Impact of Ancillary Services and Its Prices on Large-Scale Solar and Wind Power Penetration in Electricity Market*

Dinh Thanh Viet, Phan Cong Tien

Abstract - ***Nowadays, solar and wind power generation is an important part of the power sources in many countries all over the world. However, due to the variability and uncertainty of these sources, stable operation of the power system with large solar and wind power penetration is a big challenge for system operators. In order to enhance the contribution efficiency of solar and wind power in the power market, a strong ancillary service system is essential and must be reasonable priced. The ancillary services considered in this paper are spinning reserve, non-spinning reserve. In addition, a model for calculating and comparing generation costs for energy and ancillary services, with and without penetration of solar and wind power in the power market have been proposed. Consequently, this model has been developed and validated with a case study. The results show that in a power system with large proportion integration of solar and wind power, the energy and ancillary services generation costs for the power system are high. Besides, the feed-in tariffs of solar and wind power are more expensive than the traditional electricity generation, which leads to high locational marginal prices of the electricity market.***

Keywords*: Ancillary service; Electricity market; Renewable energy; Solar power; Wind power.*

I. INTRODUCTION

Renewable energy (RE) development has been growing rapidly during the last years, particularly solar and wind energy. According to the report of REN21, total installed capacity increased in 2017 for solar power is 402 GW, wind power 539 GW over the world [1]. Vietnam is not out of this way, Vietnamese government has approved the strategy for development of RE by 2030 and a vision to 2050 with target for RE sources by 2050 must be thirty percent of the system's total capacity [2].

However, the use of RE sources is facing many challenges. Currently, the cost of electricity generation from these sources is still higher than traditional energy sources. Therefore, the development of this energy source needs a mechanism supported by the Government. Secondly, the characteristics of these energy sources are variable and unpredictable, that affects operation of the power system, especially need available reserve capacity to ensure power system stability. Thirdly, there is the obstacle in the integration of RE to the power system in a competitive power market environment. Therefore, a flexible and effective ancillary service (AS) is needed to prevent curtailment of solar and wind power. Currently, the planners have introduced a feed-in-tariff (FIT) mechanism that encourages the development of RE sources. In the electricity market, if the FIT price is high while the state's subsidy does not take into account the reserve generation capacity for the system, the price of the buyer will be affected.

The publications in [3] - [5], [11] - [17] provided a review of the design and operation of several existing power markets and considered the market design for operation with high RE penetration. They highly evaluated role of capacity markets, role of AS market and co-optimization of energy and AS market. In [4], the authors assessed the ancillary services available in China and provided the modeling of the influence of wind power integration on ancillary services, where the objective function is to optimize the cost of generating electricity, the transmission lines investment, reserves cost for wind power forecasting error. In [5], the authors provided the summary on balancing system of German power market in relationship with reserve capacity and a massive expansion of variable renewables.

II. DEFINITION OF ANCILLARY SERVICES AND ITS OPERATION MACHANISM

A. Definition

In operation, the changing load, network faults, unpredictable stop of generator in power plants cause imbalance between power source and load, affecting the stability of the power system. Therefore, the power system operators need AS to balance and keep the system stable. Ancillary services include Frequency Control, Spinning Reserve, Fast Start, Voltage Control, Must run, Black Start.

Frequency control: The power generation units, which provide frequency control service, must be able to increase or decrease the power to response the frequency change of power system or automatic signals regulated by power system operators and electricity market. The power generation units must be able to change at least 4% of rated power within 10 seconds and maintain this change level at least 10 minutes.

The spinning reverse: The power generation units, which provide the spinning reserve, must be able to reach to rated power following frequency signals or other automatic signals, which regulated by power system operators and electricity market within 25 seconds and maintain this rated power at least 30 minutes.

Fast Start: The power generation unit, which provides fast boot reserve, must be able to reach to rated power within 14 minutes and maintain this power at least 8 hours.

Voltage control: The power generation units, which provide voltage control service, must be able to change reactive power to meet the requirements of power system operators and electricity market.

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Must run: The power generation units, which provide power system security, must be able to reach to rated power within 1 hour and maintain this power at least 8 hours.

Black Start: The power generation units, which provide black start service, must be able to startup from cold state without external power supply and must be able to connect power transmission grid after startup.

B. Ancillary services operation mechanism

There are four methods which the ancillary services are being procured by the system operators in the electricity market, including:

Compulsory provision: power plants must provide capacity to ancillary services. This mechanism is simple and easy to operate, but there is a disadvantage, where the cost of ancillary services is expensive due to the lack of negotiation and competition.

Bilateral contract mechanism: Capacity and AS fees will be negotiated and signed between the power system operator and the power plants. Through this mechanism, the power system operators can buy cheaper source, however, these negotiations can be long and complicated.

Tendering mechanism: The demand for the reserve capacity will be determined by the system operator and the power plants offer; while the market will decide the quantity and cost. This mechanism ensures competitiveness and transparency. However, they involve development of system, procedures and supporting mechanism, which may not be easy in the power market.

Mixed mechanism: mechanism that can combine the mechanisms above, this is the most flexible mechanism, used by many markets.

III. POWER MARKET AND POTENTIAL OF SOLAR AND WIND ENERGY IN VIETNAM

A. Vietnamese power market

The competitive electricity market of Vietnam has been implemented since 2009 with three levels. At level 1, a competitive electricity generation market has been developed. At level 2, a competitive electricity wholesale market was piloted from 2017 and will be completed by 2022. At level 3, a competitive electricity retail market will be formulated from 2022 to 2024.

In the competitive electricity generation market, all power plants with capacity of more than 30 MW must participate in the market. Bidding prices from offering power plants are determined based on the variable costs of each plant including fuel cost, variable operating cost, start-up cost, etc. The single buyer is EVN who will purchase the electricity and provide it to the customers. The selection of power plant winners based on the offer price, the volume of the offer and the power demand for each hour. In 2018, total of 106 power plants entered the electricity market with a total capacity of 36,611 MW. The proportion of different types of power plants is shown in Fig. 1 [6].

B. Vietnamese reserve capacity requirement

There are two types of reserves in grid code for Vietnamese power system, including frequency reserve and spinning reserve. Frequency reserve is determined according to the formula as follows:

$$P_{rr} = k \times P_{max} \quad (1)$$

where P_{rr}: regulation reserve (MW); k: adjustment factor; normally k=1.5%; P_{max}: forecasted peak load [7].

Spinning reserve is determined according to the formula as follows:

$$P_{sr} = \sqrt{a * P_{max} + b^2} - b \quad (2)$$

where P_{sr}: spinning reserve; P_{max}: forecasted peak load demand; a = 10 MW; b = 150 MW [7].

C. Potential of solar and wind energy in Vietnam

Vietnam is a country with great potential of solar energy, especially in the Central Highland, Southern Central and Southern regions with an average solar radiation intensity of 5kWh/m^2/day. The average number of sunshine hours per year is about 1,500 hours in the Red River Delta provinces and up to 2,700 hours in the South Central provinces. The coastal provinces, cities and highland provinces of Vietnam have high wind energy potential. It is estimated that wind power capacity in the mainland from 40,000 to 50,000 MW. The Ministry of Industry and Trade of Vietnam has approved the plan on development of wind power in some localities. In the revised Power Development Plan VII, the total installed capacity for the years 2020 and 2030 is shown in Table 1 [8] - [10].

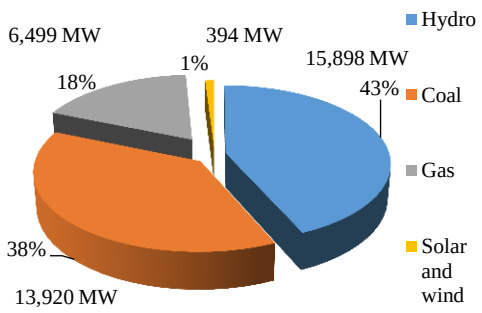


Figure 1. *Proportion and capacity of current power plants.*

TABLE 1. ESTIMATED POWER CAPACITY FOR YEAR 2020 AND 2030 [3]

Type of plant	2020 (MW)	2030 (MW)
Gas	8,940	19,037
Coal	25,620	55,167
Nuclear	0	4,600
Hydro	18,060	21,886
Solar	850 (low) 3,000 (high)	12,000
Wind	800	6,000
Other	4,290	9,195
Import	1,440	1,554
Total	60,000	129,500

IV. ALGORITHM FOR CACULATION OF ENERGY OUTPUT AND RESERVES

Normally, the reserve capacity for power system operation calculated by (1)-(2). When the power system operates with penetration of solar and wind sources, due to the rapid variability of solar and wind power with the weather change, the operating reserve needs to supplement an amount equal to solar and wind power. Algorithm for calculation of energy output and reserve output (Fig. 2) consists of the following steps:

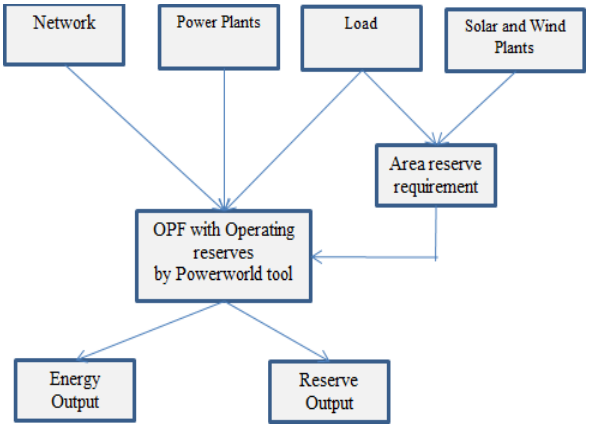


Figure 2. *Algorithm for OPF with operating reserves*

Step 1: Input parameters of the network, power plants, load into the model.

Step 2: Based on the area load, solar and wind capacity, set up the requirement of regulation reserve and spinning reserve.

Step 3: Run the Optimal Power Flow (OPF) with operating reserves by a power system specialized software; in this paper, we use Powerworld software.

Step 4: Export the results for energy output and operating reserve output.

Mathematically, the objective is to minimize:

$$C_{system} = \sum_{i=1}^{N} C_i(P_i) + \sum_{i\in I_{RU}} C_i^{RU}(RU_i) + \sum_{i\in I_{RD}} C_i^{RD}(RD_i) + \sum_{i\in I_{SP}} C_i^{SP}(SP_i) + \sum_{i\in I_{XS}} C_i^{XS}(XS_i) \quad (3)$$

Where:

C_{system}	total cost of energy and AS
$C_i(P_i)$	energy cost function
$C_i^{RU}(RU_i)$	reg up cost function
$C_i^{RD}(RD_i)$	reg down cost function
$C_i^{SP}(SP_i)$	spinning cost function
$C_i^{XS}(XS_i)$	supplemental cost function
RU_i	reg up capacity provided by power generator i
RD_i	reg down capacity provided by power generator i
SP_i	spinning capacity provided by power generator i
XS_i	supplemental capacity provided by power generator i.

The constraints of reserves described by (4)-(11):

The reg up reserve capacity must be less or equal to the maximum reg-up capacity of each generator:

$$0 \le RU_i \le RU_i^{Max} \quad (4)$$

The reg up reserve capacity must be less or equal to the maximum reg up capacity of each generator:

$$0 \le RD_i \le RD_i^{Max} \quad (5)$$

The spinning reserve capacity must be less or equal to the maximum spinning capacity of each generator:

$$0 \le SP_i \le SP_i^{Max} \quad (6)$$

The supplemental reserve capacity must be less or equal to the maximum supplemental capacity of each generator:

$$0 \le XS_i \le XS_i^{Max} \quad (7)$$

Reg up reserve total capacity of the generators is equal to the area reg up reserve total capacity:

$$\sum_i RU_i = RU^{area} \quad (8)$$

Reg down reserve total capacity of the generators is equal to the area reg down reserve total capacity:

$$\sum_i RD_i = RD^{area} \quad (9)$$

Spinning reserve total capacity of the generators is equal to the area spinning reserve total capacity:

$$\sum_i SP_i = SP^{area} \quad (10)$$

Supplemental reserve total capacity of the generators is equal to the area supplemental reserve total capacity:

$$\sum_i XP_i = XP^{area} \quad (11)$$

V. CASE STUDY

A. Simulation data

In the algorithm in Fig. 2, Powerworld version 18 used to run OPF on three buses diagram with a test power system as shown in Fig. 3, which includes different types of power plants available in Vietnamese power system including hydropower, coal thermal power, gas thermal power, solar and wind power plants. The percentage of capacity for each plant is similar capacity to real share of Vietnamese power system. The calculation conducted for three scenarios in peak load: current scenario of 2018, the 2020 scenario with the low RE penetration and the 2020 scenario with high RE penetration as shown in Table 2, Table 3. and Table 4.

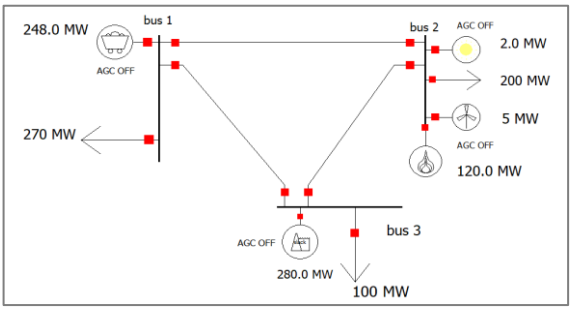


Figure 3. *3-bus diagram for the 2018 scenario*

Ancillary services in the test power system are regulation reserve (RR) and spinning reserve (SR). In case of power system operation with solar and wind penetration, the area reserve requirement added with the value of the solar and wind power. The cost function of the power plants derives from the piece-wise linear shape (Fig. 4), being equivalent to the actual offering price of the Vietnamese electricity market.

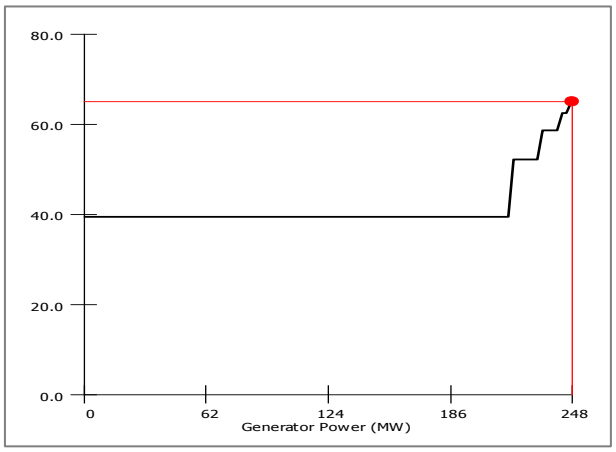


Figure 4. *Incremental cost curve of traditional power plant*

TABLE 2. POWER PLANT CAPCITY AND LOAD FOR SCENARIO YEAR 2018

Bus	Plant type	Capacity (MW)	Percentage (%)	Load (MW)
1	Coal	248	37.9	270
2	Gas	120	18.3	200
2	Solar	2	0.3	
2	Wind	5	0.8	
3	Hydro	280	42.7	100
	Total	655	100	570

TABLE 3. POWER PLANT CAPACITY AND LOAD FOR SCENARIO YEAR 2020 WITH LOW RE PENETRATION

Bus	Plant type	Capacity (MW)	Percentage (%)	Load (MW)
1	Coal	310	47.3	270
2	Gas	100	15.3	200
2	Solar	15	2.3	
2	Wind	10	1.5	
3	Hydro	220	33.6	100
	Total	655	100	570

TABLE 4. POWER PLANT CAPACITY AND LOAD FOR SCENARIO YEAR 2020 WITH HIGH RE PENETRATION

Bus	Plant type	Capacity (MW)	Percentage (%)	Load (MW)
1	Coal	310	45	270
2	Gas	100	14	200
2	Solar	50	7	
2	Wind	10	1	
3	Hydro	220	32	100
	Total	690	100	570

The highest step value of cost function is 10% lower than the ceiling price approved by the Vietnamese Electricity Regulatory Authority for each type of power plant in 2018. For solar and wind power plants, the cost function is a step function as shown in Fig. 5. The prices for 2020 scenarios do not include inflation price.

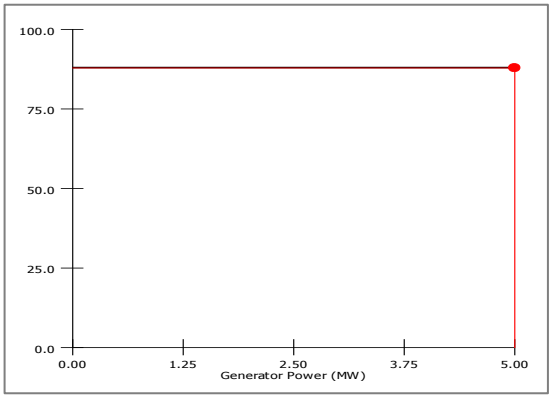


Figure 5. *Incremental Cost Curve of RE power plant*

B. Results

The results for the scenarios shown in Table 5. ÷ Table 18. The result for year 2018 scenario with and without solar and wind penetration and no ancillary services is shown in Fig. 6. The generation total cost in case of integration of both solar and wind power into the power system is highest and higher than the first case without solar and wind power by 2.6%.

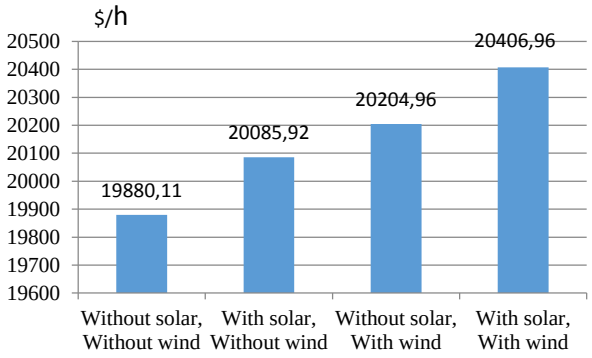


Figure 6. *The generation cost result for year 2018 scenario with and without solar and wind penetration and no ancillary services*

The results for the 2018 scenario, considering AS shown in Table 13 ÷ Table 14, Fig. 7 and Fig 8. From the results, it shows that generation total cost in the scenario considered full ancillary services and penetration of both solar and wind is higher than the scenario without RE by 8.6%. For the 2020 scenario (Fig. 9), the FIT price of solar is higher than of wind, the generation total cost of the system with solar penetration is much higher with wind penetration. The results also show that the LMP at bus 2 (connecting both of solar and wind power plants) is higher than at the other buses.

In this scenario, the generation total cost of the scenario, considering ancillary services and penetration of both solar and wind is higher than scenario without RE by 22%.

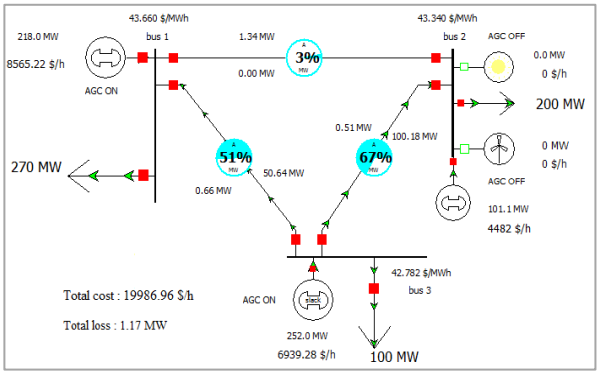


Figure 7. *The results for year 2018 scenario without solar, wind penetration and with ancillary services*

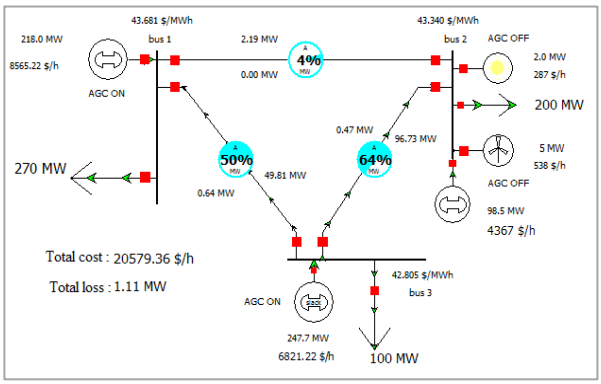


Figure 8. *The results for year 2018 scenario with solar, wind penetration and with ancillary services*

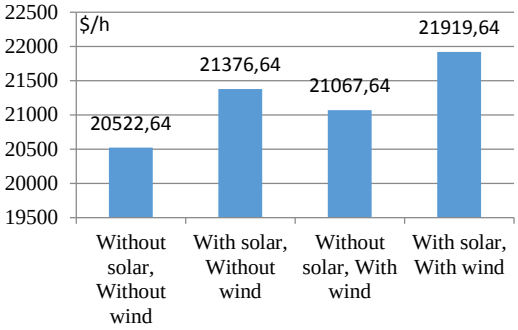


Figure 9. *The generation cost result for year 2020 scenario with solar and wind and no ancillary services*

In the 2020 scenario with high RE penetration, the results are shown in Table 17 ÷ Table 18 and Fig. 10. In this scenario, the cost of generating electricity for case with both solar and wind integration increases by 41% than case without RE.

Comparing three scenarios, the total cost including operating reserve cost in the high RE penetration 2020 scenario increases rapidly than the others (Fig. 11).

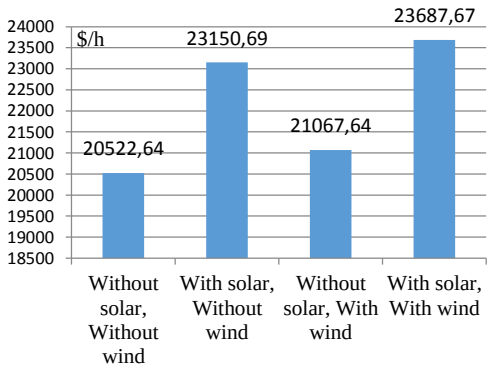


Figure 10. *The generation cost result for year 2020 scenario without ancillary services.*

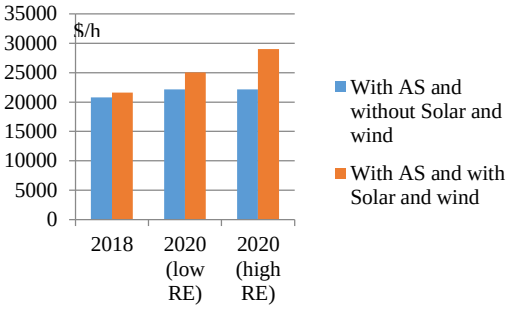


Figure 11. *The total cost results for three scenarios with ancillary services*

VI. CONCLUSION

In the paper, we found that a flexible power generator system and available operating reserves capacity are essential when integrating a high RE penetration into the power system, in particular solar and wind energy. Besides, the renewable generation investment cost of these resources are expensive while operating reserve power capacity is necessary in standby. Therefore, the high penetration of solar and wind power has raised up the cost of whole power system. The paper also shows that a reasonable penetration of RE sources in total amount of generation power needed for the developing countries including Vietnam. Moreover, an effective mechanism such as mandatory, bilateral or tender is also needed for providing flexible ancillary services in the electricity market to avoid curtailment of solar and wind power.

ACKNOWLEDGMENT

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APPENDIX

TABLE 5. THE RESULT OF SCENARIO 2018 WITHOUT SOLAR, WIND PENETRATION, AND NO ANCILLARY SERVICE

	Fuel type	Power (MW)	Generation cost ($/h)	LMP ($/MWh)
Plant 1	Coal	218	8,565.22	43.57
Plant 2	Gas	84	3,761.00	43.34
Plant 3	Solar	0	0	
Plant 4	Wind	0	0	
Plant 5	Hydro	268	7553.89	42.69
Total		570	19,880.1	

TABLE 6. THE RESULT OF SCENARIO 2018 WITH SOLAR, WITHOUT WIND PENETRATION, AND NO ANCILLARY SERVICE

	Fuel type	Power (MW)	Generation cost ($/h)	LMP ($/MWh)
Plant 1	Coal	218.0	8,565.22	43.57
Plant 2	Gas	82.6	3,680.00	43.34
Plant 3	Solar	2.0	287.00	
Plant 4	Wind	0	0	
Plant 5	Hydro	268.0	7553.70	42.69
Total		570.6	20,085.92	

TABLE 7. THE RESULT OF SCENARIO 2018 WITHOUT SOLAR, WITH WIND PENETRATION, AND NO ANCILLARY SERVICE

	Fuel type	Power (MW)	Generation cost ($/h)	LMP ($/MWh)
Plant 1	Coal	218.0	8,565.22	43.57
Plant 2	Gas	79.6	3,548.00	43.34
Plant 3	Solar	0	0	
Plant 4	Wind	5.0	538.00	
Plant 5	Hydro	268.0	7,553.74	42.69
Total		570.6	20,204.96	

TABLE 8. THE RESULT OF SCENARIO 2018 WITH SOLAR, WIND PENETRATION, AND NO ANCILLARY SERVICE

	Fuel type	Power (MW)	Generation cost ($/h)	LMP ($/MWh)
Plant 1	Coal	218.0	8565.22	43.57
Plant 2	Gas	77.6	3463.00	43.34
Plant 3	Solar	2.0	287.00	
Plant 4	Wind	5	538.00	
Plant 5	Hydro	268.0	7553.74	42.69
Total		570.6	20406.96	

TABLE 9. THE RESULT OF LOW RE SCENARIO 2020 WITHOUT SOLAR , WIND PENETRATION, AND NO ANCILLARY SERVICE

	Fuel type	Power (MW)	Generation cost ($/h)	LMP ($/MWh)
Plant 1	Coal	273.0	10,726.0	42.71
Plant 2	Gas	81.8	3,647.0	43.34
Plant 3	Solar	0	0	
Plant 4	Wind	0	0	
Plant 5	Hydro	216.0	6,149.5	42.71
Total		570.8	20,522.5	

TABLE 10. THE RESULT OF LOW RE SCENARIO 2020 WITH SOLAR AND WITHOUT WIND PENETRATION, AND NO ANCILLARY SERVICE

	Fuel type	Power (MW)	Generation cost ($/h)	LMP ($/MWh)
Plant 1	Coal	273.0	10,726.20	42.71
Plant 2	Gas	66.9	2,998.00	43.34
Plant 3	solar	15.0	1,503.00	
Plant 4	wind	0	0	
Plant 5	Hydro	216.0	6,149.47	42.71
Total		570.9	21,376.67	

TABLE 11.THE RESULT OF LOW RE SCENARIO 2020 WITHOUT SOLAR AND WITH WIND PENETRATION, AND NO ANCILLARY SERVICE

	Fuel type	Power (MW)	Generation cost ($/h)	LMP ($/MWh)
Plant 1	Coal	273	10,726.2	42.71
Plant 2	Gas	71.9	3,215	43.34
Plant 3	Solar	0	0	
Plant 4	Wind	10	977	
Plant 5	Hydro	216	6,149.47	42.71
Total		570.9	21,067.67	

TABLE 12. THE RESULT OF LOW RE SCENARIO 2020 WITH SOLAR AND WIND PENETRATION, AND NO ANCILLARY SERVICE

	Fuel type	Power (MW)	Generation cost ($/h)	LMP ($/MWh)
Plant 1	Coal	273.0	10,726.20	42.71
Plant 2	Gas	56.9	2,564.00	43.34
Plant 3	solar	15.0	1,503.00	
Plant 4	wind	10.0	977.00	
Plant 5	Hydro	216.0	6,149.47	42.71
Total		570.9	21,919.67	

TABLE 13. THE RESULT OF SCENARIO 2018 WITHOUT SOLAR, WIND PENETRATION, AND WITH ANCILLARY SERVICE

	Fuel type	Power (MW)	Generation cost ($/h)	LMP ($/MWh)	Reg up Power (MW)	Reg down Power (MW)	Spinning Power (MW)	Reserves Cost ($/h)
Plant 1	Coal	218	8,565.22	43.66			9.78	
Plant 2	Gas	101	4,482.00	43.34				
Plant 3	Solar	0	0					
Plant 4	Wind	0	0					
Plant 5	Hydro	252	6,939.00	42.78	8.55	8.55	8.26	
Total		571	19,986.22					812

TABLE 14. THE RESULT OF SCENARIO 2018 WITH SOLAR, WIND PENETRATION, AND WITH ANCILLARY SERVICE

	Fuel type	Power (MW)	Generation cost ($/h)	LMP ($/MWh)	Reg up Power (MW)	Reg down Power (MW)	Spinning Power (MW)	Reserves Cost ($/h)
Plant 1	Coal	216.0	8565.22	43.68			12.40	
Plant 2	Gas	98.5	4367.00	43.34				
Plant 3	Solar	2.0	287.00					
Plant 4	Wind	5.0	538.00				6.95	
Plant 5	Hydro	247.7	6821.22	42.85	8.55	8.55	12.60	
Total		569.2	20,578.44					1,028

TABLE 15. THE RESULT OF LOW RE SCENARIO 2020 WITHOUT SOLAR, WIND PENETRATION, AND WITH ANCILLARY SERVICE

	Fuel type	Power (MW)	Generation cost ($/h)	LMP ($/MWh)	Reg up Power (MW)	Reg down Power (MW)	Spinning Power (MW)	Reserves Cost ($/h)
Plant 1	Coal	284.8	11,339.60	52.05			13.35	
Plant 2	Gas	88.0	3,914.00	52.27				
Plant 3	Solar	0	0					
Plant 4	Wind	0	0					
Plant 5	Hydro	198.0	5,473.73	52.27	8.55	8.55	4.65	
Total		570.8	20,727.33					1,427

TABLE 16. THE RESULT OF LOW RE SCENARIO 2020 WITH SOLAR, WIND PENETRATION, AND WITH ANCILLARY SERVICE

	Type of fuel	Power (MW)	Generation cost ($/h)	LMP($/MWh)	Reg up Power (MW)	Reg down Power (MW)	Spinning Power (MW)	Reserves Cost ($/h)
Plant 1	Coal	273.0	10,726.20	42.85			21.00	
Plant 2	Gas	84.8	3,777.00	43.34				
Plant 3	Solar	15.0	1503.00					
Plant 4	Wind	10.0	977.00				6.95	
Plant 5	Hydro	187.7	5,192.82	42.86	8.55	8.55	15.00	
Total		570.5	22,176.02					2,856

TABLE 17. THE RESULT OF HIGH RE SCENARIO 2020 WITHOUT SOLAR , WIND PENETRATION, AND WITH ANCILLARY SERVICE

	Type of fuel	Power (MW)	Generation cost ($/h)	LMP ($/MWh)	Reg up Power (MW)	Reg down Power (MW)	Spinning Power (MW)	Reserves Cost ($/h)
Plant 1	Coal	284.8	11,339.60	52.05			13.35	
Plant 2	Gas	88.0	3,914.00	52.27				
Plant 3	Solar	0	0					
Plant 4	Wind	0	0					
Plant 5	Hydro	198.0	5473.73	52.27	8.55	8.55	4.65	
Total		570.8	20,727.33					1,427

TABLE 18. THE RESULT OF HIGH RE SCENARIO 2020 WITH SOLAR, WIND PENETRATION, AND WITH ANCILLARY SERVICE

	Type of fuel	Power (MW)	Generation cost ($/h)	LMP($/MWh)	Reg up Power (MW)	Reg down Power (MW)	Spinning Power (MW)	Reserves Cost ($/h)
Plant 1	Coal	271.2	10,655.50	42.95			38.80	
Plant 2	Gas	64.0	2,874.00	43.34				
Plant 3	Solar	50.0	4,775.00					
Plant 4	Wind	10.0	977.00				11.65	
Plant 5	Hydro	175.1	4,853.57	42.93	8.55	8.55	27.50	
Total		570.3	24,135.07					4,868