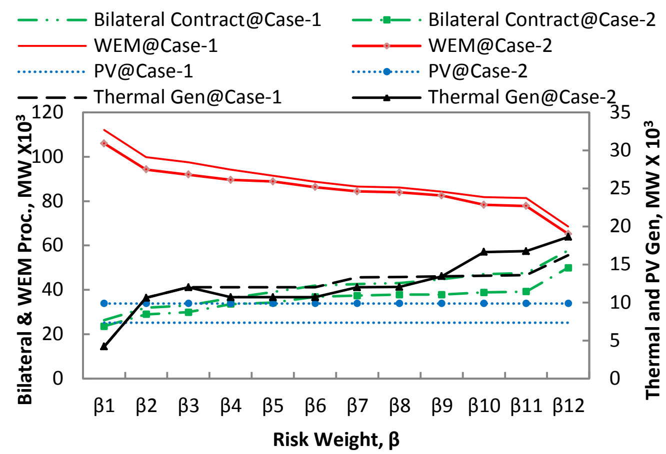
(b)

Fig. 9. LSE demand for (a). Case-5 and (b) Case-6

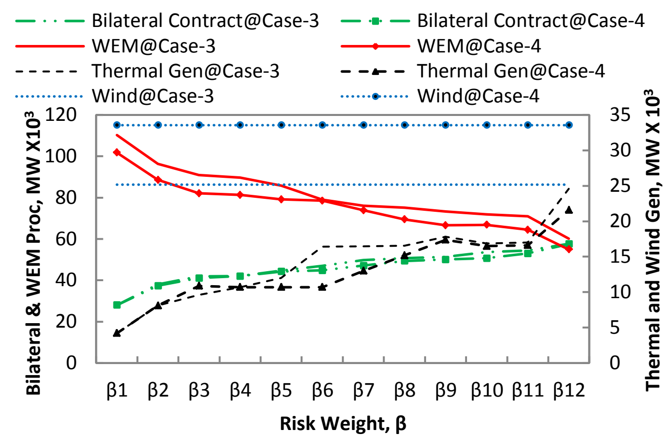
2) Impact of Risk Averseness on Decision Making

Proposed model in (25) minimizes the price risk of WEM, i.e., from procurement side, which eventually impacts decisions at sale side. Therefore, when LSE targets to minimize WEM price risk, shifts in demand is observed during hours of comparatively low volatility and low WEM prices. However, sale prices are high when WEM prices are highly volatile. It is observed that standard deviation is very high at hours 7, 18, and 22 (Fig. 3). Hence, during these hours, sale prices offered to consumer are high. This secures LSE position in highly risky market condition when both price and demand are high. However, during low WEM price risk hours, risk aversion impact is unnoticeable.

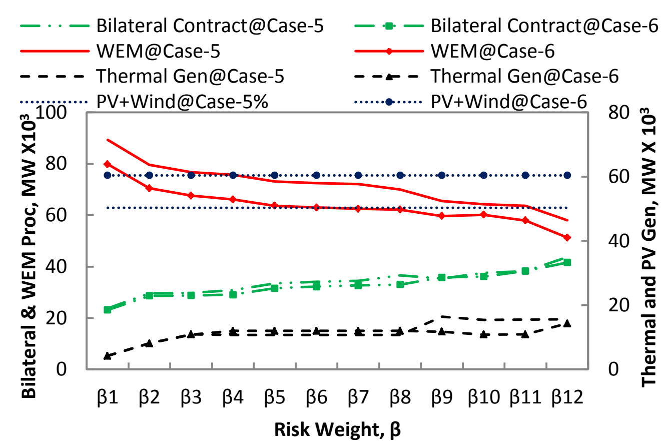
Dynamic sale prices and revised demand obtained for risk-averse LSE for different cases are shown in Figs. 4 to 9. The sale prices offered by risk-averse LSE are higher during the peak period of WEM, as compared to a risk-neutral LSE. It is noticeable for all six cases (Figs. 4, 6, and 8). Low sale prices are offered during availability of PV and wind. This is done to shift demand into these hours. Significant changes in dynamic sale prices profile are observed for case 1 and case-2 (Fig. 4). This happens because of significant increase in procurement of PV at certain hours in case-2 as compared to case-1. To completely utilize increased PV energy, sale prices are lowered in these hours to shift demand. At certain hours of PV availability, still, a part of electricity is procured from WEM to meet the consumer demand. Therefore, sale prices in these hours are also decided by value of standard deviation of WEM market. Similar observation can be drawn for other cases.



(a)



(b)



(c)

Fig. 10. Procurement from various sources for (a). Case 1 and 2 (b). Case 3 and 4 and (c) Case 5 and 6.

Fig. 10 shows the optimal procurement decisions from bilateral, thermal-generation, and WEM for different level of PV and wind, to procure revised demand. It depicts total procurement for all 24 hours and its variation with different values of risk weighing factor β. The results indicate that as β increases, procurement shifts towards less risky options to minimize risk. Hence, at $\beta = 0$, LSE procures more from WEM. As β increase, it procured more from less risky options such as bilateral contracts and thermal-generation. It is worth to note that procurement from PV or wind is constant. However, this strategy increases procurement cost, as less risky options are relatively costlier and therefore, reduce LSE profit.

Fig. 11 shows the efficient frontier between risk (standard deviation) and expected profit for six cases. For all cases, risk decreases with an increase in risk weight (β), which reduces expected profit of LSE. For risk weight $\beta = 0$, the second term in objective function becomes zero. This shows highest risk and maximum expected profit for the LSE.

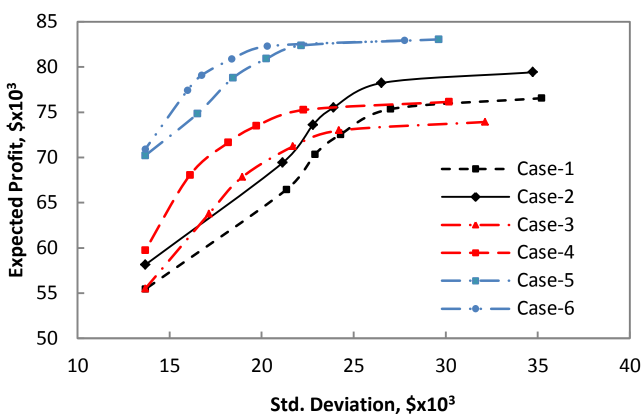


Fig. 11. Efficient frontier for case-1 to case-6.

V. Conclusion

LSE operation in electricity markets is challenging as they simultaneously manage procurement and sale sides, to maximize its profits while facing WEM price risk. This objective is targeted through decision making for optimal procurement of elastic consumer demand and offering optimal sale price. Electricity availability from PV and wind varies significantly. Therefore, its availability impacts differently on LSE's dynamic sale prices and procurement decisions. This paper analyses impact of PV and wind availability on LSE's dynamic sale prices and procurement decisions.

Analysis implies that dynamic sale prices enhance LSE's profit for each case. Demand shift from high price periods shows that LSE's costly energy purchase is reduced in corresponding hours from WEM market. This shift in demand is also influenced by energy availability from PV and Wind. Low value of sale prices is offered to utilize available PV and wind energy effectively. In case energy availability from PV and wind is sufficiently high as compared to demand, a part of energy from PV and wind is curtailed.

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