Renewable and Sustainable Energy Reviews 130 (2020) 109985

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: http://www.elsevier.com/locate/rser

Low carbon transition pathway of power sector with high penetration of renewable energy

Siyuan Chen, Pei Liu *, Zheng Li

State Key Lab of Power Systems, Department of Energy and Power Engineering, Tsinghua University, Beijing, China

ARTICLE INFO

Keywords:
Low carbon transition
Renewable energy penetration
Power generation expansion planning

ABSTRACT

The basic trend of low-carbon power sector transition is the expansion of non-fossil power, especially the power generation from renewable energy sources. With the higher penetration of renewable energy into the power system, the flexibility requirements and integration costs are important issues. The flexible generation of thermal power plants could serve as an effective solution to accommodating high share of variable renewable energy electricity. However, it brings about additional integration costs, which should be quantitatively assessed. In this paper, a long-term power generation expansion planning model incorporating integration costs for renewable energy penetration is proposed. This model is used to obtain the most cost-effective low carbon transition pathway of power sector with high penetration of renewable energy and analyze the impact of incorporating short-term integration costs on the long-term power generation planning. China is selected for a case study as it has the largest scale of thermal power plants in the world and urgent need for low carbon transition. The results indicate that thermal power plants gradually change from baseload providers to flexibility providers in the power system for higher penetration of renewable energy. The variable fuel consumption rate of thermal power plants should be taken into account otherwise the total carbon emissions and emission reduction cost would be underestimated.

1. Introduction

Renewable energy sources (RES) are playing a more important role in the low carbon transition and sustainable development of global energy system. Renewable electricity is expected to grow rapidly, accounting for around two-thirds of the growth in global power generation [1]. By 2040, renewable electricity would become the largest source of global power generation. However, high dependence on climate and weather causes renewable energy to be fluctuating and intermittent. The fluctuation of RES power output poses great challenges on the integration issues. The high penetration of renewable energy raises more requirements on flexibility to ensure the reliability of power system [2]. Alizadeh et al. [3] emphasized the importance of flexibility assessment with the increasing penetration rate of variable power generation resources into the power system. This study presents a comprehensive literature review and provides a classification of latest flexibility resources in power systems. Moreover, it discusses the current barriers and hidden potentials of power systems to deal with the high penetration of variable power generation. Papaefthymiou and Dragoon [4] indicate that the transition to power systems relying primarily on variable renewables needs expanded flexibility to maintain the stability and reliability. Through a comprehensive overview of the needed institutional frameworks, policies and technical changes to enable this transition, this study provides a basis for developing an assessment tool to deal with this issue.

Generally, solutions to integrate variable renewable energy (VRE) into the power system can be divided into four categories: supply-side solutions, grid-side solutions, demand-side solutions and system-wide storage solutions [5]. From the supply side, flexibility could be provided by decreasing variable renewable energy generation forecasting uncertainty and flexible generation of conventional power plants. The grid-side flexibility solutions include interconnected power grids, regional power markets and long-distance super-grids. In terms of demand-side solutions, distributed energy system, demand-side management and renewable energy mini-grids are potential flexibility providers. Utility-scale battery and power-to-X solutions can serve as system-wide storage flexibility solutions. Among all these solutions, flexible generation has the highest potential to increase system

* Corresponding author.
E-mail address: liu_pei@tsinghua.edu.cn (P. Liu).

https://doi.org/10.1016/j.rser.2020.109985
Received 19 February 2020; Received in revised form 26 May 2020; Accepted 8 June 2020
Available online 20 June 2020
1364-0321/

flexibility while simultaneously has moderate technology cost and non-technological challenges [5]. The flexible generation of coal and gas power plants can fully utilize the existing facilities without additional investments for large-scale infrastructures such as power grids reinforcement and energy storage units. This solution can serve as a transitional scheme, especially practical for the countries dominated by fossil fuel power plants at present. The flexible generation of thermal power plants mainly refer to more start-up and shut-down actions as well as running at part load more frequently. Therefore, incorporating these short-term operational characteristics into the long-term power generation expansion planning models draws great attention from researchers [6].

Traditional long-term power generation expansion planning models pay little attention to the operational processes of power plants. In order to deal with this problem, soft-linking the long-term planning model with the short-term scheduling model has been widely applied. Deane et al. [7] soft-link a dedicated power systems model named PLEXOS which contains detailed short-term operational features with a separate energy system model named The Integrated MARKAL-EFOM System (TIMES). The optimal capacity mix is firstly obtained from the energy system model and then input to the power systems model with high technical details to undertake detailed high resolution chronological simulation. The results indicate that wind curtailment would be underestimated and the use of baseload plants would be overestimated if the load dispatch process with high time resolution is neglected. Pina et al. [8] present a methodology framework which soft-links the long-term investment planning model TIMES with the short-term scheduling model EnergyPLAN. The investment decisions of power generation capacity are optimized with hourly balance of power supply and demand being considered. With this soft-linking modelling framework, curtailment of renewable energy sources could be reduced and overinvestment could be avoided. Diakov et al. [9] develop a soft-linking tool to onset the prescriptions of capacity planning model named The Regional Energy Deployment System (ReEDS) onto the input of power systems model PLEXOS. The soft-linking tool can smoothly translate the input and output of the two models to each other and ensure the interactions between them. The capacity expansion is simulated whilst the operational details of power system is maintained. It is noteworthy that the soft-linking approach usually applies an interactive way to solve the power generation expansion planning problems. The capacity planning model and short-term scheduling model usually run independently. Scheduling models are usually applied to provide details of operation and confirm the validity of capacity expansion predictions. However, the investment decisions of power generation capacity are not directly influenced and constrained by the operation details.

So as to reflect the direct influence of operational characteristics on capacity expansion planning, researchers directly integrate the short-term operation details into the long-term model and simultaneously optimize the capacity expansion and operation. Some researchers focus on characterizing the uncertainty of RES output. Hirth and Ziegenhagen [10] apply a probabilistic approach to estimate the individual probability density functions of forecast errors regarding electricity demand, wind and solar output based on historical data. The reserve requirements in the power system are then calculated endogenously with the joint density distribution. Ueckerdt et al. [11] propose the residual load duration curve (RLDC) approach to incorporate the fluctuation of both variable renewable energy output and electricity demand into long-term energy-economy models. The residual load duration curves change endogenously in response to the share of variable renewable energy. This method allows for a jointly optimization of investment decisions and operation decisions of non-VRE plants. Stochastic programming is also widely applied by researchers to represent uncertainty. Banzo and Ramos [12] apply a stochastic programming model to minimize the investment and operational costs for an electric power system of off-shore wind farms with the consideration of wind speed stochasticity and system reliability. Conejo et al. [13] propose a stochastic optimization model to take into account the short-term uncertainty of wind power generation and its correlation with power demand by clustering historical data. Monte-Carlo Simulation (MCS) is applied by Hemmati et al. [14] to include the uncertainty of wind power output into generation and transmission expansion planning in the competitive electricity market.

The operational flexibility needed to address the uncertainty of RES is represented by reserve capacity in early studies. Soder [15] extends the conventional hydro-thermal model to a wind-hydro-thermal model to take into account the uncertainty of wind power generation and load forecast. The instantaneous, fast, and slow reserves required for the power system are calculated. Doherty and OMalley [16] propose a methodology which quantifies the system required reserves given the uncertain nature of wind power and generator outage rates. This study uses system reliability as an objective measure and indicates that the increased wind power capacity would decrease the system reliability without increased reserve capacity. Ela et al. [17] make a comprehensive review of current studies on the needs of operating reserves with high penetration of variable renewable generation. They introduce a categorization of different types of operating reserve to help researchers better understand similar reserve definitions. The management of operating reserves today and in the future is also proposed. Although the reserve capacity can act as a method that indicates the flexibility requirements, it may differ from case to case depending on the power generation structure and RES characteristics. In order to directly describe the flexible generation of power plants, Palmintier and Webster [18] cluster the power plants with the same operation patterns and incorporate unit commitment into long-term capacity planning. The results display that the original power generation mix could be infeasible if short-term flexibility is ignored. Koltsaklis and Georgiadis [19] embed the plant-level unit commitment process in the long-term capacity expansion planning problem with a mixed-integer linear programming (MILP) model. Short-term operation details of thermal power units, such as minimum up and down time, ramping limits, start-up and shut-down decisions are integrated into the model as daily constraints. Welsch et al. [20] integrate the operational details into the open source energy system model (OSeMOSYS) through a thorough data analysis. The dispatch results match well with the results of the hybrid model with a 700 times higher temporal resolution, which is a prominent improvement compared with previous model results. The comparison of results indicates that the importance of flexibility within the power system and the cost of introducing variable renewables would be underestimated if the supply and demand variability is ignored.

Existing literature mainly focus on integrating the short-term power dispatch process into the long-term power generation expansion planning problem in order to ensure the operational feasibility of the generation portfolio with high share of VRE. However, the integration cost for RES penetration is rarely taken into account. For instance, the fuel consumption rate is much higher than the design value when thermal power plants run at part load. Higher fuel consumption rate means not only higher cost, but also higher CO_2 emissions. This study focuses on incorporating the integration costs and additional emissions incurred by the flexible generation of power plants for RES penetration into long-term power generation expansion planning for low carbon transition and assessing its impact on future power generation mix. So as to reflect the characteristics of real power system and obtain credible results, we propose an optimization model which integrates long-term power generation expansion planning and short-term operational details as well as flexibility costs. China is taken for a case study as China has a large amount of existing thermal power plants and is facing the pressure of low-carbon transition at the same time.

The paper is organized as follows: Section 2 presents the methodology. The results analysis and discussion are demonstrated in Section 3. In Section 4, the main conclusions are summarized.

2. Methodology

2.1. Model description

The model proposed in this paper aims to jointly optimize long-term planning and short-term scheduling of power system. The model determines the optimal type, size, construction time and scheduling of power plants. The structure of the model is presented in Fig. 1, comprising Input, Constraints, Objective Function and Output. Exogenous parameters should be input to the model beforehand, such as the existing installed capacity of different power generation technologies, predicted power demand in the future, costs and efficiency of all power generation technologies, resource endowment of renewable energy and fossil fuels, and relevant policy targets. The Constraints contain five categories: (1) the balance of power supply and demand; (2) operation characteristics of power plants; (3) power transmission among the regions; (4) the life cycle of power plants (construction, operation, retirement); (5) policy compliance. The model objective is to minimize the total system cost in the planning horizon. Finally, the Output can provide yearly installed capacity mix and power generation mix, short-term load dispatch profile, fuel consumption and the corresponding CO_2 emissions.

Six kinds of power generation technologies are included in this model, namely pulverized coal power (PC), natural gas combined cycle power (NGCC), nuclear power (NU), hydro power (HD), wind power (WD) and solar photovoltaic (PV). All power plants are set to be decommissioned after reaching the economic lifetime except coal-fired power plants. Due to their higher emissions, coal-fired power plants are assumed to have the option to be decommissioned earlier than the expected lifetime. Therefore, all the possible development pathways are included, which forms a superstructure model. The optimal construction plan of different types of power plants is then determined based on the objective function. The model is a multi-regional model which contains a spatial module to characterize power balance from the regional perspective so as to capture the differences of natural resources and demand profile among regions. The spatial module includes the interconnections among regions and power transmission is reflected. So as to describe the fluctuation of power load and the volatility and intermittency of renewable energy, a temporal module is incorporated to determine the hourly power output of different power generation technologies. In the temporal module, each year in the planning horizon is divided into 96 time slices, including four representative days in each season. The representative day in each season which contains 24 h is selected to characterize the hourly power balance. More flexibility is needed for load dispatch with high penetration of variable renewable energy in the power system. In this model, thermal power plants act as a big flexibility provider by flexible generation. The flexibility generation would require thermal power plants to run at part load more often. However, the fuel consumption rate of thermal power plants is strongly influenced by the load factor. When a thermal power plant runs at 30% load, the fuel consumption rate would increase by 11%. The variability of fuel consumption rate in response to the load factor is taken into account in the model.

2.2. Mathematical formulation

In order to cover different dimensions (year, region, technology, fuel type, and time slice), five subscripts (t, r, g, f and s) are set respectively for the parameters and variables. Upper-case characters are used to denote parameters and lower-case characters are used to denote variables. The detailed meanings of the abbreviations in the equations are listed in Appendix A.

2.2.1. Objective function

The model objective is minimizing the accumulated total system cost *atc* in the planning horizon (from 2016 to 2030), including capital cost $tinv_{r,t}$, operation and maintenance cost $tom_{r,t}$, fuel cost $tfc_{r,t}$, start-up and shut-down cost $tss_{r,t}$, and power transmission cost $tptrc_{r,t}$, see Eq. (1). The calculation of the five cost components is shown in Eqs. (2)–(6). The capital cost $tinv_{r,t}$ equals unit capital cost $CAP_{r,t,g}$ multiplying newly-built capacity $nb_{r,t,g}$ and are discounted equally to each year over the entire lifetime TLT_g of power plants. The operation and maintenance cost $tom_{r,t}$ equals the annual unit cost $\mu_{t,g}$ multiplying the total installed capacity $ic_{r,t,g}$. The fuel cost $tfc_{r,t}$ is obtained by multiplying fuel demand $fd_{f,r,t,g,s}$ by fuel prices $FP_{f,r,t}$ whilst the start-up and shut-down cost $tss_{r,t}$ is the product of unit start-up and shut-down cost SCC_g and capacity $su_{r,t,g,s}$, $sd_{r,t,g,s}$. The power transmission cost $tptrc_{r,t}$ is the product of power transmission volume $ideaptr_{r,r',t,s}$ and unit transmission cost $TRCOST_{r,r'}$.

$$atc = \sum_{t=2016}^{2030} \sum_{r} \frac{tinv_{r,t} + tom_{r,t} + tfc_{r,t} + tss_{r,t} + tptrc r,t}{(1+I)^{t-2016}} \tag{1}$$

$$tinv_{r,t} = \sum_{g} \sum_{t'=t-TLT_g+1}^{t} \left(CAP_{r,t',g} \cdot nb_{r,t',g} \cdot \frac{I\cdot(1+I)^{-1}}{1-(1+I)^{-TLT_g}} \right) \tag{2}$$

$$tom_{r,t} = \sum_{g} \mu_{t,g} \cdot ic_{r,t,g} \tag{3}$$

$$tfc_{r,t} = \sum_{f} FP_{f,r,t} \cdot \sum_{g,s} fd_{f,r,t,g,s} \tag{4}$$

$$tss_{r,t} = \sum_{g} \sum_{s} SSC_g \cdot (su_{r,t,g,s} + sd_{r,t,g,s}) \tag{5}$$

$$tptrc_{r,t} = \sum_{s} \sum_{r' \neq r} ideaptr_{r,r',t,s} \cdot TRCOST_{r,r'} \tag{6}$$

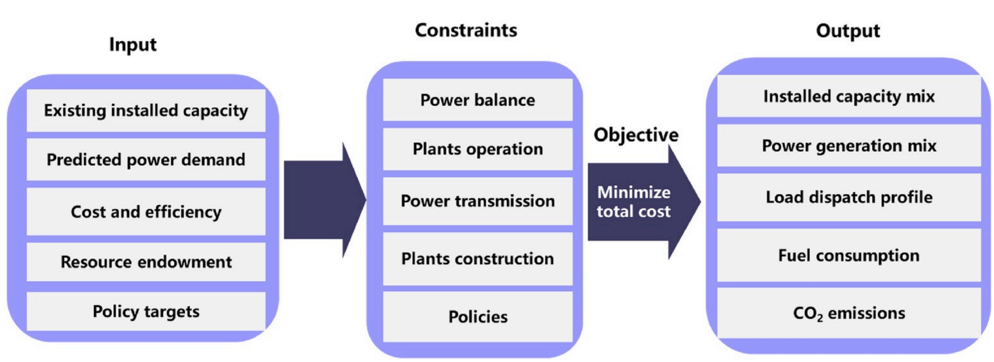


Fig. 1. Model framework.

2.2.2. Operational constraints

Power demand in each region in each time slice $PD_{r,t,s}$ is assumed to equal regional power generation $pg_{r,t,g,s}$ coupled with net power import $ptr_{r,t,s}$ (power import minus power export), as expressed in Eq. (7).

$$PD_{r,t,s} = \sum_{g} pg_{r,t,g,s} + ptr_{r,t,s} \tag{7}$$

Power output of different power generation technologies are set as free variables constrained by their load factors. For renewable energy, load factor mainly depends on resource availability, i.e. wind speed, solar radiation intensity and water flow. The constraints are shown in Eq. (8). Nuclear power normally serves as base load in the power system. It is assumed to run in a specific load range between $MINOH_{r,t,g,s}$ and $MAXOH_{r,t,g,s}$, which is also expressed in Eq. (8). In terms of thermal power plants, the operational constraints are more complicated considering operating characteristics. Eq. (9) is used to represent the start-up $st_{r,t,g,s}$ and shut-down $sd_{r,t,g,s}$ decisions of thermal power plants. Piecewise linearization method is used to represent the nonlinear relationship between fuel consumption rate $FCR_{f,g}$ and load factor as shown in Eq. (10) - (12).

$$MINOH_{r,t,g,s} \cdot ic_{r,t,g} \le pg_{r,t,g,s} \le MAXOH_{r,t,g,s} \cdot ic_{r,t,g} \quad g \in (NU, HD, WD, PV) \tag{8}$$

$$oc_{r,t,g,s+1} = oc_{r,t,g,s} + st_{r,t,g,s} - sd_{r,t,g,s} \quad g \in (SPC, UPC, NGCC) \tag{9}$$

$$MINOH^{i}_{r,t,g,s} \cdot oc_{r,t,g} - M(1-x_i) \le pg_{r,t,g,s} \le MAXOH^{i}_{r,t,g,s} \cdot oc_{r,t,g} + M(1-x_i) \quad g \in (SPC, UPC, NGCC) \tag{10}$$

$$\sum_{s,g \in PV,WD} \left(pg^{s}_{r,t,g} - \sum_{r' \ne r} idealptrg^{s}_{r',r,t,g} + \sum_{r' \ne r} \left[idealptrg^{s}_{r,r',t,g} \cdot (1 - TRLOSS_{r,r'}) \right] \right) \ge PD_{r,t} \cdot UL_r \tag{22}$$

$$pg_{r,t,g,s} \cdot FCR^{i}_{f,g} - M(1-x_i) \le fd_{f,r,t,g,s} \le pg_{r,t,g,s} \cdot FCR^{i}_{f,g} + M(1-x_i) \quad g \in (SPC, UPC, NGCC) \tag{11}$$

$$\sum_{i} x_i = 1 \tag{12}$$

The regional net power import $ptr_{r,t,s}$ is calculated as the total power transmitted into the region $ideaptr_{r',r,t,s}$ minus the total power transmitted out of the region $ideaptr_{r,r'',t,s}$, as shown in Eq. (13). The line loss of power transmission $TRLOSS_{r',r}$ is considered. Power transmission are free variables to be optimized and cannot exceed the capacity of transmission lines $TRLIMIT_{r,r',t}$ as expressed in Eq. (14).

$$ptr_{r,t,s} = \sum_{r',r'' \ne r} \left[ideaptr_{r',r,t,s} \cdot (1 - TRLOSS_{r',r}) - ideaptr_{r,r'',t,s} \right] \tag{13}$$

$$ideaptr_{r,r',t,s} \le TRLIMIT_{r,r',t} \tag{14}$$

2.2.3. Investment constraints

Coal-fired power plants are assumed to have the option to be decommissioned earlier than the expected lifetime in this model due to their high emissions. The installed capacity $ic_{r,t,g}$ of coal-fired power plants is then calculated as the constructed capacity minus the prematurely-retired capacity $er^{t''}_{r,t',g}$, as displayed in Eq. (15). The investment decision options are expressed in Eq. (16) - (17). In each year, the newly-built $nb_{r,t,g}$ and existing power plants $rm^{t'}_{r,t,g}$ can choose to retire prematurely or keep running next year. The other types of power plants are assumed to be decommissioned only after reaching their economic lifetime as expressed in Eq. (18).

$$ic_{r,t,g} = \sum_{t'=t-TLT_g+1}^{t} nb_{r,t',g} - \sum_{t'=t-TLT_g+1}^{t} \sum_{t''=t'+1}^{t} er^{t''}_{r,t',g} \quad g \in (SPC, UPC) \tag{15}$$

$$nb_{r,t,g} = er^{t+1}_{r,t,g} + rm^{t+1}_{r,t,g} \quad g \in (SPC, UPC) \tag{16}$$

$$rm^{t'}_{r,t,g} = er^{t'+1}_{r,t,g} + rm^{t'+1}_{r,t,g}, t' < t + TLT_g \quad g \in (SPC, UPC) \tag{17}$$

$$ic_{r,t,g} = \sum_{t'=t-TLT_g+1}^{t} nb_{r,t',g} \quad g \in (NGCC, NU, HD, WD, PV) \tag{18}$$

The regional maximum available capacity $IC^{ub}_{r,g}$ for renewable energy is set in order to reflect the actual resource limits, as presented in Eq. (19). In terms of fuel-based power generation technologies (i.e. nuclear, coal and gas power), the maximum annual fuel consumption FSC^{ub}_{f} is set in Eq. (20). Moreover, the annual maximum capacity addition NB^{ub}_{g} is also set for each type of technologies due to the constraint of construction speed, as expressed in Eq. (21).

$$ic_{r,t,g} \le IC^{ub}_{r,g} \tag{19}$$

$$tfd_{f,t} \le FSC^{ub}_{f} \tag{20}$$

$$nb_{r,t,g} \le NB^{ub}_{g} \tag{21}$$

Utilization target UL_r of renewable energy could be set for each region in order to increase the renewable energy share in total power supply, as displayed in Eq. (22).

2.2.4. Emission constraints

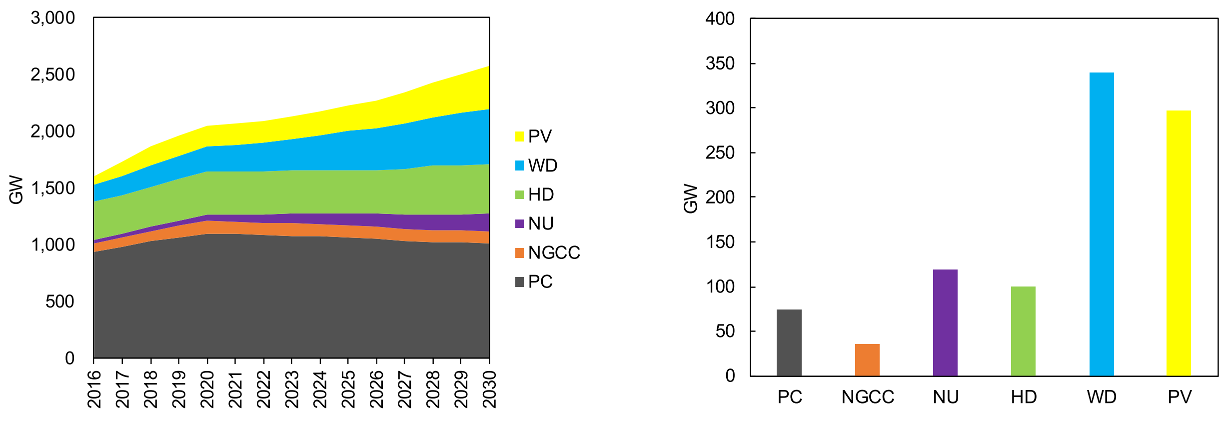
Emissions are calculated by multiplying fuel consumption $tfd_{f,t}$ by the corresponding carbon emission factors CEF_f, as expressed in Eq. (23). Total CO_2 emissions tce_t are constrained by carbon emission intensity target CEI^{ub}_{t} in Eq. (24).

$$tce_t = \sum_{f} tfd_{f,t} \cdot CEF_f \tag{23}$$

$$tce_t \le pg_t \cdot CEI^{ub}_{t} \tag{24}$$

2.3. Case study

The model described in last section is built in General Algebraic Modelling System (GAMS). Since it is a mixed-integer linear programming model, the CPLEX solver incorporated in GAMS is used to solve this problem. The model is applied to the case study of China. Two scenarios are set for analysis, namely Variable Fuel Consumption Rate (VFCR) and Constant Fuel Consumption Rate (CFCR). The variable fuel consumption rate in response to load factor of thermal power plants is incorporated in Scenario VFCR whilst it is neglected in Scenario CFCR. As Scenario VFCR is the one in line with reality, it is set to study the optimal low-carbon transition pathway, which is the suggested solution. Scenario CFCR is set to analyze the influence of not incorporating the RES integration costs on long-term capacity expansion planning by comparison with Scenario VFCR. Input parameters and boundary conditions of the case



(a) Installed capacity mix

(b) Increased capacity from 2016 to 2030

Fig. 2. The optimal power capacity expansion pathway.

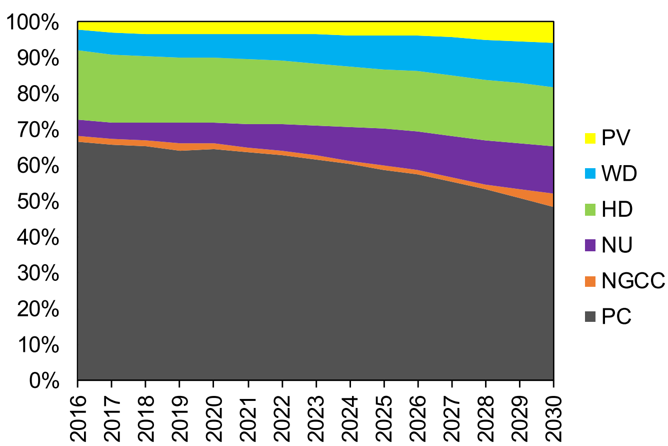


Fig. 3. Power generation structure in the planning horizon.

are demonstrated in Appendix B.

3. Results and discussion

3.1. *The optimal low-carbon transition pathway*

The optimal power capacity expansion pathway is shown in Fig. 2(a). The total installed capacity of power plants increases from 1604 GW (2016) to 2571 GW (2030) so as to meet the increasing power demand. The capacity of coal, gas, nuclear, hydro, wind and solar power plants would be 1017 GW, 106 GW, 153 GW, 432 GW, 489 GW and 374 GW respectively in 2030. Although the power sector is still dominated by coal power plants, the share of coal power capacity has decreased from 59% to 40% due to the rapid expansion of renewable energy. The capacity of wind and solar power plants increases by 229% and 384% respectively from 2016 to 2030, dominating the increased power capacity as presented in Fig. 2(b).

Fig. 3 displays the power generation structure in the planning horizon. The share of non-fossil power would increase to 47.5% by 2030 in order to realize the CO_2 emission reduction targets. The variable renewable energy (wind and solar power) accounts for 17.6% in total power generation by 2030, increasing the requirements of flexibility in the power system. The load dispatch profile at the national scale in 2030 is presented in Fig. 4. The dispatch of non-fossil power is in priority due to the nearly-zero emissions. Nuclear power serves as base load with a high load factor because of its operational characteristics. Renewable energy power is then fully utilized as long as the resources are available. The residual load, which is primary power load minus non-fossil power output, shows strong fluctuation due to the volatility of power load and renewable energy availability. The fluctuation of residual load is absorbed by the flexible generation of thermal power plants.

Fig. 5 displays the load factor of coal power plants in year 2016 and 2030. It could be noticed that coal power plants operate at a wider load range in 2030 due to the higher share of variable renewable energy compared with 2016 level. When renewable energy resources are rich, coal power plants decrease the power output to accommodate the

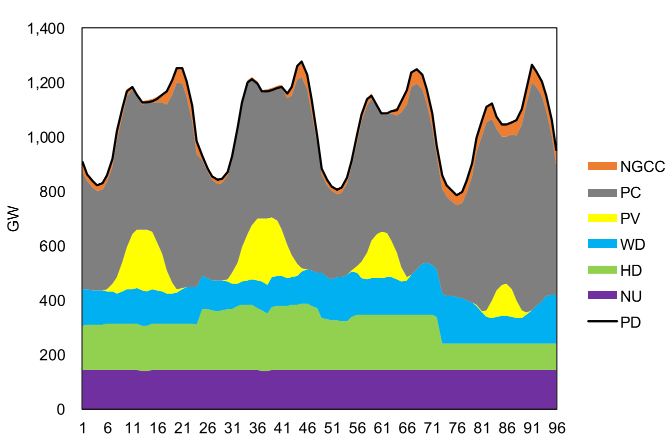


Fig. 4. Load dispatch profile in 2030.

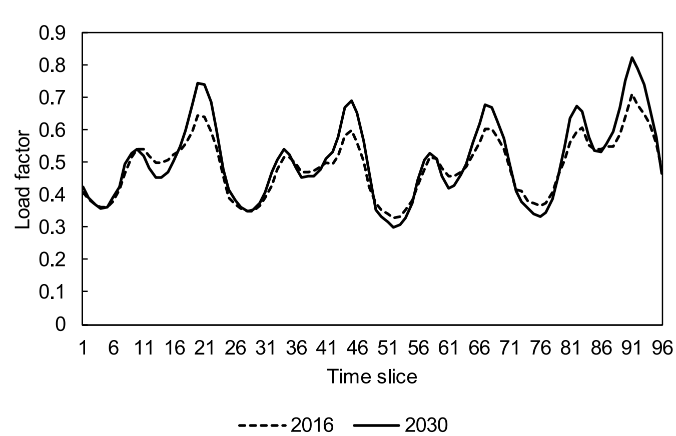


Fig. 5. Load factor of coal power plants (comparison between 2016 and 2030).

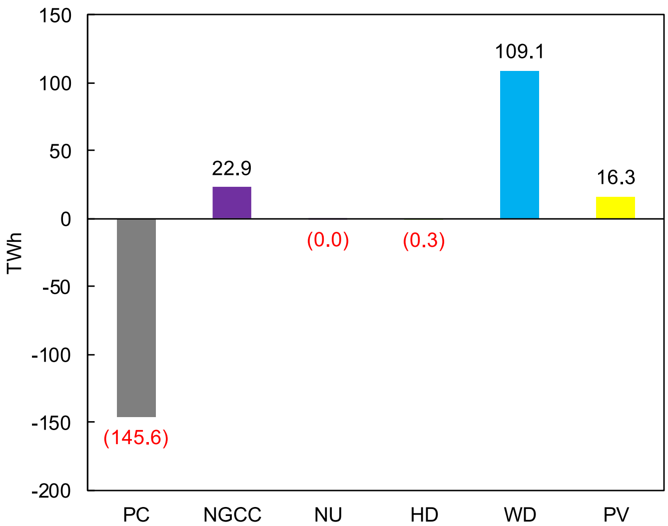


Fig. 6. Comparison of power generation in 2030 between Scenario VFCR and Scenario CFCR.

renewable power. In contrast, coal power plants increase the power output to meet the residual load when renewable energy resources are in shortage. Coal power plants are running more flexibly to integrate higher share of renewable energy into the power system. The equivalent utilization hour of coal power plants in 2030 is 4287 h.

3.2. The impact of flexible thermal power generation on long-term capacity expansion

As discussed in Section 3.1, the integration of higher share of variable renewable energy needs more flexible generation of thermal power plants. Thermal power plants tend to run at part load more frequently in order to accommodate the renewable power. Traditional power generation expansion planning usually ignores this characteristic, which is considered to have little influence on long-term planning. However, when thermal power plants have gradually been pushed back from baseload position to balancing roles in the context of low-carbon transition, neglecting the variable fuel consumption rate would lead to strong bias of the planning results. Fig. 6 displays the differences of power generation in 2030 between Scenario VFCR and Scenario CFCR. As we considered the variable fuel consumption rate of coal power plants in response to load factor in Scenario VFCR, the fuel consumption per unit of electricity generated is higher, which increases the CO_2 emission intensity of coal power plants. In order to realize the carbon emission targets, the total coal power generation decreases by 145.6 TWh in Scenario VFCR compared with Scenario CFCR. The reduced coal power output is substituted by gas and renewable power generation. Therefore, 45.1 GW more wind power plants and 13.9 GW more solar power plants are built in Scenario VFCR compared with Scenario CFCR. The increase of gas power generation is due to its lower CO_2 emission intensity and stronger flexible generation capability. The total system cost would increase by 3% (from ¥12,168 B to ¥12,535 B) if the variable fuel consumption rate of thermal power plants is taken into account.

3.3. Policy recommendations

With the higher share of renewable energy in the power system, the flexible generation would become normal state for thermal power plants. In the process of flexible generation, the fuel consumption rate of thermal power plants increases in response to part-load operation. The increase of fuel consumption rate leads to higher carbon emission intensity of thermal power plants although the total carbon emission has been reduced by the replacement of renewable energy electricity. Therefore, the planned renewable energy power plants would be insufficient to realize the carbon emission control target as expected. Policy makers should take the flexible generation characteristics of thermal power plants into account when making low-carbon development plans and strategies. More renewable energy power plants should be developed in order to offset the emission addition incurred by the flexible generation of thermal power plants.

4. Conclusions

This paper aims at obtaining the optimal low-carbon transition pathway for power sector with higher RES penetration. A long-term power generation expansion planning model, incorporating integration costs and additional emissions incurred by the flexible generation of power plants for RES penetration, is proposed. China is selected for a case study because China has large-scale existing thermal power plants and is promoting low-carbon transition at the same time.

Two scenarios are set for analysis, namely “Variable Fuel Consumption Rate” scenario and “Constant Fuel Consumption Rate” scenario. The optimal low-carbon transition pathway obtained in this study shows that the increased power demand is mainly satisfied by renewable energy. In order to realize the carbon emission control target, the capacity of wind and solar power plants in 2030 increases by 229% and 384% compare with 2016 and the share of non-fossil power increases to 47.5%. The baseload position of thermal power plants is gradually turned to balancing roles. The impact of incorporating integration costs for RES penetration on long-term capacity expansion planning of power sector is demonstrated based on scenario comparison. The results indicate that ignoring the variable fuel consumption rate of thermal power plants would underestimate their CO_2 emission intensity due to the higher emissions in the process of flexible power generation. The additional emissions from thermal power plants should be offset by more renewable power generation, requiring 45.1 GW more wind and 13.9 GW more solar power plants. Correspondingly, the total system cost would increase by 3%. Therefore, policy makers should take the short-term integration costs of RES penetration into account when making power generation expansion plans for low carbon transition so as to effectively realize the emissions control targets and accurately calculate the total cost.

The model in this paper mainly focuses on how to handle with the variable power output of renewable energy with flexible generation of thermal power plants. The output of renewable energy is input as fixed parameters, which means the model is a deterministic model. The uncertainty of renewable energy output is currently not taken into account in this model while it is also an important issue in terms of renewable energy integration. Future research would extend the model to a stochastic model to incorporate the uncertainty of renewable output as well as other input parameters. Moreover, other potential flexibility solutions for power system could be incorporated, such as energy storage system and demand response.

Credit author statement

Siyuan Chen: designed and carried out the research, wrote the first draft of the manuscript. Pei Liu: designed and carried out the research. Zheng Li: designed and carried out the research. All authors contributed to analyzing the results and writing the paper.

Acknowledgement

The authors gratefully acknowledge the support by The National Natural Science Foundation of China (71690245, 71934006), and the Phase III Collaboration between BP and Tsinghua University.

Appendix A

Table A1
Meanings of the abbreviations of variables

Abbreviations	Meaning
$pg_{r,t,g,s}$	Electricity generation of type g power units in time slice s in year t in region r
$ptr_{r,t,s}$	Net power import of region r in time slice s of year t
$ideaptr_{r,r',t,s}$	Ideal power transmission from region r to region r' in time slice s of year t
$ic_{r,t,g}$	Installed capacity of type g power units in year t in region r
$oc_{r,t,g,s}$	Operating capacity of type g power units in time slice s in year t in region r
$st_{r,t,g,s}$	Start-up capacity of type g power units in time slice s in year t in region r
$sd_{r,t,g,s}$	Shut-down capacity of type g power units in time slice s in year t in region r
$fd_{f,r,t,g,s}$	Fuel demand of type g power units in time slice s in year t in region r
$tfd_{f,t}$	Total fuel demand in year t
tce_t	Total CO_2 emissions in year t
x_i	Binary variable that indicates the load factor range
$nb_{r,t,g}$	Newly-built capacity of type g power units in year t in region r
$er^{t'}_{r,t,g}$	Prematurely-retired capacity of type g power units (built in year t) in year t' in region r
$rm^{t'}_{g,t}$	Remaining capacity of type g power units (built in year t) in year t' in region r
$tinv_{r,t}$	Total capital cost in year t in region r
$tom_{r,t}$	Total O&M cost in year t in region r
$tfc_{r,t}$	Total fuel cost in year t in region r
$tssc_{r,t}$	Total start-up and shut-down cost in year t in region r
$tptrc_{r,t}$	Total power transmission cost in year t in region r
atc	Accumulated total system cost of power sector

Table A2
Meanings of the abbreviations of parameters

Abbreviations	Meaning
$PD_{r,t,s}$	Power demand in time slice s in year t in region r
$MINOH_{r,t,g,s}$	Minimum load factor of g type power units in time slice s in year t in region r
$MAXOH_{r,t,g,s}$	Maximum load factor of g type power units in time slice s in year t in region r
$FCR_{f,t,g}$	Fuel consumption rate of g type power plants in year t
$TRLOSS_{r,r'}$	Power transmission losses from r to r'
$TRLIMIT_{r,r',t}$	Power transmission limit from r to r' in year t
$CAP_{r,t,g}$	Unit capital cost of g type power units in year t in region r
I	Discounting rate
TLT_g	Expected lifetime of g type power plants
$\mu_{g,t}$	Annual operation and maintenance cost of g type power units in year t
$FP_{f,r,t}$	Fuel price in year t in region r
SSC_g	Unit start-up and shut-down cost of g type power plants
$TRCOST_{r,r'}$	Unit power transmission cost from r to r'
$IC^{ub}_{r,g}$	Upper limit for total installed capacity of g type power units in region r
FSC^{ub}_f	Upper limit for fuel supply capability
NB^{ub}_g	Upper limit for annual newly-built capacity of g type power units
UL_r	Utilization rate limit of renewable energy in region r
CEF_f	Carbon emission factor
CEI^{ub}_t	Carbon emission intensity target in year t

Appendix B

B.1. Existing installed capacity of power generation and transmission

Basically, China's energy resources and power demand are inversely distributed [21]. Northern and north-western regions have abundant coal, wind and solar energy resources whilst southwestern regions are rich in hydropower resources. Meanwhile, electricity demand is centered in eastern regions. In this case study, China is divided into 17 regions on the basis of the resource distribution and demand characteristics as shown in Figure B1.

The details (scale, type, location, age) of the existing power generation technologies [22] are input into the model as a starting point for optimization. Fully utilizing the energy resources in western regions and transmitting electricity to eastern regions is a basic energy strategy in China. In order to achieve this purpose, the two state-owned power grid companies [23,24], have built several inter-regional Ultra-High-Voltage (UHV) power transmission lines. The capacity of these transmission lines are input as power transmission constraints.

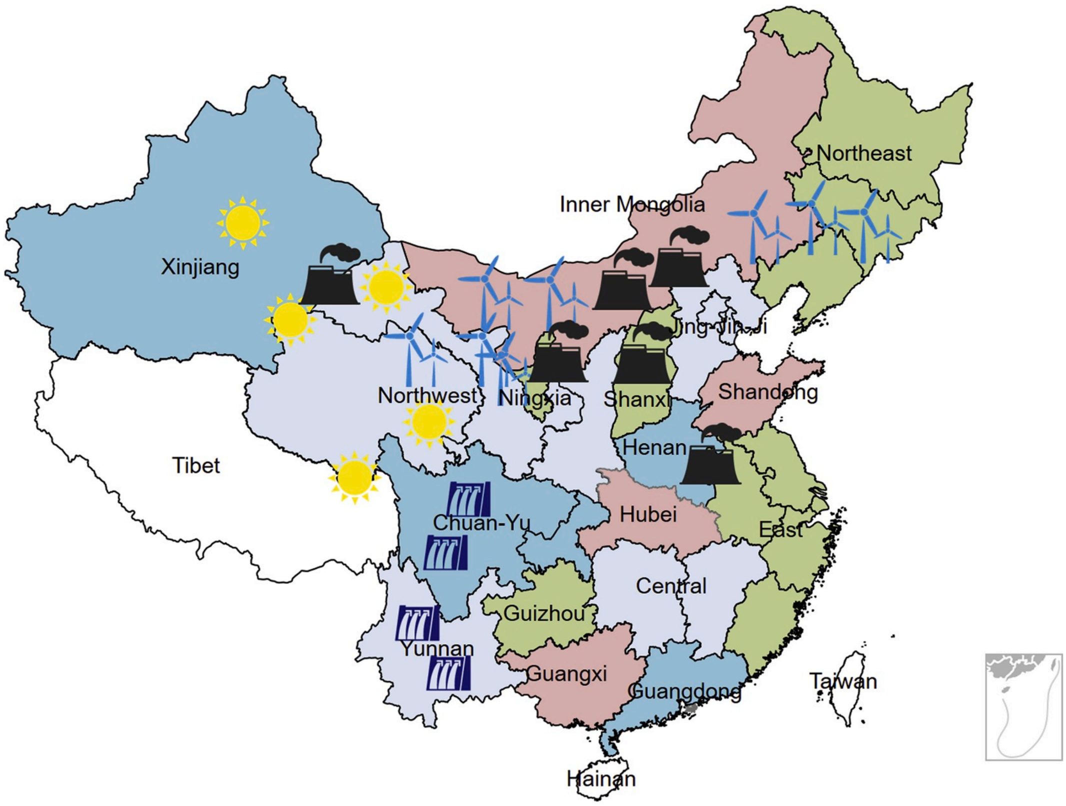


Fig. B1. Seventeen regions in China with different resource endowment.

B.2. Projected electricity demand

The projected electricity demand (see Table B1) is extrapolated based on government-issued development plan regarding power sector [25]. The electricity demand is then allocated to different regions on the basis of historical demand [22].

Table B1
Projected regional electricity demand (PWh)

Region	2020	2025	2030
Inner Mongolia	0.3430	0.4087	0.4868
Xinjiang	0.1664	0.1878	0.2119
Ningxia	0.1156	0.1319	0.1505
Shanxi	0.2575	0.2842	0.3136
Chuan-Yu	0.3647	0.3984	0.4350
Hubei	0.2157	0.2358	0.2576
Northeast	0.4572	0.4873	0.5191
Jing-Jin-Ji	0.6815	0.7521	0.8296
Shandong	0.5678	0.6347	0.7093
Northwest	0.3923	0.4351	0.4825
Henan	0.4106	0.4587	0.5123
Central	0.3258	0.3613	0.4006
East	1.8251	2.0498	2.3012
Yunnan	0.2013	0.2276	0.2571
Guizhou	0.1526	0.1684	0.1857
Guangxi	0.1711	0.1904	0.2119
Guangdong	0.6799	0.7538	0.8355

B.3. Cost and efficiency

The unit capital cost, operation and maintenance cost and economic lifetime are available in industry reports [26]. Fuel consumption rates of thermal power plants are taken from the power industry yearbook [27]. The piecewise linearization data of the fuel consumption rate for thermal power plants is shown in Table B2. Coal prices in different regions are verified by the government [28] whilst regional gas prices refer to the public information from gas industry [29]. The uranium price is taken from Nuclear Energy Agency's report [30]. Power transmission costs and line losses are set as government verified [31].

Table B2
Piecewise linearization data of fuel consumption rate change in response to load factor of thermal power plants

Range, i	Minimum load factor,%	Maximum load factor,%	Fuel consumption rate increase, FCR^i/FCR
1	30	40	1.0875
2	40	50	1.055
3	50	60	1.0375
4	60	70	1.025
5	70	80	1.017
6	80	90	1.0095
7	90	100	1.0025

B.4. Resource endowment

The technical exploitation amount of renewable energy in each region (see Table B3) refers to the measurement of China's National Energy Administration [32]. The hourly maximum load factor of wind and solar energy refers to research [33,34]. The annual maximum construction speed and maximum fuel supply are imported from previous study [21].

Table B3
Technical exploitation amount of renewable energy in each region (GW)

Region	Hydro	Wind	PV
Inner Mongolia	2.62	1610.16	497.83
Xinjiang	16.56	389.6	459.21
Ningxia	1.46	39	60.39
Shanxi	4.02	166.3	79.05
Chuan-Yu	129.85	157.27	177.87
Hubei	35.54	37.98	95.86
Northeast	15.05	345.39	254.68
Jing-Jin-Ji	1.75	240.56	98.24
Shandong	0.06	184.3	184.87
Northwest	40.39	421.93	265.54
Henan	2.88	91.16	103.26
Central	17.18	72.19	192.19
East	17.75	177.6	266.07
Yunnan	101.94	141.68	164.53
Guizhou	19.49	62.47	79.76
Guangxi	18.91	129.28	108.54
Guangdong	5.4	92.52	60.05

B.5. Policy targets

CO_2 emission constraints are set based on China's Intended Nationally Determined Contributions (INDC) in the Paris Agreement, which is to lower 2030's carbon dioxide emissions intensity by 60%–65% from the 2005 level [35].

References

[1] BP Group. BP energy outlook 2019. London, United Kondom: BP p.l.c.; 2019.
[2] Lund PD, Lindgren J, Mikkola J, Salpakari J. Review of energy system flexibility measures to enable high levels of variable renewable electricity. Renew Sustain Energy Rev 2015;45:785–807.
[3] Alizadeh M, Moghaddam MP, Amjady N, Siano P, Sheikheleslami MK. Flexibility in future power systems with high renewable penetration: a review. Renew Sustain Energy Rev 2016:1186–93.
[4] Papaefthymiou G, Dragoon K. Towards 100% renewable energy systems: uncapping power system flexibility. Energy Pol 2016:69–82.
[5] IRENA (International Renewable Energy Agency). Innovation landscape for a renewable-powered future: solutions to integrate variable renewables. 2019.
[6] Collins S, Deane JP, Poncelet K, Panos E, Pietzcker RC, Delarue E, Gallachóir BPÓ. Integrating short term variations of the power system into integrated energy system models: a methodological review. Renew Sustain Energy Rev 2017;76:839–56.
[7] Deane JP, Chiodi A, Gargiulo M, Gallachóir BPÓ. Soft-linking of a power systems model to an energy systems model. Energy 2012;42(1):303–12.
[8] Pina A, Silva CA, Ferrão P. High-resolution modeling framework for planning electricity systems with high penetration of renewables. Appl Energy 2013;112:215–23.
[9] Diakov V, Cole W, Sullivan P, Brinkman G, Margolis R. Improving power system modeling: a tool to link capacity expansion and production cost models. 2015. NREL/TP-6A20- 64905.
[10] Hirth L, Ziegenhagen I. Balancing power and variable renewables: three links. Renew Sustain Energy Rev 2015;50:1035–51.
[11] Ueckerdt F, Brecha R, Luderer G, Sullivan P, Schmid E, Bauer N, Böttger D, Pietzcker R. Representing power sector variability and the integration of variable renewables in long-term energy-economy models using residual load duration curves. Energy 2015;90:1799–814.
[12] Banzo M, Ramos A. Stochastic optimization model for electric power system planning of offshore wind farms. IEEE Trans Power Syst 2011;26(3):1338–48.
[13] Conejo AJ, Cheng Y, Zhang N, Kang C. Long-term coordination of transmission and storage to integrate wind power. CSEE Journal of Power and Energy Systems 2017;3(1):36–43.
[14] Hemmati R, Hooshmand R, Khodabakhshian A. Coordinated generation and transmission expansion planning in deregulated electricity market considering wind farms. Renew Energy 2016:620–30.
[15] Soder L. Reserve margin planning in a wind-hydro-thermal power system. IEEE Trans Power Syst 1993;8(2):564–71.
[16] Doherty R, Omalley M. A new approach to quantify reserve demand in systems with significant installed wind capacity. IEEE Trans Power Syst 2005;20(2):587–95.
[17] Ela E, Milligan M, Kirby B. Operating reserves and variable generation. https://digital.library.unt.edu/ark:/67531/metadc839479/%3c. [Accessed 17 May 2020].
[18] Palmintier BS, Webster MD. Impact of operational flexibility on electricity generation planning with renewable and carbon targets. IEEE Transactions on Sustainable Energy 2016;7(2):672–84.
[19] Koltsaklis NE, Georgiadis MC. A multi-period, multi-regional generation expansion planning model incorporating unit commitment constraints. Appl Energy 2015;158:310–31.
[20] Welsch M, Deane P, Howells M, Ó Gallachóir B, Rogan F, Bazilian M, Rogner HH. Incorporating flexibility requirements into long-term energy system models – a case study on high levels of renewable electricity penetration in Ireland. Appl Energy 2014;135:600–15.
[21] Chen S, Liu P, Li Z. Multi-regional power generation expansion planning with air pollutants emission constraints. Renew Sustain Energy Rev 2019;112:382–94.
[22] CEC (China Electricity Council). Collection of statistics information on China's power industry in 2015. Beijing: China Electricity Council; 2016 [in Chinese].

[23] SGCC (state grid corporation of China), power grids. <http://www.sgcc.com.cn/html/sgcc_main_en/col2017112610/column_2017112610_1.shtml> accessed May 17, 2020.

[24] CSG (China southern power grid), science and innovation, UHVDC. <http://eng.csg.cn/Science_Innovation/UHVDC/201512/t20151209_109562.html> accessed May 17, 2020.

[25] NDRC (National Development, Reform Commission). The 13th five-year plan for power industry development. Beijing, China: National Development and Reform Commission; 2016 [in Chinese].

[26] CEC (China Electricity Council). Annual development report of China's power industry in 2015. Beijing: China Electricity Council; 2016 [in Chinese].

[27] EBCEPY (Editorial Board of China Electric Power Yearbook). China electric power yearbook 2016. Beijing, China: China Electric Power Press; 2016 [in Chinese].

[28] CEC (China Electricity Council). China electricity coal index. [in Chinese] <http://www.cec.org.cn/guihuayutongji/zhongguodianmeicaigoujiagezhishuCECI/> accessed May 17, 2020.

[29] Gas International Web. Industrial gas. [in Chinese] <http://gas.in-en.com/Naturalgas/NaturalgasPrice/industrygas/> accessed May 17, 2020.

[30] OECD (Organization for Economic Co-operation and Development). Uranium 2014: resources, production and demand. Paris, France: OECD Publishing; 2014. https://doi.org/10.1787/uranium-2014-en.

[31] NDRC (National Development and Reform Commission). Notice on issues related to the approval of transmission prices for some special projects across provinces and districts. [in Chinese] <http://www.gov.cn/xinwen/2018-09/06/content_5319801.htm> accessed May 17, 2020.

[32] NEA (National Energy Administration). Data handbook of renewable energy in 2015. Beijing, China. [in Chinese].

[33] Pfenninger S, Staffell I. Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data. Energy 2016;114:1251–65.

[34] Staffell I, Pfenninger S. Using bias-corrected reanalysis to simulate current and future wind power output. Energy 2016;114:1224–39.

[35] NDRC (National Development and Reform Commission. Enhanced actions on climate change: China's intended nationally determined contributions. 2015. en.people.cn/n/2015/0701/c90000-8913723.html, . [Accessed 17 May 2020].