Research on the Coordinated Scheduling and Development of Renewable Energy Power Generation and Nuclear Power

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Abstract. From 2016 to 2017, China experienced a considerable degree of wind abandoning and light abandoning. The average utilization hours of nuclear power decreased significantly and the power loss of nuclear power was serious. In regions where clean energy consumption is limited, the optimal scheduling and coordinated development of renewable energy and nuclear power will be a problem for some parts of China. According to China's current energy-saving power generation scheduling method, wind power and photovoltaic power generation scheduling ranking before nuclear power. To maximum benefits of the whole society as a starting point, from the economic, environmental protection, power grid friendly, safe and international experience, analysis of wind power, solar and nuclear power scheduling sequence comparison, suggest the authorities to properly optimize existing power generation scheduling order, will arrange before the wind, nuclear power unit scheduling order also suggested that nuclear power provinces in the development of clean energy planning, the reasonable rhythm control of wind power development, facilitate clean energy given solution.

Key words: renewable energy; Wind power; Photovoltaic (pv); Nuclear power; Scheduling sequence; Economy; Environmental protection; Grid friendliness.

1. Introduction
In recent years, there has been a considerable degree of wind abandoning and light abandoning in China. Since 2015, the average utilization hours of nuclear power in China began to decline. From 2016 to 2017, the decline was more obvious, and the loss of nuclear power was serious. In 2018, the national development and reform commission issued The Clean Energy Consumption Action Plan (2018-2020) [1], which proposed that "by 2020, the problem of clean energy consumption should be basically solved". In regions where clean energy consumption is limited, it will be a problem for parts of China to coordinate the development of renewable and nuclear power. According to China's current energy-saving power generation scheduling method, wind power and photovoltaic power generation scheduling ranking before nuclear power. In this paper, by analyzing the 2016-2017 China to abandon the wind, discard and nuclear power loss situation, to the whole society benefit maximization as the starting point, from the economic, environmental protection, power grid friendly, safety, and the international experience, the clean energy dissipation the constrained region of wind power, solar and nuclear power scheduling order to carry on the analysis, Suggestions to the existing power generation scheduling
sequence optimization, puts forward various areas to develop clean energy must be considered when planning problem.

2. Related Policies

In 2006, China implemented *The Renewable Energy Law*, stipulating that "the state shall implement the full guarantee purchase system for renewable energy power generation"[2]. In 2007, the State Council issued *The Measures for Energy-saving Power Generation Dispatching (trial)*, provisions of "energy-saving power generation dispatching, according to the principle of energy saving, economy" "according to the unit energy consumption and pollutant emission levels from low to high order" to "minimize energy, resource consumption and pollutant emissions", the relevant sort for generating units: in the first place, wind power and solar energy in third place nuclear power generators[3]. In order to solve the problems of wind and light abandoning and the shortage of nuclear power in China in recent years, the national development and reform commission issued *the interim measures for ensuring the safety of nuclear power consumption* and *The implementation plan for solving the problem of water, wind and light abandoning* in 2017. In 2018, the national development and reform commission issued *the action plan on clean energy consumption* (2018-2020), which stated that "by 2020, the curtailment rate should be controlled at around 5% and the curtailment rate lower than 5%, and the nationwide nuclear power consumption should be guaranteed". In 2019, the national development and reform commission issued *the key action plan for the revolution in the energy system* (2019-2020), proposing to "implement a long-term mechanism for clean energy consumption".

3. Economic Analysis

3.1. Loss of wind, light and nuclear power in 2016-2017

3.1.1. Wind abandoning and light abandoning. According to the statistics of wind power and photovoltaic power production in grid connection of China electricity council express and national renewable energy center, the wind abandoning rate and light abandoning rate were 17.2% and 10.3% respectively in 2016. In 2017, the wind abandoning rate was 12% and the light abandoning rate was 6%. From 2016 to 2017, the national wind, optical power generation and electricity loss are shown in table 1[2-4].

| type            | Power generation(100 million kWh) | Power loss (100 million kWh) |
|-----------------|----------------------------------|------------------------------|
|                 | 2016                             | 2017                         | 2016 | 2017 |
| wind power      | 2 410                            | 3 057                        | 497  | 419  |
| photovoltaic    | 662                              | 1 182                        | 76   | 73   |

3.1.2. Power loss of nuclear power. As of December 31, 2017, China's nuclear power plants in operation were distributed in seven provinces (liaoning, jiangsu, zhejiang, fujian, guangdong, guangxi and hainan). Since no institution in China has released the situation of nuclear power loss, the average annual utilization hours of nuclear power are shown in FIG. 1.
As can be seen from figure 1, before 2015, the national nuclear power plants could basically maintain full headband base-load operation. From 2009 to 2015, the average utilization hour of nuclear power was 7,748 h. Since 2015, the average utilization hours of nuclear power began to decline, and the lowest value in 2016 was 7,061 h.

According to the data of the annual report of China electricity and power association (CTRC), the current year's nuclear power weighted installed capacity is converted according to the date of new nuclear power units' production: the current year's nuclear power weighted installed capacity = the nuclear power installed capacity at the beginning of the year + the new nuclear power installed capacity at the beginning of the year × the number of days of operation /365. It is estimated that the weighted installed capacity of nuclear power will be 30.28 million kW in 2016 and 34.93 million kW in 2017.

Taking the average utilization hours from 2009 to 2015 as the base, the annual nuclear power loss is: nuclear power loss = the difference between the weighted installed capacity of the year × the average utilization hours from 2009 to 2015. It is estimated that the loss of nuclear power in China is 20.8 billion kW·h in 2016 and 23 billion kW·h in 2017, as shown in table 2.

| Year | Average utilization hours | Use the difference in hours /h as compared to 2009-2015 | Year weighted installed capacity / 10,000 kW | Annual nuclear power loss / (100 million kW·h) |
|------|---------------------------|-------------------------------------------------|---------------------------------|---------------------------------|
| 2016 | 7,061                     | -687                                           | 3,028                           | 208                             |
| 2017 | 7,089                     | -659                                           | 3,493                           | 230                             |

3.1.3. Comparison of power generation and loss of wind power, photovoltaic power and nuclear power in nuclear power provinces. According to the statistical data of grid connected wind power and photovoltaic power production of China telecom express and national renewable energy center, the situation of wind abandoning, light abandoning and nuclear power loss in 7 nuclear power provinces in China from 2016 to 2017 is shown in table 3 [2-4].
Table 3. Wind power, photovoltaic and nuclear power generation and curtailment in nuclear power province in 2016—2017

| type                      | Power generation (100 million kW·h) | Power loss (100 million kW·h) |
|---------------------------|-------------------------------------|-------------------------------|
|                           | 2016                                | 2017                         | 2016  | 2017  |
| Wind power and photovoltaic| 451                                | 635                          | 19    | 13.2  |
| Nuclear power             | 2,132                              | 2,481                        | 208   | 230   |

It can be seen from table 3 that in 2016 and 2017, China's new energy generation in nuclear power provinces was 45.1 billion kW·h and 63.5 billion kW·h, respectively, which were both greater than the 20.8 billion kW·h and 23 billion kW·h of nuclear power losses.

Among the nuclear power provinces, Liaoning has curtailment due to the need to ensure the operation of heating units during the winter heating period, as shown in table 4.

Table 4. Wind photovoltaic power generation and curtailment of Liaoning province in 2016—2017

| Year | Wind power generation (100 million kW·h) | Wind abandoning power (100 million kW·h) |
|------|------------------------------------------|------------------------------------------|
| 2016 | 129                                      | 19                                       |
| 2017 | 150                                      | 13.2                                     |

It is estimated that the loss of nuclear power in Liaoning is 11.1 billion kW·h in 2016 and 11.08 billion kW·h in 2017, as shown in table 5.

According to the comparison, in 2016 and 2017, Liaoning's wind power generation was 12.9 billion kW·h and 15 billion kW·h, respectively, both of which were greater than the 11.1 billion kW·h and 11.08 billion kW·h of the nuclear power loss in Liaoning.

Table 5. Nuclear power curtailment of Liaoning province in 2016—2017

| Year | Nuclear power generation/(100 million kW·h) | Generating hours | With the national average of 2009-2015 power generation hours /h | Annual nuclear power loss/(100 million kW·h) | Nuclear power loss/(100 million kW·h) |
|------|---------------------------------------------|------------------|---------------------------------------------------------------|---------------------------------------------|-------------------------------------|
| 2016 | 200                                         | 4,982            | -2,766                                                        | 401                                         | 111.0                               |
| 2017 | 236                                         | 5,273            | -2,475                                                        | 448                                         | 110.8                               |

3.2. Calculation of renewable energy subsidies in nuclear power provinces

According to China's trial measures on the management of renewable energy power generation price and cost sharing, "the portion of the feed-in tariff of renewable energy power generation projects that is higher than the benchmark feed-in tariff of local desulfurized coal-fired units can be solved by imposing additional tariff on power users"[13]. China has implemented the benchmark electricity price policy for wind power since August 2009, and the benchmark electricity price policy for photovoltaic since July 2011. So far, the benchmark electricity price for wind power and photovoltaic has been lowered for many times.

3.2.1. Calculation of renewable energy subsidy price in nuclear power provinces

(1) Situation in 2016.

In 2016, the average benchmark electricity price of wind power and photovoltaic in nuclear power provinces (including desulfurization, denitration and dust removal) is shown in table 6.

In 2016, the average wind power price in the nuclear power provinces was 0.197 yuan/(kW·h) higher than the benchmark price of coal power, and the average photovoltaic price was 0.562 yuan/(kW·h) higher than the benchmark price of coal power.
(2) Situation in 2017. In 2017, benchmark prices of coal power (including desulfurization, denitration and dust removal), wind power and photovoltaic power in nuclear power provinces are shown in table 7. Since July 1, 2017, some provinces and regions in China have adjusted the benchmark price of coal power[3]. The data in table 7 is the weighted average price of that year. The weighted average benchmark price of coal power = the pre-adjustment price \times the number of months before the adjustment /12 + the adjusted price of the year \times the number of months after the adjustment/12. Since the date of adjustment of electricity price in 2017 is July 1, the weighted average benchmark price of coal power in that year=(electricity price before adjustment+price after adjustment)/2.

The average electricity price of wind power in nuclear power provinces was 0.193 yuan/(kW·h) higher than the benchmark electricity price of coal power, and the average electricity price of photovoltaic power was 0.4287 yuan/(kW·h) higher than the benchmark electricity price of coal power.

(3) Calculation of weighted subsidy price of wind power and photovoltaic. Taking the annual power generation of wind power and photovoltaic in nuclear power provinces as the weight[4], the wind-light weighted subsidy price is calculated, as shown in Table 6. Weighted subsidy price of wind power and photovoltaic = weight of wind power generation + weight of photovoltaic power generation. It can be seen from Table 6 that the weighted subsidy price of wind power and photovoltaic power in nuclear power provinces in 2016 is 0.2637 yuan/(kW·h) and 0.2606 yuan/(kW·h) in 2017. Conversion of power lost from nuclear power into weighted subsidy for wind power and photovoltaic power = weighted subsidy for wind power and photovoltaic power lost from nuclear power.

According to calculation, in 2016 and 2017, the nuclear power loss converted into the weighted subsidies for wind power and photovoltaic power are 5.5 billion yuan and 6 billion yuan, respectively, as shown in Table 7. The benchmark electricity price of the implementation of wind power and photovoltaic projects put into operation before 2016 and 2017 is higher, and the actual renewable energy subsidy cost will be higher than the above estimated amount.

**Table 6.** Renewable energy subsidy weighted price calculation in nuclear power provinces

| Year | 2016 | 2017 |
|------|------|------|
| Wind power generation/(100 million kW·h) | 369 | 453 |
| Proportion of wind power/% | 81.82% | 71.34% |
| Photovoltaic power generation/(100 million kW·h) | 82 | 182 |
| Photovoltaic proportion/% | 18.18% | 28.66% |
| Wind power subsidy price(yuan·(kW·h)⁻¹) | 0.1972 | 0.193 |
| Photovoltaic subsidized electricity price/(yuan·(kW·h)⁻¹) | 0.5629 | 0.4287 |
| Weighted subsidized electricity price of wind power and photovoltaic/(yuan·(kW·h)⁻¹) | 0.2637 | 0.2606 |

**Table 7.** Estimation of subsidy amount of renewable energy for nuclear power curtailment

| Year | Nuclear power loss/(100 million kW·h) | Weighted subsidized electricity price of wind power and photovoltaic/(yuan·(kW·h)⁻¹) | The electricity loss from nuclear power is converted into wind power and photovoltaic weighted subsidy / 100 million yuan |
|------|--------------------------------------|--------------------------------------|------------------------------------------------------------------|
| 2016 | 208 | 0.2637 | 55 |
| 2017 | 230 | 0.2606 | 60 |

3.3. Calculation of nuclear fuel loss

The nuclear fuel cost consists of natural uranium cost, conversion cost, enrichment cost, component cost and recovery cost. According to the technical specification of nuclear power operation, the refueling period of nuclear power units is relatively fixed, and the refueling period is usually 12 months or 18 months. In the refueling cycle, whether the unit is full, power down or standby, the nuclear fuel must be replaced after the end of a fuel cycle. Frequent power rise and fall during the operation will lead to
insufficient fuel combustion and waste. Insufficient combustion of nuclear fuel will lead to waste of uranium resources and increase the cost per KWH. According to relevant studies[4], the average fuel KWH cost of nuclear power in China is 0.057 yuan/(kW·h).

Nuclear fuel loss cost = nuclear power loss power × KWH nuclear fuel cost.

The additional cost of the whole society caused by the failure of nuclear power units to run at full capacity is the sum of the electricity lost from nuclear power converted into renewable energy subsidies and nuclear fuel losses. The cost of renewable energy subsidies shall be borne by all power users. Nuclear fuel loss is a waste of resources and is borne by nuclear power enterprises.

According to calculation, the above expenses are 6.69 billion yuan in 2016 (including 5.5 billion yuan of subsidies for renewable energy and 1.19 billion yuan for nuclear fuel) and 7.31 billion yuan in 2017 (including 6 billion yuan of subsidies for renewable energy and 1.31 billion yuan of nuclear fuel).

3.4. Analysis of wind power and photovoltaic power on par

In November 2017, the national development and reform commission issued the opinions on comprehensively deepening the reform of the pricing mechanism, proposing to "implement the retrograde mechanism of feed-in tariff for wind power, photovoltaic and other new energy sources, and achieve the same feed-in tariff for wind power and coal-fired power generation, and the same feed-in tariff for photovoltaic power and power grid sales by 2020"[5]. In 2020, when the on-grid electricity price of photovoltaic is the same as the grid sales price, the part of the photovoltaic electricity price higher than the benchmark price of coal power still needs the national renewable energy subsidies. Because China's wind power and photovoltaic projects are subsidized for 20 years, existing wind power projects still need 20 years of renewable energy subsidies, even after wind power equals the feed-in tariff of coal-fired power generation.

By the end of June 2019, China has 45 nuclear power units in operation[5]. According to the calculation of the latest planned electricity price of all nuclear power units in July 2019, the average planned on-grid electricity price of nuclear power units is 0.0074 yuan/(kW·h) lower than the local average benchmark electricity price of coal power, as shown in table 11. Wind and solar energy can be obtained at zero cost, wind abandoning and light abandoning will not increase additional costs, while nuclear power generation is not enough to increase the loss of nuclear fuel, in addition to the additional waste disposal costs, so from the economic perspective, nuclear power units should run at full capacity.

4. Coordinated scheduling and development analysis of renewable energy power generation and nuclear power

4.1. Environmental protection

During the operation of nuclear power units with base charge is conducive to promoting the emission reduction of nuclear power units. In addition to the control rod regulation, the reactor boron concentration regulation is also an important means to adjust the power. During the boron concentration dilution process, a certain amount of radioactive waste liquid will be released from the primary circuit. According to the French nuclear power operation experience, the frequent and deep adjustment of power of nuclear power units will greatly increase the generation and treatment of radioactive waste, and only the waste liquid production is 3 to 5 times of the base-load stable operation.

4.2. Grid friendliness

Wind power and photovoltaic power generation have the characteristics of intermittence and volatilility, and wind power has the characteristics of anti-peak-regulation. Wind power output changes almost all the time and is irregular. Generally, the wind power output is smaller in peak load period and larger in trough load period, which produces the anti-peak-regulation effect on the system. The sunrise force of different wind farms varies greatly and fluctuates obviously.

The output power of photovoltaic power is affected by the weather and environmental factors such as illumination, temperature, etc., so its output power presents significant randomness. However, it is
basically consistent with the power consumption load and does not belong to the inverse peak-regulating power supply.

Wind power has the characteristics of anti-peak regulation, which requires the grid to be equipped with backup and peak regulation power, which will increase the operation cost of the grid. Photovoltaic power generation does not belong to inverse peak-regulating power supply; Nuclear power unit load is stable and predictable, suitable for operating as a base-load power supply.

4.3. Safety Perspective

From the perspective of safety, nuclear power frequently participates in load regulation. Firstly, it will increase the probability of human error, secondly, it will increase the risk of fuel cladding damage, and thirdly, it will affect the reliability of the equipment. The operating data of nuclear power units in France, the United States and South Korea show that French nuclear power units participate in load regulation more, and the average number of unplanned shutdown hours per year is much higher than that in the United States and South Korea[6], which to some extent indicates that frequent load regulation will increase the probability of unplanned shutdown.

4.4. International experience

According to international experience, nuclear power plants in countries with a large proportion of nuclear power, such as the United States, the United Kingdom and the republic of Korea, generally operate with base-load. Due to the high proportion of nuclear power installed in France, on the premise of safety, a small number of nuclear power units, after transformation, will properly participate in grid load regulation in the early and middle of the nuclear fuel life. According to relevant studies, it is technically feasible for nuclear motor teams to participate in grid peak regulation, but they need to pay a high price, including reducing the safety, operating life and operating reliability of nuclear power plants, as well as carrying out technical transformation of original nuclear power plants and obtaining the approval of government nuclear safety regulatory authorities. It is not a safe or economic option for nuclear power units to participate in grid peaking, and France is sending electricity to other countries through market means to minimize peaking.

5. Conclusion

Both wind and solar power are renewable sources of energy, which can be developed and used for the same time as the earth's life. The uranium resources as nuclear fuel are non-renewable resources and the number of natural uranium deposits on earth's surface is limited. International data indicate that the world's identified uranium resources can only meet the global needs of more than 430 units for 135 years[7]. From the point of view of economy, environmental protection, safety and international experience, the nuclear motor group is suitable to operate as base-load power supply. From the point of view of grid friendliness, the power quality of nuclear power is better than that of wind power and photovoltaic power.

According to statistics from China electricity federation, by the end of June 2019, among the nuclear power provinces in China, Liaoning has the highest proportion of wind power installed, which is 15.16%. The consumption contradiction between wind power and nuclear power is prominent. Guangdong is currently the largest nuclear power installation province in China, with 14.38 million kW of nuclear capacity in operation as of July 2019. According to the development plan of offshore wind power in Guangdong province (2017-2030)[8], the total planned installed capacity of offshore wind power in Guangdong is 66.85 million kW. Construction will start on 12 million kW in 2020 and 30 million kW in 2030. With a large number of offshore wind power projects coming into operation, Guangdong is expected to soon face the problem of scheduling wind power and nuclear power during the low load period. It is suggested that nuclear power provinces, when formulating clean energy plans, give full consideration to the proportion of renewable energy and nuclear power installed, determine the scale of wind power development according to the capacity of clean energy consumption, and reasonably control
the pace of wind power development, so as to achieve the goal of basically solving the problem of clean energy consumption proposed by the Chinese government.

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