# ANALYZING THE ELECTRICITY MARKETS BY INTEGRATING THE RENEWABLE ENERGY SOURCES TO POWER SYSTEM

**Chiduruppula Sharath Kumar**
PG Student
Dept of EEE
SNIST
Hyderabad, India

**Koganti Sri Lakshmi**
Assistant Professor
Dept of EEE
SNIST
Hyderabad, India

**Pallikonda Ravi Babu**
Professor
Dept of EEE
SNIST
Hyderabad, India

**Abstract**

*This paper proposes the behavior of electricity markets when Renewable energy generations are integrated into power system. The Electricity market regulators intention is to reduce the cost of power, so as to benefit the customers. The mathematical model proposed in this paper will be analyzed from market operator (MO) point of view, Henceforth, deterministic optimization model will be utilized to diminish the cost of power in both day ahead market and real-time market. The optimization results will be analyzed to show the effect of renewable energy power penetration into the electricity markets. The optimal results will be compared between only and exclusive wind power integration is considered and also both wind and solar power integration is considered. This paper will be concluded by specifying that wind and solar power plants in the hands of one power producer will yield significant profits to the renewable power producer and also reduces the penalties on renewable power producer, thereby reduces total cost of power generation in the power system.*

***Keywords**: Deterministic optimization; Electricity markets; power markets; wind integration; wind and solar integration*

## Nomenclature

***Indices and sets:***

| | |
|---|---|
| t | Index for time periods, running from 1 to T |
| i | Index for conventional power producers, running from 1 to I |
| j | Index for wind power generating units owned by the strategic producer, running from 1 to J. |
| g | Index for solar power generating units owned by the strategic producer, running from 1 to G. |
| d | Index for demands, running from 1 to D. |
| b | Index of energy blocks offered by a power producer, running from 1 to B. |
| l | Index for demand blocks, running from 1 to L. |

***Decision Variables:***

| | |
|---|---|
| $\lambda_{bjt}^{WD}$ | Offer price of block b of the wind generating unit J in a period t in the day-ahead market. |
| $\lambda_{bgt}^{SD}$ | Offer price of block *b* of the solar generating unit $g$ in a period *t* in the day-ahead market. |
| $\lambda_{jt}^{WR}$ | Offer price of the wind generating unit *j* in a period *t* in the real-time market. |
| $\lambda_{jt}^{SR}$ | Offer price of the large Generating unit $g$ in a period *t* in the real-time market. |
| $p_{bjt}^{WD}$ | Produced power of block *b* of the wind generating unit *j* in a period *t* in the day-ahead market. |
| $p_{bgt}^{SD}$ | Produced power of block *b* of the wind generating unit $g$ in a period *t* in the day-ahead market. |
| $p_{jt}^{WR}$ | Rescheduled power of the wind generating unit *j* in a period *t* in the real-time market. |
| $p_{gt}^{SR}$ | Rescheduled power of the wind generating unit $g$ in a period *t* in the real-time market. |
| $p_{bit}^{CD}$ | Power of block *b* produced by the conventional power producer *I* in a period *t* in the day-ahead market. |
| $p_{it}^{CR+}/p_{it}^{CR-}$ | Increased/decreased power of the conventional power producer *I* in a period *t* in the real-time market. |
| $p_{ldt}^{LD}$ | Power bought of block *l* of the demand *d* in a period *t* in the day-ahead market. |
| $p_{dt}^{LR}$ | Accepted deviation of the demand *d* in a period *t* in the real-time market. |
| $\lambda_{mt}^{DA}$ / $\lambda_{mt}^{RT}$ | Day-ahead/real-time locational marginal price (LMP) at bus *m* in a period *t*. |

$R_{it}^{U}/R_{it}^{D}$ Up/down reserve scheduled for the conventional power producer $i$ in a period $t$.

$R_{t}^{U}/R_{t}^{D}$ Total up/down reserve scheduled in a Period $t$.

$r_{it}^{U}/r_{it}^{D}$ Up/down reserve deployed for the conventional power producer $i$ in a period $t$.

***Random Variables:***

$\lambda_{bit}^{CD}$ Offer price of block $b$ of the Conventional power producer $i$ in a period $t$ in the day-ahead market.

$p_{jt}^{Sf}$ Forecasted production of the solar generating unit $g$ in a period $t$.

$p_{jt}^{Wf}$ Forecasted production of the wind generating unit $j$ in a period $t$.

$p_{dt}^{LRf}$ Forecasted deviation of demand $d$ in a Period $t$ in the real-time market.

***Other Variables:***

$p_{bit}^{CDmax}$ Capacity of block $b$ of the Conventional power producer $i$ in a period $t$ in the day-ahead market.

$\lambda_{ldt}^{LD}$ Bidding price of block $l$ of the demand $d$ in a Period $t$ in the day-ahead market.

$p_{ldt}^{LDmax}$ Capacity of block $l$ of the demand $d$ in a period $t$ in the day-ahead market.

$\lambda_{it}^{RU}$ / $\lambda_{it}^{RD}$ Offer price of the up/down reserve of the conventional power producer $i$ in a period $t$.

$\lambda_{it}^{CR+}$ / $\lambda_{it}^{CR-}$ Offer price of the increased/decreased power of the conventional power producer $i$ in a period $t$ in the real-time market.

$\lambda_{dt}^{LR}$ Bidding price of the deviated demand $d$ in a period $t$ in the real-time market.

$\sigma_{t}^{D}$ Standard deviation of the total forecasted demand in a period $t$.

$\sigma_{jt}^{W}$ Standard deviation of the forecasted power of the wind generating unit $j$ in a period $t$.

$\sigma_{kt}^{S}$ Standard deviation of the forecasted power of the solar generating unit $g$ in a period $t$.

***Constants and Parameters:***

$p_{i}^{max}$ Maximum output of the conventional power producer $i$.

$p_{j}^{Wmax}$ Installed capacity of wind power generating unit $j$.

$p_{j}^{Smax}$ Installed capacity of solar power generating unit $g$.

$R_{i}^{Umax}$ Maximum up reserve that can be Provided by the conventional power producer i.

$R_{i}^{Dmax}$ Maximum down reserve that can be provided by the conventional power producer i.

$k$ Factor relating the system reserve requirement to the standard deviations of load and wind power.

## 1. Introduction

The renewable energy sources are becoming important in electricity sector, not only because they are eco friendly, but also they offer several advantages [1]-[5]. However, they pose some drawbacks too, when it comes to concept of deregulation. The energy sources which will be adopted usually in renewable energy sources is wind and solar. Since, these resources are available throughout the world, the new technologies are emerging around them daily.

The wind and solar energy sources plays very crucial role in deregulation process. The solar power producers and wind power producers adopt different strategies in order to maximize their profits. one of which is PPA agreements [6].

However, PPA agreements does not giving enough revenues to the power producers. As a result, they are effectively participating in electricity markets. Right now, some of the U.S. market operators, e.g., the Midwest Independent System Operator (MISO), Electric Reliability Council of Texas (ERCOT), Pennsylvania-New Jersey-Maryland Interconnection (PJM), and New York ISO, permit wind power producers to offer their day-ahead power commitments into the markets. However, the rules and regulations imposing on conventional generators, also follows to RES power producers. As a result, they are subjected into risk. Due to intermittency nature of wind and solar, they must pay heavy penalties when they do not meet the power requirements. Hence, they has to follow different strategies in order to mitigate the risk.

The forecasting values of wind power and solar power are generated in the form of scenarios from ARIMA and reduced by different advanced methods like probability distance method, fast forward algorithm etc., which are advanced forecasting techniques implemented based on historical values of renewable energy power plants.

The locational marginal price (LMP) is a crucial factor in determining the profits of power producers in electricity markets. The LMPs will be calculated by market operator (MO) in each type of electricity markets i.e., Day ahead market, reserve market and real-time market. From the literature point of view, the solar and wind power producers are price takers, but not price makers. Apart from eco friendly nature, the marginal price of RES power plants is less than that of conventional generators, the RES power producers must be considered as price makers, but not price takers.

In this paper, the electricity market clearing process will be performed with deterministic optimization [7] because the problem has been analyzing from market operator point of view, and the results will be analyzed and compared that was generated from electricity market clearing models. The profits, penalties will be compared between wind only power producer and both wind and solar power producer using case study. The total minimized costs will be compared between wind only integrated power system and both wind and solar integrated power system along with conventional generators in both the cases.

## 2. Model description

### *2.1. Market Framework*

In electricity markets, the market operator request power suppliers including wind power and solar power producers to bid into the market at each hour of next day. This market is known as day ahead market and simultaneously reserve market is held at the same time of day ahead market, in which only conventional generators participate. After these markets are closed, the MO will aggregate the bids and calculate day ahead LMP, reserve market LMP and also cleared energy volumes in both the markets. The renewable energy producers if not generated their energy quantities what were scheduled in day ahead market in the real time market will be penalized. To maintain the power balance in real time power delivery, the MO will depend on reserve power what were scheduled in reserve power market.

Though renewable energy producers does not have operational costs unlike conventional power producers, they are exposed to heavy penalties, if not generated required power that was scheduled in the day ahead market.

The conventional power producers clearly take the advantage of intermittent nature of renewable energy generators. The MO only depends on conventional generators for scheduling reserve power that was required in real-time market.

### *2.2. Forecasting of future values*

Wind and solar resources are intermittent in nature, forecasting the future values of wind power and solar power is essential in order to participate in day ahead electricity markets.

#### *2.2.1. Scenario generation and reduction*

Forecasting future values of wind power and solar power is performed on ARIMA [8], in which the future values as scenarios will be calculated based on historical values of the renewable energy power plants of time *t* of previous days. Various techniques like probability distance method will be used for scenarios reduction. However, in this paper, the cumulative forecasting values will be taken from ERCOT.

### *2.3. Uncertainty modeling of Reserve market*

The reserve market is used for deviations of power generation and demand, which will be dispatched in real time market. Due to high penetration of wind power and solar power, the power scheduled in reserve market increases with increased penetration of wind power and solar power. Due to increased power scheduling in reserve market, the total minimized cost of reserve market also increases.

The uncertainties of the model in this paper come from three main sources: 1) system load; 2) wind power production; and 3) solar power production. Modeling the seuncertainties is very important for a wind power producer and solar power producer to achieve the optimal bidding strategy.

The main uncertainties in the day-ahead market clearing process come from the load, wind and solar forecast errors.

The load, wind and solar forecast errors cannot be overcome and depends only on the advanced forecasting models. In this paper, these forecasting errors are managed by up and down reserves, which are scheduled as functions of the standard deviations of the forecasted wind power, forecasted solar power and the total forecasted demand of the system as follows [9]- [10].

$$R_t^U = R_t^D = k\sqrt{\sigma_t^D + \sum_j \sigma_t^W + \sum_k \sigma_t^S} \quad (1)$$

$$\sigma_t^X = \sqrt{\frac{\sum (D_n - F_n)^2}{n-1}}$$

where $\kappa$ is a parameter selected by the market operator and is selected to be 3 in this paper. D is the realized parameter and F is the forecasted parameter. n is the number of time periods.

$$Min \sum_i \lambda_{it}^{RU} R_{it}^U + \lambda_{it}^{RD} R_{it}^D \quad (2a)$$

Subject to

$$0 \le R_{it}^U \le R_i^{Umax} \quad (2b)$$

$$0 \le R_{it}^D \le R_i^{Dmax} \quad (2c)$$

$$\sum R_{it}^U = R_t^U \quad (2d)$$

$$\sum R_{it}^D = R_t^D \quad (2e)$$

The objective function (2a) is to minimize the total price of reserve. Constraints (2b) and (2c) are the reserve bounds for each thermal unit, which are generally eligible for reserve requirements. The reserve requirement is met in constraints (2d) and (2e).

Only conventional generators will participate in reserve market, since they are not intermittent in nature.

### 2.4. Day ahead market modelling

$$\text{Min} \sum_{bi} \lambda_{bit}^{CD} p_{bit}^{CD} + \sum_{bj} \lambda_{bjt}^{WD} p_{bt}^{WD} + \sum_{bk} \lambda_{bkt}^{SD} P_{bt}^{SD} - \sum_{ld} \lambda_{ldt}^{LD} p_{ldt}^{LD} \quad (3a)$$

Subject to

$$\sum_l p_{ldt}^{LD} - \sum_b p_{bit}^{CD} - \sum_b p_{bjt}^{WD} - \sum_b p_{bkt}^{SD} = 0 : \lambda_{mt}^{DA} \quad (3b)$$

$$0 \le p_{bit}^{CD} \le p_{bit}^{CDmax} \quad (3c)$$

$$0 \le p_{bjt}^{WD} \le p_{bjt}^{Wf} : b = 1 \quad (3d)$$

$$0 \le p_{bkt}^{SD} \le p_{bkt}^{Sf} : b = 1 \quad (3e)$$

$$0 \le p_{ldt}^{LD} \le p_{ldt}^{LDmax} \quad (3f)$$

The objective function (3a) minimizes the total price of energy offered by both thermal, wind power and solar power producers minus the revenue from supplying demand in each period. Equation (3b) enforces the day-ahead power balance. Constraints (3c) to (3e) represent the bounds of the power offered by the thermal and wind power and solar power units in each block. Constraint (3f) represents the limits of the demand in each block.

### 2.5. Real time market modelling

$$\text{Min} \sum_i (\lambda_{it}^{CR+} p_{it}^{CR+} - \lambda_{it}^{CR-} p_{it}^{CR-}) + \sum_j \lambda_{jt}^{WR} p_{jt}^{WR} + \sum_k \lambda_{kt}^{SR} P_{kt}^{SR} + \sum_i (\lambda_{it}^{RU} r_{it}^U + \lambda_{it}^{RD} r_{it}^D) - \sum_d \lambda_{dt}^{LR} p_{dt}^{LR} \quad (4a)$$

Subject to

$$\sum (p_{dt}^{LR} + \sum_l p_{ldt}^{LD}) - \sum_b p_{bit}^{CD} - \sum_i (p_{it}^{CR+} - p_{it}^{CR-} + r_{it}^U - r_{it}^D) - \sum_b p_{bjt}^{WD} - \sum_j p_{jt}^{WR} + \sum_b p_{bkt}^{SD} - \sum_k p_{kt}^{SR} = 0 : \lambda_{mt}^{RT} \quad (4b)$$

$$0 \le p_{it}^{CR+} \le p_i^{max+} \quad (4c)$$

$$0 \le p_{it}^{CR-} \le p_{bi}^{max-} \quad (4d)$$

$$p_{it}^{CR+} \le p_i^{max+} - \sum_b p_{bit}^{CD} \quad (4e)$$

$$p_{it}^{CR-} \le \sum_b p_{bit}^{CD} \quad (4f)$$

$$-\sum p_{bjt}^{WD} \le p_{jt}^{WR} \le p_{bjt}^{Wf} - \sum p_{bjt}^{WD} \quad (4g)$$

$$-\sum p_{bkt}^{SD} \le p_{kt}^{SR} \le p_{bkt}^{Sf} - \sum p_{bkt}^{SD} \quad (4h)$$

$$0 \le r_{it}^U \le R_{it}^U \quad (4i)$$

$$0 \le r_{it}^D \le R_{it}^D \quad (4j)$$

The objective function (4a) minimizes the total cost of dispatching energy and deploying reserve minus the revenue from the deviation demand in each period. Equation (4b) enforces the real-time power balance. Constraints (4c) (4f) limit the power of each thermal generator that can be sold into the real-time market. The amount of wind power and solar power that can be sold in the real-time market in each period is limited by the forecasted wind power in that period, as described by (4g)-(4h). The deployed up and down reserves are limited by the scheduled up and down reserves in the reserve market, respectively, as expressed in (4i) and (4j), respectively.

## 3. Case study

### *3.1. ERCOT*

The data to implement the model is taken from the ERCOT (Electric Reliability council of Texas) [11]. The forecasted and actual data of solar and wind power (west region) is taken from the ERCOT website.

However, the data of 12convention generators is taken from the book "Decision

## 3. Case study

### *3.1. ERCOT*

The data to implement the model is taken from the ERCOT (Electric Reliability council of Texas) [11]. The forecasted and actual data of solar and wind power (west region) is taken from the ERCOT website.

However, the data of 12convention generators is taken from the book "Decision making under uncertainty in electricity markets". Power data of total 12 conventional generators along with one wind power plant and one solar power plant will be considered in our proposed models. Reserve power data of these 12 conventional generators are taken from the same book, to produce the required outputs of reserve power requirements.

### *3.2. Data for forecasting future values*

**Table 1**

Demand forecasted data and actual(realised) data

| Demand | | |
|---|---|---|
| No. of periods | Forecast | Actual |
| 1 | 1273.38 | 1210.23 |
| 2 | 1128.02 | 1158.95 |
| 3 | 1114.71 | 1134.12 |
| 4 | 1108.26 | 1097.82 |
| 5 | 1077.78 | 1087.67 |
| 6 | 1079.44 | 1093.91 |
| 7 | 1110.13 | 1082.61 |
| 8 | 1084.83 | 1091.73 |
| 9 | 1116.81 | 1107.31 |
| 10 | 1147.91 | 1166.14 |

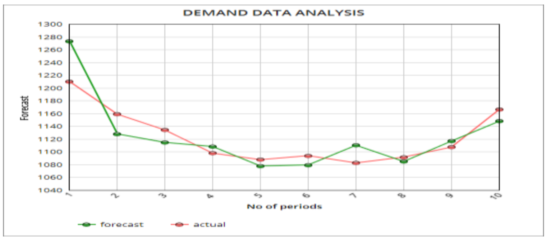


**Fig. 1.** Demand data analysis between forecasted and actual values

**Table 2**

Wind forecasted data and actual (realized) data

| Wind power | | |
|---|---|---|
| No. of periods | Forecast | Actual |
| 1 | 674.7 | 726.67 |
| 2 | 770.1 | 437.23 |
| 3 | 575.8 | 562.38 |
| 4 | 710.1 | 706.71 |
| 5 | 847.2 | 572.59 |
| 6 | 743.2 | 712.44 |
| 7 | 956.1 | 796.79 |
| 8 | 813.3 | 710.92 |
| 9 | 657.1 | 215.48 |
| 10 | 330.8 | 181.2 |

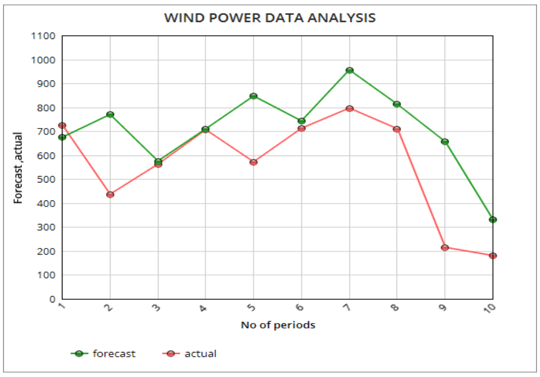


**Fig. 2.** Wind power data analysis between forecasted and actual values

**Table 3**
Solar forecasted data and actual (realized) data

| Solar power | | |
|---|---|---|
| No. of periods | Forecast | Actual |
| 1 | 0 | 0 |
| 2 | 0 | 0 |
| 3 | 0 | 0 |
| 4 | 0 | 0 |
| 5 | 0 | 0 |
| 6 | 0 | 0 |
| 7 | 1.9 | 0.3 |
| 8 | 83.1 | 99.04 |
| 9 | 413.3 | 361.03 |
| 10 | 610.7 | 644.43 |

Since, wind and solar resources are intermittent nature, the forecasting of wind power and solar power is essential, these forecasting values are produced by ARIMA and probability distance method by considering historical values of wind and solar power values (actual values).

### *3.3 Reserve market modelling*

We consider that 12 conventional generators participate in the reserve market to address the intermittent nature of wind and solar power. Below is the table mentioning offer costs of bids of 12 conventional generators and the maximum limits of each

**Table 4**
Data for reserve market modelling

| S.no | Offer costs($/MWh) | Maximum limits |
|---|---|---|
| 1 | 3.99 | 121.6 |
| 2 | 3.99 | 121.6 |
| 3 | 4.54 | 300 |
| 4 | 5.53 | 384.15 |
| 5 | 6.08 | 60 |
| 6 | 2.25 | 155 |
| 7 | 2.25 | 155 |
| 8 | 1.41 | 300 |
| 9 | 1.41 | 300 |
| 10 | 0.00 | 0 |
| 11 | 2.25 | 201.5 |
| 12 | 2.93 | 210 |

**Table 5**
Reserve power optimization solutions

| Up Reserves | Down Reserve | Values |
|---|---|---|
| $R_6^U$ | $R_6^D$ | 12.28 MW |
| $R_7^U$ | $R_7^D$ | 12.28 MW |
| $R_8^U$ | $R_8^D$ | 300 MW |
| $R_9^U$ | $R_9^D$ | 300 MW |
| $R_{11}^U$ | $R_{11}^D$ | 12.01 MW |
| | Minimum cost | 1856.7 dollars |

### *3.4. Day ahead market modelling*

The generating stations along with wind and solar plants will submit offers in the day ahead market for the next day scheduling. The MO will take these bids and calculates the LMP (Locational marginal price) and determine the scheduled power of each generating station.

Only those bids whose price is less than LMP will be going to match with demand bids whose price higher than LMP. All other bids will be neglected.

The below tables indicate that each generator will offer 4 bids for power scheduling for the next day.

**Table 6**
Offer costs of bids for day-ahead market

| Offer costs ($/MWh) | | | |
|---|---|---|---|
| Bid - 1 | Bid - 2 | Bid - 3 | Bid - 4 |
| 11.46 | 11.96 | 13.89 | 15.97 |
| 11.46 | 11.96 | 13.89 | 15.97 |
| 18.60 | 20.03 | 21.67 | 22.72 |
| 19.20 | 20.32 | 21.22 | 22.13 |
| 23.41 | 23.78 | 26.84 | 30.40 |
| 9.92 | 10.25 | 10.68 | 11.26 |
| 5.31 | 5.38 | 5.53 | 5.66 |
| 5.31 | 5.38 | 5.53 | 5.66 |
| 0.00 | 0.00 | 0 | 0 |
| 9.92 | 10.25 | 10.68 | 11.26 |
| 10.08 | 10.66 | 11.09 | 11.72 |
| 2.25 | 0 | 0 | 0 |

**Table 7**
Maximum limits of bids in day ahead market

| Maximum limits | | | |
|---|---|---|---|
| Bid - 1 | Bid - 2 | Bid - 3 | Bid - 4 |
| 30.40 | 45.60 | 45.60 | 30.40 |
| 30.40 | 45.60 | 45.60 | 30.40 |
| 75 | 75 | 90 | 60 |
| 206.85 | 147.75 | 118.20 | 118.20 |
| 12 | 18 | 18 | 12 |
| 54.25 | 38.75 | 31 | 31 |
| 100 | 100 | 120 | 80 |
| 100 | 100 | 120 | 80 |
| 300 | 0 | 0 | 0 |
| 108.50 | 77.50 | 62 | 62 |
| 140 | 87.50 | 52.50 | 70 |
| 330.8 | 0 | 0 | 0 |

**Table 8**
Optimal solution of Day a head market

| Scheduled power | values |
|---|---|
| $p_{29}^{CD}$ | 100 MW |
| $p_{30}^{CD}$ | 100 MW |
| $p_{31}^{CD}$ | 58.55 MW |
| $p_{33}^{CD}$ | 100 MW |
| $p_{34}^{CD}$ | 100 MW |
| $p_{35}^{CD}$ | 58.55 MW |
| $p_{37}^{CD}$ | 300 MW |
| $p_{49}^{WD}$ | 330.8 MW |
| LMP $\lambda_t^{DA}$ | 5.53 $/MWh |
| Minimum cost | 3530 Dollars |

***3.5. Real time market***

This market is intended to resolve issues that was not settled what was scheduled in the day ahead market. Mostly the issue that was going to settle in real time market is power balance. For this, reserves deployment and bids acceptance from the power producers and consumers is performed by MO.

In this paper, bid acceptance for real market is not considered, only reserve deployment what was scheduled in reserve market is considered.

**Table 9**
Optimal solution of Real time market

| Schedule reserve power | Values |
|---|---|
| $R_8^U$ | 83.5 MW |
| $R_9^U$ | 83.5 MW |
| LMP $\lambda_t^{RA}$ | 1.41 $/MWh |
| Minimum cost | 235.47 Dollars |

***3.6. Comparison of Results***

Now we will compare what will be the consequences when high amount of wind penetration is allowed into the electricity markets.

**Table 10**
Wind power effect on total cost in real time

| According to the data (W = 180 MW) | |
|---|---|
| Generation | 1166 MW |
| Cost | 3765.47 Dollars |

**Table 11**
Wind power effect on total cost as per scheduled

| (W = 330.8 MW) | |
|---|---|
| Generation | 1166 MW |
| Cost | 3555.38 dollars |

**Table 12**
Wind power effect on total cost, with zero generation in real time

| (W = 0 MW) | |
|---|---|
| Generation | 1166 MW |
| Cost | 4021.8 dollars |

Surprisingly, though generation is same in above three tables, the final cost is always varying. This is due to wind power integration into total power system. Now we will see why the cost is varying due to wind integration from below tables.

***3.7. Penalty***

The cost is varying due to wind power integration. since wind is intermittent in nature, whatever scheduled in day ahead market, if not satisfied by the wind power producers, reserve power deployment takes place. Since, reserve power is scheduled from conventional generators, the MO has to pay the price to conventional power producers for their reserve power offering.

The MO will charge Wind power producers for not maintaining the scheduled power in real time, this penalty amount will be transferred to conventional power producers for their reserve power offering.
Below tables will show this very clearly.

**Table 13**
Penalty on wind power producer in real time

| According to the data (W = 180 MW ) | |
|---|---|
| Total Cost | 3765.47 dollars |
| Wind penalty | - 211.218 dollars |
| Consumer Cost | 3554.252 dollars |

**Table 14**
Penalty on wind power producer as per scheduled

| (W = 330.8 MW ) | |
|---|---|
| Total Cost | 3555.38 dollars |
| Wind penalty | 0 dollars |
| Consumer Cost | 3554.252 dollars |

**Table 15**
Penalty on wind power producer with zero generation

| (W = 0 MW) | |
|---|---|
| Total Cost | 4021.8 dollars |
| Wind penalty | - 466.428 dollars |
| Consumer Cost | 3554.252 dollars |

From the above tables, it was confirmed that the final consumer cost is always constant. The variation in the total power generation cost calculated by MO is due to heavy penalties on wind power producers. The negative sign indicates it is a penalty. So, though the operation costs of wind power plants is almost negligible unlike most conventional generating stations, there will be heavy penalties on wind power producers, if not maintained in real time as per scheduled in day ahead market.

The same is the case with solar power plants, if you consider solar power plants exists in the power system.

### *3.8. Profits of wind power plants*

We have seen wind power producer's penalties, now we will see wind power producer's profits. We will see profits in each type of market.

**Table 16**
Profit of wind power producer as per the data

| According to the Data (W = 180 MW) | |
|---|---|
| Day-ahead market | 1829.324 dollars |
| Real time market | - 211.218 dollars |
| Total profit | 1618.106 dollars |

**Table 17**
Profit of wind power producer as per scheduled

| (W = 330.8 MW) | |
|---|---|
| Day-ahead market | 1829.324 dollars |
| Real time market | 0 dollars |
| Total profit | 1829.324 dollars |

**Table 18**
Profit of wind power producer with zero generation

| (W = 0 MW) | |
|---|---|
| Day-ahead market | 1829.324 dollars |
| Real time market | - 466.428 dollars |
| Total profit | 1362.896 dollars |

In table 18, you can see that the wind power producer is getting profit without any generation from his plants. This is situation only arise when real time LMP is less than Day ahead LMP. But it is too risky for wind power producer. Because generally real-time market takes place only few minutes before actual power delivery, the real time LMP in most cases higher than Day ahead LMP.
Consider below table, where real time LMP is slightly higher than Day ahead LMP.

**Table 19**
Penalty on wind power producer when Real time LMP is higher than Day ahead LMP

| Real time LMP = 6.00 $/MWh | |
|---|---|
| (W = 0 MW) | |
| Day-ahead market | 1829.324 dollars |
| Real time market | - 1984.8 dollars |
| Total profit | - 155.5 dollars |

The above explains us that there will be heavy penalty if wind power producer does not generate any power from his plants. Since, he cannot predict whether real time LMP is greater or less than Day ahead LMP, this is a great limitation for wind power producers in electricity markets.

### *3.9. Wind and solar integration*

Now, how to overcome this limitation of wind power plants are process the solar power plants. The wind power producer should also possess a solar power plant, to overcome the penalties imposed on him due to not maintaining the scheduled power in real time. In this way, his penalties will be significantly reduced, if one renewable power generating station does not work as intended as other renewable generating station.

When wind power plants do not work as per scheduled, the demand taken by wind power plants is diverted to conventional generating stations in the form of reserve power deployment by conventional generators.

In order to mitigate this solar power plants are essential along with wind power plants.

**Table 20**

Total savings between exclusively wind power case and wind and solar power case

| | Only wind W=180MW | Both wind and solar (W=180 MW; S=644.43MW) | Total saving |
|---|---|---|---|
| Day ahead market | 3530 dollars | 2295 dollars | 1235 dollars |
| Real time market | 235.47 dollars | 187.95 dollars | 47.52 dollars |
| Total Minimized cost | 3765.4 dollars | 2482.95 dollars | 1282.4 dollars |

**Table 21**

Extra profit between exclusively wind power case and wind and solar power case

| | Only wind (W=180MW) | Both wind and solar (W=180 MW; S=644.43MW) | Extra Profit |
|---|---|---|---|
| Day ahead market | 1829.324 Dollars | 2543.7 dollars | 714.376 dollars |
| Real time Market | -211 dollars (penalty) | - 163 dollars (penalty) | -48 dollars (penalty) |
| Total profit | 1618 dollars | 2380.7 dollars | 666.376 dollars |

From Table – 20 and Table – 21, we can compare these two tables and understands that when only wind plants is considered in power system, the total minimized cost is much higher compared to integration of both wind and solar plants in power system.

### *4. Market power*

When conventional power producers try to influence the LMP, then it is known as Market power. The MO will use different strategies to mitigate this market power. One is the integration of wind and solar power plants. Because wind and solar power plants power production cannot be estimated exactly, if the conventional power producers try to influence the LMP by offering their bids at higher cost, they may not be considered in day ahead market power scheduling, because renewable power plant producers offer their bids at much lower costs.

As a result, the conventional power plants have to shut down their generating stations, which will incur heavy losses to them.

### 5. Conclusion

The behavior of electricity markets when renewable energy power plants integrated into the power system will be studied in this paper.

The profits and penalties of wind power producer and also reducing penalties by possessing solar power plant in the same hands of wind power producers has been described.

By integrating both wind and solar power plants, the total cost of power scheduling is reduced and also it helps in mitigating the market power and yields greater profits and reduce penalties.

### Acknowledgement

We express our profound gratitude and deep regards to Ting Dai and Wei Qiao who are IEEE members for their exemplary guidance in our research work. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

### References

*[1] Integrating Wind Power into the Electric Grid- Prospectives for Policymakers. National Conference of State Legislature. [Online]. Available: http://www.uwig.org/ncsl_wind_integration.pdf*

*[2] K.A. Folly, "Wind Energy Integration into the South African Grid: Prospects and Challenges", Wind Energy-developments, Potential and Challenges pp.93-120, Nova Publisher, new York,2016.*

*[3] J. R. Abbad, "Electricity market participation of wind farms: the success story of the Spanish pragmatism," Energy Policy, vol. 38, no. 7, pp. 3174-3179, Jul 2010.*

*[4] E. Bitar et al., "Bringing Wind Energy to Market," To Appear, IEEE Transactions on PowerSystems, 2012.*

*[5] North American Electric Reliability Corporation (NERC), "Accommodating High Levels of Variable Generation," Special Report, Princeton, NJ, USA, April, 2009.*

*[6] R. Wiser and M. Bolinger, "2012 wind technologies market report,"Lawrence Berkeley Nat. Lab., Berkeley, CA, Tech. Rep. DOE/GO-102013-3948, Aug. 2013 [Online]. Available:http://www1.eere.energy. gov/wind/pdfs/2012_wind_technologies _market_report.pdf*

*[7] M. Rahimiyan, J. M. Morales, and A. J. Conejo, "Evaluating alternative offering strategies for wind producers in a pool," Appl. Energy, vol. 88 , no.12, pp. 4918–4926, Dec.2011.*

*[8] J. M. Morales, A. J. Conejo, and J. Perez-Ruiz,"Economic valuation of reserves in powersystems with high penetration of wind power," IEEE Trans. Power Syst., vol. 28, no.4, pp.4645– 4654,Nov.2009.*

*[9] GE Energy, "Analysis of Wind Generation Impact on ERCOT Ancillary Services Requirements," Prepared for ERCOT, Final Report, March 28,2008.*

*[10] Lange M, Focken U. Physical approach to short- term wind power prediction. Berlin:Springer; 2005.*

*[12] P. Vassilopoulos, "Models for the identification of market power in wholesale electricity markets," UFR Sciences of Organizations, DEA 129, 2003.*

*[13] Lange M, Focken U. Physical approach to short-term wind power prediction. Berlin:Springer; 2005.*

*[14] Lang SJ, McKeogh EJ. Forecasting wind generation, uncertainty and reserve requirement on the Irish power system using an ensemble prediction system.Wind Engineering 2009;33(5):433e48.*

*[15] Gabrel V, Muraty C, Thiele A. Recent advances in robust optimization and robustness: an overview. Working paper; 2012.*

*[16] Thiele A. A robust optimization approach to supply chains and revenue management. PhD dissertation. Massachusetts Institute of Technology;2004.*

*[17] N. Hatziargyriou and A. Zervos, "Wind power development in Europe,"Proc. IEEE, vol. 89, no. 12, pp. 1765–1782, Dec. 2001.*

*[18] E. A. DeMeo, "Advances in insights and methods for wind plant integration,"IEEE Power & Energy Mag., vol. 5, no. 6, pp. 68–77,Dec.2007.*

*[19] Global Wind Energy Council, "Global Wind 2005 Report". [Online].Available: http://www.gwec.net.*

*[20] T.Ackermann, "Impact of high wind penetration on balancing and frequency control in europe," IEEE Power & Energy Mag., vol. 5, no. 6,pp. 91–103, Dec. 2007.*

*[21] E. Denny and M. O'Malley, "Wind generation, power system operation, and emissions reduction," IEEE Trans. Power Syst., vol. 21, no. 1, pp.341–347, Feb. 2006.*

*[22] F. D. Galiana, F. Bouffard, J. M. Arroyo, and J. F. Restrepo, "Scheduling and pricing of coupled energy and primary, secondary, and tertiary reserves," Proc. IEEE, vol. 93, no. 11, pp.1970–1983, Nov. 2005.*

## AUTHORS BIOGRAPHY

**Chiduruppula sharath Kumar** received the B.Eng. degree in electrical engineering from Nalla Narasimha Reddy Education Society's Group of Institutions, Telangana, India, in 2015. Currently, he is pursuing Master's degree in electrical engineering at the Sreenidhi Institute of Science and Technology, Ghatkesar, Telangana, India. His research interests include renewable energy integration, electricity market planning and optimization Techniques.

**Koganti srilakshmi** was born in India in1983. She received the B.Tech. and M.Tech. Degrees in electrical engineering from the JNTU University, Hyderabad, A.P., India, in 2006 and 2009, respectively, currently, She is working as Assistant Professor in Electrical Engineering department of SNIST. Her current Research interests include Renewable energy, Smart Grid, power quality, FACTS and HVDC.

**Pallikonda Ravi Babu** is currently working as Professor in department of Electrical and Electronics Engineering at Sreenidhi institute of science and technology. He received his Ph.D. from JNTUH in the year 2010, Hyderabad, AP, India. He received his B.E. degree in Electrical and Electronics Engineering in 1996 and M. Tech degree in Power Systems in 1999 from University of Mysore, Karnataka, India.

He has 14 years of teaching experience and 5 years of research experience and also he published 75 technical papers in International journals and conferences. .His current area of research is Demand Side Management in power systems and energy conservation studies. His special fields of interest include minimization of $I^2R$ losses and service restoration in electrical distribution systems using Fuzzy logic, Ant colony Algorithms, Genetic algorithms and Simulated Annealing techniques and non conventional energy resources.