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Co-benefits of Local Air Pollutants and Greenhouse Gas Reduction Achieved by Hydropower Development in Xizang (Tibet) Autonomous Region, China

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Abstract: Hydropower development in Xizang (Tibet) Autonomous Region plays a vital role in co-control of local air pollutants and greenhouse gas (GHG) in China. According to emission factors of local air pollutants and GHG of coal-fired power industry in different hydropower service regions, we estimate the effect and synergy of local air pollutants and GHG reduction achieved by hydropower development in Tibet, examine the main factors constraining the effect and synergy, using correlation analysis and multiple regression analysis. The results show that: 1) During the period from 2006 to 2012, the effect of local air pollutants and GHG reduction achieved by hydropower development in Tibet decreased as a whole, while the synergy increased first and decreased afterwards. 2) The effect and synergy of local air pollutants and GHG reduction achieved by hydropower development in Tibet vary significantly across different hydropower service regions. The effect based on emission levels of Central China power grid (CCPG) and Northwest China power grid (NCPG) was more significant than that based on emission level of national power grid (NPG) from 2006 to 2012, and the synergy based on emission levels of CCPG and NCPG was also more significant than that based on emission level of NPG from 2010 to 2012. 3) The main factors constraining the effect and synergy based on emission levels of NCPG and CCPG included SO_2 removal rate and NO_x removal rate, the effect and synergy based on emission level of NPG was mainly influenced by net coal consumption rate. 4) Transferring hydropower from Tibet to NCPG and CCPG, and substituting local coal-fired power with hydropower can greatly help to co-control local air pollutants and GHG, transform the emission reduction pattern of the power industry and optimize energy structure.

Keywords: hydropower development; co-control; synergy; Tibet, China

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1 Introduction

With fast economic development, industrialization and urbanization, China faces increasing pressures on carbon emission reduction, and especially on air pollutants (SO_2, NO_x, particulate matter) reduction (Dong *et al.*, 2015). ′The Twelfth Five-Year Plan for National Economic and Social Development of the People′s Republic of China′ set reduction of CO_2 emissions per unit of gross domestic product (GDP), total SO_2 emission and total NO_x emission as obligatory targets. Most of the local air pollutants (e.g., SO_2, NO_x) and greenhouse gas (GHG) have a common source such as fossil fuel combustion, indicating an opportunity to simultaneously

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fulfill the above obligatory targets (West *et al*., 2004). 'The Law of the People's Republic of China on the Prevention and Control of Atmosphere Pollution' released in 2015 stipulates clearly that the prevention of air pollution should co-control local air pollutants and GHG. Thus pursuing co-benefits is an effective approach to simultaneously respond to both air pollutant and carbon problems (Dong *et al*., 2015).

In recent years, studies on co-control or co-benefits focus on local air pollutants emission reduced simultaneously by GHG abatement measures and GHG emission reduced simultaneously by local air pollutants reduction measures (Rypdal, 2007; Tollefsen *et al*., 2009; Yeora, 2010; Mao *et al*., 2012; Dong *et al*., 2015), which referred to steel industry (Mao *et al*., 2013; Zhang *et al*., 2014), cement industry (Zhang *et al*., 2015), power industry (Mao *et al*., 2012; Mao *et al*., 2014), transportation (Gao *et al*., 2014; Dhar and Shukla, 2015) and sewage treatment (Li *et al*., 2014). The important nature of 'co-control' or 'co-benefit' is the control of multipollutants in an integrated manner. To reflect the co-control effectiveness of multipollutant reduction, the air pollutant equivalence (AP_{eq}) indicator was formulated, which is calculated to combine all of the pollutants (e.g., SO_2, NO_x and CO_2) into one 'integrated' pollutant (Mao *et al*., 2013; Mao *et al*., 2014). Quantitative calculation of degree of synergetic relations between main local pollutants reduction and CO_2 reduction was also made (Zhou *et al*., 2013). As a giant energy consumer and polluter, the Chinese power industry possesses tremendous energy conservation and emission reduction potential, a series of emission reduction measures for the power industry have been already implemented in China (Mao *et al*., 2014). When it comes to reduction cost, hydropower is listed as the most preferred technology, because of less reduction cost than other structure-adjustment measures, such as substituting large-sized units for small-sized units and employing new power generation technologies (e.g., natural gas power generation, nuclear power generation, wind power generation) for newly constructed power plants or increased power capacity (Mao *et al*., 2012; Mao *et al*., 2014). Moreover, among the registered clean development mechanism (CDM) projects of China, both total amount and annual reduction of hydropower projects were more than other kinds of CDM projects (Yan *et al*., 2013). Therefore, hydropower development serves as the primary approach to preventing air pollution and addressing climate change in China.

The exploitable capacity of hydropower resources in Xizang (Tibet) Autonomous Region is 1.1×10^8 kilowatts (kW), accounting for 20% of total amounts in China, which takes second place in provinces, autonomous regions and municipalities. But less than 1% of the hydropower resources in Tibet have been exploited, thus Tibet has tremendous potential for hydropower development (Xiao and Dai, 2011). In recent years, a series of hydropower stations (e.g., Zangmu hydropower station, Laohuzui hydropower station) in Tibet was put into operation successively, resulting in significant increase of hydropower supply capacity, even considerable surplus of hydropower during high flow periods (Jia, 2014). Besides, the operation of Qinghai-Tibet grid interconnection project and Sichuan-Tibet grid interconnection project made transferring surplus hydropower from Tibet to the outside viable (Liu *et al*., 2011), which could be used to substitute coal-fired power and co-control local air pollutants and GHG. However, under the influence of resource endowment, power generation technologies and emission reduction measures, the emission factors of local air pollutants and GHG of coal-fired power industry vary across different regions, thus co-benefits of local air pollutants and GHG reduction achieved by substituting hydropower for coal-fired power of different hydropower service regions (HSR) would be also different significantly. The existing studies on effects of hydropower development usually utilize the single and fixed emission factors to calculate the amount of local air pollutants or/and GHG that could be reduced by hydropower development (Zhao *et al*., 2009; Li, 2010; Wu *et al*., 2011; Lu *et al*., 2013). In general, there is a lack of research on co-benefits of local air pollutants and GHG reduction achieved by substituting hydropower for coal-fired power, studies on regional difference and dynamic change of the co-benefits are even more limited.

According to emission factors of local air pollutants and GHG of coal-fired power industry in HSR, we estimate the effect and synergy of local air pollutants and GHG reduction achieved by hydropower development in Tibet, and examine main factors constraining the effect and synergy, in order to provide scientific support for optimizing the allocation of hydropower resource, especially getting hydropower development to fully play its key role in co-control of local air pollutants and GHG in the Chinese power industry.

2 Materials and Methods

2.1 Methods

Based on the definition of co-benefits, co-control and relevant concept (Xie and Li, 2013; Mao *et al.*, 2014; Dong *et al.*, 2015), co-benefits of hydropower development in Tibet could be estimated, using the effect and synergy of SO_2, NO_x and CO_2 reduction achieved by substituting hydropower for coal-fired power of HSR. In this study, HSR include Northwest China power grid (NCPG), Central China power grid (CCPG) and national power grid (NPG), which was interconnected with Tibet power grid through Qinghai-Tibet grid interconnection project and Sichuan-Tibet grid interconnection project. First, local air pollutants and GHG reduction achieved by hydropower development in Tibet were calculated, according to emission factors of local air pollutants and GHG of coal-fired power industry in HSR. Then, effect index (EI) and synergetic index (SI) were formulated to reflect co-benefits of hydropower development in Tibet. Finally, main factors constraining the effect and synergy of local air pollutants and GHG reduction achieved by hydropower development in Tibet were examined, using correlation analysis and multiple regression analysis.

2.1.1 Local air pollutants reduction

Based on emission factors of SO_2 and NO_x of coal-fired power industry in HSR, local air pollutants reduction achieved by hydropower development in Tibet were calculated as follows:

$$AP_S = P \times (1 - \gamma) \times E_S \times 10^{-6} \tag{1}$$

$$AP_N = P \times (1 - \gamma) \times E_N \times 10^{-6} \tag{2}$$

where AP_S and AP_N are the amount of SO_2 and NO_x that could be reduced by substituting hydropower from Tibet for coal-fired power of HSR in ton, respectively; P is the annual supply of hydropower in kWh; γ represents line loss rate; E_S and E_N are the emission factors of SO_2 and NO_x of coal-fired power industry in HSR in g/kWh, respectively.

The annual supply of hydropower was calculated, using power generation and power consumption rate of hydropower plants in Tibet, which were derived from 'China Electric Power Yearbook (2007–2013)'. Emission factors of SO_2 and NO_x of coal-fired power industry were calculated, according to total SO_2 emission, total NO_x emission, power generation and power consumption rate of coal-fired power plants in provinces, autonomous regions and municipalities covered by HSR. Table 1 shows emission factors of local air pollutants of coal-fired power industry in HSR.

2.1.2 GHG reduction

According to studies on GHG emission and GHG reduction of hydropower development (Gagnon *et al.*, 1997; Zheng, 2001; Ma, 2002; Liang and Fan, 2004; Wu *et al.*, 2008; Sui and Liao, 2010), GHG reduction achieved by hydropower development in Tibet is the difference between the amount of CO_2 reduced by substituting hydropower for coal-fired power and CO_2 emission of hydropower development, which are calculated as follows:

$$AP_C = ER_B - ES_W \tag{3}$$

$$ER_B = P \times (1 - \gamma) \times EF_B \times 10^{-6} \tag{4}$$

$$ES_W = \varphi \times P \times EF_B \times 10^{-6} \tag{5}$$

Table 1 Emission factors of local air pollutants of coal-fired power industry in HSR (g/kWh)

Year	Emission factors of SO_2			Emission factors of NO_x		
	CCPG	NCPG	NPG	CCPG	NCPG	NPG
2006	7.8407	7.3218	5.1924	3.8059	2.4136	2.8350
2007	6.4664	6.1459	4.3292	3.0745	2.3568	2.8134
2008	5.8291	5.7390	3.8438	3.2269	3.1564	2.7026
2009	4.5948	4.9721	3.1175	3.3970	3.1485	2.6104
2010	3.5381	3.3674	2.6083	3.3302	3.4905	2.6643
2011	2.7564	2.8145	2.2358	3.4073	3.5967	2.9280
2012	2.4601	2.2022	1.9140	3.1811	3.1373	2.6598

Notes: The regions covered by Central China power grid (CCPG) include Jiangxi Province, Henan Province, Hubei Province, Hunan Province, Sichuan Province and Chongqing Municipality. The regions covered by Northwest China power grid (NCPG) include Shaanxi Province, Gansu Province, Qinghai Province, Hui Autonomous Region of Ningxia and Uygur Autonomous Region of Xinjiang. NPG, national power grid

$$EF_B = (EF_{OM} + EF_{BM}) / 2 \tag{6}$$

where AP_C is the amount of CO_2 that could be reduced by substituting hydropower from Tibet for coal-fired power of HSR in ton; ER_B represents the amount of CO_2 reduced by substituting hydropower for coal-fired power in ton; ES_W is CO_2 emission of hydropower development in ton. EF_B, EF_{OM} and EF_{BM} are baseline emission factor, power margin emission factor and capacity margin emission factor of regional power grid in g/kW·h, respectively. φ represents the ratio of emission factor of hydropower generation to that of coal-fired power generation.

In this study, baseline emission factors of CCPG and NCPG are obtained from 'Announcement on Baseline Emission Factors of Regional Power Grid in China' released by National Development and Reform Commission. Based on the aggregated indexes (e.g., power generation, power consumption rate, fossil fuel consumption, power capacity) of coal-fired power plants in provinces, autonomous regions and municipalities covered by CCPG, NCPG, North China power grid, Northeast China power grid, East China power grid and South China power grid, baseline emission factors of NPG were calculated, using the methods and parameters obtained from 'Announcement on Baseline Emission Factors of Regional Power Grid in China' .

2.1.3 Effect index (EI) and synergetic index (SI)

According to the difference among local air pollutants and GHG, such as environmental damage, control target, emission factor and so on (Gao *et al.*, 2014), effect index (*EI*) and synergetic index (*SI*) were formulated to reflect the effect and synergy of local air pollutants and GHG reduction achieved by hydropower development in Tibet. EI and SI were calculated as follows:

$$EI = \alpha \cdot AP_S + \beta \cdot AP_N + \delta \cdot AP_C$$

$$SI = (\alpha \cdot AP_S + \beta \cdot AP_N) / (\delta \cdot AP_C)$$

where *EI* and *SI* are the effect and synergy of local air pollutants and GHG reduction achieved by hydropower development in Tibet, respectively. α, β and δ are effect coefficients of SO_2, NO_x and CO_2, respectively. A higher *EI* indicates more significant effect, a lower absolute value of the difference between *SI* and 1.0 indicates more significant synergy.

On the basis of weight factors of local air pollutants and GHG, as well as relevant valuation results (Mao *et al.*, 2012; Gao *et al.*, 2014; Mao *et al.*, 2014), effect coefficients of SO_2, NO_x and CO_2 were determined to be 0.419, 0.577 and 0.004, taking into account the pollutant trading price in the Chinese pilot market schemes and the certified emission reduction price of CDM, especially the targets for reduction of SO_2 and NO_x emission during 12th Five-Year Plan period.

2.1.4 Impact analysis on co-benefits of hydropower development

Net coal consumption rate, percentage of solid fuel, percentage of liquid fuel, percentage of gas fuel, SO_2 removal rate and NO_x removal rate were chose as characteristic indicators of coal-fired power industry in HSR and its provinces. Then, according to the characteristic indicators, as well as EI and SI based on emission factors of HSR and its provinces during the period from 2006 to 2012, correlation analysis and multiple regression analysis were conducted, to examine main factors constraining co-benefits of local air pollutants and GHG reduction achieved by hydropower development in Tibet.

2.2 Data source

In this study, data were obtained from China Electric Power Yearbook (Editorial board of China Electric Power Yearbook, 2007–2013), China Energy Statistical Yearbook (Department of Energy Statistics of Bureau of Statistics, 2007–2013), Annual Statistical Report on Environment in China (Ministry of environmental protection, 2007–2013), Announcement on Baseline Emission Factors of Regional Power Grid in China, China Statistical Yearbook on Environment (National Bureau of Statistics, Ministry of Environmental Protection, 2007–2013), Complication of Statistic on Hydropower Plants in Tibet Autonomous Region, Complication of Statistic on Power Industry in China, and so on.

3 Results and Analyses

3.1 Effect of local air pollutants and GHG reduction

According to emission levels (in terms of emission factors of SO_2, NO_x and CO_2 of coal-fired power industry) of different power grids, the effect of local air pollutants and GHG reduction achieved by hydropower development in Tibet vary significantly (Fig. 1). The amount of SO_2, NO_x and CO_2 that could be reduced by hydropower development in Tibet is shown in Table 2. In general, during the period from 2006 to 2012, the accumulated EI based on emission levels of CCPG, NCPG and NPG were 1.695 × 10^5 t, 1.654 × 10^5 t and 1.470 × 10^5 t, respectively. Thus the reduction effect of hydropower development in Tibet based on emission level of CCPG was most significant, the reduction effect based on emission level of NCPG took second place, and the reduction effect based on emission level of NPG was less significant than that based on emission levels of CCPG and NCPG.

During the period from 2006 to 2012, the effect of local air pollutants and GHG reduction achieved by hydropower development in Tibet decreased as a whole (Fig. 1). According to emission levels of CCPG, NCPG and NPG, the amount of local air pollutants and GHG that could be reduced by hydropower development in Tibet decreased gradually, especially SO_2. The annual amount of SO_2 reduction based on emission levels of CCPG, NCPG and NPG decreased by 60.6%、62.2% and 53.7% by 2012, compared with the 2006 level (Table 2). The main reason for the decrease of SO_2 reduction is the implement of energy-saving and emission reduction

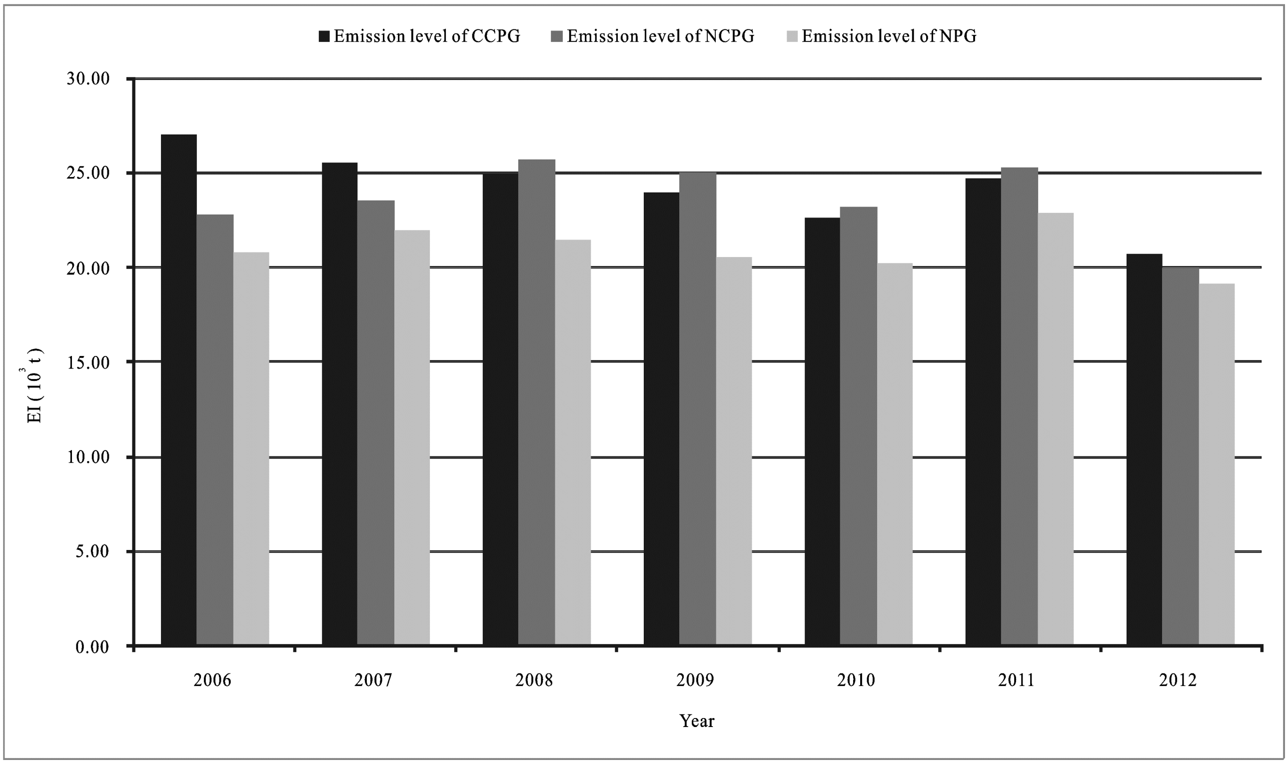

Fig. 1 Effect index (EI) of local air pollutants and GHG reduction achieved by hydropower development in Tibet according to emission levels of different power grids

Table 2 Amount of local air pollutants and GHG that could be reduced by hydropower development in Tibet according to emission levels of different power grids (10^4 t)

Year	Emission level of CCPG			Emission level of NCPG			Emission level of NPG		
	SO_2	NO_x	CO_2	SO_2	NO_x	CO_2	SO_2	NO_x	CO_2
2006	0.922	0.447	114.287	0.861	0.284	100.536	0.611	0.333	98.780
2007	0.862	0.410	110.804	0.819	0.314	108.348	0.577	0.375	108.018
2008	0.811	0.449	104.548	0.798	0.439	114.118	0.535	0.376	106.916
2009	0.668	0.494	102.744	0.723	0.458	112.417	0.454	0.380	105.538
2010	0.519	0.489	105.029	0.494	0.512	109.566	0.383	0.391	107.940
2011	0.460	0.568	120.109	0.470	0.600	120.646	0.373	0.488	122.112
2012	0.363	0.470	104.054	0.325	0.463	101.385	0.283	0.393	107.457

measures (e.g., flue gas desulfurization, flue gas denitrification) in Chinese coal-fired power plants, which made emission factors of coal-fired power industry, as well as local air pollutants and GHG emission reduced by substituting hydropower for coal-fired power decrease (Table 1). However, considering the accomplishment of flue gas desulfurization and flue gas denitrification, especially the increase of hydropower capacity in Tibet, reduction effect of hydropower development in Tibet would be assumed to increase considerably.

3.2 Synergy of local air pollutants and GHG reduction

During the period from 2006 to 2012, the synergy of local air pollutants and GHG reduction achieved by hydropower development in Tibet increased first and decreased afterwards. The synergy based on emission levels of CCPG and NCPG was most significant in 2011, the most significant synergy based on emission level of NPG appeared in 2007. According to the emission level of NPG from 2007 to 2012, and emission levels of CCPG and NCPG in 2012, SI of local air pollutants and GHG reduction achieved by hydropower development in Tibet was less than 1.0. It indicates that the effect of GHG reduction achieved by hydropower development in Tibet became more significant than that of local air pollutants. In general, compared with the effect of GHG reduction, the effect of local air pollutants reduction achieved by hydropower development in Tibet decreased faster, which was closely related to the significant decline in emission factors of SO_2 and NO_x of coal-fired industry in HSR (Table 1).

According to emission levels of different power grids, the synergy of local air pollutants and GHG reduction achieved by hydropower development in Tibet vary significantly (Fig. 2). During the period from 2006 to 2009, the synergy of local air pollutants and GHG reduction based on emission level of NPG was more significant than that based on emission levels of CCPG and NCPG. But from 2010 to 2012, the synergy based on emission levels of CCPG and NCPG was more significant than that based on emission level of NPG.

3.3 Impact analysis on local air pollutants and GHG reduction

3.3.1 Impact analysis on effect of local air pollutants and GHG reduction

Correlation analysis on EI of local air pollutants and

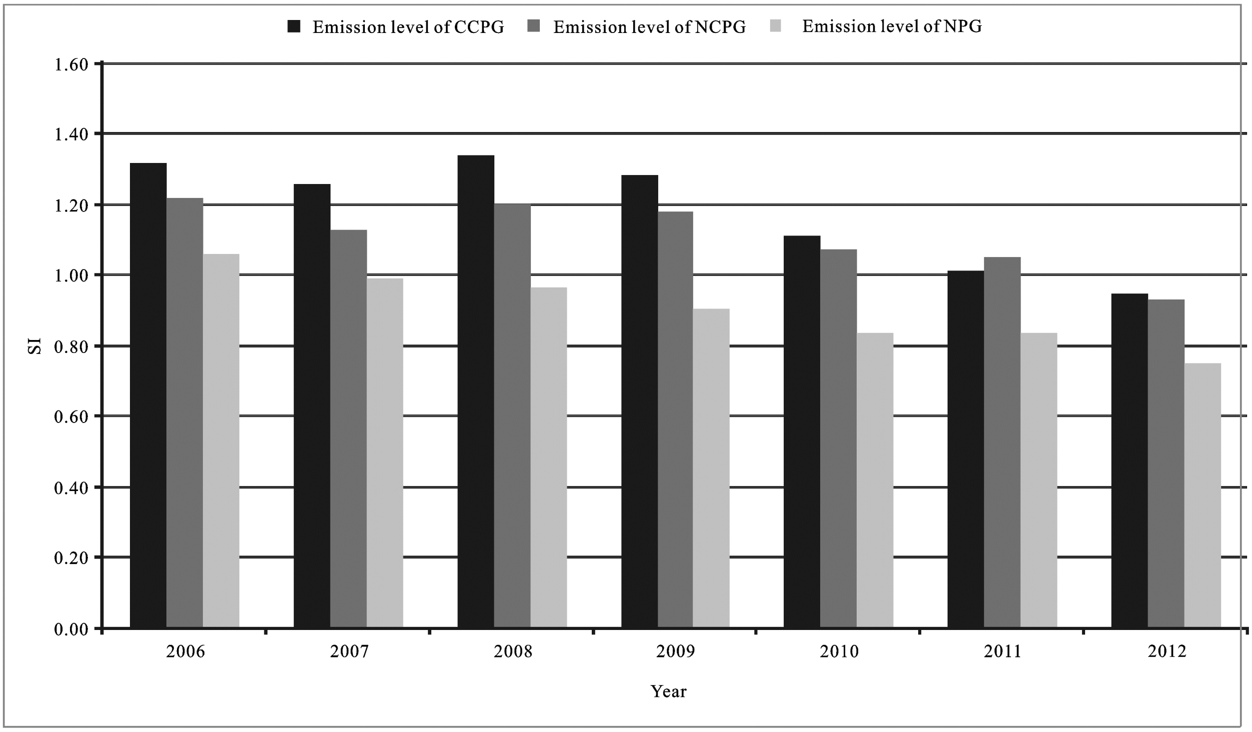

Fig. 2 Synergetic index (SI) of local air pollutants and GHG reduction achieved by hydropower development in Tibet according to emission levels of different power grids

GHG reduction achieved by hydropower development in Tibet showed that, according to emission levels of CCPG, NCPG and NPG, there was always a significant positive correlation between EI and net coal consumption rate, as well as a significant negative correlation between EI and SO_2 removal rate (Table 3). During the period from 2006 to 2012, net coal consumption rate of CCPG and NCPG was higher than that of NPG, and SO_2 removal rate of CCPG and NCPG was lower than that of NPG. Meanwhile, reduction effect of hydropower development in Tibet based on emission levels of CCPG and NCPG was more significant than that based on emission level of NPG.

Multiple regression analysis on EI of local air pollutants and GHG reduction achieved by hydropower development in Tibet showed that, SO_2 removal rate was the only variable of regression equations for EI based on emission levels of CCPG and NCPG, net coal consumption rate was the only variable of regression equation for EI based on emission level of NPG (Table 4).

Therefore, net coal consumption rate and SO_2 removal rate are main factors constraining difference among reduction effects of hydropower development in Tibet based on emission levels of different power grids. According to emission levels of CCPG and NCPG, the effect of local air pollutants and GHG reduction achieved by hydropower development in Tibet was mainly influenced by SO_2 removal rate of coal-fired industry in HSR, while the effect according to emission level of NPG was mainly influenced by net coal consumption rate of coal-fired industry in HSR.

3.3.2 Impact analysis on synergy of local air pollutants and GHG reduction

Correlation analysis on SI of local air pollutants and GHG reduction achieved by hydropower development in Tibet showed that, according to emission levels of CCPG, NCPG and NPG, there was always a significant positive correlation between SI and net coal consumption rate, as well as a significant negative correlation between SI and SO_2 removal rate (Table 5).

Multiple regression analysis on SI of local air pollutants and GHG reduction achieved by hydropower development in Tibet showed that, SO_2 removal rate, NO_x removal rate and net coal consumption rate was the only variable of regression equations for SI based on emission levels of CCPG, NCPG and NPG, respectively (Table 6).

Thus Net coal consumption rate, SO_2 removal rate and NO_x removal rate are main factors constraining difference among reduction synergy of hydropower development in Tibet based on emission levels of different power grids. According to emission level of NPG, the synergy of local air pollutants and GHG reduction achieved by hydropower development in Tibet was mainly influenced by net coal consumption rate of coal-fired power industry in HSR, while the synergy according to emission levels of CCPG and NCPG was mainly influenced by SO_2 removal rate and NO_x removal rate of coal-fired power industry in HSR, respectively.

4 Discussion

Local air pollutants and GHG reduction achieved by substituting hydropower for coal-fired power is the main form of co-benefits of hydropower development, including the effect and synergy of local air pollutants and GHG reduction. From this perspective, the co-benefits of hydropower development mainly depend on emission factors of local air pollutants and GHG of coal-fired

Table 3 Correlation analysis on EI of local air pollutants and GHG reduction achieved by hydropower development in Tibet

Variable	EI of per unit hydropower supply (Y_1)		
	Emission level of CCPG	Emission level of NCPG	Emission level of NPG
Net coal consumption rate (X_1)	0.942^{**}	0.830^{*}	0.989^{**}
Percentage of solid fuel (X_2)	0.776^{*}	–0.133	0.701
Percentage of liquid fuel (X_3)	–0.077	0.877^{**}	0.971^{**}
Percentage of gas fuel (X_4)	$–0.788^{*}$	0.039	$–0.841^{*}$
SO_2 removal rate (X_5)	$–0.981^{**}$	$–0.943^{**}$	$–0.989^{**}$
NO_x removal rate (X_6)	–0.408	$–0.864^{*}$	0.267

Notes: ** represents that correlation is significant at the 0.01 level (2-tailed); * represents that correlation is significant at the 0.05 level (2-tailed)

Table 4 Regression analysis on EI of local air pollutants and GHG reduction achieved by hydropower development in Tibet

Emission level	Regression equation
CCPG	$Y_1 = 25.771 - 0.154X_5$, $R\_a = 0.954$
NCPG	$Y_1 = 19.846 - 0.070X_5$, $R\_a = 0.868$
NPG	$Y_1 = -23.385 + 0.112X_1$, $R\_a = 0.974$

Note: R_a is adjusted R square

power industry in HSR. Hence the co-benefits of hydropower development vary significantly across different years, as well as different HSR. This study also showed that co-benefits of hydropower development in Tibet vary significantly, according to emission levels of different years, as well as different HSR. As far as different years are concerned, EI of hydropower development in Tibet based on emission level of CCPG decrease by 30.57%, and SI based on emission level of NPG decrease by 41.40% by 2012, compared with the 2006 level. As far as different HSR are concerned, the maximal difference between EI based on emission levels of CCPG and NPG was up to 30.17%, while the maximal difference between SI based on emission levels of CCPG and NPG was up to 41.91%. Therefore, taking into account emission level and its dynamic change of local air pollutants and GHG of coal-fired power industry in HSR, the approach we proposed can greatly improve the scientificity and accuracy of assessment on co-benefits of hydropower development, and strengthen its role in optimizing the allocation of hydropower resource.

Table 5 Correlation analysis on SI of local air pollutants and GHG reduction achieved by hydropower development in Tibet

Variable	SI (Y_2)		
	Emission level of CCPG	Emission level of NCPG	Emission level of NPG
Net coal consumption rate (X_1)	0.794^{*}	0.861^{*}	0.972^{**}
Percentage of solid fuel (X_2)	0.606	−0.052	0.817^{*}
Percentage of liquid fuel (X_3)	0.104	0.740	0.919^{**}
Percentage of gas fuel (X_4)	−0.630	−0.029	-0.914^{**}
SO_2 removal rate (X_5)	-0.853^{*}	-0.835^{*}	-0.968^{**}
NO_x removal rate (X_6)	−0.616	-0.913^{**}	0.032

Notes: ** represents that correlation is significant at the 0.01 level (2-tailed); * represents that Correlation is significant at the 0.05 level (2-tailed)

Table 6 Regression analysis on SI of local air pollutants and GHG reduction achieved by hydropower development in Tibet

Emission level	Regression equation
CCPG	$Y_2 = 1.558 - 0.007X_5$, $R\_a = 0.673$
NCPG	$Y_2 = 1.209 - 0.035X_6$, $R\_a = 0.801$
NPG	$Y_2 = -1.461 + 0.007X_1$, $R\_a = 0.933$

Note: R_a is adjusted R square

During the period from 2006 to 2012, the effect of local air pollutants and GHG reduction achieved by hydropower development in Tibet based on emission levels of CCPG and NCPG was more significant than that based on emission level of NPG. While from 2010 to 2012, the synergy of local air pollutants and GHG reduction achieved by hydropower development in Tibet based on emission levels of CCPG and NCPG was more significant than that based on emission level of NPG. The above comparison shows that current emission factors of local air pollutants and GHG of coal-fired industry in CCPG and NCPG were larger than that in NPG; during the period from 2010 to 2012, the effect and synergy of local air pollutants and GHG reduction achieved by transferring hydropower from Tibet to CCPG and NCPG, and substituting hydropower for local coal-fired power was more significant, compared with that based on emission level of NPG. Therefore, co-control of local air pollutants and GHG could be achieved by transferring hydropower from Tibet to CCPG and NCPG, as well as substituting hydropower for local coal-fired power.

The effect and synergy of local air pollutants and GHG reduction achieved by hydropower development in Tibet based on emission levels of different power grids, that is, the effect and synergy of substituting hydropower from Tibet for coal-fired power of different HSR were influenced by different factors. The main factors constraining the effect and synergy of substituting hydropower from Tibet for coal-fired power of CCPG and NCPG include SO_2 removal rate and NO_x removal rate, while the effect and synergy of substituting hydropower from Tibet for coal-fired power of NPG was mainly influenced by net coal consumption rate. Otherwise, SI based on emission levels of CCPG and NCPG was more than 1 during the period from 2006 to 2011, which indicated that the effect of local air pollutants reduction achieved by substituting hydropower from Tibet for coal-fired power of CCPG and NCPG was more significant, compared with the effect of GHG reduction. Considering the reduction coefficient of emission reduction measures for the power industry (Mao *et al*., 2014; Sui and Liao, 2010), emission reduction of power industry in CCPG and NCPG rely mainly on the end-of-pipe control measures (i.e., flue gas desulfurisation and flue gas denitrification) in recent years. Therefore, transferring hydropower from Tibet to CCPG and NCPG, and substituting for local coal-fired power, would be of great significance to transforming the emission reduction pattern of the power industry and optimizing energy structure in CCPG and NCPG.

5 Conclusions

Based on emission levels of CCPG and NCPG, the effect and synergy of local air pollutants and GHG reduction achieved by hydropower development in Tibet was more significant during the period from 2010 to 2012, compared with that based on emission level of NPG. Transferring hydropower from Tibet to CCPG and NCPG, and substituting hydropower for local coal-fired power could get hydropower to fully play its key role in co-controlling local air pollutants and GHG of power industry, and promoting green and low-carbon development.

The effect and synergy of local air pollutants and GHG reduction achieved by substituting coal-fired power of NPG with hydropower from Tibet was mainly influenced by net coal consumption rate, the main factors constraining the effect and synergy of substituting coal-fired power of CCPG and NCPG include SO_2 removal rate and NO_x removal rate. Emission reduction of power industry in CCPG and NCPG rely on end-of-pipe control measures, substituting coal-fired power of CCPG and NCPG with hydropower from Tibet could transform the emission reduction pattern of power industry and optimize energy structure in CCPG and NCPG.

The approach would improve the scientificity and accuracy of assessment on co-benefits of hydropower development, and strengthen its role in optimizing the allocation of hydropower resource, because it takes into account the emission level and its dynamic change of local air pollutants and greenhouse gas of coal-fired power industry in HSR. Cost-benefit analysis on local air pollutants and GHG reduction achieved by hydropower development in Tibet should be conducted to support hydropower feed-in tariff, ecological compensation and so on.

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