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Comprehensive review of renewable energy curtailment and avoidance: A specific example in China

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ABSTRACT

Concerns over climate change (global warming) are driving innovation for stabilizing and reducing greenhouse gas (GHG) emissions. Technologies like carbon capture and storage (CCS) as well as renewable energy sources including wind and solar have been increasingly used and integrated into existing energy systems. The global installed renewable energy capacity booms, but many problems regarding grid integration appears due to the variability and uncertainty in the output of renewable energy generation. Therefore, large amount of curtailed electric energy (CEE) exists, which means some of the renewable energy generation must be wasted to keep real-time balance between load and generation in power system. In this paper, the definition of CEE is introduced, and the main causes for CEE are discussed. Then, the worldwide CEE is estimated, especially in China. Moreover, to evaluate the utilization priority of various generation resources, the potential of reducing fossil fuel consumption, GHG emissions and air pollutants as well as the potential of capturing CO_2 with CEE are analyzed. Possible CEE reduction strategies are also presented.

Contents

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1. Introduction

Renewable energy sources, such as hydropower, geothermal, solar, wind and marine energies, can serve as environmentally responsible alternatives to reduce dependence on fossil fuels due to their zero or near-zero emissions of both air pollutants and GHGs [1,2]. Renewable energy sources are steadily becoming a greater part of the global energy mix, in particular in the power sector. According to the "World Energy Outlook 2013" (International Energy Agency, IEA), the share of global renewable energy in electricity supply was 20% in 2011 and it was expected to increase to 31% by 2035 [3]. In China, according to the 12th Five-Year Plan (2011–2015), non-fossil fuel energy is supposed to account for 11.4% and 15% of the total primary energy consumption by 2015 and 2020, respectively [4].

Renewable energy generation is uncertain because its output is determined by the underlying meteorological factors. The abundant renewable energy may have to be curtailed because real-time balance between load and generation must be maintained, and electric generation cannot be economically stored on a large scale. In addition, renewable energy generation cannot be utilized in case of equipment maintenance, upgrade works or failure. Renewable energy curtailment in these cases is called curtailed electric energy (CEE). The massive CEE has caught more attention with a higher penetration of renewable energy worldwide, especially in China. In 2011, the curtailed wind power generation in "three-N region" (North China, Northeast, and Northwest) was up to 12.3 billion kW h, eventually causing a loss of 6.6 billion CNY for wind farm investors, and 16.23% of wind power generation in the "three-N region" is lost [5]. In addition, compared with 20 billion kilowatt-hours to curtailment in 2012, China's wind power sector lost as much as 16.2 billion kW h wind energy in 2013 [6]. In Spain, the curtailed wind energy totaled 0.315 billion kW h in 2010 and it was approximately 45–50% in Texas, USA from January to August 2008 [7].

The amount of CEE is important for power grid planning, construction, operation management, dispatching, and CO_2 emissions reduction. Hence, it is crucial to estimate CEE and find possible strategies to reduce or utilize it.

Overall, the main causes for CEE are analyzed in detail as follows:

(1) For renewable energy power itself, CEE is caused by equipment maintenance or failure [8], or other technical problems such as lack of fault ride through capability for certain generators [5], low generation flexibility [9], incorrect protection parameters setting, defective control strategy, and improper grounding measures in power plants and generators.
(2) For grid integration of large-scale renewable energy sources, CEE is caused by mismatched electrical demand. For real-time power balance, if renewable energy generation is abundant (like high wind power output due to strong wind speed), the load should be increased or the output of conventional power generators should be reduced. Due to transmission constraints, uncoordinated scheduling among dispatch centers, or the lack of any coordination mechanisms, large amounts of CEE occurs. In Fig. 1, the curtailed wind energy in large-capacity wind farms is illustrated.
(3) For grid integration of distributed small-capacity renewable energy sources, CEE occurs because distributed small-capacity renewable energy sources are not considered in generation scheduling for their small-capacity and low wind power forecasting accuracy. Once an imbalance happens, the outputs of renewable energy sources would be restricted.
(4) In addition, the common causes include shortage in adjustable load and adjustable power sources, and complicated electromagnetic interaction restrictions in proportion of renewable generation to the total generation of a power system.

Particularly, it is common for wind farms to experience generation curtailment due to turbine failures, or lack of network transmission capability or peak load regulation ability [8]. Curtailment of variable renewable generation, particularly wind and solar energy is discussed by many researchers. National Renewable Energy Laboratory (NREL) defined curtailment as a reduction in the output of a generator from what it could otherwise produce given available resources like wind or sunlight [10]. EirGrid and System Operator for Northern Ireland (SONI) pointed out that dispatch-down of wind caused curtailment and they also classified the dispatch-down [11]. Dispatch-down of wind for system-wide reasons (such as system stability requirements, operating reserve requirements, voltage control requirements, and system non-synchronous penetration limit) is called curtailment; dispatch-down of wind generation for more localized network reasons (more wind generation than the capacity of the network, maintenance, upgrade works or faults) is called constraint. In this paper, CEE contains both of the curtailment and constraint. A comprehensive analysis of constraints on the effective utilization of wind power in China has been conducted on the basis of infrastructural factors and operational factors [12]. The infrastructural factors include weak grid structure, concentrated wind sources far away from load centers, large proportion of coal-fired power plants and the absence of sufficient market mechanisms. The operational factors include unfavorable feed-in tariffs, unreasonable dispatch priorities, lack of grid codes for wind power integration and low wind power forecasting accuracy.

The objective of this paper is to give a comprehensive review of global and China's CEE. A method for CEE estimation is proposed. Based on the estimated CEE, the potential of reducing fossil fuel consumption and greenhouse gas emissions as well as the

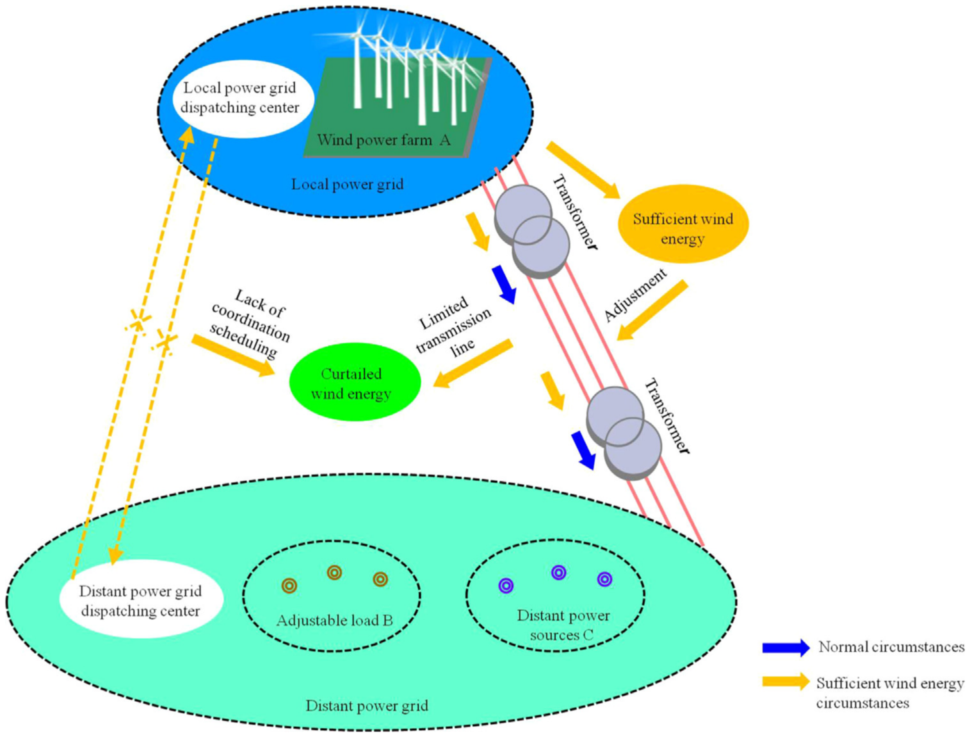

Fig. 1. Schematic diagram of curtailed wind energy occurrence in large-scale wind power plants. The blue arrow represents the lack of curtailed wind energy under normal circumstances; the yellow arrow represents curtailed wind energy deriving from the transmission line exceeding its limit and the lack of coordination mechanisms under circumstances of sufficient wind power. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

potential of capturing CO_2 with CEE are discussed. In addition, in order to address the gap between renewable energy development and CEE, issues and strategies associated with CEE reduction are also presented and analyzed in this study.

2. Method for CEE estimation

Different CEE calculation methods are adopted in different countries [8,9,13,14]. CEE calculation methods have not yet been widely agreed. Therefore, global CEE estimation in this paper only reflects a general method and trend.

The most common renewable energy sources include wind, solar, and hydro power. Because of zero or near-zero GHG emissions, CEE estimated in this paper is mainly about wind, solar and hydro power. CEE estimation associates with the cumulative installed capacity of renewable energy, annual available power generation utilization hours and actual power generation of renewable energy. The corresponding data can be found from relevant agencies and organizations like the Intergovernmental Panel on Climate Change (IPCC), EIA (Energy Information Administration), IEA, European Photovoltaic Industry Association (EPIA), World Wind Energy Association (WWEA), and British Petroleum (BP). In this paper, the global and China's CEE from 2008 to 2013 are estimated.

2.1. Calculation process of CEE

An estimation method for curtailed renewable energy based on real-time power balance is proposed in this paper. The method is based on the annual cumulative installed capacity, the actual power generation and the annual available power generation utilization hours of renewable energy.

CEE can be calculated by the following equations.

$$\Delta W_i = \sum_{j=1}^{N} (\overline{W}_{i,j} - W_{i,j}) \tag{1}$$

$$\overline{W}_{i,j} = \overline{P}_{i,j} \times h_j \tag{2}$$

where ΔW_i represents the total CEE of a given year i; N represents the types of renewable energy sources ($j=1$, wind power; $j=2$, solar power; $j=3$, hydropower); $\overline{W}_{i,j}$ represents the maximum power generation of renewable energy j in year i; $W_{i,j}$ represents the actual power generation of renewable energy j; $\overline{P}_{i,j}$ represents the cumulative installed capacity of renewable energy j in year i; $h_j$represents the annual available power generation utilization hours of renewable energy j. CEE is the annual maximum power generation minus annual actual power generation of renewable energy, and in this paper the annual global CEE includes curtailed wind, solar and hydro electric energy.

In order to measure the degree of curtailed electric renewable energy, an index is defined, as described in (3). $\eta_{i,j}$ is the ratio of curtailed renewable energy to the actual power generation in a given year.

$$\eta_{i,j} = \frac{\overline{W}_{i,j} - W_{i,j}}{W_{i,j}} \times 100\% \tag{3}$$

2.2. Cumulative installed capacity of renewable energy

The "Renewable Energy Policy Network for the 21st Century" and the "BP Statistical Review of World Energy" provide data of global cumulative installed capacity of renewable energy by 2013 [15,16]. The global renewable energy cumulative capacity reached 1560 gigawatts (GW) in 2013, an increase of more than 8% over 2012, as shown in Table 1. Hydropower rose by 4% to approximately 1000 GW and made the largest contribution to

Table 1
Global cumulative installed capacity of renewable energy from 2005 to 2013.
Source: Renewable Energy Policy Network for the 21st Century, BP Statistical Review of World Energy, June 2014.

	Hydropower (GW)	Wind power (GW)	Solar power (GW)	Total renewable energy (GW)
2005	816	59.186	5.048	930
2006	843	74	6.619	1020
2007	920	94.091	9.291	1085
2008	950	121.789	16.063	1150
2009	915	160.139	24.265	1170
2010	945	197.718	41.330	1260
2011	970	238.967	71.218	1360
2012	990	284.491	102.076	1470
2013	1000	319.907	139.637	1560

Table 2
China's cumulative installed capacity of renewable energy from 2005 to 2013.
Source: Renewable Energy Policy Network for the 21st Century, BP Statistical Review of World Energy, June 2014 and China National Renewable Energy Center.

	Hydropower (GW)	Wind power (GW)	Solar power (GW)	Total renewable energy (GW)
2005	117.39	1.264	0.068	120.75
2006	130.29	2.588	0.08	135.48
2007	148.23	5.875	0.1	157.23
2008	172.60	12.121	0.14	188.16
2009	196.29	25.853	0.3	227.07
2010	216.06	44.781	0.8	267.17
2011	232.98	62.412	3.3	305.72
2012	248.90	75.372	7.0	340.60
2013	260.00	91.460	18.3	378.00

Table 3
Global power generation of renewable energy from 2005 to 2013.
Source: BP Statistical Review of World Energy, June 2014.

	Hydropower (billion kW h)	Wind power (billion kW h)	Solar power (billion kW h)	Total renewable energy (billion kW h)
2005	2924.6	104.3	3.7	3300.9
2006	3043.7	133.1	5.0	3465.0
2007	3094.8	170.6	6.7	3574.0
2008	3217.7	219.1	11.2	3764.2
2009	3260.7	277.8	19.1	3890.5
2010	3464.4	343.2	30.5	4207.0
2011	3517.1	435.9	59.2	4422.8
2012	3684.1	522.1	94.1	4748.3
2013	3782.0	628.2	124.8	5016.3

the cumulative installed capacity, followed by wind, and solar power.

In recent years, China has made significant progress in the exploitation and utilization of renewable energy. Renewable energy development from 2005 to 2013 is illustrated in Table 2 [16,17]. By the end of 2013, the installed capacities of hydro, wind and solar power were 260.0 GW, 91.46 GW and 18.3 GW respectively, and the proportions of them to the country's total renewable energy capacities were 68.8%, 24.2% and 4.8%, respectively.

2.3. Annual power generation of renewable energy

The global generation of hydro, wind and solar power as well as the total renewable energy is shown in Table 3. In 2013, the global hydro, wind and solar power generation were 3782 billion kW h, 628.2 billion kW h and 124.8 billion kW h, respectively and the proportions of them to the total global renewable energy generation were 75.4%, 12.5% and 2.5%, respectively.

In China, grid integrated wind, solar, and hydro power generation were 131.9 billion kW h, 11.9 billion kW h, and 911.6 billion kW h in 2013, respectively. Power generation of renewable energy in China has achieved rapid growth in recent years, as shown in Table 4. The total renewable energy generation in 2013 is almost three times of that in 2005.

2.4. Annual available power generation utilization hours

Due to the different geographical and climatic conditions, the annual available power generation utilization hours of renewable energy vary from country to country. And in most wind, solar, and hydro installations, it is not feasible to generate power at full capacity 24 h per day because there is not sufficient primary energy to maintain generators at full power. A uniform data for worldwide level is adopted in this paper by considering (1) annual average power generation equipment utilization hours in a design life; (2) the profit of power generation enterprises; (3) annual available primary energy under the existing technical conditions.

For a standard year consisting of 365 days, there are 8760 h in a year.

Wind turbines can operate in a design economic lifetime of 20 years with 120,000 h of active operation [18]. It is also estimated that wind turbines only work 30% of the time in a standard year [19]. The annual available power generation utilization hours of wind power is determined as follows,

$$h_1 = \min\left(\frac{120,000\ \text{h}}{20}, 8760\ \text{h} \times 30\%\right) = 2628\ \text{h} \quad (4)$$

A challenge economic lifetime of photovoltaic panels could be 25 years [20]. Generally, a solar energy system will provide output for about 5 h per day [21]. Thus, the annual available power generation utilization hours of solar power is,

$$h_2 = \min(8760\ \text{h},\ 365 \times 5\ \text{h}) = 1825\ \text{h} \quad (5)$$

The default value of hydro turbine is 150,000 h [22] and the economic lifetime for hydro turbine is 30 years [23]. The capacity utilization factor for hydro seems to be mostly under 50% worldwide [24]. The annual available power generation utilization hours of hydro power is,

$$h_3 = \min\left(\frac{150,000}{30}\ \text{h},\ 8760\ \text{h} \times 50\%\right) = 4380\ \text{h} \quad (6)$$

Above all, the annual available power generation utilization hours of wind, solar, and hydro power are summarized in Table 5.

Table 4
Power generation of renewable energy in China from 2005 to 2013.
Source: BP Statistical Review of World Energy, June 2014.

	Hydropower (billion kW h)	Wind power (billion kW h)	Solar power (billion kW h)	Total renewable energy (billion kW h)
2005	397.0	1.9	0.1	401.7
2006	435.8	3.7	0.1	442.3
2007	485.3	5.5	0.1	493.5
2008	585.2	13.1	0.2	601.1
2009	615.6	27.6	0.4	646.2
2010	722.2	44.6	0.9	779.9
2011	698.9	70.3	3.0	808.2
2012	872.1	96.0	6.2	1020.3
2013	911.6	131.9	11.9	1101.3

Table 5
The annual available power generation utilization hours of wind, solar, and hydro power.

Renewable energy types	Wind power	Solar power	Hydropower
Annual power generation equipment utilization hours	2628 h	1825 h	4380 h

Table 6
Estimation of global CEE from 2008 to 2013.

	Wind power			Solar power			Hydropower		
	Installed capacity (GW)	Power generation (billion kW h)	CEE estimation (billion kW h)	Installed capacity (GW)	Power generation (billion kW h)	CEE estimation (billion kW h)	Installed capacity (GW)	Power generation (billion kW h)	CEE estimation (billion kW h)
2008	121	219.1	98.89	16.06	11.2	18.11	950	3217.7	943.3
2009	159	277.8	140.05	24.27	19.1	25.19	915	3260.7	747.0
2010	198	343.2	177.14	41.33	30.5	44.93	945	3464.4	674.7
2011	238	435.9	189.56	71.22	59.2	70.78	970	3517.1	731.5
2012	283	522.1	221.62	102.08	94.1	92.20	990	3684.1	652.1
2013	320	628.2	212.76	139.64	124.8	130.04	1000	3782.0	598.0

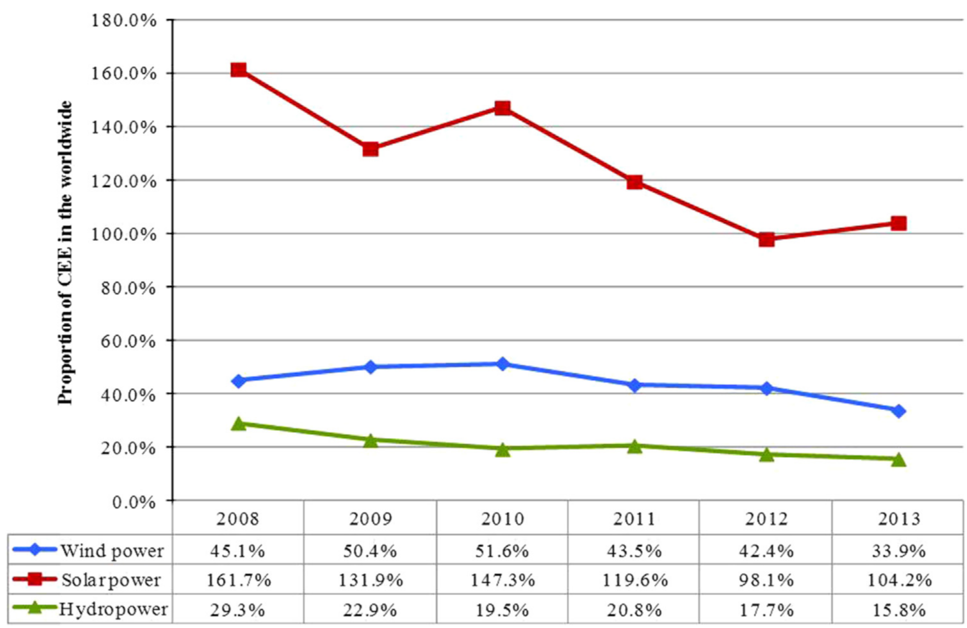

Fig. 2. Proportion of curtailed electric energy worldwide.

3. The global CEE

3.1. The global curtailed wind power energy

The cumulative capacity of the global wind reached 320 GW at the end of 2013, achieving an annual growth of more than 13.1% (see Table 1). In 2013, the global wind power generation reached 628.2 billion kW h (see Table 3) and the global curtailed wind energy was estimated at 212.76 billion kW h.

$$\overline{W}_1 - W_1 = 320\ \text{GW} \times 2628\ \text{h} - 628.2\ \text{billion kW h} = 212.76\ \text{billion kW h} \tag{7}$$

3.2. The global curtailed solar power energy

According to the "Global market outlook for photovoltaic until 2016" (EPIA), 27.70 GW of solar power was added around the world in 2011, making the global accumulative installed capacity up to 67.40 GW with a growth of 70% from 39.70 GW at the end of 2010 [25]. In 2013, the cumulative installed capacity and power generation of global solar reached 139.64 GW (see Table 1) and 124.8 billion kW h (see Table 3), respectively. Then the global curtailed solar energy was estimated to be 130.04 billion kW h.

$$\overline{W}_2 - W_2 = 139.64\ \text{GW} \times 1825\ \text{h} - 124.8\ \text{billion kW h} = 130.04\ \text{billion kW h} \tag{8}$$

3.3. The global curtailed hydropower energy

The accumulative installed capacity of hydropower around the world reached 970 GW in 2011, with an increase of 25 GW compared with that in 2010, and in 2013, the cumulative capacity of global hydropower reached 1000 GW (see Table 1). The global hydropower generation in 2013 was 3782 billion kW h (see Table 3), and the global curtailed hydro energy was estimated at

598 billion kW h.

$$\overline{W}_3 - W_3 = 1000 \text{ GW} \times 4380 \text{ h} - 3782 \text{ billion kW h} = 598 \text{ billion kW h} \quad (9)$$

3.4. The global CEE

In conclusion, the total amount of CEE is rather amazing. The summary of global CEE estimation from 2008 to 2013 is presented in Table 6. In 2013, the total amount of curtailed global wind, solar and hydro energy was estimated at 940.8 billion kW h. Fig. 2 shows the proportions of global curtailed wind, solar and hydro energy from 2008 to 2013. It can be seen that the proportion of curtailed wind energy from 2008 to 2013 changed slightly from 45.1% to 33.9%. In 2008, the proportion of curtailed solar energy and hydro energy reached 161.7% and 29.3%, respectively. While in 2013, the proportions fell to 104.2% and 15.8%, respectively.

4. The China's CEE

4.1. The China's curtailed wind power energy

In China, the cumulative installed capacity of wind power reached 62.41 GW in 2011, ranking first in the world with a share of 26.24%, and it reached 91.46 GW by the end of 2013 (see Table 2). In 2009, the curtailed wind power was about 0.912 billion kW h, accounting for 3.3% of the national total wind power generation in the same year, and in 2010 approximately 1.963 billion kW h wind power was curtailed, with an annual growth rate of 115.24% [12]. In 2012, the curtailed wind energy in China was about 20 billion kW h, and it reached 16.2 billion kW h in 2013 [6].

4.2. The China's curtailed solar power energy

In China, the accumulative installed capacity of solar power reached 3.3 GW in 2011, and 15 GW solar power was added during 2012 and 2013, making China's accumulative installed capacity up to 18.3 GW in 2013 (see Table 2). Grid-connected PV power generation and concentrating solar thermal power was approximately 11.9 billion kW h in 2013 (see Table 4). Then the curtailed solar energy in China in 2013 was estimated to be 21.49 billion kW h.

$$\overline{W}_2 - W_2 = 18.3 \text{ GW} \times 1825 \text{ h} - 11.9 \text{ billion kW h} = 21.49 \text{ billion kW h} \quad (10)$$

4.3. The China's curtailed hydropower energy

In China, the accumulative installed capacity of hydropower reached 260.0 GW in 2013, with an increase of 11.1 GW compared with that in 2012 (see Table 2). And the hydro power generation in

Table 7
Estimation of China's CEE from 2008 to 2013.

	Wind power			Solar power			Hydropower		
	Installed capacity (GW)	Power generation (billion kW h)	CEE estimation (billion kW h)	Installed capacity (GW)	Power generation (billion kW h)	CEE estimation (billion kW h)	Installed capacity (GW)	Power generation (billion kW h)	CEE estimation (billion kW h)
2008	12.121	13.1	–	0.14	0.2	0.06	172.60	585.2	170.79
2009	25.853	27.6	0.91	0.3	0.4	0.15	196.29	615.6	244.15
2010	44.781	44.6	1.96	0.8	0.9	0.56	216.06	722.2	224.14
2011	62.412	70.3	12.30	3.3	3.0	3.02	232.98	698.9	321.55
2012	75.372	96.0	20.80	7.0	6.2	6.58	248.90	872.1	218.08
2013	91.460	131.9	16.20	18.3	11.9	21.49	260.00	911.6	227.2

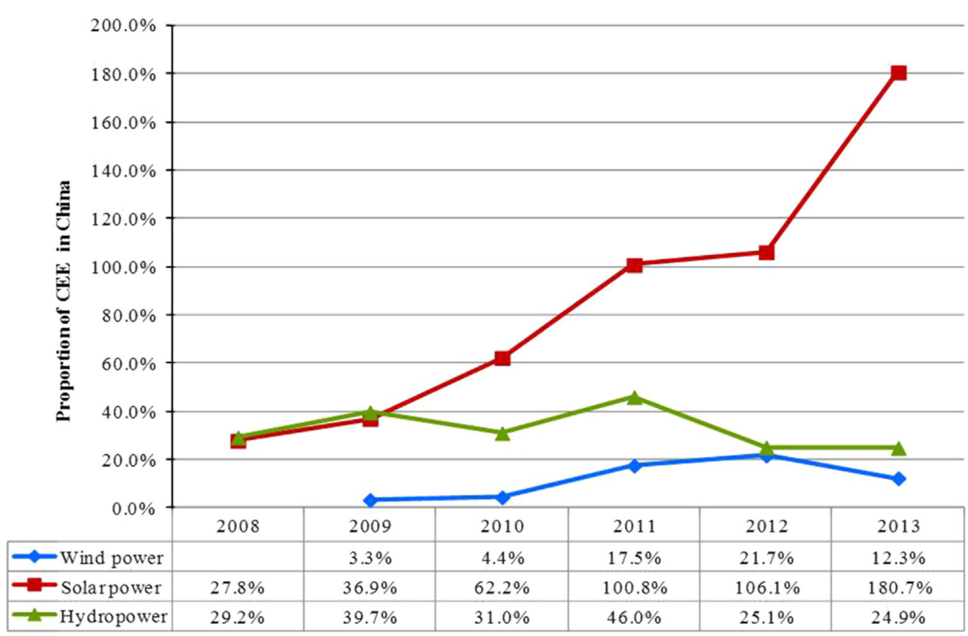

Fig. 3. Proportion of curtailed electric energy in China.

2013 was 911.6 billion kW h (see Table 4). Then, the curtailed hydro energy in China was estimated to be 227.2 billion kW h.

$$\overline{W}_3 - W_3 = 260\text{ GW} \times 4380\text{ h} - 911.6\text{ billion kW h} = 227.2\text{ billion kW h} \quad (11)$$

4.4. The China's CEE

The summary of China's CEE estimation is presented in Table 7. With the increasing of renewable energy installed capacity, annual power generation and estimated CEE of wind and solar power basically show an uptrend. However, the estimated CEE of hydro power is volatile, and it peaked at 321.55 billion kW h in 2011. In 2013, the total amount of curtailed wind, solar and hydro energy in China was estimated at 264.89 billion kW h. Fig. 3 shows the proportions of curtailed wind, solar and hydro energy from 2008 to 2013. The proportions have gradually increased during these years. For solar power, the proportion of curtailed energy is relatively high. In 2008, it was only 27.8% while it reached 180.7% in 2013.

5. Potential utilization of CEE

CEE has negative impacts on energy sustainability, climate change and economic development. Regarding energy sustainability, renewable energy cannot be made full use of, causing a remarkable waste of energy. Also, the underutilization of renewable energy may cause more fossil fuel consumption and more GHG emissions. As far as economic development goes, renewable generation enterprises suffer from economic losses. Renewable energy projects may not be able to get the expected economic benefits because of CEE. These impacts affect not only current renewable energy projects but also future investment in the renewable energy industry. Therefore, it is necessary to reduce CEE. In this section, the potential utilization of CEE is estimated from different perspectives.

5.1. The potential of reducing fossil fuel consumption, GHG emissions and air pollutants with CEE

Fossil fuel plays a pivotal role in the worldwide energy and is mainly used to produce electricity. For example, fossil fuels comprised 78.4% of global final energy consumption in 2012, and this was enough to supply approximately 77.9% of global electricity [15]. The largest emitters of GHGs are the fossil fuels fired conventional power plants. According to the IEA, electricity and heat generation, contributing 42% of global CO_2 emissions in 2011, is the largest emitter [26].

Global warming has become a serious threat to human beings, as global CO_2 average concentration reached 400 ppm (ppm) in the atmosphere in May 2013 and global CO_2 emissions are still growing rapidly [27,28]. "International Energy Outlook 2013" by the EIA predicted that CO_2 emissions would increase to 36.4 billion tonnes by 2020 and 45.5 billion tonnes by 2040 [29].

CEE utilization can save billions of fossil fuel and avoid tonnes of CO_2 and other air pollutants worldwide. The potential of reducing fossil fuel consumption, GHG emissions and air pollutants by making use of CEE is shown as follows. The depictions are on the basis of data in Tables 8 and 9 [30].

The potential for reducing fossil fuel consumption, GHG emissions and air pollutants with global CEE includes:

- Saving 357.50 million tonnes of coal;
- Reducing 940.8 million tonnes of CO_2 emission;
- Reducing 3.48 million tonnes of SO_2 emission;
- Reducing 1.72 million tonnes of NO_2 emission; and
- Reducing 0.30 million tonnes of PM emission.

The potential for reducing fossil fuel consumption, GHG emissions and air pollutants with China's CEE includes:

- Saving 86.35 million tonnes of coal;
- Reducing 264.89 million tonnes of CO_2 emission;
- Reducing 1.54 million tonnes of SO_2 emission;
- Reducing 0.48 million tonnes of NO_2 emission; and
- Reducing 0.11 million tonnes of PM emission.

Table 8
The global average fossil fuel consumption, GHG emissions and air pollutants from coal-fired power plants.
Source: IEA.

Global CEE in 2013 (billion kW h)	Coal consumption (g/kW h)	Intensity factor (g/kW h)			
		CO_2	SO_2	NO_x	$PM_{2.5}$
940.8	380	1000	3.7	1.83	0.32

Table 9
Fossil fuel consumption, GHG emissions and air pollutants from coal-fired power plants in China.
Source: IEA and China Electricity Council.

China's CEE in 2013 (billion kW h)	Coal consumption (g/kW h)	Intensity factor (g/kW h)			
		CO_2	SO_2	NO_x	$PM_{2.5}$
264.89	326	1000	5.8	1.8	0.4

5.2. The potential of capturing CO_2 with CEE

CCS technology, as an effective way to address global warming, has been developing rapidly [31,32]. According to the IEA roadmap [33], continued increase in coal use scale up CCS, and CCS can account for 14% of cumulative global emissions reductions. Large amounts of electricity must be consumed in the carbon capture process. For example, according to the IEA GHG, the energy requirement for CCS was 0.306 kW h per kilogram of CO_2 (kW h/kg) in 2005, and it continuously decreases, reaching to 0.196 kW h/kg CO_2 in 2015 and later [34]. Regarding to trends in global CO_2 emission in 2012 and examples of global wind and solar curtailment [7,9,27], a distribution map of large CO_2 emitter countries/regions and CEE in regions is provided in Fig. 4. The results demonstrate that regions with high CO_2 emissions have large amounts of CEE. Carbon capture devices can be driven by CEE rather than thermal generators so that the CEE could be fully utilized. The energy requirement for carbon capture is represented by the variable a. The m_{total} and m'_{total} represent the amount of the captured CO_2 worldwide and in China by making use of CEE, respectively.

$$m_{total} = \Delta W / a = 940.8\text{ billion kW h}/(0.196\text{ kW h/kg}) = 4.80\text{ billion tonnes} \quad (12)$$

$$m'_{total} = \Delta W' / a = 264.89\text{ billion kW h}/(0.196\text{ kW h/kg}) = 1.35\text{ billion tonnes} \quad (13)$$

Global CO_2 emissions were approximately 34.5 billion tonnes in 2012, and China's CO_2 emissions were 9.9 billion tonnes [27]. The data of CO_2 emissions in 2013 is not available currently, so the data

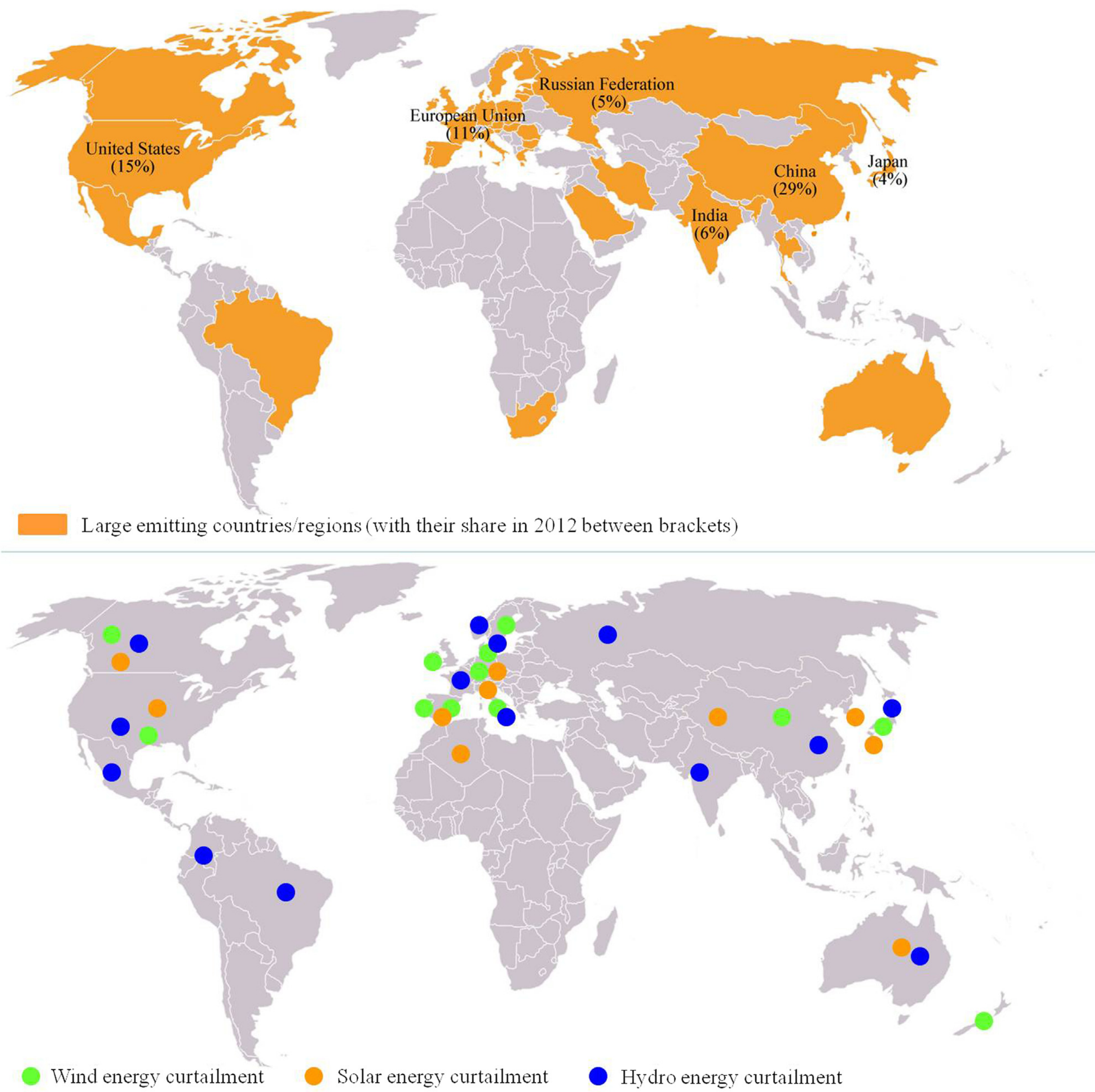

Fig. 4. Global distribution of large CO_2 emitter countries/regions and CEE. On the upper half of the map, large sources are clustered in six countries/regions: China (29%), the United States (15%), the European Union (EU271) (11%), India (6%), the Russian Federation (5%) and Japan (4%); on the bottom half of the map, green, yellow, and blue dots indicate the curtailed wind, solar, and hydro energy, respectively. Areas with more concentrated dots show more CEE. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

of 2012 will be represented 2013's level. p represents the ratio of the global captured CO_2 to the global emissions and p' represents the ratio of China's captured CO_2 to the entire country's emissions. Let p'' be the proportion of the captured CO_2 with CEE to the 2020 reduction targets in China (reducing approximately 2 billion by 2020).

$$p = \frac{4.80}{34.5} \times 100\% = 13.91\% \tag{14}$$

$$p' = \frac{1.35}{9.9} \times 100\% = 13.63\% \tag{15}$$

$$p'' = \frac{1.35}{2} \times 100\% = 67.5\% \tag{16}$$

In summary, the global captured CO_2 with CEE is approximately 4.80 billion tonnes, accounting for 13.91% of the global net emissions. While in China, the potential amount of captured CO_2 is 1.35 billion tonnes, accounting for 13.63% of the country's net emissions and 67.5% of the emission reduction plan.

5.3. The potential of driving heating systems with CEE

Combined heat and power (CHP) systems become more and more attractive due to the low exergy efficiency of the stand-alone systems [35]. The parallel operation of CHP plants and renewable energy is possible and helpful for the integration of renewable sources in the energy system, especially in the areas that need long-term heating. For example, CHP solar generators [36] and CHP wind turbines are becoming popular due to their ability of providing both electrical and thermal power with high overall conversion efficiency [37,38]. Parallel operation of CHP plants and renewable energy can significantly improve the off-peak load rate and wind power consumption, and it can be used as an effective alternative to conventional heating system.

6. Strategies for reducing CEE

Efforts have been devoted to reducing curtailment of renewable energy sources, including changes in the way reserves and conventional generation management, automation of curtailment signals, market design issues such as negative pricing, transmission planning, and renewable energy forecasting. In general, the strategies to reduce CEE can be considered from two perspectives: policies and technologies.

6.1. CEE reduction from the aspect of policies

6.1.1. Incentive policies for electric grid construction

(1) EU
Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources pointed out that the member states are to establish national action plans, setting the share of energy from renewable sources consumed in transport, electricity and heating [39]. For 2020, procedures for the reform of planning, pricing schemes, access to electricity networks as well as promoting energy from renewable sources will be established.

(2) U.S.A.
"American Recovery and Reinvestment Act of 2009 (ARRA)" was an economic stimulus package enacted by the 111th United States Congress in February 2009 [40]. In terms of energy efficiency and renewable energy research and investment, the Ministry of Finance was obligated to provide loan of an accumulated total amount of 3250 million USD for power transmission system upgrades for the Western Area Power Administration; an accumulated total amount of 3250 million USD for power transmission system upgrades for the Bonneville Power Administration; 6 billion USD for renewable energy and electric transmission technologies loan guarantees; 190 million USD in funding for wind, hydro, and other renewable energy projects.

(3) Denmark
"Promotion of Renewable Energy Act" (Act No. 1392 of December 27, 2008) is promulgated to ensure the fulfillment of increasing the proportion of renewable energy sources [41]. According to act, the Minister for Climate and Energy may set conditions for approval of the requirements regarding construction, design, installation, erection, operation, dismantling of the renewable energy plants as well as financial, technical, safety and environmental conditions in connection with establishment and operation. And Energinet.dk shall be responsible for construction of the connection to the grid onshore to the electricity producer.

(4) China
The National Development and Reform Commission (NDRC) put forth the subsidy standards for grid connection expenses in "Notice of the National Development and Reform Commission on Issuance of the Interim Measures for Allocation of Income from Surcharges on Renewable Energy Power Prices" (No. 44 [2007]) [42]. According to the Notice, the subsidies for grid connection are presented. Grid connection expenses of renewable energy power generating projects include the investment on power transmission and transformation, and operational and maintenance expenses. The subsidy standards of grid-connection expenses are: 1 fen per kW h within 50 km; 2 fen per kW h for 50–100 km; and 3 fen per kW h for 100 km and above.

Two national solar subsidy programs (the Building Integrated Photovoltaic subsidy program, established in March 2009; the "Golden Sun" demonstration project, established in July 2009) are announced by the NDRC, aimed to promote renewable energy generation [43]. The government will subsidize 50% of investment for solar power projects as well as relevant power transmission and distribution systems that connect to grid networks.

6.1.2. Priority dispatch generation

Priority dispatch of renewable generation could maintain the safe, secure operation of the power system. In Ireland, priority dispatch of renewable generation is dispatched down and a specific ranking order is defined with the principle of preserving least-cost dispatch [9]. "Policy for Implementing Scheduling and Dispatch Decisions SEM-11-062", a comprehensive operational policy in use in Ireland, pointed out variable price-taking generation is prior to dispatch-down before autonomous units [44]. In order to increase the capability of power system operating at a high Non-Synchronous Penetration (SNSP), the fundamental issues are addressed in "Delivering a Secure Sustainable Electricity System (DS3) programme" published by EirGrid and SONI [45]. The DS3 programme was designed to reduce curtailment, launched in August 2011.

There are many studies underway to investigate the optimization of operational policy and to minimize energy curtailment.

6.1.3. Policy guidance for a well-functioning market

Market induced wind power curtailment is explored and imbalance prices would induce voluntary curtailment of output. In order to optimize wind power trading in day-ahead electricity markets under uncertainty in wind power and prices, a new model is presented, which can effectively control the trade-off between risk and return for wind power producers [46]. Well-functioning market is crucial to promote renewable energy power utilization.

Nordic power market, one of the first free electric-energy markets in Europe, consists of two main markets: the Nordic Power Exchange (NPX), and the transmission system operators' (TSOs) real-time electricity markets [47]. It includes large geographic areas and enables an economical way of sharing balancing resources. In Denmark, wind power is traded in the Nordic power markets. The guidance of the price helps to reduce the wind and solar curtailment because positive electricity price promotes the scheduling, while negative price reduces the dispatch [48]; in Italy, the transmission capacity within and between market zones is increased due to significant grid investments and the amount of curtailment is reduced for TSO's incentive; in the U.S.A, the Electric Reliability Council of Texas (ERCOT) implements market-based solutions to reduce curtailment levels by shifting power from a zonal congestion market with 15-min dispatch to a nodal market with 5-min dispatch [13].

Power market in China is comparatively closed. The closed market structure is not conducive to power trade over large geographic areas, such as intra-provinces or intra-regions [12]. Hence, further power market reform should be pushed like expanding the scope of renewable power trade, improving the electricity trade mechanism, and implementing flexible pricing and so on.

6.1.4. Cost allocation

In China, the NDRC promulgated "the Trial Measures for Management of Prices and Cost allocation for Renewable Energy Power Generation" in January 2006, and 38 renewable power generating projects (wind, solar and biomass power generation) won a total subsidy of 260 million CNY [49]. The balance cost of renewable energy electricity price to the feed-in tariff benchmarking of local desulfurization coal-fired units is shared in feed-in tariff sales at the provincial level and above power grid in the country.

In Denmark, model for cost allocation of grid connection is implemented in wind power generation [50]. Costs will be jointly shared by the power company and project owner. For example, connection costs from the point of coupling to the grid are paid by the grid company, including costs for substations and transformers; costs from the turbine to the coupling point are paid by the project owner.

6.2. CEE reduction from the aspect of technologies

6.2.1. Capability of renewable energy generators

(1) Improved operational reliability of renewable energy generators.
Generator is the most important element in power system. Reliable generator operation can increase the working time of normal operation, reduce the failure rate, and enhance the energy efficiency of renewable energy. There are series of methods to improve the reliability of renewable energy generator. The drivetrain converts wind power to usable shaft power and is a crucial element in the wind generation system. New technologies to improve the wind power operational reliability by improving the reliability of wind turbine drivetrain are proposed in [51]. Reliability and efficiency of wind-powered generators can be improved by better controlling of integration [52].

(2) Improved generation flexibility of renewable energy generators.
There are two primary drivers behind renewable energy curtailment: transmission constraints and generation flexibility [53]. Conventional generators can be scheduled to address the volatility and uncertainty of the renewable energy sources and provide adequate operating reserves when the renewable energy sources are integrated into grid. With high penetrations of renewable energy sources, if the flexibility of conventional generators' output is constrained, the excess renewable energy cannot be used locally and should be curtailed. Improved conventional generation flexibility can accommodate the integration of renewable generation.

(3) Advanced maintenance plan and forecast technique.
In power systems, balance is maintained through continuously adjusting generation capacity and controlling demand. An advanced maintenance plan is urgently needed to reduce generation equipment shutdown and increase system stability. Predictive maintenance is an effective method to improve maintenance planning. It can be used to avoid possible mechanical and electrical failures of the wind generators by taking the measures such as vibration analysis, infrared thermography and monitoring electrical conditions [54].
Renewable energy sources are intermittent, and accurate wind power forecasting (WPF) is critical. For grid operators, accurate WPF is helpful for time frames ranging from minutes to days, local grid congestion prediction, and overall planning procedures; for many energy traders, day-ahead WPF on an aggregated level is used, and when the wind is sufficient, the price of wind power decreases and wind power displaces expensive fossil fuel units [48]. The impact of WPF on unit commitment (UC) and economic dispatch is investigated, which is possible for operators to determine spinning reserves accurately [55]. WPF is quickly becoming an important topic for power systems and state-of-the-art WPF models and their application to power systems operations are reviewed and analyzed [56]. There are many enterprises and organizations participating in power output forecast. IBM announced a new system, known as Hybrid Renewable Energy Forecasting (HyRef) which predicted the availability of renewable energy by big data analytics [57]. With advanced analytics, accurate local weather forecasts as far as one month, or 15 min in advance can be obtained through the data assimilation based on HyRef within a wind farm. WPF techniques are being increasingly improved and will one day reach an accuracy level, which is sufficient for the detailed day-ahead planning of wind as firm scheduled generation.

(4) Advanced fault ride-through capability.
Low voltage ride through (LVRT) capability, or fault ride through (FRT) capability, is a capability of electrical devices, especially wind generators, to be able to operate through lower grid voltage [58]. Efforts are conducted to enhance the FRT capability of generators [59]. Superconducting fault current limiter (SFCL) is used to reduce the fault current level on the stator side and improve FRT capability of generators [60]. Some new controller design strategies for power converter-based wind turbine generators have been proposed to maintain converter currents to enhance the wind-turbine generators' FRT capability. Dynamic voltage restorer (DVR) is proposed to enhance the LVRT capability of wind power generation [61] and unified power flow controller (UPFC) is used for solving FRT problems of the interaction of wind energy conversion system (WECS) and power grid [62]. FACTS controllers like SVC and STATCOM are also employed to improve the FRT of WECS [63]. Advanced FRT capability can ensure that the generator does not run off-grid.

6.2.2. Power system coordinated scheduling and planning

Matched distribution between renewable resources and power consumption and alignment between renewable power planning and network planning is the main causes of grid integration and curtailment problems [5]. Coordinated power system scheduling and planning is needed to renewable energy grid integration.

The increasing penetration of renewable generation sources causes more uncertainties to power systems. Methods and technologies for UC with uncertain wind power output are studied such as price-based UC [64], robust UC [65], and chance-constrained two-stage stochastic program for UC [66]. Renewable energy sources are an important component of a microgrid. A stochastic microgrid energy scheduling model is proposed for accommodating the intermittent nature of renewable energy resources [67]. The day-ahead scheduling for smart grids with high penetration of distributed generation and electric vehicles (EVs) was solved by a modified PSO algorithm [68]. Coordinated scheduling enhances the penetration of renewable energy sources. By scheduling the wind power and pumped storage plants, the penetration of renewable energy sources is increased [69].

Some researchers also considered renewable distributed generation (RDG) in optimal planning. An integrated planning methodology for low-carbon distribution systems is proposed and can improve the efficiency of RDG operations and CO_2 mitigation [70]. The optimal sizing and sitting of RDG are of the main concerns. A comprehensive analysis of different approaches such as analytical methods, optimal power flow and other artificial intelligent optimization techniques (like evolutionary algorithm, simulated annealing, and PSO) and so on for optimal distributed renewable generation planning is reviewed [71]. In practice, China is planning to develop distributed wind power and slow down the construction of large scale wind power farms in central and eastern areas [5]. Technically, distributed and small-scaled wind power can be widely used by local power customers, achieving stable wind power output effectively.

Coordinated scheduling and optimal planning have been applied in the power system with a high penetration of renewable generation. However, with the increasing penetration of renewable energy in power systems, the uncertainties of renewable energy resources make it hard to achieve a satisfactory result, and advanced methodology is still needed to enable coordinated scheduling and planning.

6.2.3. Energy storage technologies

Energy storage technologies are vital for the integration of intermittent renewable energy sources since they could ensure secure and continuous supply to the consumer from distributed and intermittent supply base. The role of energy storage in the electricity grid with high penetration of renewable energy sources is explored [72]. The applications of energy storage include load leveling, firm capacity, operation reserves, transmission and distribution replacement and deferral, and end-use application and so on. The variability of renewable energy sources poses technical and economical challenges when integrated on a large scale. Concerns over the deployment of energy storage increase. An updated review of energy storage for mitigation the variability of renewable electricity sources is conducted [73].

Energy storage can reduce renewable energy curtailment for the two primary mechanisms: (1) time-shifting generation away from congested periods; (2) providing operating reserves to improve the inherent grid flexibility [53]. The two primary mechanisms above are considered from the viewpoint of transmission constraints and grid flexibility. Many wind resources are far from the major load centers, and have limited ability to integrate into grid. Alternatively, co-location of wind and energy storage would increase transmission utilization and decrease transmission costs [74]. Grid flexibility and energy storage contribute to very high penetration of variable renewable sources and results show that in a highly flexible system, the penetration could reach about 50% with curtailment rates of less than 10% [75].

6.2.4. Grid-friendly technologies

Electric energy systems are developing toward smart grid, renewable energy integration, and climate change mitigation [76]. Under the background of the smart grid, grid-friendly technologies play an important role in CEE reduction. Grid-friendly technologies refer to smart operations of power generator or consumer electrical equipment which provide efficient support for safe and economic power system operation [77]. Grid-friendly technologies are classified from two perspectives: generation side and power end user side.

Grid-friendly technologies of power generation side focused on renewable energy power generation, mainly on improving its predictability, stability and controllability. Renewable energy sources are considered not only environmentally friendly but also “grid friendly”, if they are operated in a manner enhancing electrical power grid reliability and offering stable frequency or voltage support actively. Grid-friendly technologies can achieve full power segment shift and maintain low total harmonic distortion (THD) in grid-connected PV power generation [78]. Grid-friendly integration of constant-speed wind turbines can mitigate adverse power quality impacts, especially on inductive grids [79]. A systematic control strategy for an interconnected PV system is proposed, which is effective to provide the designated power commanded from the main grid and makes the interconnected PV systems more grid-friendly [80].

Grid-friendly technologies of power end user side focused on consumer electrical equipment participating in instantaneous balance actively. Demand response (DR) is the representative. According to Federal Energy Regulatory Commission, DR can be described as: “based on the notice of direct compensation in induced decrease in load or the pricing signal of electricity given by power suppliers, end use customers change their inherent consumption patterns to reduce load or transfer load from on-peak to off-peak periods in response to a stable, reliable power supply” [81]. Some grid-friendly technologies of power end user side have been proposed, such as hydrogen-based grid-friendly zero energy buildings [82], grid-friendly charging schemes for the electric vehicles [83,84]. Interactions among plug-in hybrid electric vehicles (PHEVs) charging, wind power and DR programs are analyzed and these interactions contribute to feasible and reasonable integration of large amounts of wind generation [85]. China has achieved much in DR on the number, severity, and duration reduction of wider power outages and system load factors improvement, illustrating the potential of DR to displace involuntary load shedding [86]. DR is expected to play a critical role in improving the efficiency of generator and reducing carbon emissions. Residential demand response to time-of-use (TOU) rates is studied and it indicates that reasonable TOU rates can improve the efficiency of power generation [87]. Automation of DR is essential, especially given the variability and uncertainty associated with wind and solar power. Automation of DR has been applied in commercial and industrial sectors [88] and is increasingly popular both home and abroad.

Grid-friendly technologies have been applied in large-scale wind farms and grid-connected PV systems and can promote the integration of intermittent renewable generation.

7. Conclusions

Global CO_2 average concentration hit a record high of 400 ppm in the air in 2013 and it continued growing at a historic rate, resulting in climate change. Renewable energy can serve as environmentally responsible alternatives to reduce dependence on fossil fuels. Although the installed capacity of renewable energy booms, many problems regarding grid integration appears, resulting in energy curtailment. In this paper, the analysis of CEE is important for evaluation of renewable energy and associated power grid planning, construction, operation management, dispatching, and CO_2 emission reduction.

Curtailment of variable renewable generation, particularly wind, solar and hydro power, is becoming common worldwide as wind, solar and hydro power development expands across the country and penetrations increase. The causes of CEE are analyzed, and a corresponding estimation method is proposed in this paper. Our analysis shows massive amounts of CEE exist worldwide, especially in China. The analysis on CEE utilization is also performed. The results show that efficient global CEE utilization in 2013 could (1) save 357.5 million tonnes of coal; (2) reduce 940.8 million tonnes of CO_2 emission; (3) reduce 3.48 million tonnes of SO_2 emission, 1.72 million tonnes of NO_2 emission and 0.30 million tonnes of PM. While in China, efficient CEE utilization in 2013 could (1) save 86.35 million tonnes of coal; (2) reduce 264.89 million tonnes of CO_2 emission; (3) reduce 1.54 million tonnes of SO_2 emission, 0.48 million tonnes of NO_2 emission and 0.11 million tonnes of PM. In addition, in 2013 the global CEE and the China's CEE could capture approximately 4.8 billion tonnes of CO_2 and 1.35 billion tonnes of CO_2, respectively.

The research in this paper reveals the avoidance of renewable energy curtailment. If the CEE were reduced, renewable energy can make more contribution to fossil fuel saving and GHG emissions reduction. As penetrations of wind, solar and hydro power increase, strategies to reduce renewable energy curtailment become increasingly important.

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