CHEMICAL ENGINEERING TRANSACTIONS

VOL. 76, 2019

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Petar S. Varbanov, Timothy G. Walmsley, Jiří J. Klemeš, Panos Seferlis

ISBN 978-88-95608-73-0; **ISSN** 2283-9216

DOI: 10.3303/CET1976185

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-BP Clean Energy Center, Tsinghua University, 100084 Beijing, China
liu_pei@tsinghua.edu.cn

Increasing the share of renewable energy in total power generation is an important trend in the global power system. However, the volatility and intermittency of renewable energy resources pose a great challenge to the high penetration of renewable energy. In order to absorb large amount of renewable energy electricity, thermal power plants should increase their operational flexibility such as more start-up and shut-down actions as well as running at part load more often. It brings about integration costs for renewable energy penetration, which should be quantitatively assessed. In this paper, a long-term power generation expansion planning model incorporating short-term operational characteristics of power generation units is proposed. This model is used to find the most cost effective low carbon transition pathway of power sector with high penetration of renewable energy and the impact of incorporating short-term integration costs on long-term power generation planning. China is selected for a case study as it is the largest carbon dioxide emitter in the world and has urgent need for low carbon transition.

1. Introduction

Renewable energy sources (RES) are playing a more important role in the low carbon transition of global energy system due to its zero-emission and sustainability. Global renewable energy consumption grows from 93.2 Mtoe (2016) to 419.6 Mtoe (2020) at an annual rate of 14.1 percent (BP Group, 2017a) and would continue to increase by three times in the next twenty years (BP Group, 2017b). However, renewable energy is highly dependent on climate and weather, which leads to the volatility and intermittency of RES. The variable and non-schedulable output of RES pose great challenge to the power grids, especially with higher RES share. In order to handle this problem, more operational flexibility is needed in the power system. This operational flexibility could be provided by thermal power plants, including more start-up and shut-down actions as well as running at part load more often. Long-term power generation expansion planning models should take these short-term operational characteristics into account to ensure the feasible and realistic results (Collins et al., 2017).

Some researchers focus on the characterization of high-resolution variable RES output. Hirth and Ziegenhagen (2015) estimated the individual probability density functions of forecast errors regarding electricity demand, wind and solar production from historical data using a probabilistic approach. The reserve requirements in the power system are then determined endogenously with the joint density distribution. Ueckerdt et al. (2015) proposed the RLDC (residual load duration curve) approach to incorporate short-term variability of RES output into a long-term energy model. The residual load duration curves change endogenously depending on the share and mix of RES.

In order to deal with the short-term uncertainties raised by RES, many researchers incorporate the short-term scheduling details into the long-term power generation expansion planning. Deane et al. (2012) proposed a soft-linking methodology that makes a chronological simulation in a power system model with detailed short-term operational features based on the optimal power generation portfolio results in a specific year from the energy system model. Koltsaklis and Georgiadis (2015) proposed a mixed-integer linear programming (MILP) model that integrates short-term unit commitment problem (UCP) with long-term generation expansion problem (GEP). Daily constraints at an hourly level such as minimum up and down time, ramping limits, start-up and shut-down decisions of thermal power units are integrated in the model so as to capture short-term operation details.

Paper Received: 13/03/2019; Revised: 08/04/2019; Accepted: 08/04/2019
Please cite this article as: Chen S., Liu P., Li Z., 2019, Low Carbon Transition Pathway of Power Sector with High Penetration of Renewable Energy, Chemical Engineering Transactions, 76, 1105-1110 DOI:10.3303/CET1976185

Existing literature mainly focus on the dispatch problem of balancing variable and intermittent RES output in the power system but rarely consider the corresponding costs. The start-up and shut-down processes would incur extra costs whilst the fuel consumption rate of thermal power plants at part load is much more than the design value. These extra costs can be called integration costs for RES penetration. This study focuses on incorporating these integration costs into long-term power generation expansion planning for low carbon transition and assessing its impact on future power generation mix.

2. Methodology

2.1 Model structure and assumptions

The model considered seven types of power generation technologies: Subcritical and Supercritical Pulverized Coal (SPC), Ultra-Supercritical Pulverized Coal (UPC), Natural Gas Combined Cycle (NGCC), Nuclear power (NU), Hydro power (HD), Wind power (WD) and Solar Photovoltaic (PV). Coal plants are assumed to have the option to retire earlier than its expected lifetime whilst other power plants are assumed to be decommissioned until the end of their lifetime. Therefore, a superstructure problem is formed to determine the optimal construction plan of different power plants from all possible alternatives.
Power generation and power consumption are balanced on a regional basis instead of a single entity. Besides, the characteristics of natural resources and electricity demand in different regions differ from each other. The model contained a spatial module to reflect the power balance region by region. The connections among regions are also included into the spatial module so that power transmission are allowed among regions which is closer to reality.
In the real power system, the fluctuation of power load requires load dispatch at every moment. Besides, the volatility and intermittency of renewable energy increase the uncertainty of power system as they are non-schedulable power sources. In order to reflect this temporal characteristic of power system, the hourly power balance is reflected in the temporal module. In this module, each year is divided into four seasons (spring, summer, autumn, winter). The hourly power load and renewable energy power generation are reflected in a representative day of each season. It means that each year is divided into ninety-six time blocks in total.
The fuel consumption rate of thermal power generators is strongly influenced by the load factor. As shown in Figure 1, the fuel consumption rate would increase by 11 % at 30 % operating load. With the high penetration of renewable energy, thermal power plants may often run at part load to provide flexibility for the power system. The variability of fuel consumption rate in response to the load factor would bring about integration cost for renewable energy, which is taken into account in the model.

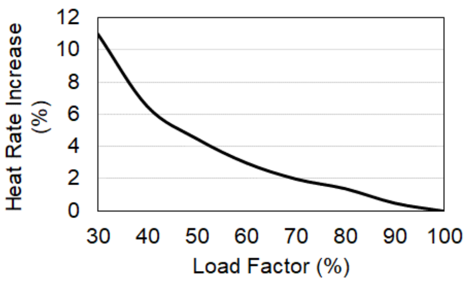

Figure 1: Fuel consumption rate increase of thermal power generators with operating load factor (Liu et al., 2018)

2.2 Mathematical formulation

Mathematical formulas of the optimization model are presented in this section, including objective function and model constraints. Five sets, t, r, g, f and s stand for year, region, power generation type, fuel type, and time block respectively. All parameters are denoted by upper-case characters and variables are denoted by lower-case ones. Physical meanings of the main variables and parameters are listed in Table 1.

2.2.1 Objective function

The objective function of this model is to minimize total system cost of power sector from year 2016-2030, as expressed in Eq(1). The total cost of power sector constitutes five parts: capital cost (*tinv*), O&M cost (*tom*), fuel cost (*tfc*), power transmission cost (*tptrc*) and start-up/shut-down cost (*tss*). The calculating formula of the five parts of costs are listed in Eq(2) – Eq(6).

Table 1: Physical meanings of the main variables and parameters

Symbol	Unit	Physical meaning
$nb_{r,t,g}$	GW	Newly-built capacity of g-type power plants in region r in year t
$ic_{r,t,g}$	GW	Installed capacity of g-type power plants in region r in year t
$oc_{g,t,r,s}$	GW	Operating capacity of g-type power plants during time block s in region r in year t
x_i	/	Binary variable that indicates the load factor range
$TRCOST_{r',r}$	¥/kWh	Unit cost of power transmission from region r to r'
$TRLOSS_{r',r}$	%	Line loss ratio of power transmission from region r to r'
$MINOH_{r,t,g,s}$	hour	Minimum operating hours for g-type power plant during time block s in region r in year t
$MAXOH_{r,t,g,s}$	hour	Maximum operating hours for g-type power plant during time block s in region r in year t

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

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

$$tom_{r,t} = \sum_{g}\mu_{t,g}\cdot ic_{r,t,g} \quad (3)$$

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

$$tptrc_{r,t} = \sum_{s}\sum_{r'\neq r}ideaptr_{r,r',t,s}\cdot TRCOST_{r,r'} \quad (5)$$

$$tss_{r,t} = \sum_{g}\sum_{s}SSC_g\cdot(su_{r,t,g,s} + sd_{r,t,g,s}) \quad (6)$$

2.2.2 Physical constraints

The most important physical constraint is power balance, which ensures that power demand of each time block in each region could be satisfied. In this model, power demand (*PD*) is satisfied by local power generation (*pg*) and inter-regional power transmission (*ideaptr*), as shown in Eq(7). In terms of power transmission among regions, line loss is considered in the model so that net power imports (*ptr*) into one region is calculated as shown in Eq(8).

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

$$ptr_{r,t,s} = \sum_{r',r''\neq r}[ideaptr^{s}_{r',r,t}\cdot(1-TRLOSS_{r',r}) - ideaptr^{s}_{r,r'',t}] \quad (8)$$

Power generation of different power plants is constrained by resource availability (renewable energy) and operating characteristics (thermal power plants). For renewable energy and nuclear energy, the constraints are expressed by Eq(9). In terms of thermal power plants, start-up (*st*) and shut-down (*sd*) decisions are expressed by Eq(10). In order to reflect the relationship between fuel consumption rate (*FCR*) and load factor, piecewise linearization method is used as shown in Eq(11) – Eq(13).

$$MINOH_{r,t,g,s}\cdot ic_{r,t,g} \le pg_{r,t,g,s} \le MAXOH_{r,t,g,s}\cdot ic_{r,t,g} \quad g\in(NU,HD,WD,PV) \quad (9)$$

$$oc_{g,t,r,s+1} = oc_{g,t,r,s} + st_{g,t,r,s} - sd_{g,t,r,s} \quad g\in(SPC,UPC,NGCC) \quad (10)$$

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

$$pg_{r,t,g,s}\cdot FCR^{i}_{f,g} - M(1-x_i) \le fd_{f,r,t,g,s} \le pg_{r,t,g,s}\cdot FCR^{i}_{f,g} + M(1-x_i) \quad g\in(SPC,UPC,NGCC) \quad (12)$$

$$\sum_i x_i = 1 \tag{13}$$

In this model, coal plants are assumed to have the option to retire earlier than its expected lifetime whilst other power plants are assumed to be decommissioned until the end of their lifetime. Therefore, the installed capacity of SPC and UPC power plants could be expressed as the sum of newly-built capacity during the past several decades (i.e. lifetime of SPC and UPC plants) minus the early-retired capacity (*er*), as shown in Eq(14). The installed capacity of other power plants is just the sum of newly-built capacity in the past, as expressed in Eq(15).

$$ic_{r,t,g} = \sum_{t'=t-TLT_g+1}^{t} nb_{r,t',g} - \sum_{t'=t-TLT_g+1}^{t} \sum_{t''=t'+1}^{t} er_{r,t',g}^{t''} \qquad g \in (SPC, UPC) \tag{14}$$

$$ic_{r,t,g} = \sum_{t'=t-TLT_g+1}^{t} nb_{r,t',g} \qquad g \in (NGCC, NU, HD, WD, PV) \tag{15}$$

In order to reflect resource endowment of different regions, an upper bound for renewable energy installed capacity in each region (*IC*) is set as presented in Eq(16). As for fossil-fuel power generation technologies, an upper bound for annual fuel supply (*FSC*) is set as presented in Eq(17). Besides, annual newly-built capacity of power plants should not exceed the limit of construction speed (*NB*), as expressed in Eq(18).

$$ic_{r,t,g} \le IC_{r,g}^{ub} \tag{16}$$

$$tfd_{f,t} \le FSC_f^{ub} \tag{17}$$

$$nb_{r,t,g} \le NB_g^{ub} \tag{18}$$

Carbon emission intensity (*CEI*) constraint is considered in this model to comply with national policy target, as shown in Eq(19).

$$tce_t \le pg_t \cdot CEI_t^{ub} \tag{19}$$

2.3 Key parameters

In this model, China is used for case study. Existing installed capacity, unit capital costs, unit O&M costs, start-up/shut-down costs, expected lifespan and fuel consumption rates are taken from the yearbook of China's power industry (EBCEPY, 2016). Future power demand refers to the BP energy outlook (BP Group, 2017b). Carbon emission intensity limit is taken from China's INDC in the Paris Agreement (NDRC, 2015). The piecewise linearization data of the fuel consumption rate variability for thermal power plants is shown in Table 2. Other parameters such as regional resource limits, power transmission capacity and losses among regions, and regional fuel supply and capacity construction limits are imported from the previous study (Guo et al., 2016).

Table 2: Piecewise linearization data of fuel consumption rate change in response to load factor of thermal power plants

Range, i	Load factor range (%)		Fuel consumption rate increase,
	MIN	MAX	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

3. Results and discussion

General Algebraic Modelling System (GAMS) is used for modelling and the Mixed Integer Programming (MIP) solver CPLEX is used to solve the optimization problem. The proposed model is a MILP model which has 4,815,285 variables and 1,440,173 equations. It took 4485.86 seconds to achieve a solution using a PC with 8 GB RAM. Two scenarios, namely Base Scenario and Reference Scenario, are set to study the optimal low-carbon transition pathway and the impact of incorporating integration costs for RES penetration on long-term capacity expansion planning of power sector. In Base Scenario, the start-up/shut down costs and variable fuel consumption rates of thermal power plants are neglected whilst these are included in Reference Scenario.

3.1 Optimal low-carbon transition pathway for power sector

The optimization results of Reference Scenario are presented in this section. Figure 2 shows the development pathway of installed capacity mix and power generation percentage in the planning horizon. In order to meet the increasing power demand, installed capacity of coal, gas, nuclear, hydro, wind and PV would reach 1,166 GW, 105 GW, 158 GW, 389 GW, 366 GW and 181 GW, respectively by 2030. Although coal plants still dominate China's power structure, renewable energy has a significant increase in scale to realize the national policy target of carbon emission intensity reduction. Installed capacity of wind and solar power plants increase by 146 % and 134 % respectively from year 2016 to 2030. For power generation, non-fossil power including nuclear and renewables which are assumed to be zero-emission would increase to 42 % of total power supply.

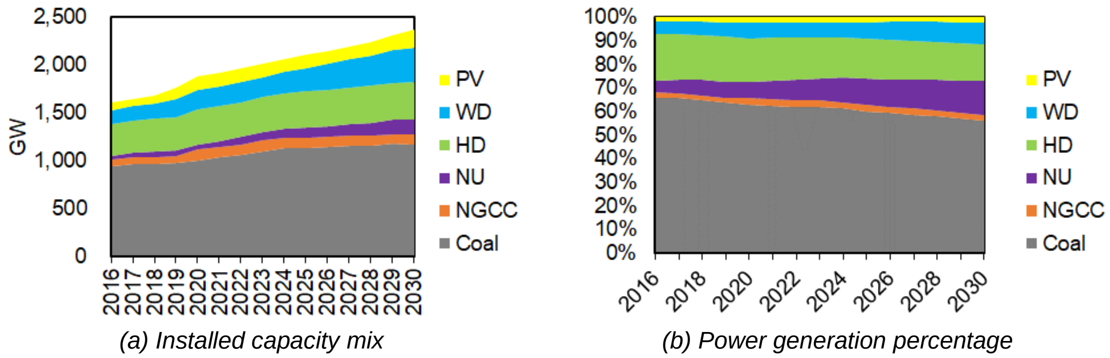

Figure 2: Development pathway of (a)Installed capacity mix and (b)power generation percentage

Load dispatch file in 2030 is shown in Figure 3. Nuclear power is used as base load in the power system due to its lower cost. Renewable energy power is then in priority as its marginal cost is nearly zero. The fluctuation is absorbed by coal and gas power plants with flexible operation, mainly by coal plants due to its large capacity. The average load factor of coal plants in 2030 is 0.49, which means the utilization hour is 4,287 h.

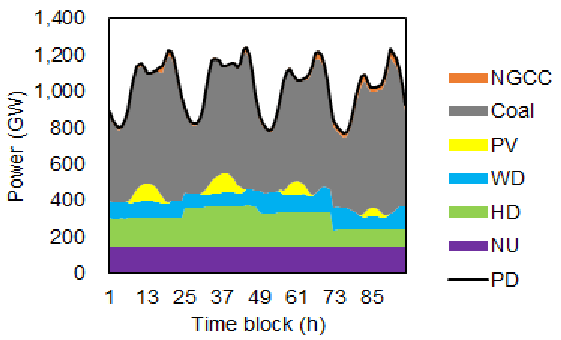

Figure 3: Load dispatch profile in 2030

3.2 Impact of short-term integration cost on long-term expansion planning

Figures 4 shows the differences between Reference Scenario and Base Scenario in terms of installed capacity and power generation by 2030. With higher RES penetration, coal power plants tend to run at part load more often. Owing to the negative correlation between fuel consumption rate and load factor, coal power plants would consume more fuel when generating the same electricity and thus emit more carbon dioxide. In order to realize the carbon emission target in the Reference Scenario, renewable energy power plants would substitute nearly 20 TWh of electricity which would have been generated by coal power plants (Figure 4b). Accordingly, 4.6 GW more wind plants and 11 GW more PV plants would be built in the Reference Scenario (Figure 4a). Besides, the total system cost of power sector would increase by 1 % (from ¥11,381 B to ¥11,498 B) due to the introduction of short-term integration costs.

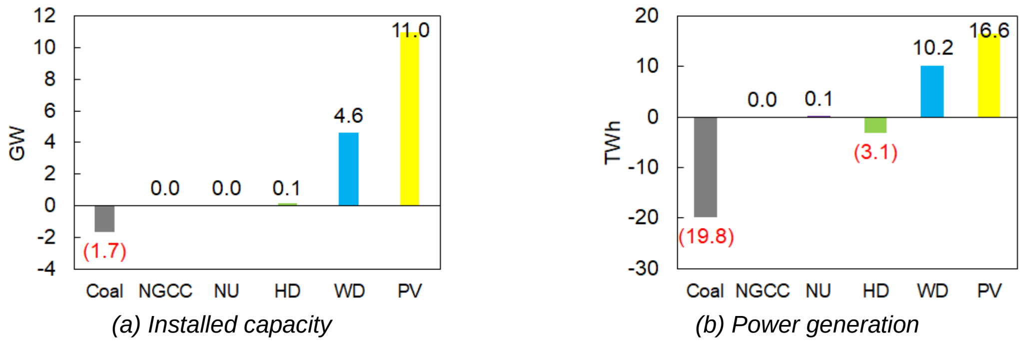

Figure 4: Differences between Reference Scenario and Base Scenario in terms of (a)Installed capacity and (b)Power generation

4. Conclusions

In order to obtain the optimal low-carbon transition pathway for power sector with higher RES penetration, this paper proposes a long-term power generation expansion planning model incorporating short-term integration costs for RES penetration, including start-up/shut-down costs and increasing fuel consumption costs at part load for thermal power plants. The impact of incorporating these factors is demonstrated based on scenario comparison. Due to higher emission of thermal power plants in the flexible operation process, neglecting short-term operation characteristics would underestimate total carbon emissions. Thus, the planned renewable power plants would be insufficient to realize the carbon emission control target. Total system cost would also be underestimated by 1 % for the case of China's power sector. Future research would focus on the introduction of other potential flexibilities for power system, such as energy storage system and demand response.

Acknowledgments

The authors gratefully acknowledge the support by the National Key Research and Development of China (2018YFB0604301), National Natural Science Foundation of China (71690245), and the Phase III Collaboration between BP and Tsinghua University.

References

BP Group, 2017a. BP Statistical Review of World Energy 2017. BP p.l.c., London, United Kindom.

BP Group, 2017b. BP Energy Outlook 2017, BP p.l.c., London, United Kondom.

Collins S., Deane J.P., Poncelet K., Panos E., Pietzcker R.C., Delarue E., Gallachóir B.P.Ó., 2017, Integrating short term variations of the power system into integrated energy system models: A methodological review, Renewable and Sustainable Energy Reviews, 76: 839-856.

Deane J.P., Chiodi A., Gargiulo M., Gallachóir B.P.Ó., 2012, Soft-linking of a power systems model to an energy systems model. Energy, 42(1): 303-312.

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

Guo Z., Ma L.W., Liu P., Jones I., Li Z., 2016, A multi-regional modelling and optimization approach to China's power generation and transmission planning, Energy, 116: 1348-1359.

Hirth L., Ziegenhagen I., 2015, Balancing power and variable renewables: Three links. Renewable and Sustainable Energy Reviews, 50: 1035-1051.

Koltsaklis N.E., Georgiadis M.C., 2015, A multi-period, multi-regional generation expansion planning model incorporating unit commitment constraints, Applied energy, 158: 310-331.

Liu W.H., Ho W.S., Lee M.Y., Hashim H., Lim J.S., Hoo P.Y., Klemeš J.J., 2018, Optimising thermal power plant with generation flexibility and heat rate factor, Chemical Engineering Transactions, 70, 1981-1986.

NDRC (National Development and Reform Commission), 2015, Enhanced actions on climate change: China's intended nationally determined contributions. <en.people.cn/n/2015/0701/c90000-8913723.html> accessed 11.03.2019

Ueckerdt F., Brecha R., Luderer G., Sullivan P., Schmid E., Bauer N., Böttger D., Pietzcker R., 2015, Representing power sector variability and the integration of variable renewables in long-term energy-economy models using residual load duration curves. Energy, 90: 1799-1814.