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Could Wind and PV Energies Achieve the Grid Parity in China until 2020?

Hong Li[a,b], Yang Yu[b], Yuantao Xie[c], Jing Zhang[b]

[a] *School of Economics, Peking University, Haidian District, 5 Yi HeYuan AV., Beijing 100871, PR China*
[b] *Center for National Resource Economy Studies, Beijing, P.R. China*
[c] *School of Insurance and Economics, UIBE, Beijing, 100029*

Abstract. Grid parity targets of wind and solar power are proposed in China Energy Development Strategy Action Plan 2014–2020. The paper intends to exam this proposal and pinpoints factors that may influence the achievements of these targets. The method of levelized cost of electricity is adopted tocompare the price trends of wind, PV and coal poweron the utility's transmission and distribution grids. The environmental cost of coal-fired power is estimated and accounted into the price comparison. Results show that the levelized prices of wind and PV power will decrease considerably during the period of Action Plan.Neither wind nor PV power is competitive with coal power from the utility or retail side in 2013. But wind power is approaching the utility cost in 2020 and achievesthe grid parity in provinces with the favorable wind resources and unfavorable coal electricity costs. Distributed PV stations can reach the grid parity on the retail level for business or even industrial consumerswhen utility-scale solar plantsstill do not. The extent that the environmental cost is accounted extensively influences the time for wind and solar power at grid parity. These findings implicatethatthe electricity price policies for wind and solar power should be positioned to betterpromote their cost reductions and better reflect theirenvironmental values.

1. Introduction

The strategic development of green, cost-effective electricity alternatives is proposed in *China Energy Development Strategy Action Plan 2014–2020* (2014) by the State Council on Dec 19, 2014. It plans that by 2020, the cumulated installations for wind and solar power will be raised to 200 GW and 100 GW, respectively. The land wind farms are expected to achieve grid parity at the utility transmission side and distributed solar stations will stand at grid parity at the retail side. These targets imply that the share of wind and solar power will double and amount to nearly half of non-fuel energies. The escalating subsidies for renewable energies can be suspended when their cost turn to be competitive. The market pricing reform of electricity will become much easier. In view of these strategic importances, the paper intends to exam and forecast the cost development of wind and solar power in China during 2014–2020.

The common approaches to analyzing the cost developments of wind and photovoltaic (PV) power are based on the application of learning curve or bottom-up assessment of component costs (Azevedo et al.,

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Corresponding author: Hong Li
Email address: lihongpku2012@163.com (Hong Li)

2013). The learning curve serves the strategic promotion of renewable energies in the long-run perspective (IEA, 2000). The bottom-up approach explores the different sources of cost reduction of renewable energies in a mid-term perspective (NREL, 2012). However, the results can be very different when the applied system boundaries and time frames vary in studies (Neil, 2008).

The environmental external cost for uses of coal has been intensively discussed in the Extern E project for European countries. But studies for the external cost in coal power generation in China are still very limited, due to the difficulty in data collection and method adjustments. And there is no literature to forecast the environment cost when stricter environmental rules are to be implemented. It is very necessary to estimate environment cost changes and impact of cost internalization on the competitiveness of different electricity technologies.

1.1. *Electricity cost development of China wind power*

The learning curve is widely applied to the cost evolution of China wind power. Qiu and Anadon (2012) construct a multi-factor learning curve to exam cost effects of Learning-by-doing (LBD), learning-by-searching (LBS) and wind resource conditions. The joint learning rate amounts to 4% or the wind power cost reduces by 4% with the doubling of both cumulative installation and knowledge stock. Chen and Lu (2012) estimate the cost effects of cumulative installation, R&D spending and scale of capacity. The joint learning rate is12.62%. Other studies use the one factor learning curve to test the LBD effect and the learning rate ranges in 5–14% (Di et. al, 2012; Zhu et. al., 2012; Xu and Liu, 2008). It is clearly that China wind power cost reductions follow the experience rule but the progress rate varies with the included cost factors and sampled periods.

The representative study for China wind power cost trend is *China Wind Energy Development Roadmap 2050* (ERI, 2011). Based on the component cost method, it forecasts the investment cost of China land and sea wind farms will decrease to CNY 7500/kWh and CNY 14000/kWh by 2020, respectively. The corresponding grid price will come to CNY 0.51/kWh and CNY 0.77/kWh, still higher than current benchmark price of coal-fired power. According to the 2013 Statistic Assessment Report on China Wind Farm Constructions (2013), the budget estimate and the final account forland wind farm constructions have decreased to CNY 9036/kW and CNY 7958/kW, respectively. A 12% cost gap for wind farm investments indicates that it is highly possibility wind power cost could fall below the prediction in the Road map 2050. Xu and Lin (2008) predicted that the cost of China wind power would be equal to that of coal power in 2020 when the LBD rate is 14% in the one factor learning curve. Therefore, it is very necessary to re-exam the cost trend of wind power in China.

1.2. *Electricity cost development of China solar power*

The electricity cost development of China solar power in literature differs widely, so does the result for wind and solar grid parity. Zhang et al. (2013) estimate that the learning rate of PV power ranges from 15% to 25% during 2005–2010 and forecast that the PV power cost would fall into CNY 0.3/kWh when the learning rate is 25%. Sui (2012) reports that the learning rate is 17% during 2005–2010 and the PV power cost would be CNY 0.65/kWh, or the utility price level. Guo (2011) finds that the learning rate amounts to 32.1% in 2000–2010 and PV power cost is reduced to CNY 0.211/kWh in 2019, competitive tothe cost of coal power. Ma (2010) adopts the component cost method and assumes a 10% learning rate for PV power and a 3% cost increase for coal power. His results demonstrate that PV power cost can fall to the level of coal power (CNY 0.73/kWh) in 2015 if the external cost is fully accounted. And the grid parity (CNY 0.39/kWh) can be achieved until 2020 if the external cost is not considered. *China Solar PV Power Policy Report* (2013) assumes an annual 3–5% cost decrease and estimates that PV power cost will fall to CNY 0.65–0.97/kWh until 2020, depending on the solar resources and technologies. Clearly, the specification of the impact factors is the key to the precise cost assessment of solar power.

1.3. *External cost estimations of China coal power*

It is controversial in the literature about how to assess and internalize the external costs caused by coal-fired power generation. Generally, it is accepted that not all environmental costs are included in the electricity price.

In early studies for the utilization of coal in China, more attention is paid to the external cost of coal mining. Various methods, such as marginal cost model of externality, environmental cost evaluation, economy loss evaluation of environment pollution and ecosystem damage, green national economy assessment and so on, are used to analyze the unsafe mining, land degradation and ecological destruction. The results support that the land and eco-environmental losses are not fully compensated (Li and Zhang, 2011; Zhou et al., 2009). If more external costs, such as protection expenditure and treatment cost for restoration are included (Wu, 2008; Dang et al., 2007; Ai and Xu, 1999), the external cost amounts to CNY 19.9–63.79/ton (Zhang and Lian, 2008).

Recent literatures focus on the assessment of environment values along the whole industrial chains of coal mining, transportation and usage. Mao et al. (2008) is the early study to considered regulation price distortion as well as the external loss in the environment, society and economy. The external damage cost is up to CNY 160/ton or 23.1% of coal price. And the total cost takes up 7.1% of GDP in 2007. Chinese Academy for Environmental Planning (2014 a, b) estimated external costs in twice. The 2010 data shows that the environmental external cost of coal was CNY 204.76/ton or 28% of coal price. Of which, external costs in coal mining, transportation, processing and use were CNY 68/ton, 52/ton and 85/ton respectively. The loss of health takes the largest share along the whole progress, which was up to 55%. The 2012 data exhibits that environment and health losses raised to CNY 260/ton, while the environmental tax and sewage charges were only CNY 30–50/ton and CNY 5/ton respectively, much lower than external costs. Jiang et al. (2008) estimated the environmental value of external damages along coal-fired power chains (including mining, transportation, electricity production, waste and power plant construction). The total losses of human health, crops, forests and ecosystem, material use, cleaning, global warming and accidents in coal mining amount to CNY 0.38/kWh. In view of significant health damage in the coal use, Green peace (2010), Zhang et al. (2007) and Zhang et al. (2008)calculated the loss of direct, indirect economy and quality of life in China coal utilization. In 2005, the economy loss due to the health damage in the coal use was CNY 44.8/ton, accounting for 49% of external costs. The health cost in some provinces reached 97% of the total economy loss and coal was the main factor.

The above literature review supports that the analysis of wind and solar power cost competitiveness depends on the identification of major cost drivers, reasonable cost coverage of electricity production and inclusion of external costs in coal power generation. However, these three aspects are insufficiently discussed in the cost comparison of different electricity technologies in China. The paper intends to specify these aspects and discusses the grid parity of China wind and solar power from the following three aspects: (1) classified discussions of electricity costs on the utility and retail sides, (2) the impact of internalized environmental costs on electricity costs, and (3) provincial comparisons of wind and solar power cost.

The remainder of the paper is arranged as follows. Section 2 illustrates the methodology. The levelized cost of electricity (LCOE) is adopted for the cost calculation of electricity production. The environmental value method is used to calculate the external cost of coal power. Section 3 specifies the data used for technical and financial variables of different electricity technologies. Section 4 reports the cost trends and competitiveness of different electricity technologies. Section 5 provides the conclusions and suggestions.

2. Methodology

2.1. LCOE of wind and PV power

NREL (2014) defines LCOE as the price at which electricity is generated from a specific source to break even over the lifetime of the project. Since LCOE allows the comparison of electricity technologies of unequal life times and capacities, it has been widely used as to compare the cost of different electricity sources. When the LCOE take the internal rate of return, it can also be expressed as the levelized price. If the LCOE of renewable energies, such as wind and solar power, falls below the utility cost, it is said that renewable energies achieve the grid parity. If the LCOE of self-consumed electricity by solar power fall below the retail price, it is also called that solar power achieve the grid parity at the retail side. The LCOE by IRENA (2012) is expressed as:

$$\mathrm{LCOE} = \frac{\sum_{t=1}^{n} \frac{\mathrm{ICC}_t + O\&M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \quad (1)$$

where LCOE is the levelized cost of electricity for wind and PV power. ICC_t is initial capital cost at time t. $\mathrm{O\&M}_t$ is the operating & maintenance expense at time t. F_t is the fuel cost. In wind and PV power generation, F_t is assumed to be zero. r is the discount rate.

Based on equation (1), the LCOE for wind and PV power can be expressed to include depreciation and tax effects of income and value-added charges. The equation is extended as follows:

$$\mathrm{LCOE} = \frac{\sum_{t=0}^{n} \frac{(\mathrm{ICC} * \mathrm{CRF})_t + (O\&M_t + \mathrm{LE}_t + \mathrm{Ins}_t + \mathrm{Int}_t) * (1 - t_I) - t_I * \mathrm{Dep}_t}{(1+r)^t (1 - t_I) * (1 - t_v (1 + t_{\mathrm{vsc}}))}}{\sum_{t=0}^{n} \frac{E_t}{(1+r)^t}} \quad (2)$$

where ICC is initial capital cost. CFR is capital recovery factor. $\mathrm{O\&M}_t$, LE_t, INS_t and INT_t are the operating & maintenance expense, labor expense, insurance and interest expenses at time t, respectively. t_i, t_v and t_{vsc} are the income tax, value-added tax and value-added tax surcharge, respectively. Dep_t is the depreciation at time t. E_t is the energy production at time t, depending on the capacity factor and resource conditions.

ICC cost includes expenses of equipments, installation engineering, construction engineering, project preparations and others. The changes of ICC can be express as:

$$\Delta\mathrm{ICC} = \sum \Delta C_{cf} \quad (3)$$

where ΔC_t and $\Delta C_{cf,t}$ are cost changes of ICC and disaggregated cost changes of core factors (equipments, installation engineering and construction engineering) at time t.

Since the historical data is unavailable for the ICC of wind and solar power in China, previous studies generally estimate the learning rate of wind turbines or PV modules to exam the cost trends of wind and solar power. However, such estimations are likely to exaggerate learning effects and lead to wider variations of learning rates, which is not appropriate for the short-term forecasts of wind and solar power cost changes. It is better to separately estimate the cost trends of equipments and other component in ICC. The learning curve is adopted to forecast the equipment costs and is adopted to forecast other component costs of capital investments. The learning curve is presented as follows:

$$C_{\mathrm{EQ},t} = C_{\mathrm{EQ},0} \left(\frac{\mathrm{CQ}_{\mathrm{EQ},t}}{\mathrm{CQ}_{\mathrm{EQ},0}} \right)^{-b} \quad (4)$$

$$\mathrm{LBD} = 1 - 2^{-b} \quad (5)$$

where $C_{\mathrm{EQ},0}$ and $C_{\mathrm{EQ},t}$ are the capital costs of wind turbines and solar systems at the initial time and time t. $\mathrm{CQ}_{\mathrm{EQ},0}$ and $\mathrm{CQ}_{\mathrm{EQ},t}$ are the cumulative productions at the initial time and time t. b is the index of LBD. Equation (5) is used to estimate the learning rate.

Other component costs ($C_{\mathrm{OC},t}$), such as other electronic and electric equipments ($C_{\mathrm{OEQ},t}$), installation engineering ($C_{\mathrm{IE},t}$), construction engineering ($C_{\mathrm{CE},t}$) are presented as follows:

$$C_{\mathrm{OC},t} = C_{\mathrm{OEQ},t} + C_{\mathrm{IE},t} + C_{\mathrm{CE},t} = \mathrm{CC}_{\mathrm{OEQ}} * C_{\mathrm{OEQ},t-1} + \mathrm{CC}_{\mathrm{IE}} * C_{\mathrm{IE},t-1} + \mathrm{CC}_{\mathrm{CE}} * C_{\mathrm{CE},t-1} \quad (6)$$

where $\mathrm{CC}_{\mathrm{OEQ}}$, $\mathrm{CC}_{\mathrm{IE}}$, $\mathrm{CC}_{\mathrm{CE}}$ are the average annual cost rates of change for other equipments, installation engineering and construction engineering. Other component costs at time t are calculated by the annual cost rates of change multiplying the cost at time $t-1$ ($\mathrm{CC}_{\mathrm{OEQ},t-1}$, $\mathrm{CC}_{\mathrm{IE},t-1}$, $\mathrm{CC}_{\mathrm{CE},t-1}$).

As for project preparation and other expenses, such as construction land fees, construction management fees, production preparation fees and others, theyare designated as per following regulations. They are *Classification and design safety standard of wind power projects FD 002-2007* (CREEI, 2007), *Notice of National Planning Commission on regulation of projects exploration and design charge management* (2002) and *Notice of National planning Commission and China Construction Bank on surveillance scope and charge standard of project quality supervision organizations* (1986).

2.2. *Costs of coal-fired power*

2.2.1. *LCOE of coal-fired power*

Different from wind and PV power, fuel cost should be incorporated in the LCOE equation for coal-fired power. Equation (2) can be extended as follows:

$$\mathrm{LCOE} = \frac{\displaystyle\sum_{t=0}^{n} \frac{(\mathrm{ICC} * \mathrm{CRF})_t + (O\&M_t + \mathrm{LE}_t + \mathrm{Ins}_t + \mathrm{Int}_t + \mathrm{Fuel}_t) * (1 - t_I) - t_I * \mathrm{Dep}_t}{(1+r)^t (1 - t_I) * (1 - t_v (1 + t_{\mathrm{vsc}}))}}{\displaystyle\sum_{t=0}^{n} \frac{E_t}{(1+r)^t}} \tag{7}$$

The cost of coal consumed for power generation can be expressed as:

$$F_t = \frac{3600 F_p}{\eta (1 - \mathrm{s})} \tag{8}$$

Where F_t – fuel cost of coal, CNY/kWh

F_p – fuel price, CNY/GJ

η – annual average power of generator.

s: line loss rate of power generation side; Commonly, coal-fired power plants ignore s or s is assumed to be zero.

The capital investment of coal-fired power units is much stable than that of renewable energies. The main uprising costs are construction land fees, construction management fees, operating & maintenance expense and labor expense. The most fluctuating cost is the price of coal. Other variables, like coal consumption per kilowatt hour, dust, SO_2 and NO_x emissions, are mainly under control by national plans.

2.2.2. *The cost of coal*

As the coal price is set in the market rather by China government after 2002, the price of power coal in domestic market tends to co-move with that in international markets. Australia is the world leading coal export countries and has been one of major exporter to China. The representative prediction for Australia coal price changes can be used as references for China.

2.2.3. *External costs of coal-fired power generation*

In China, electricity is mainly produced by coal-fired power plants. The paper will mainly estimate the environmental external costs along the coal-fired power chain. The environmental external cost assesses the economic value of damages induced in coal mining, transportation, power construction and generation, and spontaneous combustion. Jiang (2008) methods are adopted in the estimation and the relevant price indices are adjusted, see Table 1. In view of the differences of cost boundaries, assessment approaches and data sources, the estimated environmental external costs of different studies will be also compared.

Table 1: Environmental external cost assessment of coal power chain

Damage costs	Methods (Jiang, 2008)	Price index adjustments
forests	Market evaluation	Purchasing price index for wood and paper pulps
Crops	Market evaluation	Producer price index for primary agricultural products
Health hazard (air pollution)	Payment willing approach	Per-capita disposable income index of urban residents
Material replacement	Replacement approach	Price index of construction materials
cleaning	Market evaluation, replacement approach	Clothing consumption expenditure index
Health hazard (radiological impact)	cost of illness approach	Consumer price index
Global warming	American environmental standard	Average annual price of carbon trading in China in2013–2014
Mining accidents	Compensation standard	
Ecosystem	Market evaluation	

2.3. *The cost competitiveness of different electricity technologies*

The grid parity of wind and solar power will be assessed through the comparison of LCOE in 2013–2020 at both utility and retail sides for national average and provincial areas. The externalization of environmental external costs will be accounted to judge the timing of grid parity of wind and solar power. The wind curtailment problem will be considered in the estimation of LCOE which is used to compare the current level and changes of feed-in tariff for wind and solar plants in China.

3. Data

3.1. *Wind power*

3.1.1. *Technical and cost indicators*

The main cost components of wind farms include wind turbines, raw material of steel, electronic, electrical and communication equipments, construction and installation engineering. The learning curve for wind turbines is estimated with the available data in 2006–2013. The steel price is based on the world data for lack of statistics in China. The cost data of construction and installation engineering are based on China wind farm statistics in 2011–2013. The data details are presented as follows:

Wind turbine price. The historical price data of wind turbines is provided by CWEA (2013). The explanatory variables are set according to the cost reduction of different factors in literature, such as production capacity, turbine size and raw materials.

Cumulative production capacity of wind turbines. The historical data is provided by CWEA (2013) and the scale in 2020 is set according to the Plan (2014).

Unit size of wind turbines. The historical data is provided by CWEA (2013), and it is expected that the unit size of mainstream turbines will expand to 3 MW in 2020.

Steel price. Main raw materials of wind turbines include iron, steel, copper, aluminum, fiberglass/resin, concrete and permanent magnet. Literature supports that steel price is the main cost changes in raw materials (EWEA, 2009). The historical data is sourced from the World Bank (WB, 2014) and the annual price rate of change is calculated based on the historical trend.

Costs of electronic, electrical and communication equipments. The historical data is unavailable. We use the collected data from typical wind farm project reports as references. According to the statistics of annual real price movements of electronic and electrical equipments in Europe, prices of other equipments are expected to decrease by 5% annually.

Construction and installation engineering. Only 2011–2013 data is available and provided by CREEI. The annual cost rate of change is set to be 10% on the basis of historical trend.

Table 2: Main technical indications of wind power in China

	2013	**2020**
Cumulative Installed Capacity (GW)	91	200
Average unit size (MW)	1.5–2	3
Annual operation hours (hrs*)	1700–2600	1700–2600
System efficiency (%)	85	85

Sources: CWEA database, GOSC (2014)
Note: * hours (hrs)

3.1.2. *Financial indicators*

Financial indicators and data are set as per national policies of finance and tax, engineering project regulations and wind project routines (Table 3).

Table 3: Financial indications of land wind farms in China

Operation Period (years)	20	Depreciation Period (years)	15
Fixed Assets Formation Rate (%)	90	Value Added Tax Rate (%)	17
Loan Ratio (%)	70	Income Tax Rate (%)	25
Loan Period (%)	15	Surtax Rate (%)	10
Loan Interest (%)	6.55	Internal Rate of Return (%)	8.00

Sources: NDRC (2006)

3.1.3. *Wind resources and electricity production*

Electricity production of a wind farm is influenced not only by resource conditions but also grid capacity sufficiency. In 2011–2013, wind curtailment rates of major wind energy bases are over 10%, considerably below available effective hours. However, the inter-provincial power transmission capability will be extensively improved by 2020 as the ultra-high voltage transmission network 2020 plans. Therefore, available effective hours are set to 1700–2600 hrs/yr and the wind curtailment rate is set to 5% in 2020.

3.2. *Solar power*

3.2.1. *Technical and cost indicators*

The main cost components of PV plants include modules, balance of system, construction and installation engineering. The learning curve for PV modules is estimated with the available data in 2007–2013. The component cost model for PV balance of system is estimated with the available data in 2010–2013. The cost data of construction and installation engineering is sourced from typical solar farm project reports as references. The main technical and cost data sources are presented as follows:

PV module prices. The module price data is sourced from IEA. The explanatory variables are set according to the cost reduction of different factors in literature, such as polysilicon, silicon thickness and cell efficiency. The polysilicon price is sourced from PV in sights (2014) and silicon thickness and cell efficiency data are provided by SEMI (2013).

PV balance of system. PV balance of system includes all other components of a PV system other than modules. The largest cost component is the inverter. The price rate of change for other electronic, electrical and communication equipments is set as those of wind plants.

Construction and installation engineering. Since the historical data is unavailable, we use the collected data from typical PV plant reports as references. The annual cost rate of change is set to be 5% in the ground stations and distributed plants of 10 MW and 1 MW capacity scale.

Cumulative production capacity. In view of China's dominant share in the module manufacturing, the cumulative production capacity is set on the basis of global cumulative installation capacity growth (see Table 4). The solar installation capacity is set in accordance to GOSC (2014).

Table 4: Technical indicators of solar power in China

	2013	**2020**
Cumulative produced Capacity (GW)	25	60
Silicon thickness (μm)	180	100
Silicon usage (g/W)	6	3
Cell efficiency (%)	18.5–18.9 (PM*)	20–21 (PM*)
	17.5–17.6 (MM*)	19.5–20 (MM*)
System efficiency (%)	75	79–89
Efficiency degradation (%)	< 15	< 15
Annual operation hours (hrs)	800–2200	800–2200

Sources: SEMI(2013), IEA (2011), GOSC (2014).
Note: * polycrystalline modules (PM), monocrystalline modules (MM)

3.2.2. Financial indicators

Financial indicators and data are set as per national policies of finance and tax, engineering project regulations and wind project routines (see Table 5 and 6)

Table 5: Financial indicators of PV stations and roof tops in China

Operation Period (yrs)	25	Depreciation Period (yrs)	15
Fixed Assets Formation Rate (%)	90	Value Added Tax Rate (%)	17
Loan Ratio (%)	70	Income Tax Rate (%)	25
Loan Period (%)	15	Surtax Rate (%)	10
Loan Interest (%)	6.55	Internal Rate of Return (%)	8

Sources: NDRC (2006)

3.2.3. Solar resources and electricity production

According with the solar resource conditions and in 2012, the annual available effective hours for PV plants are set to 800–2200 hrs/yr. The grid curtailment is not serious in solar power and not considered to significantly affect the electricity production.

3.3. Coal-fired power

3.3.1. Technical and cost indicators

Unit size and coal consumption of coal-fired power generating units. They are set as per the unit capacity requirement and admission control of newly-built coal-fired power generating units in NDRC file [2004]864 (2004) and NDRC file [2014]2093 (2014) (see Table 6).

Water and electricity consumption in coal-fired power generation. The historical data of water consumption per kilowatt hour is sourced from China Electronic Power Yearbooks (2006–2013) and the annual rate of change is calculated based on the historical trend (see Table 6).

Annual operation hours and operation period. Based on the average operation hour of coal-fired power plants in 2013 and unoptimistic planning of plants in 2014–2020, it is assumed that the annual operation hour is about 5000 hours in 2020. The operation period of coal-fired power generating units is set to be 20 years and won’t change in 2014–2020.

Table 6: Technical indicators of coal power plants in China

	2013	2020
Size of power unit (MW)	600*	600
Coal consumption/kWh (g)	321	300
Annual operation hours (hrs/yr)	5012	5000
Water consumption (kg/kWh)	2.15**	0.98
Power plants electricity consumption (%)	6.08**	5.46
Operation period (t, yrs)	20	20

Sources: CEC (2014), China Electric Power Yearbook (2006–2013).
Note: *Since 2012, 600MW coal power unit is current mainstream unit, accounting for 40.15% of total coal power capacity.
**2012 data.

3.3.2. *Financial indicators*

Financial indicators and data are set as perthe *Reference Price Indices for Quoted Design of Thermal Power Projects* (2013). It is assumed that they won't change in 2020. (See Table 7).

Table 7: Financial indicators of coal power plants in China

Fixed Assets Formation Rate (%)	60	Depreciation Period (yrs)	15
Operation Period (yrs)	20	Value Added Tax Rate (%)	17
Loan Ratio (%)	70	Income Tax Rate (%)	25
Loan Period (%)	15	Surtax Rate (%)	10
Loan Interest (%)	6.55	Internal Rate of Return (%)	8

3.3.3. *Coal price*

Fig.1 plots the nominal price of coal trades in China market and exports from Australian, expressed by CNY/ton, for 2008–2014. The series are obtained from IEA and China Mining Industry Yearbook (2009–2014). It is apparently that China coal price, following the peak in 2010, decline sharply in 2013–2014. Australia has been the most important coal exporter to China and two price series have been more commoving since 2012 (Fig.1 and 2). According to Statista (2014) prediction on 4.5% trading price decline of Australia coal in 2020, it is assumed that China coal price will decline by 4–5% in 2020 as well.

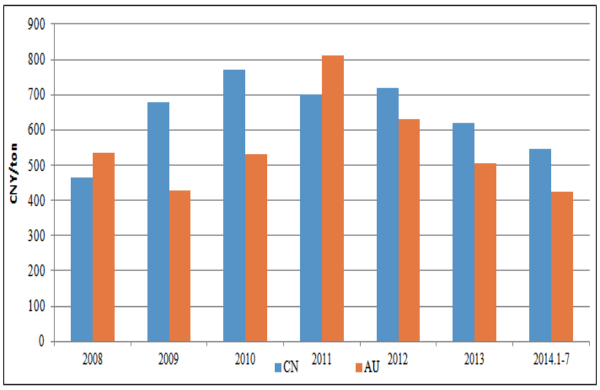

Figure 1: China and Australian coal price movements

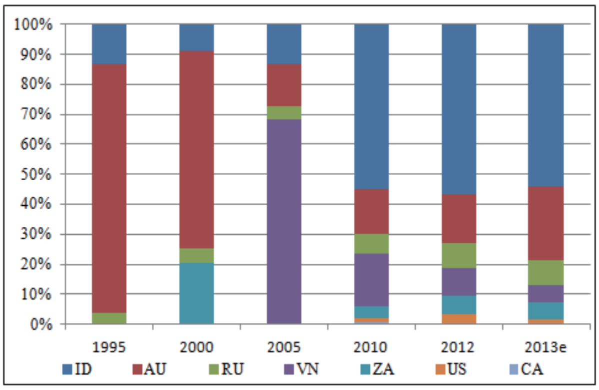

Figure 2: China steam coal imports by country

Sources: IEA
Note: Indonesia (ID), Australia (AU), Russia (RU), Vietnam (VN), South Africa (ZA), the United States (US), Canada (CA).

3.3.4. *External cost indicators*

Technical indicators to evaluate environmental external costs of coal-fired power chain are set as Jiang (2008). The data are provided in accordance with policy documents of *Upgrade and Transformation Project of*

Energy Conservation and Emission Reduction of Coal (2014–2020), *Announcement for Executing Special Emission Limit of Air Pollution [2013]14* and *Emission Standard for Air Pollution of Coal Plant (GB 13223-2011)*.

In file [2013]14, special emission limits of dust, SO_2 and NO_x are 20 mg/m^3, 50 mg/m^3 and 100 mg/m^3 respectively. In 2014–2020 project document, the emission limits are controlled to 10 mg/m^3, 35 mg/m^3 and 50 mg/m^3, half of the standard in file [2013]14. Based on the emission of turbo set power generation in 2013 (CEC, 2013) and emission limits of 2014–2020 project document, dust, SO_2 and NO_x emissions are set to 0.2 g/kWh, 1.0 g/kWh and 0.95 g/kWh in 2020. Table 8 compares these indicators with those of Jiang (2008). It is apparently that Jiang's data will overestimate external costs in coal-fired power chain for 2020.

Table 8: Technical indicators of external costs in coal-fired power generation

	2013	2020	Jiang (2008)
SO_2 emission (g/kWh)	1.86	0.95 (or 35–200 mg/m^3)	7.56
NO_x (g/kWh)	2.0	1.0 (or 50–100 mg/m^3)	3.6
Smoke (g/kWh)	0.36	0.2 (or 10–30 mg/m^3)	3.18
CO_2(g/kWh)	853	798	907.1

Sources: Wang (2014), NDRC (2014), Jiang (2008).

4. Results

4.1. LCOE changes of wind power

4.1.1. LCOE and feed-in tariff of wind power

Based on the available data of different variables and LCOE equation (2), the capital investment equation (3), (4) and (6), the levelized price of wind power is calculated and compared with the current feed-in tariff (FiT) for China wind plants in four resource zones (Table 9 and 10). The levelized price of wind power ranges in CNY 0.50–0.63/kWh, depending on the different resource, construction and grid curtailment conditions. The levelized price is higher than expected in wind bases of China north areas where the wind curtailment rate even tops 20.65%. Current FiTis barely to cover the LCOE of wind plants in China wind resource zone I, II and III.

Table 9: FiT and LCOE for China wind plants

Wind zones	Annual EUH (HRS/year)	FiT (CNY/KWh)	LCOE (CNY/KWh)	Covering Areas
I	> 3000	0.51	0.5–0.54	IM (except Chifeng, Tongliao, Hinggan League and Hulun Buir), XJ (Urumchi, Ili Kazak Autonomous Prefecture, Changji Hui Autonomous Prefecture, Karamay and Shihezi)
II	2500–3000	0.54	0.57–0.63	HB1 (Zhangjiakou and Chengde), IM (Chifeng, Tongliao, Hinggan League and Hulun Buir), GS (Zhangye, Jiayuguan and Jiuqua)
III	2000–2500	0.58	0.54–0.63	JL (Baicheng and Songyuan), HLJ (Jixi, Shuangyashan, Qitaihe, Suihua, Yichun and Daxinganling), XJ (except Urumchi, Ili Kazak Autonomous Prefecture, Changji Hui Autonomous Prefecture, Karamay and Shihezi), NX
IV	< 2000	0.61	< 0.61	Other areas

Sources: NDRC (2009)

Note: equivalent utilization hours (EUH).

4.1.2. FiT estimates of wind power in 2014-2020

Under the assumption that the wind curtailment rate is under control of 5%, the FiT for different wind resource zones is estimated on the basis of the LCOE changes. Results in Table 10 show that the LCOE for different wind resource zones will decline extensively, compared with current FIT, in 2014–2020. In 2017, the FiT can decline by more than 14% to CNY 0.42, 0.46, 0.50 and 0.53/kWH. In 2020, the FiT can decline by more than 25% to CNY 0.36, 0.40, 0.43 and 0.46/kWH.

Table 10: FiT estimates of China land wind farms, 2014–2020 (CNY/kWh)

Wind zones	2014	2015	2016	2017	2018	2019	2020
I	0.49	0.48	0.45	0.42	0.39	0.37	0.36
II	0.53	0.52	0.49	0.46	0.43	0.41	0.40
III	0.58	0.56	0.54	0.5	0.47	0.45	0.43
IV	0.61	0.59	0.57	0.53	0.49	0.47	0.46

4.2. LCOE changes of wind power

4.2.1. LCOE and feed-in tariff of solar power

Based on the available data of different variables and LCOE equation (2), the capital investment equation (3), (4) and (6), the levelized price of solar power is calculated and compared with the current feed-in tariff (FiT) for China PV plants in three resource zones (Table 11 and 12). The levelized price of solar power ranges in CNY 0.8–1.01/kWH, depending on the different resource, construction and technological conditions. The current FiT is high enough to cover the LCOE of PV plants in different zones.

Table 11: FiT for China PV plants, 2013–2014

Irradiation Zones	Annual EUH (hours/year)	FiT (CNY/kWh)	LCOE (CNY/KWh)	Covering Areas
I	> 1600	0.9	0.8–0.85	NX, QH (Haixi), GS (Jiayuguan, Wuwei, Zhangye, Jiuquan, Dunhuang, Jinchang), XJ (Kumul, Tacheng, Altay, Karamay), IM (except Chifeng, Tongliao, Hinggan League and HulunBuir)
II	1400–1600	0.95	0.8–0.9	BJ, TJ, HLJ, JL, LN, SC, YN, IM (Chifeng, Tongliao, Hinggan League and HulunBuir), HB1 (Chengde, Zhangjiakou, Tangshan, Qinhuangdao); SX1 (Datong, Shuozhou and Xinzhou), SX2 (Yunlin and Yanan), QH, GS, Other XJ areas
III	1000–1400	1.0	0.9–1.01	Other areas

Sources: NDRC (2013)

4.2.2. FiT estimates of solar power in 2014–2020

Based on the LCOE changes, the FiT for different wind resource zones is estimated for 2014–2020 (See Table 12). Regardless of installation and distribution differences, the capital investment of large scale PV ground stations and rooftops can fall below CNY 7400/kWH in 2020. The FiT can fall to CNY 0.53, 0.60 and 0.70/kWh in three different irradiation zones, lower by CNY 0.37, 0.35 and 0.30/kWh than those in 2013. In consideration of installation capacity differences, the capital cost of distributed PV plants ranges in CNY 7400–8800/kWh by 2020. The LCOE of small-scale distributed PV plants in good irradiation zones is close to the level of FiT in bad irradiation zones.

Table 12: FiT estimates for China PV plants, 2014–2020 (CNY/kWh)

Irradiation Zones	2014	2015	2016	2017	2018	2019	2020
I	0.75	0.71	0.66	0.62	0.58	0.55	0.53
II	0.85	0.81	0.75	0.71	0.66	0.63	0.60
III	1	0.95	0.87	0.82	0.77	0.73	0.70

4.3. LCOE and external cost changes of coal-fired power chain

4.3.1. LCOE of coal-fired power

Based on the available data of different variables and LCOE equation (7), the levelized price of coal-fired poweris estimated in 2013 and 2020. Results show that the LCOE is CNY 0.34/kWh in 2013 under the national average annual operation hours and will rise slightly to CNY 0.36/kWh in 2020 under the similar operation hours. The rise of LCOE of coal-fired power is mainly caused by the construction and land fees.

4.3.2. Environmental external costs in 2013 and 2020

With adjusted methods, technical indicators and price indices listed in Table 1 and 8, the environmental external cost is estimated for the coal power chain in 2013 and 2014 (Table 13 and 14). Results show that the environmental external cost is not low and should not be neglected. In 2013, the external cost amounts to CNY 0.254/kWh, of which the cost health damage takes up the largest share to 48% or CNY 0.121/kWh. The external costs of global warming and eco-system destruction total to CNY 0.1/kWh or take up 40% cost contribution. Along the coal power chain, the power generation leads to CNY 0.155/kWh or 61% share of external costs, followed by the coal mining of CNY 0.0791/kWh or 31% of costs. In 2020, the external cost along the coal power chain will increase to CNY 0.2.94/kWh, mainly due to the improved payment willing to avoid or reduce health damage.

Table 13: Environmental external costs of coal power chain, 2013

	Coal mining	Coal Transportation	Power generation	spontaneous combustion	Total
Health damage (air pollution)	$3.96{*}10^{-2}$	$4.27{*}10^{-3}$	$7.26{*}10^{-2}$	$4.38{*}10^{-3}$	$1.21{*}10^{-1}$
Crops	$4.12{*}10^{-3}$	$3.93{*}10^{-4}$	$5.71{*}10^{-3}$	$4.53{*}10^{-4}$	$1.07{*}10^{-2}$
Forests	$2.12{*}10^{-3}$	$2.03{*}10^{-4}$	$2.96{*}10^{-3}$	$2.35{*}10^{-4}$	$5.52{*}10^{-3}$
Ecosystem	$2.12{*}10^{-2}$	$2.03{*}10^{-3}$	$2.96{*}10^{-2}$	$2.35{*}10^{-3}$	$5.52{*}10^{-2}$
Material replacement	$1.45{*}10^{-3}$	$1.38{*}10^{-4}$	$2.01{*}10^{-3}$	$1.59{*}10^{-4}$	$3.75{*}10^{-3}$
Cleaning		$1.62{*}10^{-4}$	$6.17{*}10^{-3}$	$8.11{*}10^{-6}$	$6.34{*}10^{-3}$
Health hazards (radiation)	$2.67{*}10^{-4}$		$5.36{*}10^{-5}$	$2.73{*}10^{-3}$	$3.05{*}10^{-3}$
Global warming	$9.85{*}10^{-3}$	$1.68{*}10^{-3}$	$3.57{*}10^{-2}$	$4.72{*}10^{-4}$	$4.77{*}10^{-2}$
Mining accidents	$4.14{*}10^{-4}$				$4.14{*}10^{-4}$
Total	$7.91{*}10^{-2}$	$8.88{*}10^{-3}$	$1.55{*}10^{-1}$	$1.08{*}10^{-2}$	$2.54{*}10^{-1}$

Table 14: Environmental external cost estimates of coal power chain, 2020

	Mining	Transportation	Power generation	spontaneous combustion	Total
Health damage (air pollution)	$5.65{*}10^{-2}$	$6.10{*}10^{-3}$	$1.04{*}10^{-1}$	$6.25{*}10^{-3}$	$1.72{*}10^{-1}$
Crops	$5.54{*}10^{-3}$	$5.27{*}10^{-4}$	$3.91{*}10^{-3}$	$6.09{*}10^{-4}$	$1.06{*}10^{-2}$
Forests	$2.37{*}10^{-3}$	$2.27{*}10^{-4}$	$1.69{*}10^{-3}$	$2.63{*}10^{-4}$	$4.56{*}10^{-3}$
Ecosystem	$2.37{*}10^{-2}$	$2.27{*}10^{-3}$	$1.69{*}10^{-2}$	$2.63{*}10^{-3}$	$4.56{*}10^{-2}$
Material replacement	$1.72{*}10^{-3}$	$1.64{*}10^{-4}$	$1.22{*}10^{-3}$	$1.90{*}10^{-4}$	$3.30{*}10^{-3}$
Cleaning		$2.37{*}10^{-4}$	$5.00{*}10^{-3}$	$1.18{*}10^{-5}$	$5.25{*}10^{-3}$
Health hazards (radiation)	$3.64{*}10^{-4}$		$7.30{*}10^{-5}$	$3.71{*}10^{-3}$	$4.15{*}10^{-3}$
Global warming	$9.85{*}10^{-3}$	$1.68{*}10^{-3}$	$3.57{*}10^{-2}$	$4.72{*}10^{-4}$	$4.77{*}10^{-2}$
Mining accidents	$4.14{*}10^{-4}$				$4.14{*}10^{-4}$
Total	$1.01{*}10^{-1}$	$1.12{*}10^{-2}$	$1.68{*}10^{-1}$	$1.41{*}10^{-2}$	$2.94{*}10^{-1}$

In order to compare different external cost studies, the paper adjusts their results with the price index for different sample periods. Results show that the health damage cost is inflated to CNY 0.063/kWh and CNY 0.067/kWh in the 2013 CNY for Green Peace (2008) and Chinese Academy for Environmental Planning (2014 b). It is apparently that results differ substantially. In order to minimize the result differences caused by the cost boundaries, assessment approaches and data sources, the paper designates that the external cost ranges in CNY 0.063–0.254/kWh in 2013 and CNY 0.063–0.294/kWh in 2020.

4.4. The cost competitiveness of different electricity technologies

Based on the LCOE changes of different electricity technologies, China wind and solar power costs will decrease substantially in 2014–2020 and the grid parity is likely to be achieved at the utility or retail side. When the external cost of coal-fired power is accounted into the electricity price, the cost competitiveness of wind and solar power in China will be further enhanced.

(1) Levelized prices at the utility side. In 2013, the levelized prices of China wind and solar power are still uncompetitive with that of coal-fired power under the average annual operation hours (2013). Even when the external cost is completely accounted, the levelized price of wind power is still CNY 0.04/kWh lower, less than that of the solar power (Fig. 3). In 2020, the wind power is close to the grid parity, while the solar power is still not. The levelized price of wind power is only CNY 0.03/kWh higher than the desulfurated, denitrificated and dust green electricity price of coal-fired plants, and CNY 0.03/kWh and CNY 0.25/kWh lower than the low end and high end of environmental external cost. Fig. 4 shows that the time wind power achieves grid parity is sensible to the extent that the external cost is included into the electricity price. Wind power can fall below the LCOE before 2018 even when the low level environmental cost is included.

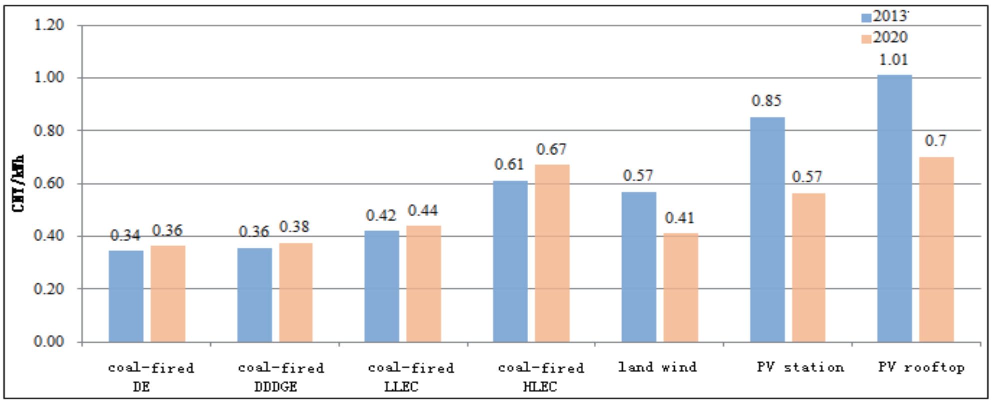

Figure 3: Levelized price estimates of wind, PV and coal-fired power in China, 2013 and 2020

Note: desulfurated electricity (DE), desulfurated, denitrificated and dust green electricity (DDDGE), low level external cost (LLEC), high level external cost (HLEC)

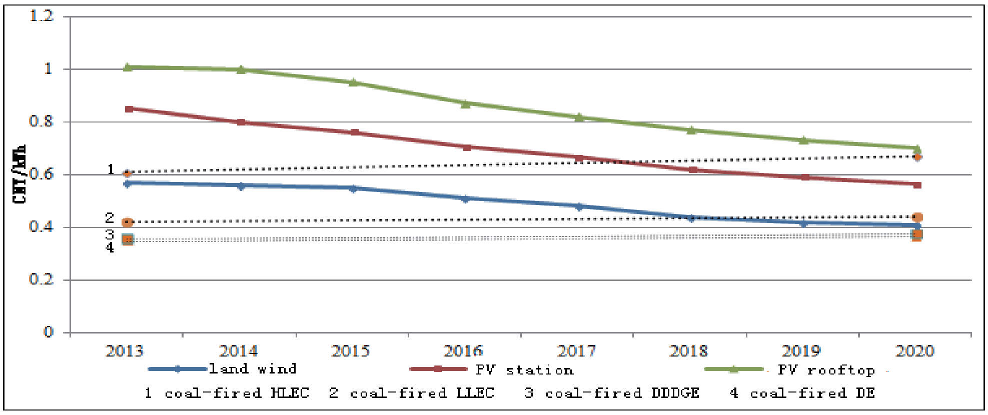

Figure 4: Levelized price estimates of wind, PV and coal-fired power in China in 2013–2020

(2) Provincial levelized prices at the utility side. Fig 5–8 shows that some provinces can achieve the grid parity of wind power in or before 2020, while no provinces can get the grid parity of solar power before 2020 except the high level external cost (HLEC) is included. Regardless of environmental external costs, nine provinces in wind resource zone IV: SH, ZJ, JX, HB2, HN2, GD, GX, HN3, SC and HB1II. There are eight provinces that wind power falls by only CNY 0.02/kWh higher than the utility price. If the low level external cost (LLEC) is accounted, all provinces except QH, GZ, YN, NX, XJ, GS and IMII areas can achieve the grid parity. If the HLEC is accounted, all provinces achieve the grid parity.

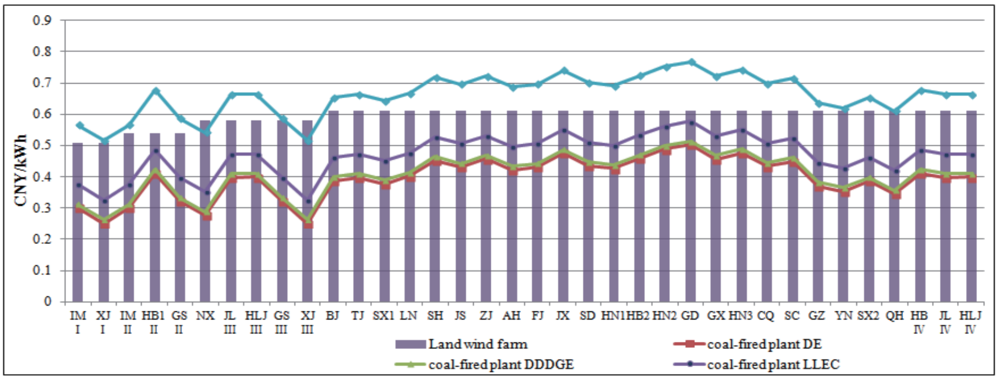

Figure 5: Benchmark prices of wind and coal-fired power for China provinces, 2013

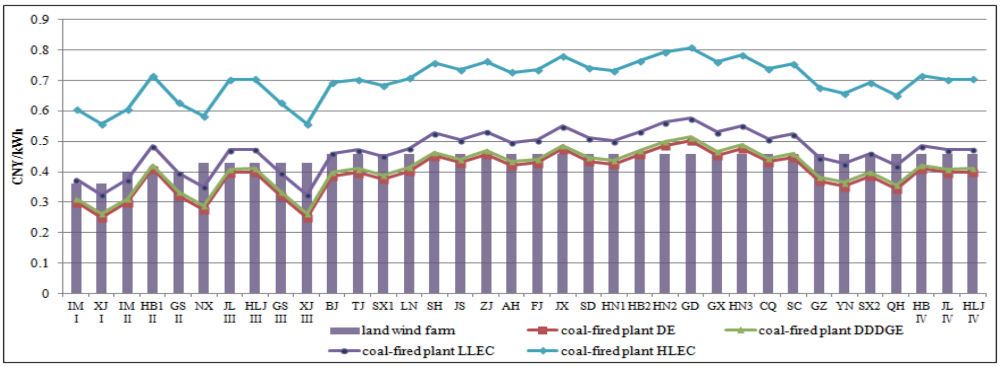

Figure 6: Levelized price estimates of wind and coal-fired power for China provinces, 2020

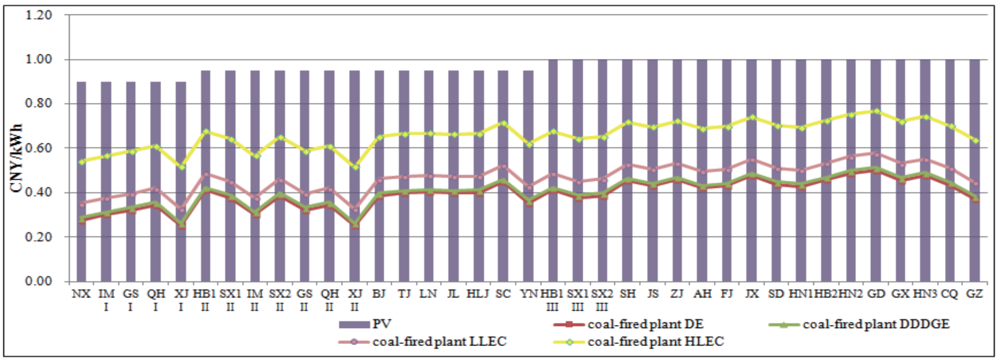

Figure 7: Benchmark prices of PV and coal-fired power for China provinces, 2013

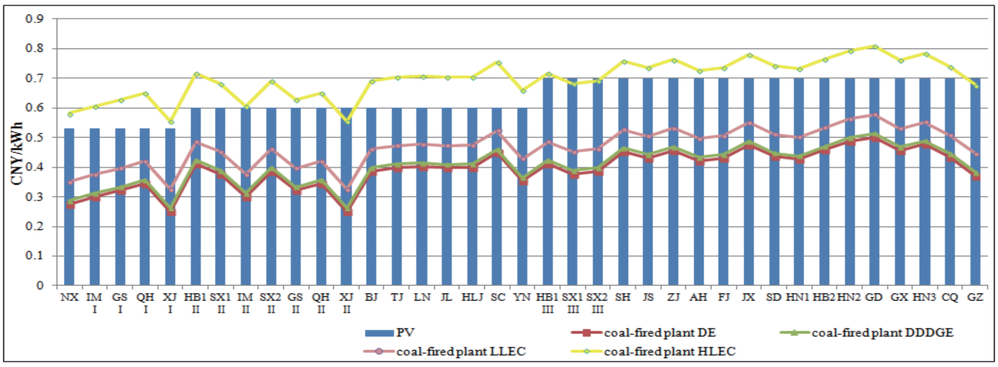

Figure 8: Levelized price estimates of PV and coal-fired power for China provinces, 2020

(3) Levelized prices at the retail side. Fig. 9 and 10 show that the price competitiveness of PV changes at the retail side in 2014–2020. In 2013, the FiT for distributed PV is still higher than retail prices. In 2020, the LCOE for self-consumed electricity of PV power will generally fall below the retail price for business. In provinces of wind resource zone II and III, such as BJ, TJ, HLJ, SC, ZJ, SD and GD, the LCOE for self-consumed electricity of PV power will fall below the retail price for industry. However, the LCOE of solar power still cannot compete with the retail price for residents in all provinces by 2020.

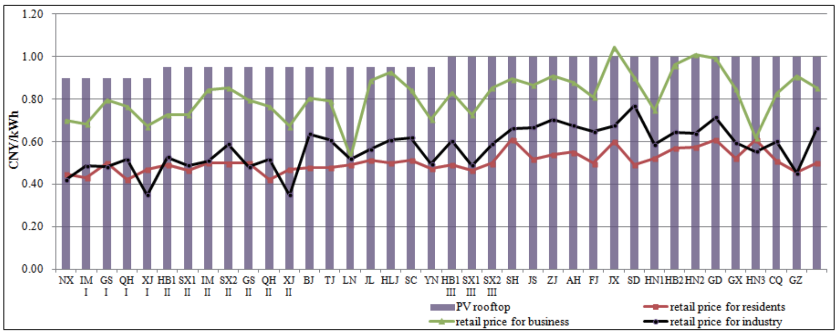

Figure 9: PV rooftop levelized prices and retail electricity prices for China provinces, 2013

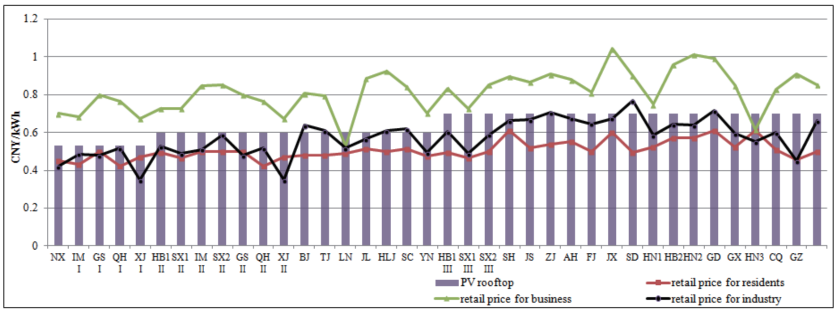

Figure 10: PV rooftop levelized and retail electricity price estimates for China provinces, 2020

5. Conclusions and policy implications

The paper explores the cost changes of China wind, solar and coal-fired power in 2013–2020 and the way that wind and solar power achieve the grid parity by 2020. The LCOE method is adopted and environment external cost is assessed in the cost comparison of different electricity technologies at the utility and retail sides. Results demonstrate that wind and PV power cost is still uncompetitive to that of coal-fired power for national average and provincial areas in 2013. By 2020, half of provinces with resource conditions and higher electricity price will fall at or below the grid parity. In most provinces, the LCOE for self-consumed electricity of PV power will fall below the retail price for business. And in some provinces of solar irradiation zone II and III can achieve the grid parity for self-consumed electricity of PV power at the retail price for industry. When the environmental external cost is accounted, both wind and solar power can achieve the grid parity much earlier. The resolution of the wind curtailment problem can extensively improve the cost competitiveness of wind plants in north China.

The results have very important implications for policy formulation and renewable energy developments. From the perspective of grid price, FiT policy and pricing mechanism of wind and PV power need to be improved. It should be adjusted to reflect the LCOE changes of different electricity sources, to optimize renewable energy fund usage and ensure the environment benefits of renewable energies. From the perspective of grid planning, more specific plan and effective measurements are needed to be formulated and adjusted to guarantee rational construction and operation of wind and solar power projects, efficient usage of land and fund as well as construction and management of grid-connected facilities.

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