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Generation-network-storage Collaborative Planning of Jiangsu Power Grid Towards Carbon Neutrality

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***Abstract*—Under the goal of carbon neutrality, high shares of renewable energy will be integrated into power systems rapidly. However, as the largest electricity consumption province, Jiangsu faces considerable challenges in transforming the energy supply structure because of renewable energy's intermittent and variable nature. The generation, transmission network and storage need to be coordinated to facilitate carbon emission reduction. In this paper, the carbon-neutral path of the Jiangsu power grid is investigated using Generation-network-storage collaborative planning (GNS-CP). A multi-year and multi-area GNS-CP is conducted with the Generation & Transmission Expansion Planning (GTEP) tool developed by Tsinghua University. Besides, two sensitivity analyses are carried out to investigate the impacts of receiving-end and regional differentiation features of Jiangsu power grid.**

Keywords—carbon neutrality, renewable energy, generation-network- storage collaborative planning, empirical research

I. Introduction

Under the pressure of global warming and fossil fuel depletion, the low-carbon transformation of the energy system has attracted more and more attention from various countries. Demark set an ambitious goal to establish a 100% renewables integrated power system[1]. NREL has also investigated the possibility of renewable energy to supply 80% of the electricity of the USA in 2050[2]. Since the 75th session of the UN General Assembly, carbon neutrality has become the consensus of various industries in China. As the link of energy systems in China, the power system has the responsibility to undertake the critical task of restructuring the energy supply side. High shares of variable renewable energy (VRE) will be rapidly integrated into power systems, which will exert tremendous pressure on the flexibility of power systems. On the one hand, replacing thermal units with less controllable renewable generations will decrease the regulations resources in power systems. On the other hand, the intermittence and uncertainty of VRE will significantly increase the peak-to-valley difference and volatility of the net load curve[3]. Furthermore, if flexible resources are not reasonably allocated at the planning level, the power system may encounter significant renewables curtailment and even cause security issues[4]. Consequently, the primary consideration of power system planning will gradually shift from the balance of power and electricity related to conventional generators to the balance of flexibility related to renewables [5].

Several studies investigate how to incorporate short-term operation constraints into planning models, which is the key technology of planning consider flexibility. On the generation side, Belderbos *et al.* proposed a generation planning model considering the short-term technical operational constraints and analyzed the impacts of intermittence of VRE on the generator portfolio[6]. On the network side, Zhuo et al. studied the transmission expansion planning incorporating massive renewables scenarios and proposed an accelerated solution algorithm based on Benders decomposition and multiple parametric linear programming (MPLP)[7]. On the storage side, Stiphout et al. introduced a generic storage model into the generation expansion planning model and quantified the substitution effect of energy storage on conventional and renewable generations[8].

Though the relevant studies promote VRE accommodation, actual power systems' planning needs to further explore the flexibility potential. Thus, it is necessary to study generation-network-storage collaborative planning (GNS-CP). With the enormous electricity consumption, Jiangsu power grid faces a series of challenges in achieving carbon neutrality. First, Jiangsu faces heavy pressure in the energy supply transition as about 56% of the electricity supply still relies on coal generators in 2020. Second, Jiangsu power grid is a receiving-end grid with more than 15% electricity provided by an external power. The high proportion of external power will significantly affect the flexible operation of internal generators. Third, the regional differences of Jiangsu power grid are apparent. The load is mainly distributed in southern Jiangsu, but the power supply is installed in northern Jiangsu. As a result, transmission planning is closely related to generation planning in Jiangsu. Thus, Jiangsu is in urgent of GNS-CP under the goal of carbon neutrality.

In this paper, we conduct empirical research on the carbon-neutral path of the Jiangsu power grid. A multi-year and multi-area GNS-CP is completed with the Generation & Transmission Expansion Planning (GTEP) tool developed by Tsinghua University. The rest of this paper is arranged as follows. Section II gives a brief introduction to the GTEP tool. The empirical research on Jiangsu grid is demonstrated in Section III. Section IV concludes this paper.

II. GTEP Tool

A. The framework of the GTEP Tool

In this paper, we adopt the GTEP tool to achieve the GNS-CP of Jiangsu power grid. The GTEP tool is developed by Tsinghua University. The framework of this tool is shown in Fig. 1.

The primary function of the GTEP tool is to complete the multi-year GNS-CP for multi-regional power systems. GTEP models the GNS-CP as a two-stage optimization problem. The objective function of GTEP is to minimize the sum of investment cost and operation cost. The fist-stage of GTEP is the coupling constraints of investment decision variables,

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including investment budget constraints, VRE penetration requirements, installed capacity limits, carbon emission limits and multi-year association constraints. The second stage of GTEP is multi-year and multi-area operational constraints. Some details of operating constraints will be introduced in part B of this section.

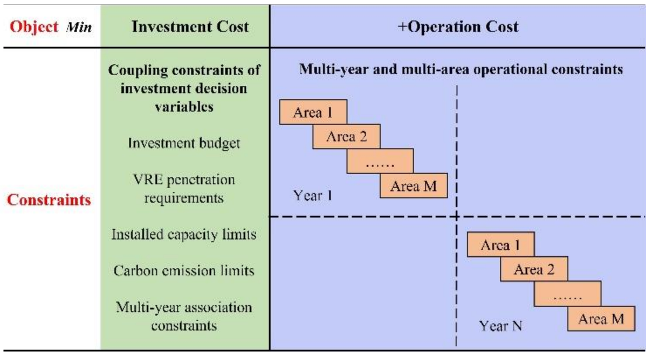

Fig. 1. The framework of the GTEP tool.

The essence of the second stage is to embed the short-term operation model into the long-term planning model. Thus, operating costs will be affected by system flexibility and renewables curtailments, which will guide power system investment decisions to achieve better collaboration of generations, transmission networks, and storage.

B. Operational constraints of the GTEP

The second stage of GTEP is modified from the unit commitment (UC) model. To overcome the excessive computation burden of traditional UC models, GTEP adopts the network-constrained relaxed clustered unit commitment (NC-RCUC) model first proposed in [9]. The detailed constraints on conventional generators are listed below. Equation (1) limits the output power of the cluster of generators. Equations (2) and (3) constrain the output power of each generator. Equation (4) describes the start-up and shut-down behaviors of the cluster. Equations (5) and (6) indicate the minimum online/offline time constraints of the cluster.

$$0 \le \lambda_i^{G,Min} O_{i,t}^G \le \sum_{g\in\Omega_i^G} P_{g,t}^G \le O_{i,t}^G \le \sum_{g\in\Omega_i^G} Cap_g^G, \forall i, \forall t \quad (1)$$

$$0 \le P_{g,t}^G \le Cap_g^G, \forall g, \forall t \quad (2)$$

$$-\alpha_g^{G,DN} Cap_g^G \le P_{g,t}^G - P_{g,t-1}^G \le \alpha_g^{G,UP} Cap_g^G, \forall g, \forall t \quad (3)$$

$$O_{i,t}^G - O_{i,t-1}^G = SU_{i,t}^G - SD_{i,t}^G, \forall i, \forall t \quad (4)$$

$$O_{i,t}^G \ge \sum_{\tau=t-T_i^{G,On}}^{t-1} SU_{i,\tau}^G, \forall i, \forall t \quad (5)$$

$$O_{i,t}^G \le \sum_{g\in\Omega_i^G} Cap_g^G - \sum_{\tau=t-T_i^{G,Off}}^{t-1} SD_{i,\tau}^G, \forall i, \forall t \quad (6)$$

where Ω_i^G indicates the set of thermal units belonging to the cluster i. $O_{i,t}^G$, $SU_{i,t}^G$ and $SD_{i,t}^G$ represent the online capacity, start-up capacity and shut-down capacity of the cluster i at period t, respectively. $T_i^{G,on}$ and $T_i^{G,off}$ are the minimum on/off period of the cluster i. $P_{g,t}^G$ is the output power of the generator g. Cap_g^G, $\alpha_g^{G,UP}$ and $\alpha_g^{G,DN}$ are the installed capacity, ramp up rate and ramp down rate of generator g.

To achieve GNS-CP, the second stage of GTEP also includes network constraints and the storage model. The network constraints are the classic DC power flow model consisting of (7) and (8). The storage constraints use a generalized model including (9)-(11). Equation (9) limits the charging and discharging power of each battery. Equation (10) links the state of charge (SOC) with the charging behavior of storage. Equation (11) limits the SOC of storage.

$$F_{l,t} = B_l\left(\theta_{l(+),t} - \theta_{l(-),t}\right) \quad (7)$$

$$-\pi \le \theta \le \pi \quad (8)$$

$$0 \le P_{b,t}^{B,cha}, P_{b,t}^{B,dis} \le Cap_b^B, \forall b, \forall t \quad (9)$$

$$SOC_{b,t}^B - SOC_{b,t-1}^B = \eta_b P_{b,t}^{B,cha} - P_{b,t}^{B,dis} / \eta_b, \forall b, \forall t \quad (10)$$

$$0 \le SOC_{b,t}^B \le H_b^B Cap_b^B, \forall s, \forall t \quad (11)$$

With relaxing online capacity to a continuous variable, NC-RCUC transforms the mix-integer linear programming (MILP) based traditional UC model into an entirely linear programming (LP) model. Thus, the second stage of GTEP performs well in computational efficiency and can even support hourly operational scenarios (8760 hours) of multi-year and multi-area power systems. The impacts of intermittent VRE can be well assessed in planning with such massive scenarios. Consequently, generation, transmission network and storage can be collaboratively allocated to satisfy the flexible requirements in power systems.

III. Empirical Research

Empirical research on the carbon neutrality path of Jiangsu grid is carried out through GNS-CP with the GTEP tool. This section consists of three parts. The first part provides the basic data of Jiangsu power grid and discusses some planning settings. The second part gives the base case results of GNS-CP and analyzes ist operating characteristics. The third part conducts several sensitivity analyses to investigate the impacts of receiving-end and regional differentiation features of Jiangsu power grid.

A. Basic Data of GNS-CP

Jiangsu is the largest electricity consumption province in China, with a peak load of 115.13GW and annual electricity consumption of 637.4TWh in 2020. Fig. 2. shows the forecast of peak load and electricity consumption of Jiangsu power grid in the next 40 years. The changing trend of peak load and electricity consumption is a little bit different. Peak load shows a trend of rapid growth first and then saturation. However, electricity consumption has two periods of significant growth. The first one between 2020 and 2030 is related to the carbon emission target in 2030, while the second one between 2045 and 2050 is associated with electricity replacement of Jiangsu province.

As the planning for the next ten years is relatively determined, this paper mainly focuses on the carbon neutrality path of Jiangsu power grid from 2030 to 2060. We simplified the Jiangsu power grid as a three-bus system, as shown in Fig. 3. The eight cities north of the Yangtze River are Northern

Jiangsu (NorJS) bus while the other five cities are Southern Jiangsu (SouJS) bus. And an extra bus is added to reflect the external power. The forecasted peak load and electricity consumption of different regions are shown in Fig.4 and Fig. 5. In general, the significant increases in peak load and electricity consumption come from NorJS, so the ratio of SouJS to NorJS continues to decline. Thus, load distribution in Jiangsu will be more balanced in the future.

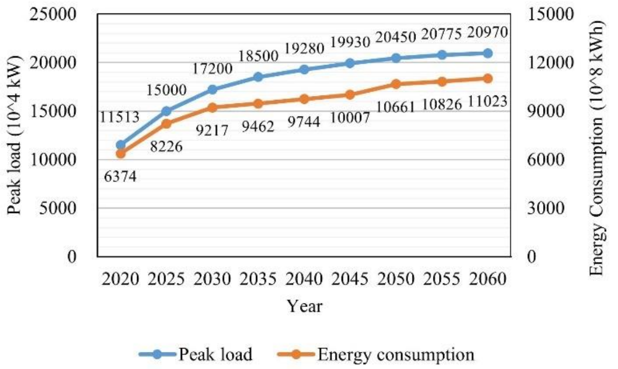

Fig. 2. Forecast of peak load and electricity consumption of Jiangsu power grid in the next 40 years.

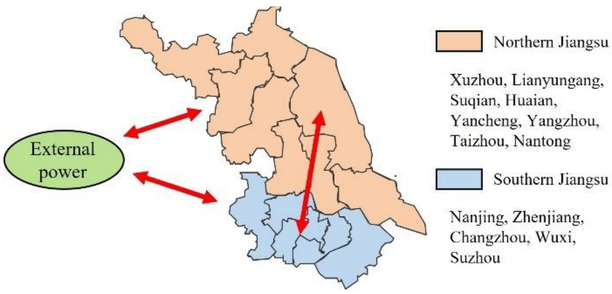

Fig. 3. The three-bus system simplified from Jiangsu power grid.

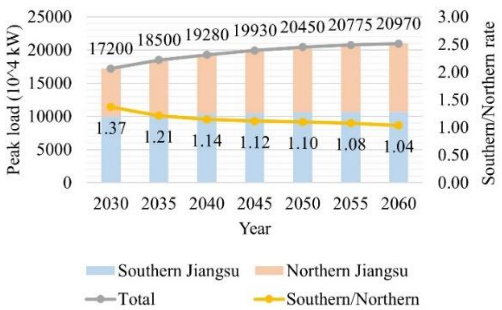

Fig. 4. The forecasted peak load of different regions in Jiangsu power grid between 2030 and 2060.

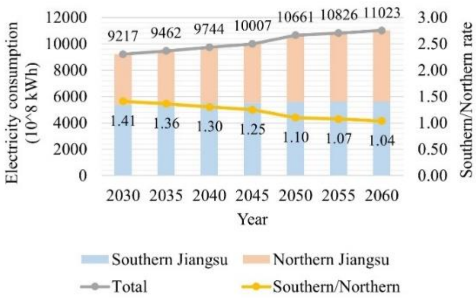

Fig. 5. The forecasted electricity consumption of different regions in Jiangsu power grid between 2030 and 2060.

The curves of load and renewables output of each season are clustered into one week. Thus the scenarios of a year can be represented by four typical weeks, namely, 672 hours. The curves of load and renewables are shown in Fig.6-Fig.9.

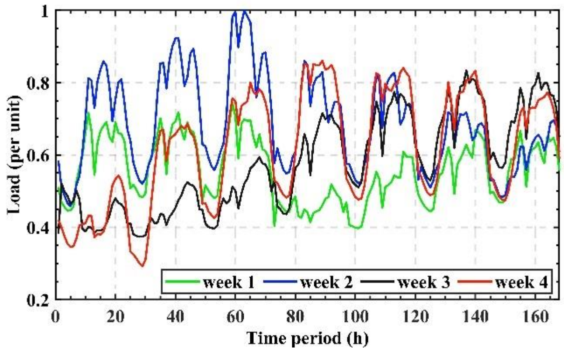

Fig. 6. Load curves of selected scenarios.

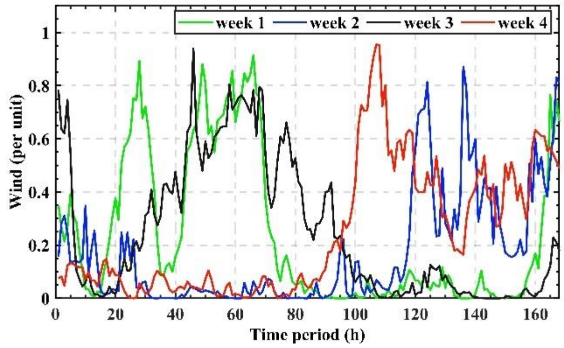

Fig. 7. Wind output curves of selected scenarios.

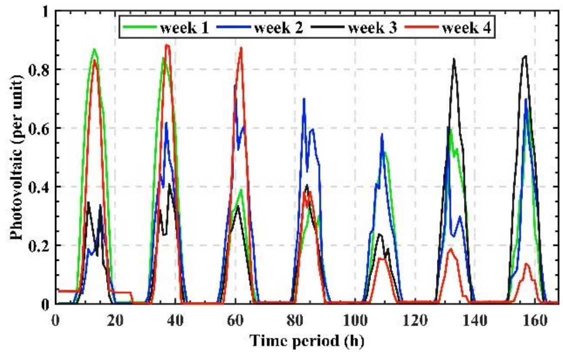

Fig. 8. Photovoltaic(PV) output curves of selected scenarios.

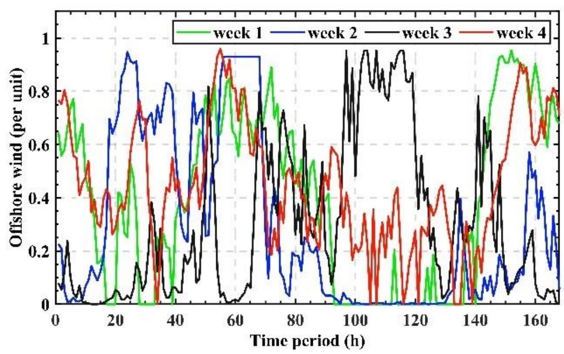

Fig. 9. Offshore wind output curves of selected scenarios.

The cost and installed capacity of generators are set in Table I and Table II.

TABLE I. INVESTMENT COST OF DIFFERENT TYPES OF GENERATORS

10^4 ¥/(MW • Year)

	2035	2040	2045	2050	2055	2060
Coal	420	400	380	360	340	320
Gas	430	410	390	370	350	330
Nuclear	950	930	910	890	870	850
Wind (NorJS)	640	620	600	580	560	540
Wind (SouJS)	680	660	640	620	600	580
PV	380	360	340	320	300	280
Offshore wind	1600	1550	1500	1450	1350	1250
Biomass	700	680	660	640	620	600
Storage(NorJS)	270	265	255	240	220	190
Storage(SouJS)	280	275	265	250	230	200

TABLE II. INSTALLED CAPACITY IN 2030

10^4 kW

	Coal	Gas	Nuclear	Wind	PV	Bio	Storage	Pump
NorJS	2641	936	902	4470	5914	204	484	120
SouJS	2158	2191	0	30	1586	146	66	395
Total	4799	3127	902	4500	7500	350	550	515

* Bio: biomass; Pump: pumped storage power station.

B. Base Case

In the base case, we set the renewables penetration and curtailment limits as Table III. The total capacity of transmission lines between NorJS and SouJS is set to the fixed 30000 MW. Then, a three-region and six-year generation planning is carried out with the GTEP tool. The results are shown in Fig.10–Fig. 14.

TABLE III. INVESTMENT COST OF DIFFERENT TYPES OF GENERATORS

10^4 ¥/(MW • Year)

	2035	2040	2045	2050	2055	2060
Penetration requirement	40%	45%	50%	55%	58%	60%
Curtailment limit	10%	10%	10%	10%	10%	10%

The significant increment of installed capacity comes from wind power and PV. The installed capacity of intermittent VER has increased rapidly from 120GW in 2030 to 368GW in 2060. In terms of spatial distribution, the increment of PV is mainly in SouJS, while the increased wind power is installed primarily in NorJS. From the time scale, the growth of installed capacity is multi-stage. Before 2050, the growth rates of installed capacity of wind power and PV are roughly the same. However, offshore wind power is the significant increment in the system installed capacity after 2050. For accommodating VRE, energy storage will also begin to increase significantly in 2050. By 2060, the installed energy storage capacity has reached 39.7GW, accounting for 7.9% of the installed capacity in Jiangsu Province. The curtailment rate of VRE is showing an upward trend, approaching 9% in 2050. With the increase of installed energy storage capacity, the curtailment rate of VRE is effectively controlled below 10%.

From the perspective of generated electricity, the proportion of intermittent VER continues to increase, from 30.7% in 2035 to 50.1% in 2060. Considering the hydropower from external power, the planning results can meet the requirements in Table III. In 2060, wind power contributes the major generated electricity, reaching 31.7%, and PV also provides 18.4% of generated electricity. Meanwhile, the proportion of coal generators in the province declines, from 30.8% in 2035 to 12.7% in 2060. The changing trend of carbon emissions of Jiangsu is also similar, from 24868 t CO_2 to 14510 t CO_2, in line with the carbon neutrality requirements of Jiangsu power grid.

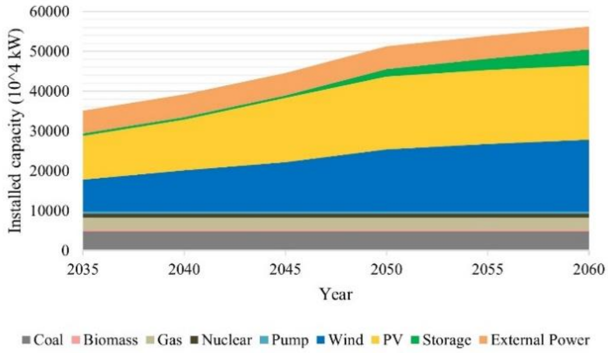

Fig. 10. Installed capacity of Jiangsu Province between 2035~2060.

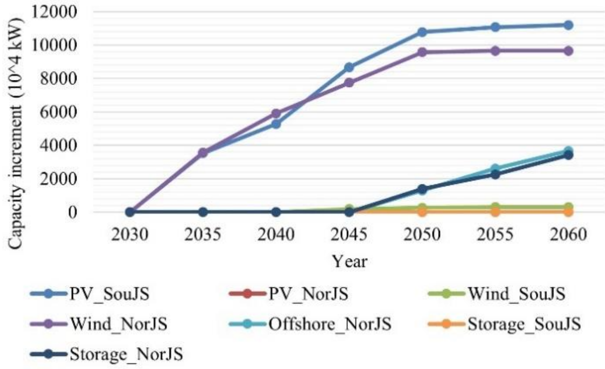

Fig. 11. New installed capacity of Jiangsu Province between 2035~2060.

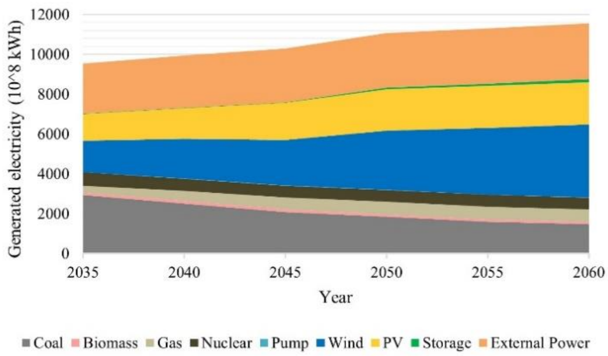

Fig. 12. Generated electricity of Jiangsu Province between 2035 and 2060.

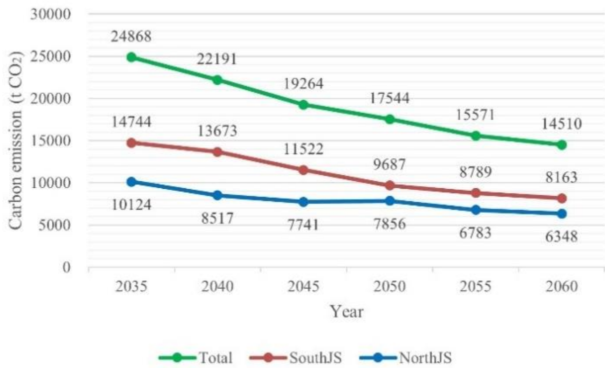

Fig. 13. Carbon emission of Jiangsu power grid between 2035 and 2060.

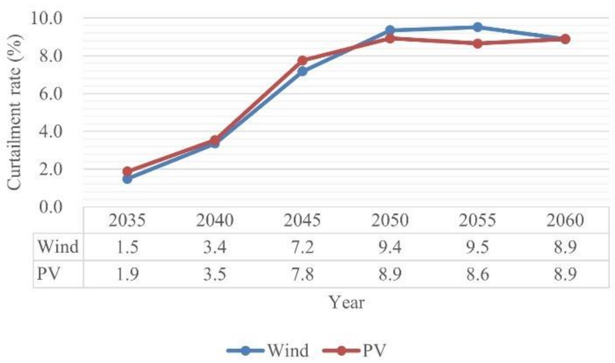

Fig. 14. Carbon emission of Jiangsu power grid between 2035 and 2060.

The change of the generation mix has a significant impact on the operation of Jiangsu power grid. Fig. 15 displays the VRE instantaneous penetration rate (VRE-IP) in 2035 and 2060. As we can see, the VRE-IP in 2060 is higher than that of 2035. In some extreme moments, VRE-IP in 2060 may even exceed 100% with the help of storage charging, which will not happen in 2035. Fig. 16 shows the operation scenarios of a typical week in 2035 and 2060. The results indicate that the intermittent nature of wind power and PV will have an increasingly significant impact on the system's operation with the growth of VRE penetration. The online capacity of thermal generators will be deficient when the outputs of wind power and PV are large, which may bring low inertia issues to Jiangsu power grid [10]. Fig. 17 demonstrates the operation of storage in another typical week. In order to accommodate VRE, the storages experience much more charging and discharging cycles within a day in 2060 than those in 2035. The increase of energy storage utilization and the decrease of its costs are the two main reasons for the substantial increase of energy storage after 2050.

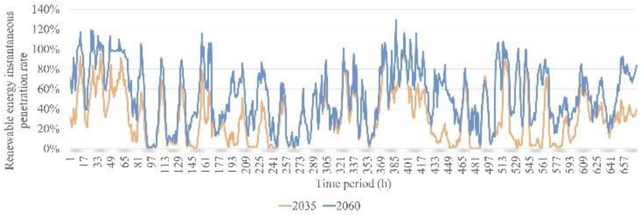

Fig. 15. Comparison of renewable energy instantaneous penetration rate of 2035 and 2060.

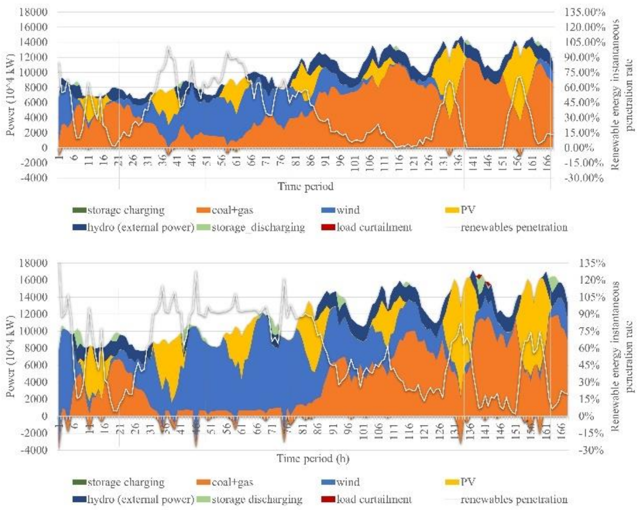

Fig. 16. Operation scenarios of week 3, typical week in summer, in 2035 and 2060 (upper: 2035, lower: 2060).

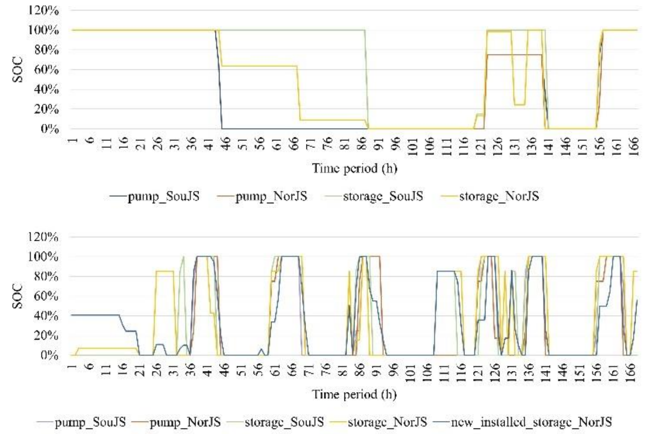

Fig. 17. Behaviors of storage in week 2, typical week in autumn, in 2035 and 2060 (upper: 2035, lower: 2060).

C. Sensitivity Analysis

Considering receiving-end and regional differentiation features of Jiangsu power grid, we conduct two sensitivity analyses on the regulation ability of the external power and transmission capacity between NorJS and SouJS in this part.

1) Regulation Ability of the External Power

We set three different cases to investigate the impacts of the regulation capacity of the external power delivery on planning results.

Case 1: the thermal generators of the external power keep their outputs as the half of their capacity in all four weeks.

Case 2: the thermal generators of the external power keep their outputs as 0.35, 0.75, 0.3, 0.6 of their capacity in four weeks, respectively. Table IV shows the relationship between the set output of external power and average load of each week.

Case 3: the thermal generators of the external power freely adjust their output in all four weeks.

TABLE IV. INSTALLED CAPACITY OF STORAGE

	week 1	week 2	week 3	week 4
Set output (per unit)	0.35	0.75	0.3	0.6
Average load (per unit)	0.5574	0.6877	0.5754	0.6180

The installed capacity of storage and renewables curtailment rates are shown in Table V and Fig. 18. Among the three cases, the installed capacity of Case 3 is the lowest, however, the renewables curtailment rate of Case 3 is also the lowest. This result indicates the significance of the flexible regulation ability of high proportion of the external power in Jiangsu power grid. Moreover, according to the comparison of Case 1 and Case 2 in 2060, even semi-flexible regulation ability can also improve the economics of system planning with appropriate settings.

TABLE V. INSTALLED CAPACITY OF STORAGE

10^4 kW

	2035	2040	2045	2050	2055	2060
Case 1	550	1464	1464	2344	3032	4867
Case 2	550	1256	1676	3349	3370	4634
Case 3	550	550	550	2055	3032	4296

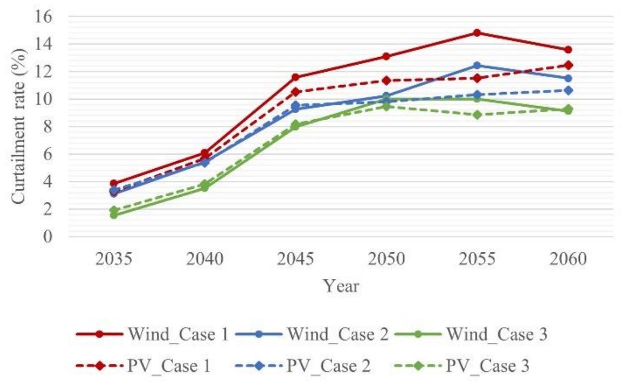

Fig. 18. Impacts of regulation ability of the external power on renewables curtaiment.

2) *Transmission Capacity between NorJS and SouJS*

High shares of renewable energy will exert significant pressure on the transmission lines between NorJS and SouJS. Fig. 19 shows the transmission congestion of base case (Case1). It is evident that transmission congestion will be very frequent after 2045. Thus, we conduct a sensitivity analysis here to investigate the effect of generation & transmission collaborative planning completed by the GTEP tool (Case 2). The investment cost of the transmission line is listed in Table VI.

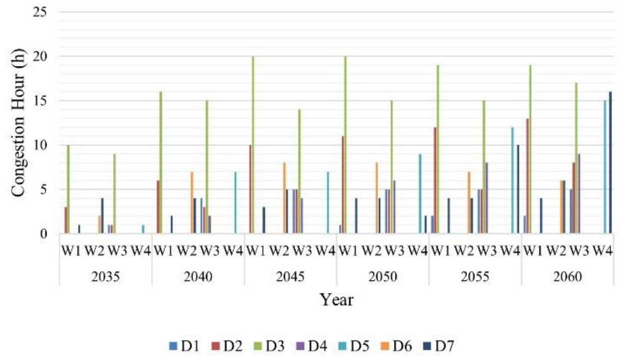

Fig. 19. Transmission congestion between NorJS and SouJS in base case.

TABLE VI. INVESTMENT COST OF TRANSMISSION LINE

10^4 ￥/(MW • Year)

	2035	2040	2045	2050	2055	2060
Cost	20	18	16	14	12	10

Fig. 20 display the capacity of transmission line between NorJS and SouJS in two cases. The capacity of transmission line between NorJS and SouJS will increase from 2045 to 2060 to relieve the congestion. The average congestion time will be significantly reduced, as shown in Table VII. This sensitivity analysis reflects the importance of the collaborative planning.

TABLE VII. AVERAGE CONGESTION TIME OF TRANSMISSION LINE BETWEEN NORJS AND SOUJS

hour per day

	2035	2040	2045	2050	2055	2060
Case 1	1.14	2.36	2.89	3.21	3.68	4.29
Case 2	1.11	2.39	2.29	2.68	2.75	2.86

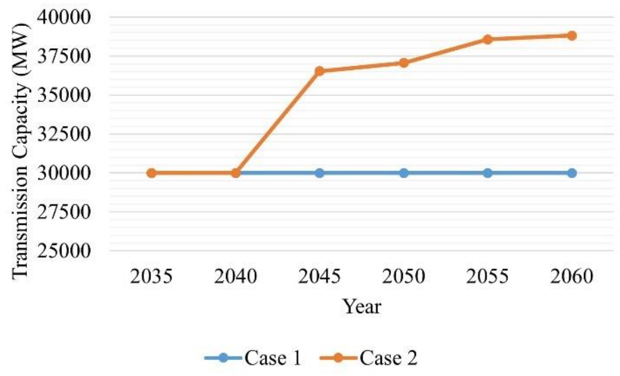

Fig. 20. Transmission capacity between NorJS and SouJS in two cases.

IV. CONCLUSION

This paper discusses the long-term planning of the power system with large-scale VRE integration. The uncertainty and intermittence of VRE will exert tremendous pressure on the flexibility of power systems. Thus, it is necessary to study the GNS-CP. Using GNS-CP, we conduct empirical study on the carbon-neutral path of Jiangsu power grid with the GTEP tool developed by Tsinghua University. And two sensitivity analyses are carried out to investigate the impacts of Jiangsu power grid's receiving-end and regional differentiation features.

Through this study, three conclusions can be drawn: 1) Flexibility is a scarce resource in the power system under carbon neutrality. Therefore, energy storage will play an increasingly important role in the future. For Jiangsu power grid, energy storage will account for 7.9% of the total installed capacity in 2060. 2) For the receiving-end system similar to Jiangsu power grid, the flexible regulation ability of the external power is of great value to VRE accommodation and planning investment reduction. 3) Collaborative planning has a significant effect in relieving transmission congestion with high shares of VRE.

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