Challenges faced when energy meets water: CO_2 and water implications of power generation in Inner Mongolia of China

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Abstract

Energy-water nexus studies have been increasing recently due to the significant linkages between energy generation and water consumption. Few studies have looked at both water quantity and quality impacts of electricity production. Using integrated hybrid life cycle analysis, this study examines the life cycle impacts of pulverized coal, wind power and solar power on carbon dioxide (CO_2) emissions, water consumption and water quality in Inner Mongolia, China. Our research findings show that pulverized coal emits 1,213.5 grams of CO_2 per kilowatt-hour (g/kWh) of electricity output, compared with 34.4 g/kWh for wind power and 67.4 g/kWh for solar photovoltaic. Water consumption for pulverized coal, wind power and solar photovoltaic are 3.3, 0.7 and 0.9 litres per kilowatt-hour, respectively. The water requirement to dilute the life cycle chemical oxygen demand (COD) discharge would increase water consumption during production processes of pulverized coal, wind power and solar photovoltaic systems by 0.11, 0.09 and 0.19 litres per kilowatt-hour, respectively. Given that the State Grid Corporation of China aims to increase the power generation capacity that provide power supply to regions outside Inner Mongolia to 120 GW by 2020, electricity outflows could contribute to 520 million tonnes of CO_2 emissions that would be similar to the CO_2 emission in the UK in 2010, and 1,460.8 million m^3 of water. This study reveals that substantial reductions in CO_2 emissions and water consumption can be attained only if the existing coal-dominated power generation was substituted by wind power in Inner Mongolia.

Keywords: CO_2 emissions, water consumption, chemical oxygen demand, integrated hybrid life cycle analysis, Inner Mongolia, China

1 Introduction

Energy and water are inextricably linked to one another. On the one hand, energy production emits greenhouse gases (GHG) that are considered one of the major causes of climate change which can have significant impact on hydrological systems, such as change in precipitation, an increase in sea level and flooding [1]. On the other hand, energy production requires substantial amounts of water during its production life cycle, including processes ranging from the mining of fuels to the cooling of power generators [2].

A number of studies have been carried out to examine water requirements of energy production [3-5]. For the conventional energy production, water requirements can be substantial. For instance, in the United States (U.S.), thermo-electric water withdrawal for cooling purposes accounts for approximately 50% of total water withdrawal [6]. These considerable water requirements in energy production have caused water shortages. For example, Averyt et al. [7] highlighted that water requirements of power generation contributed to water supply stress in approximately 80 watersheds across the U.S.. The issue regarding water demands of energy production cannot be ignored. Furthermore, in recent years, transitions to a low carbon future have increased employment of renewable energy technologies around the globe. Some renewable energy sources require less water in energy production than conventional power generation technologies. For instance, in the U.S., water consumption of photovoltaic power generation is only one eighth of water consumption for fossil fuel-based power generation [8]. However, some renewable energy technologies are also high water consumers. Burkhardt et al. [9] pointed out that concentrated solar power systems with wet-cooling can consume up to 4.7 litres of water to generate one kilowatt hour of electricity (kWh). In addition, power generation can result in water quality impact during its life cycle phase. For example, according to Song et al. [10], there is significant relationship between coal production and wastewater discharge at the Yellow River of China, which has resulted in severe water pollution.

China has become the largest electricity producer since 2011, according to BP [11]. Power generation is the second largest water withdrawal sector in China while the agriculture sector ranks the highest. However, there have been very few studies investigating water requirements in energy production in China. Li et al. [12], is one of the first energy-water nexus studies to calculate the life cycle carbon dioxide (CO_2) emissions and water consumption required by wind power in China. The authors concluded that wind power could be seen as carbon and water saving solutions to the coal-dominated power generation system in China. Although this study has provided a holistic view of the general relationship between energy and water for the country as a whole, a nationwide analysis may not be useful and effective to highlight the water situation at specific regions in China. Furthermore, the focus of the existing literature is largely oriented toward water quantity impacts of power generation [13-15], while very limited studies have aimed to examine the water quality impacts of power generation during its life cycle phase. To the best of our knowledge, no research study has been conducted to address both water quantity and quality impacts of electricity production in China. Last but not least, owing to the significant differences in the regional power mix, the extent to which the application of renewable energy sources could contribute to CO_2 emission reduction in each region in China is not yet known.

Due to the above, this paper aims to address these shortcomings by conducting a detailed regional analysis of the water requirements (both water quantity and quality) of different electricity generation technologies implemented in China, with a specific focus on Inner Mongolia in order to better understand the "local" energy and water situations to aid future energy strategy and plan.

Based on integrated hybrid life cycle analysis, our study is focused on three electricity generation systems, namely, coal power, wind power and solar power, with regard to their impacts on CO_2 emissions, water consumption and water quality in Inner Mongolia, China.

2 Inner Mongolia – a future energy hub facing water challenges

Located in the north of China (see Figure 1), Inner Mongolia has a total area of 1.18 million square kilometres, which covers 12.3% of the territory of China [16]. Inner Mongolia is endowed with various natural resources, including rare earth minerals (first place in the world ranking list), wind power (one fifth of total wind power potential in China) and coal (largest reserve in China with 808.1 billion tonnes of reserves) [17]. Average annual Gross Domestic Product (GDP) growth of Inner Mongolia has been over 20% between 2004 and 2005 [18] and over 15% between 2006 and 2010 [19].

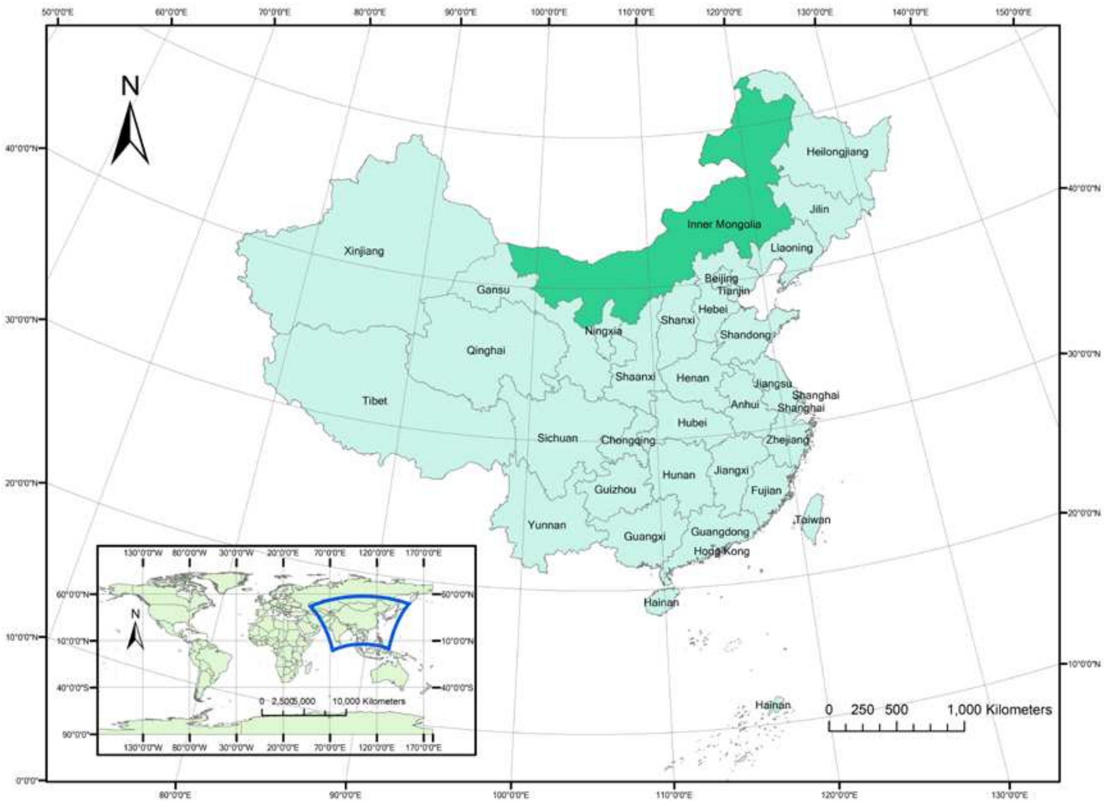

Figure 1 Location of Inner Mongolia in China

2.1 Energy Production in Inner Mongolia

Inner Mongolia is the largest coal producer in China. In 2011, total coal production in Inner Mongolia amounted to 979 million tonnes [20], which represented 27.8% of the total coal production (3,520 million tonnes) in China [21]. The growth of energy intensive industries, such as coal mining and processing, raw chemical materials and products and non-ferrous smelting and processing, has stimulated power demand in Inner Mongolia [22]. At the end of 2010, Inner Mongolia was ranked the third largest power generation capacity (64.6 gigawatt) (GW) among all the regions in China, with coal contributing 240.7 billion kWh out of the total 260 billion kWh power generation [23]. At present, Inner Mongolia has outpaced all the other regions in China in terms of growth in newly installed power generation capacity, power generation per capita and domestic power exports [24].

Also, Inner Mongolia is one of the first regions to use wind power in China, which can be traced back to the 1970s [25]. Decentralized wind power was mainly used for providing electricity supply for herdsmen in remote areas during the early stage of wind power development. Centralized wind power was not introduced until 1989, in which a wind farm with total generation capacity of 1 megawatt (MW) was deployed with financial support from the U.S. [26]. Wind power generation capacity increased from 8.2 MW in 1995 to 13,858 MW in 2010 (see Figure 2), which is projected to reach 31.2 GW by 2015 and 59.1 GW by 2020[1] [27]. Inner Mongolia also has one of the largest potentials for solar power in China [28]. Since the Chinese government has committed to promoting renewable energy sources, the percentage share of renewable energy to total energy supply will be considerable in the future, particularly in the region like Inner Mongolia.

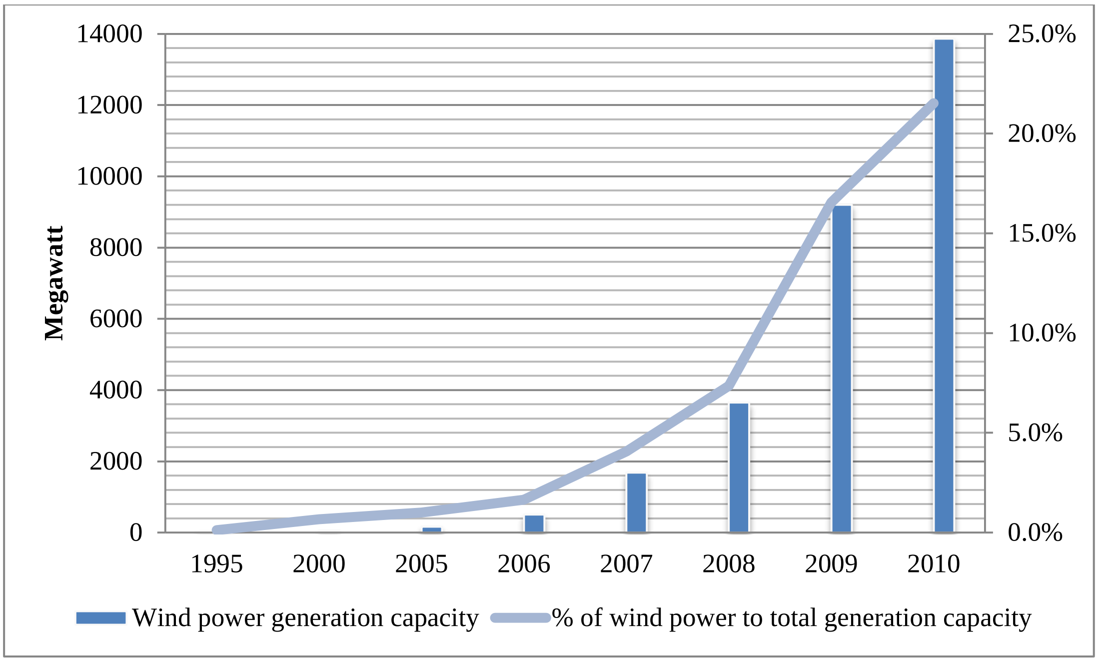

Figure 2 The growth in installed wind power capacity and share of wind power to total power generation in Inner Mongolia

Source: for wind power [19]; share of wind power to total power generation capacity: own calculation, total generation capacity figures from various China Electric Power Yearbook [29-33].

[1] Our calculation is based on figures provided in reference [27]. In East Inner Mongolia, total installed capacity is projected to increase to 13.2 GW and 20.8 GW by 2015 and 2020, respectively. In West Inner Mongolia, total installed capacity is projected to increase to 17.95 GW and 38.3 GW by 2015 and 2020, respectively.

2.2 Water resources and consumption in Inner Mongolia

Total water availability in Inner Mongolia amounts to 38.9 billion cubic metres, of which 52.7 % is surface water and 47.3 % is ground water [34]. Compared to other arid northern regions in China, Inner Mongolia has higher water availability on a per capita basis. For example, in 2010, water availability per person was 1576.1 m^3 in Inner Mongolia compared to 124.2 m^3 in Beijing and 195.3 m^3 in Hebei [19]. Yet, it was still below the national average, which was 2310.4 m^3 in 2010. Water resources are unevenly distributed in Inner Mongolia, East Inner Mongolia, which covers 27% of the territory and accounts for 18% of the total population and 20% of the farmland, is endowed with 65% of water resources. For West Inner Mongolia, which covers 26% of the territory and has 66% of the total population and 30% of farmland, accounts for 25% of the water resources [35]. Total water shortage is expected to increase from 1 billion m^3 in 2011 to 3 billion m^3 in 2020 [36]. Furthermore, according to 2010 records, 54.6% of the watersheds in Inner Mongolia were severely polluted [34]. The problem of water pollution compounds the pressing issues of freshwater availability and distribution.

Orszag [37] estimated that coal power generation would account for almost 40% of the increase in China's water consumption over the coming decade. Inner Mongolia is ranked the third largest power generation capacity in China and the majority are coal-fired power plants and yet, this region is not rich in water resources. Thus, it is necessary to examine the impacts of different power generation technologies on water (both quantity and quality) in Inner Mongolia in order to aid future energy strategy and plan.

3 Methods and Data

3.1 Integrated hybrid life cycle analysis: an introduction

Integrated hybrid life cycle analysis is a combination of conventional process-based life cycle analysis (LCA) and input-output analysis. Conventional process-based LCA (PRO-LCA) often underestimates the environmental impacts of a product due to the arbitrary selection of the system boundary, which refers to processes that are included or excluded in the analysis [38]. Upstream impacts beyond the selected system boundary are often neglected [38].

Integrating LCA with input-output analysis (IO) has provided a viable means to complementing the system boundary of conventional LCA approaches. The early application of IO in LCA can be traced back to the early 1990s from the estimation of life cycle CO_2 emissions of an automobile in Japan by Moriguchi et al. [39]. Later on, Lave et al. [40] presented an environmental input-output based life cycle analysis (EIO-LCA) to assess the environmental repercussions of five products in the U.S., including automobiles, refrigerators, computer purchases, paper cups and plastic cups. However, EIO-LCA is suffering from an aggregation problem due to the representation of data at sectoral level rather than individual process level. The IO and LCA systems have been treated individually until Suh [41] postulated a linkage between LCA and IO, which is now often known as the integrated hybrid life cycle analysis.

Integrated hybrid LCA has been used in a number of LCA studies [42-45]. Suh and Huppes [43] provided a review of methods in life cycle analysis. The authors compared the computational structure of both conventional and hybrid LCA and concluded that results generated by integrated hybrid LCA are more reliable compared to its counterparts. A couple of studies applied integrated hybrid life cycle analysis to examine the environmental impacts of energy systems. For example, Acquaye et al. [46] demonstrated the application of the integrated hybrid life cycle analysis in the estimation of GHG emissions of rape methyl ester (RME) biodiesel in the U.K. Wiedmann et al. [47] compared three LCA techniques (i.e. PRO-LCA, input-output based hybrid LCA and integrated hybrid LCA) in assessing GHG emissions of wind energy in the U.K..

3.2 A general framework of integrated hybrid life cycle analysis

A general framework of the integrated hybrid LCA, which is developed by Suh [41], is given in Table 1. Two matrices are introduced to link input-output analysis (represented by A) and conventional life cycle analysis (represented by $\tilde{A}$) in the integrated hybrid life cycle analysis. One matrix (represented by U) presents the upstream cut-off flows from the economic sectors in the input-output system to the process system. The downstream cut-off flows from the process system to the IO system is represented by another matrix (represented by D).

	Processes	Industries	Functional unit
Products	Physical flow matrix ($\tilde{A}$)	Downstream cut-off (D)	Functional unit of process analysis
Industries	Upstream cut-off (U)	Input-output matrix (A)	Functional unit of IO
Environmental Impacts	Environmental impacts of LCA	Environmental impacts of IO	

Table 1 A general framework of integrated hybrid life cycle analysis

The mathematical formulation of the integrated hybrid LCA approach is depicted as in Equation 1:

$$G_{IH} = \begin{bmatrix} \tilde{B} & 0 \\ 0 & B \end{bmatrix} \begin{bmatrix} \tilde{A} & -D \\ -U & I - A \end{bmatrix}^{-1} \begin{bmatrix} f \\ 0 \end{bmatrix} \qquad (1)$$

Where G_{IH} is the total environmental intervention matrix, which describes total direct and indirect environmental impacts of the product system; $\tilde{B}$ and B are the environmental intervention matrices for the conventional LCA system and the I-O system, respectively; $\tilde{A}$ represents inflows and outflows of products to processes in the conventional LCA system; A represents the flows among economic sectors in the input-output system; U is the upstream cut-off matrix; D is the downstream cut-off matrix; f represents the functional unit of the LCA system, which is one kilowatt hour in this study.

3.3 Data

Several types of data were used in this research study, including process-based life cycle data of selected power generation technologies, the input-output table of Inner Mongolia, and sectoral CO_2 emissions, water consumption and chemical oxygen demand (COD) discharge data. Data source and compilation methods are depicted in the following subsections.

3.3.1 Process-based life cycle data

The process-based life cycle datasets were taken from the Ecoinvent Database[2], from which we obtained data on 300 MW pulverized coal power from China, 800 kilowatt (kW) wind power and 3 kW solar photovoltaic (PV) systems.

Data on coal power plants (with total generation capacity over 1 GW) were drawn from the China Electric Power Yearbook [48]. For Inner Mongolia, 11 coal power plants with a total generation capacity of 23.7 GW (57% of the total power generation capacity in Inner Mongolia) were listed. Each coal power plant has a combination of different power generation units, ranging from 100 MW to 600 MW. 300 MW power generation units represent 21 out of 58 power generation units. Although 600 MW power generation units account for 23 out of 58 power generation units, process-based data of 600 MW coal power system is not available in China. Thus, in this study, we have chosen the 300 MW power generators instead.

Estimation of impacts from 800 kW wind power system is based on wind power generation in Switzerland. The decision of using 800 kW wind turbine in this study is based on two reasons: 1) In 2007, Inner Mongolia had 1,736 wind turbines deployed with a total generation capacity of 1.56 GW[3], which had a turbine size of 898.6 kW on average [49]. 2) Wind turbines produced in China are with licences from European partners and thus, we assume the material used and the manufacturing processes of wind turbines in China are similar to the ones described in the database for European countries.

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[2] 2010 Ecoinvent database v2.2 from the Ecoinvent Centre at http://www.ecoinvent.ch/. The Ecoinvent process database provides a process matrix, which includes almost 4000 goods and processes.

[3] There is a disparity in the statistical figures given by the China Electric Power Yearbook [48] and Shi [49] on the 2007 total generation capacity. The disparity may be due to the differences in the statistical methods used. The China Electricity Council only takes the wind farms in operation into account in calculating wind power generation capacity. The manufacturers of wind turbine use the sales figures instead of using wind power generation capacity. It is beyond the scope of this study to investigate the statistical methods used in these two studies. Since Shi's study contains data on the number of wind turbines and the total generation capacity, we have opted for using these figures in our study.

3kW Solar PV is based on electricity production with grid-connected photovoltaic power plants mounted on buildings with slanted roofs in Switzerland.

3.3.2 Input-output table

Following the standard compilation scheme established by the National Bureau of Statistics, 30 regional IO tables[4] have been compiled in China since 1987. In this study, the latest 2007 input-output table for Inner Mongolia is used.

3.3.3 Upstream and downstream cut-off matrix

We adopted the methods used by Acquaye et al. [46] and Wiedmann et al. [47] to compile the upstream cut-off matrix (matrix U). First, physical inputs of the examined product system (e.g. coal-fired power, wind power and solar power in our study) were extracted from the physical flow matrix. Monetary value of the product system was then estimated by multiplying physical inputs with cost of the product system. The cost data were extracted from the China Price Yearbook [50]. Since all physical inputs were covered in the IO system, the estimated monetary value of the physical inputs was deducted in order to avoid double counting with the remaining values representing elements of the upstream cut-off matrix. We assumed that all the power outputs were consumed by the electricity sector in the input-output table. Thus, downstream cut-off matrix D was set to zero, which meant the goods inputs from the process system to the IO system were negligible. The uncertainty and limitation of setting matrix D to zero are discussed in section 3.4.

3.3.4 CO_2 emission data

Following the compilation method introduced by Peters et al. [51], we estimated the sectoral CO_2 emission data for Inner Mongolia by using the sectoral energy consumption data from the Inner Mongolia Statistical Yearbook [52].

3.3.5 Water consumption data

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[4] It includes 22 provinces, 4 municipalities and 4 autonomous regions. Hong Kong, Macao, Taiwan and Tibet are not included.

The water consumption data of Inner Mongolia was extracted from the China Statistical Yearbook [18]. However, only seven sectors were recorded, which are agriculture, forestry and fishing, industry, services, households, and ecological compensation. As suggested by Yang and Suh [53], the incorporation of environmental impact indicators from other sources could help to improve the results. Hence, in this study, we incorporated the sectoral wastewater discharge data, which was extracted from the Inner Mongolia Bureau of Statistics [52], and the water recycling rate, from the Industries Water Requirement Quota and Standards of Inner Mongolia [54], to compile the sectoral water consumption data. The compilation of sectoral water consumption follows two steps. Firstly, sectoral water withdrawal data was estimated using sectoral wastewater discharge data and water recycling rates. Sectoral wastewater discharge data has 38 industries included, which provides more detail than the water consumption data from the China Statistical Yearbook. Secondly, the results were multiplied by water consumption rates for industry, which were obtained from the Inner Mongolia Water Bulletin [55], to generate the sectoral water consumption data.

The water recycling rate presents the percentage of water that is available for reuse [54]. For example, for coal mining and processing, the water recycle rate is 90%, which means 90% of the water withdrawal can be reused in the coal mining and processing industry. For other industries such as manufacturing of food, there are large variations in the water recycle rate ranging from 35% to 70% dependent on the food product. Equation 2 depicts the calculation of the recycling rate.

$$R = \frac{V_r}{V_i + V_r} \times 100\% \qquad (2)$$

Whereas R represents recycling rate in percentage; V_r represents total amount of reuse water at a given time period; V_i represents new water intake at a given time period.

The denominator of Equation 2 represents total water withdrawal of the industry (V); thus, we have Equation 3 depicted as below.

$$V_i + V_r = V \qquad (3)$$

In this study, we assumed that water losses from evaporation were negligible. Consequently, new water intake V_i was equivalent to wastewater discharge for each economic sector, which can be obtained from the Inner Mongolia Statistical Yearbook [56]. Since the water recycle rate included almost 400 products, we aggregated them in accordance with the sectoral classification of wastewater discharge data. A list of water recycle rate for industries[5] are given in Appendix A. Then, sectoral water withdrawal was calculated using Equation 4 which is derived from Equations 2 and 3.

$$V = \frac{V_i}{1-R} \qquad (4)$$

The calculated total water withdrawal with lower recycle rate was 17.2 billion m^3, which is not far from the total water withdrawal (17.5 billion m^3) recorded in the Inner Mongolia Water Bulletin [55]. Then, the sectoral water withdrawal data were multiplied by the water consumption rate, which was extracted from the Inner Mongolia Water Bulletin [55]. Based on the bulletin, the industrial water consumption rate was 61.4% of total water withdrawal. The sectoral water consumption data can be found in Appendix B.

3.3.6 Chemical oxygen demand (COD) discharge data

The concentration of COD is higher than the Class IV water quality standard[6] in Songhua River, Liao River and Yellow River that flows through Inner Mongolia. In this study, we use COD to assess the water quality impacts of power generations in Inner Mongolia due to two reasons. Firstly, COD is one of the most important indicators in assessing water quality. Secondly, data on COD is available at sectoral

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[5] The input-output table assumes that industries have homogeneous products within each sector. However, detailed information about the classification of industries for water recycle rate can be obtained. For example, manufacturing of food has a wide range of water recycle rates - from 35% for manufacturing of canned meat to 70% for manufacturing of milk. Thus, we listed the lower and higher recycle rates and estimate the lowest and highest water withdrawals for each industry.

[6] In China, water quality grading is based on two standards: the water quality standard, which refers to the quality of watersheds such as rivers and lakes; the wastewater discharge standard, such as COD concentration. To clarify, the Class IV water quality standard is for the quality of water bodies in watersheds such as rivers and lakes, which is different from the industrial wastewater discharge standard. Water quality level higher than Grade IV is considered not suitable for direct human contact.

level from the Inner Mongolia Statistical Yearbook while other pollutants, such as heavy metals, are only available in total discharge volume. However, it does not imply that power generation leads to COD discharge. Since this study aims to examine the life cycle water quality impacts of power generation, upstream activities such as coal mining and processing can have significant COD impacts are taken into account.

Guan and Hubacek [57] presented a hydrological model to investigate the relationship between COD and water availability in North China[7]. The authors calculated the water requirements to dilute COD discharges so that the mixed water (wastewater contains COD plus dilution water) can be used for other purposes. However, this model is not feasible in this study as the data recorded in the Inner Mongolia Statistical Yearbook [52] on wastewater discharge does not separate into surface water and ground water. Due to this, in this study, we only incorporate the general principle of mass balancing in Guan and Hubacek's model and our estimation procedures are depicted in detail in Appendix C.

3.4 Limitations

Firstly, since the detailed sectoral water withdrawal data is not available in most regions in China, the use of wastewater discharge data in the compilation of sectoral water withdrawal data has been adopted by a couple of studies [58, 59]. The assumption of using wastewater discharge in this study is that water loss in production and from evaporation is negligible. Although such an assumption is valid as only a minor fraction of water is consumed in industries at the present time, this study can further be improved by incorporating detailed water data when they are available in the near future.

Secondly, we do not take into account the use of inputs from the process system to the IO system by setting downstream cut-off matrix to zero ($D = 0$). The compilation of downstream cut-off matrix requires sales information (e.g. the distribution structure) of the product that is not always accessible to an LCA practitioner using commercial

[7] In China, North China (also known as Northern China) refers to those provinces and regions which are found around the Yellow River plain and north to the Middle and Lower Yangtze River.

databases [60]. In fact, the contribution of downstream cut-offs on total environmental impacts is minor, especially if a demand on the functional unit is used [61]. Thus, for simplicity, we do not take into account the downstream cut-offs in this study. However, we acknowledge that the results can be improved if relevant information for compiling downstream cut-offs is available.

Thirdly, the choice of representative power generation technologies might lead to uncertainty in the estimation of their environmental impacts. It is due to the following reasons: 1) the selected power generation technologies (i.e. 300 MW coal power, 800 kW wind power and 3 kW solar PV) may not fully represent the power generation system; 2) In general, process-based life cycle emissions of power generation technologies in European countries are lower than those produced in China. Hence, the use of PRO-LCA data based on European countries (in this case study, we use 800kW wind turbine and 3kW solar PV manufactured in Switzerland) could underestimate the environmental impacts of the power generation technologies in China. However, since these Chinese data are presently not available, our approach is regarded as the most viable means to estimate the life cycle environmental impacts of China's power generation system at the moment.

4 Research Findings

4.1 CO_2 emissions

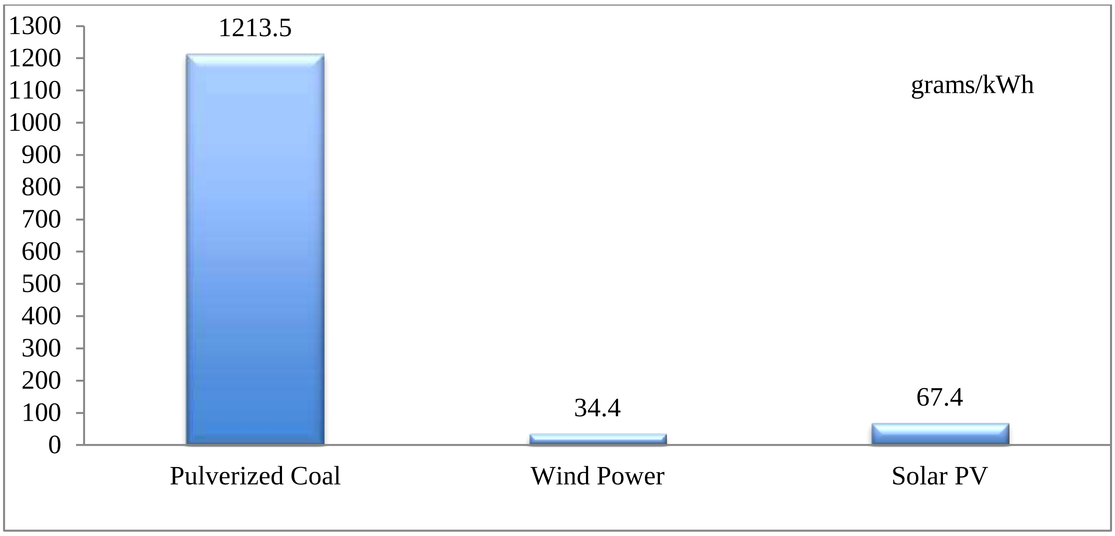

Figure 3 Life cycle CO_2 emissions of pulverized coal, wind power and solar PV systems per kWh in Inner Mongolia, China.

Figure 3 compares the life cycle CO_2 emissions of pulverized coal, wind power and solar PV systems. Pulverized coal emits 1,213.5 grams of CO_2 per kilowatt-hour (g/kWh) of electricity output, compared with 34.4 g/kWh and 67.4 g/kWh for wind power and solar PV systems, respectively. The significant differences in CO_2 emissions between different energy production systems reveal that substantial reduction in CO_2 emissions could be achieved through a substitution from the existing coal-dominated power generation technology to renewable energy technologies.

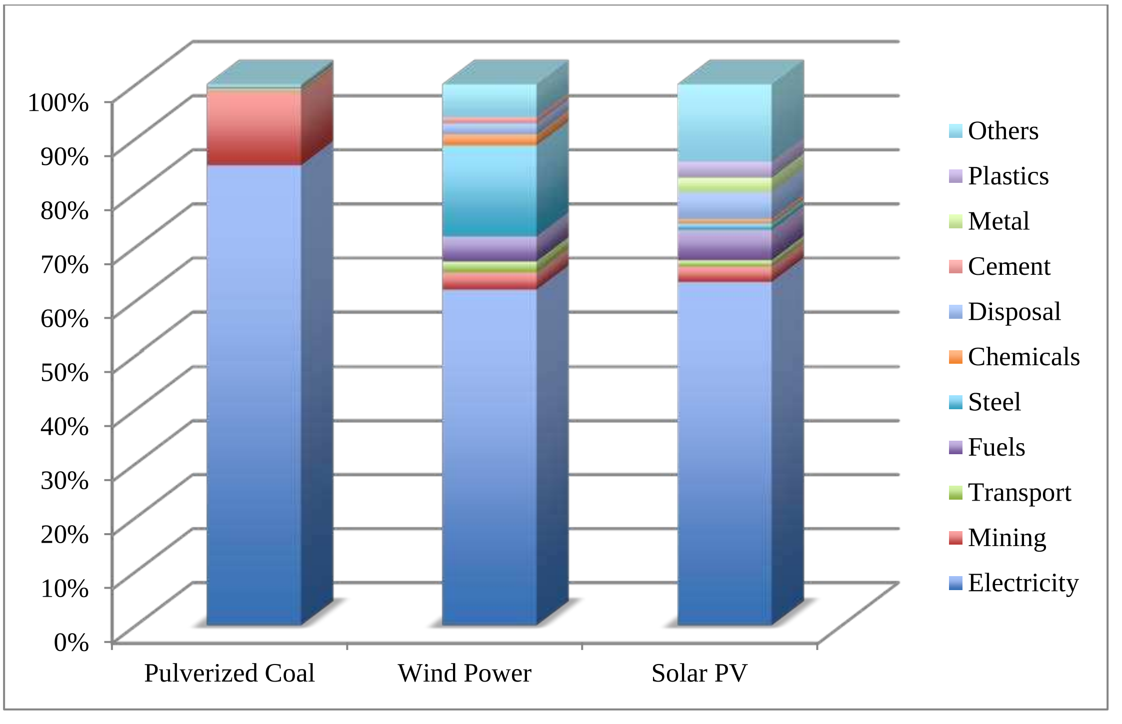

Figure 4: A breakdown of sectoral CO_2 emissions generated from pulverized coal, wind power and solar PV systems in Inner Mongolia, China.

In Figure 4, a breakdown of the CO_2 emissions by sectors shows that the electricity sector contributes most to the life cycle emissions of all power generation technologies in Inner Mongolia. For pulverized coal power generation, coal combustion at plant accounts for most of the emissions (1031.8 g/kWh), followed by the coal mining (165.2 g/kWh) and transportation (6.3 g/kWh). Activities related to power plant construction, such as steel production (2.1 g/kWh), account for a minor proportion of the total emissions. For wind power, electricity generation accounts for more than 50% of the total CO_2 emissions and it is followed by steel production due to the large input of steel for wind turbine. Similar results are found in Li et al. [12], which provides a national level analysis on CO_2 emissions of wind power in China.

4.2 Water consumption

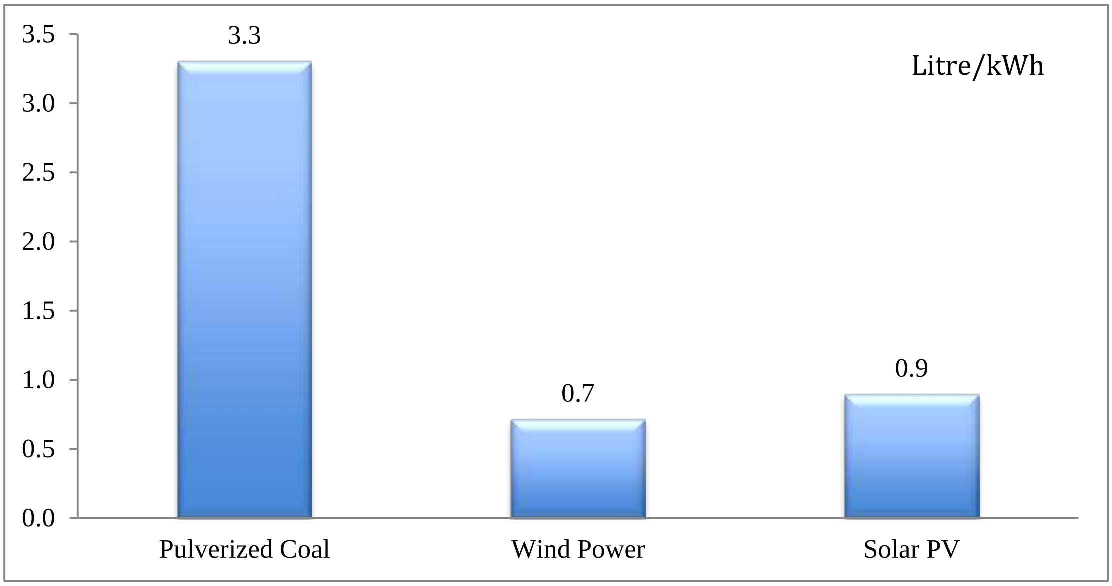

Figure 5: A comparison of life cycle water consumption of pulverized coal, wind power and solar PV systems in electricity generation in Inner Mongolia, China.

Figure 5 presents the life cycle water consumption required by pulverized coal, wind power and solar PV systems to generate electricity in Inner Mongolia. Pulverized coal consumes 3.3 litres of water per kilowatt-hour (l/kWh) of electricity output compared to 0.7 l/kWh and 0.9 l/kWh for wind power and solar PV systems, respectively. Therefore, a switch from a pulverized coal power generation to wind power and solar PV not only reduces CO_2 emissions but also decreases water consumption of power generation significantly.

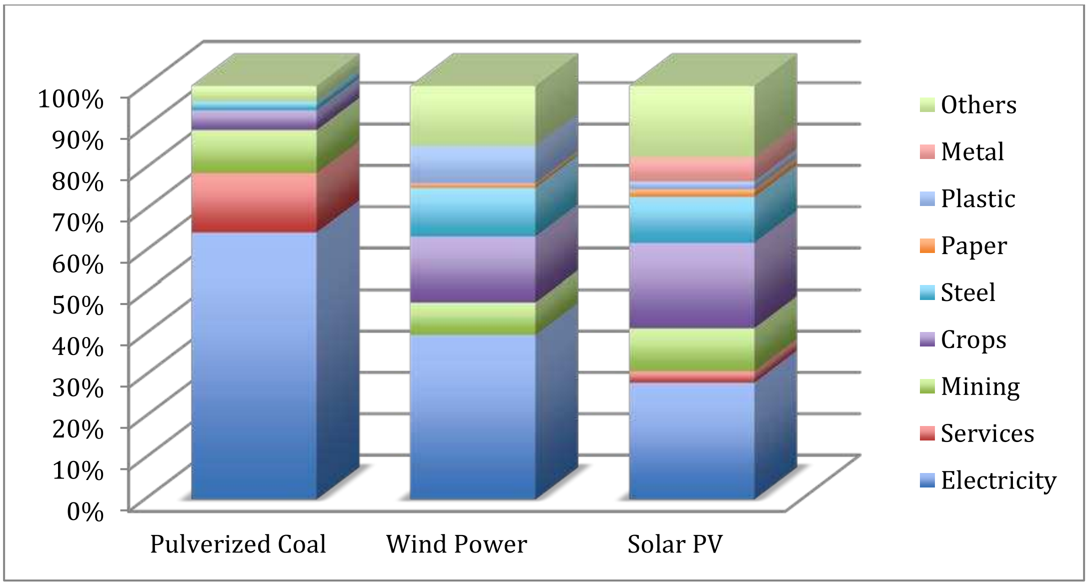

Figure 6: Breakdown of sectoral water consumption of pulverized coal, wind power and solar PV systems in electricity generation in Inner Mongolia, China.

As shown in Figure 6, the electricity input accounts for approximately 60% (or 2.13 l/kWh) of the life cycle water consumption for pulverized coal based electricity generation technology. Most water sources are consumed for cooling purposes. However, electricity input accounts for about 40% of total life cycle water consumption in wind power (0.28 l/kWh out of 0.71 l/kWh in total) and 30% in solar PV (0.27 l/kWh out of 0.90 l/kWh).

4.3 COD discharge

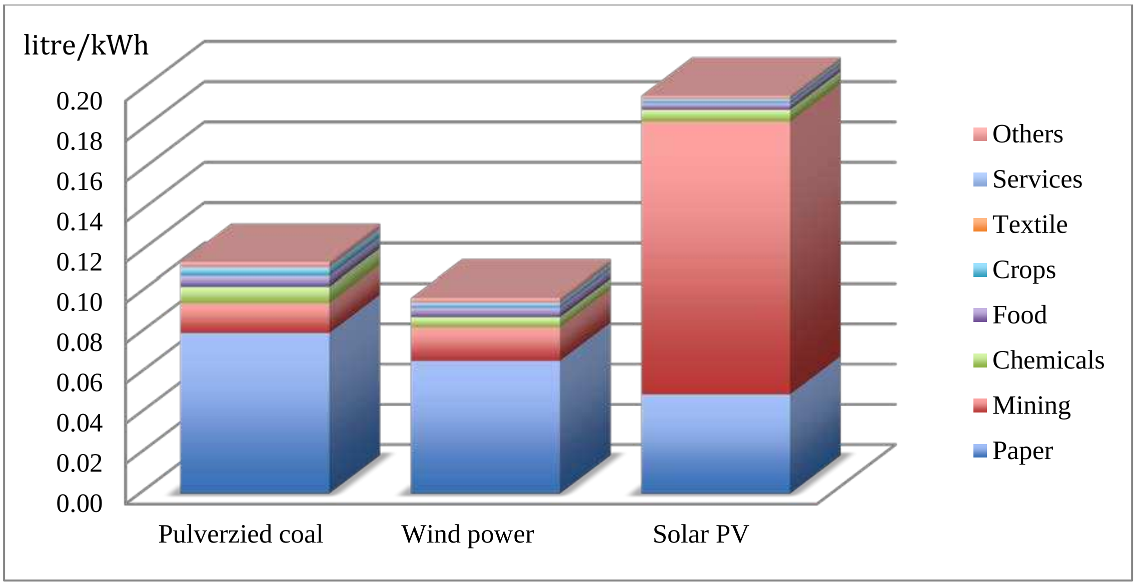

Figure 7: Dilution water required for electricity generation in pulverized coal, wind power and solar PV systems in Inner Mongolia, China.

COD discharge is estimated as additional water consumption since the discharge with excessive COD contents needs to be diluted in order to achieve the water quality standard. From Figure 7, dilution water to purify the discharged wastewater from pulverized coal, wind power and solar PV amounted to 0.11, 0.09 and 0.19 litres per kWh, respectively. COD discharge from paper production uses most of the dilution water for pulverized coal (0.08 l/kWh) and wind power (0.07 l/kWh) due to the concentration of COD in the paper industry's wastewater (1659.9 grams/m^3), which is higher than all the other industries in Inner Mongolia (See a full list of sectoral COD concentration in Appendix D). By contrast, mining of metals accounts for the highest proportion of dilution water for solar PV (0.13 l/kWh), and it is followed by paper, chemicals and food production.

5 A scenario analysis of CO_2 emissions and water impacts of power generation in Inner Mongolia by 2020

Presently, Inner Mongolia is the largest coal producer in China, which is located at a considerable distance from the demand centres on the east coast. The uneven distribution of energy sources in China has called for the construction of a long-distance power transmission system, which has been initiated by the State Grid

Corporation of China (SGCC). One of the primary targets of Inner Mongolia is to increase power generation capacities that provide power supply to regions outside Inner Mongolia to 120 GW by 2020. Since the changes in outflow power generation capacity would have significant impact on carbon emissions, water availability and water quality in Inner Mongolia, we adopt the scenario analysis technique to project the total amount of CO_2 emissions and water requirements in 2020 based on the projection from SGCC.

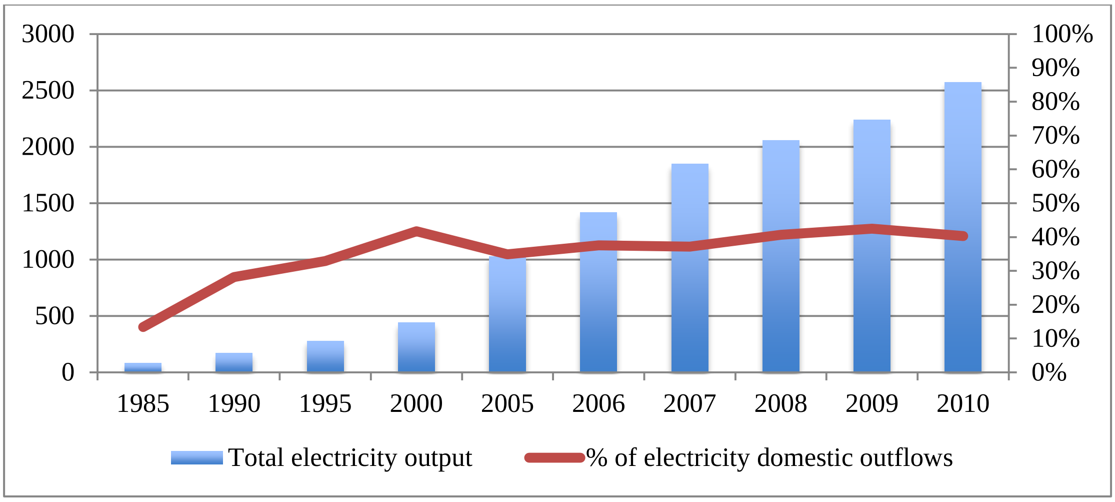

Figure 8 Total electricity outputs in Inner Mongolia (TWh) and shares of exports

Source: Various Inner Mongolia Statistical Yearbooks [56, 62-66]

Figure 8 gives the total electricity outputs and shares of domestic outflows to total outputs in Inner Mongolia between 1985 and 2010. Total electricity outputs increased from 80.46 terawatt hours (TWh) in 1985 to 2571.82 TWh in 2010. Shares of exports increased from 13.4% in 1985 to 41.7% in 2000 and have remained stable around 40% since 2000.

We assume that domestic outflows would remain at 40% of the total power outputs in Inner Mongolia by 2020. Thus, total power generation capacity would reach 300 GW by 2020. According to Li et al. [27], 58.1 GW of wind power would be deployed in Inner Mongolia by 2020. Solar power has been at its early stages of development. Total power generation capacity was 0.02 GW by 2010. The Inner Mongolia Energy Bureau projected that total power generation capacity of solar PV would reach 0.8 GW by 2015 [67], with 0.155 GW of solar PV installed annually between 2010 and

2015. We assume that annual installed capacity would be identical between 2016 and 2020. Thus, solar PV would have total installed capacity of approximately 1.6 GW by 2020. Hydropower accounts for a minor proportion of total power generation capacity and has remained stable for years in Inner Mongolia. Hence, we take the contribution of hydropower to total power generation capacity for granted in 2020. Besides wind power and solar PV, the remainder of the 300 GW power generation capacities would come from coal power. Table 2 shows the power generation capacity, total CO_2 emissions and water requirements of each power generation technology by 2020.

	Coal power	Wind power	Solar PV
Power generation capacity (Gigawatt = 10^9 watt)	240.0	58.4	1.6
Total power generation (Gigawatt hour = 10^9 watt hour)	1,070,718.4	103,660.4	2,080.0
Total CO_2 emissions (million tonnes)	1,299.3	3.6	0.1
Water consumption (million m^3)	3,533.4	72.6	1.9
Dilution water (million m^3)	117.8	9.3	0.4
Total water consumption (million m^3)	3,651.1	81.9	2.3

Table 2 Total power generation capacities and annual power generation by source in 2020

Source: For total power generation, own calculation. Operating hours for coal power, wind power and solar PV are from [68] and [69].

Jin [70] estimated that coal power generation would contribute to 680 million tonnes of CO_2 emissions in Inner Mongolia by 2020. However, Jin's study might underestimate the CO_2 emissions from coal power generation since it does not take life cycle emissions into account. The CO_2 emission coefficient was set at 810 g/kWh in her study, which is almost one third lower than the calculated life cycle CO_2 emission coefficient (1213.5 g/kWh) in our study. From Table 2, total CO_2 emissions from coal power generation would reach 1,299.3 million tonnes by 2020. 40% of the emissions (i.e. 520 million tonnes) would result from power supply to regions outside Inner Mongolia; this would be similar to the total CO_2 emissions in the U.K. in 2010 (547.9 million tonnes) [71]. In addition, coal power generation would consume 3651.2 million m^3 of water by 2020. For wind power and solar PV, the estimated water requirements are 81.9 and 2.3 million m^3, respectively. According to the Inner Mongolia Ministry of Water Resource, total water consumption was 12,080 million m^3 in 2010 with an annual growth rate of 2.3% [34]. If annual growth rate remains constant in the coming decade, coal power generation would represent 24.1% of total water consumption (3,651.2 out of 15,164.3 million m^3) in Inner Mongolia by 2020. Again, 40% of the water consumption would come from power generation for regions outside Inner Mongolia, which amount to 1,460.8 million m^3 of water.

6 Discussion and concluding remarks

Renewable energy technologies are regarded as carbon and water saving solutions for the existing coal-dominated power generation system in Inner Mongolia. It shows that wind power and solar PV have considerable environmental advantages to coal power in terms of CO_2 emission and water consumption, and wind power has the lowest impact on water quality among all the energy production technologies. Results from our scenario analysis reveal that electricity outflows would contribute to a significant amount of CO_2 emissions and water demands in Inner Mongolia. Switching from coal to wind power not only significantly reduces CO_2 emissions but also relieves the pressure on local water resources and the ecosystem in Inner Mongolia.

This study also reveals that, other than carbon emissions, different power generation technologies have different impacts on water in terms of both quantity and quality. Our result shows that solar PV has higher COD levels than wind power due to mining of metals. Presumably, the environmental repercussions of solar PV can be more considerable if emissions of other pollutants such as cadmium are taken into account.

There are many factors that need to be considered in optimizing the power system from a technical point of view, such as system operation to environmental issues and mitigation of CO_2 emissions. A coherent energy policy should consider as many sustainability indicators as possible. For example, besides carbon emissions and water impacts examined in this study, coal-fired power plants are the most significant contributors to mercury emissions in China, which amounted to 304 tonnes in 2010 according to Yang et al. [72]. Whether the switch from coal to renewable energy sources can deal with mercury emissions needs to be examined from a supply chain perspective. Further investigation of other sustainability indicators are required to ensure the current choice of power generation technologies will not compromise sustainability in the future considering the substantial life-span of power generation systems.

The existing LCA database does not have much information about China's power generation system, regardless of the fact that China has the second largest power generation capacity in total, the largest wind power generation capacity and is one of the most pioneering countries in solar power in the world. Considering the significant environmental impacts of China's power generation - both domestically and internationally - it is necessary to compile the LCA database for the Chinese power generation system in the near future.

We conclude this study by highlighting a future research direction. In this study, we assume that the selected power generation technologies are produced in Inner Mongolia, and ignore the environmental impacts of imports from and exports to other regions. Establishing linkages between Inner Mongolia and other regions in China by using multi-regional input-output analysis would be an important step forward to further understand the environmental impact of power generation technologies from a consumption perspective. In addition, as constrained by data availability, we have to use COD as our water quality impact indicator. Other pollutants such as heavy metal can also be used as indicators to demonstrate water quality, which can also be a future research direction when data is available.

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8 Appendices

Appendix A: Industrial water recycle rate

Economic sector	Recycle rate	
	Lower	Upper
Coal mining & processing	90%	90%
Petroleum & Natural Gas Pumped	90%	90%
Mining & Dressing of Ferrous Metals	50%	85%
Mining & Dressing of Non-ferrous Metals	35%	90%
Mining & Dressing of Non-metal Minerals	95%	95%
Processing of Agricultural Side-Line Food	75%	85%
Manufacturing of Food	35%	95%
Manufacturing of Beverages	70%	80%
Tobacco Products	85%	85%
Textile Industry	50%	65%
Textile, Clothes, Shoes & Hats	50%	65%
Leather, Furs, Down & Related Products	50%	65%
Timber Processing, Bamboo, Cane	90%	95%
Palm Fibre & Straw Products	90%	90%
Paper-making & Paper Products	60%	85%
Printing & Record Pressing	90%	90%
Petroleum Processing, Coke Products & Processing of Nuclear Fuel	50%	95%
Chemical Materials & Products	60%	95%
Manufacturing of Medicine	80%	90%
Plastic Products	70%	85%
Non-metal Mineral Products	60%	70%
Smelting & Pressing of Ferrous Metals	95%	95%
Smelting & Pressing of Non-ferrous Metals	90%	95%
Metal Products	80%	90%
General-Purpose Equipment	70%	80%
Special Equipment	35%	80%
Transported Equipment	60%	60%
Electric Equipment & Machinery	60%	80%
Manufacturing of Telecoms, Computer & Other Electronic Equipment	30%	90%
Instruments, Meters, Cultural & Office Machinery	30%	90%
Production & Supply of Electric Power	92%	95%
Production & Supply of Gas	92%	95%
Production & Supply of Water	92%	95%

Source: [54]

Appendix B: sectoral water consumption and water coefficients

Economic sectors	**Water consumption (10,000 m^3)**	**Economic output (10,000 yuan)**	**Water consumption coefficient (m^3/10,000 yuan)**
Agriculture	779200.0	6421574.0	1213.4
Forest, fishing, livestock	127500.0	6342863.0	201.0
Coal mining & processing	20558.3	7629806.4	26.9
Petroleum & Natural Gas Pumped	12.4	630965.8	0.2
Mining & Dressing of Ferrous Metals	349.4	2341200.7	1.5
Mining & Dressing of Non-ferrous Metals	2338.7	2021735.9	11.6
Mining & Dressing of Non-metal Minerals	212.5	1628769.9	1.3
Processing of Agricultural Side-Line Food	4666.1	912753.5	51.1
Manufacturing of Food	2161.3	8914647.1	2.4
Manufacturing of Beverages	3006.5	1254994.5	24.0
Tobacco Products	28.5	386674.8	0.7
Textile Industry	440.9	1425883.0	3.1
Textile, Clothes, Shoes & Hats	49.7	1639205.6	0.3
Leather, Furs, Down & Related Products	34.6	108823.2	3.2
Timber Processing, Bamboo, Cane	2398.7	859677.6	27.9
Palm Fibre & Straw Products	548.5	196560.3	27.9
Paper-making & Paper Products	5469.6	374270.4	146.1
Printing & Record Pressing	93.7	390490.8	2.4
Petroleum Processing, Coke Products & Processing of Nuclear Fuel	206.0	1587319.4	1.3
Chemical Materials & Products	2660.0	3867593.5	6.9

Manufacturing of Medicine	1817.0	575195.6	31.6
Plastic Products	45.2	453652.5	1.0
Non-metal Mineral Products	376.1	3773112.8	1.0
Smelting & Pressing of Ferrous Metals	41496.8	7032359.4	59.0
Smelting & Pressing of Non-ferrous Metals	2202.8	10513854.2	2.1
Metal Products	2.2	38571.3	0.6
General-Purpose Equipment	19.8	760220.0	0.3
Special Equipment	174.3	840643.9	2.1
Transported Equipment	25.2	2065849.2	0.1
Electric Equipment & Machinery	15.4	421611.8	0.4
Manufacturing of Telecoms, Computer & Other Electronic Equipment	8.2	845809.3	0.1
Instruments, Meters, Cultural & Office Machinery	5.9	162573.1	0.4
Production & Supply of Electric Power	31938.7	7780758.0	41.0
Production & Supply of Gas	26.5	751728.3	0.4
Production & Supply of Water	2131.8	146129.5	145.9
Construction	5852.9	11705703.3	5.0
Transport and warehousing	3123.5	10075826.0	3.1
Post and telecommunication	309.7	1290483.6	2.4
Wholesale and retail trade	1538.4	6992825.7	2.2
Eating and drinking places	566.2	2573768.2	2.2
Passenger transport	136.8	427536.0	3.2
Finance and insurance	709.7	3226008.0	2.2
Real estate	321.6	1461761.7	2.2
Social services	263.2	1461970.6	1.8
Health Services, social welfare	1186.7	3596116.6	3.3
Education and culture	617.5	1992087.5	3.1

Scientific research	45.8	190703.1	2.4
General technical services	100.9	252170.8	4.0
Public and other services	3141.9	6283872.6	5.0
Total	**1050136.1**	**136628711.7**	**76.9**

Source: Water consumption data are own calculation. Economic output data are from the 2007 Inner Mongolia input-output table.

Appendix C:

We incorporate the general principle of mass balancing in Guan and Hubacek's model which is the quantity of COD in wastewater (m_1) equals to the quantity of COD after dilution (m_2) as depicted in Equation E1.

$$m_1 = m_2 \tag{E1}$$

The quantity of COD in wastewater (m_1) equals the total volume of wastewater (v_1) multiplied by the concentration of COD in the wastewater (ρ_1). Furthermore, the quantity of COD after dilution (m_2) equals the total volume of water needed to dilute the COD content in wastewater (v_2) multiplied by the standard concentration of COD[8] (ρ_2). Thus, Equations E2 and E3 are derived and they are depicted as follows.

$$m_1 = v_1 \times \rho_1 \tag{E2}$$

$$m_2 = v_2 \times \rho_2 \tag{E3}$$

Since $m_1 = m_2$ in Equation E1, we have

$$v_1\rho_1 = v_2\rho_2 \tag{E4}$$

[8] Standard concentrations of COD follow the stipulation of industrial wastewater discharge standards by the General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China in 1996. Details of the standard are discussed later.

The sectoral COD discharge data (m_1) and wastewater discharge data (v_1) for 37 industries are extracted from the Inner Mongolia Statistical Yearbook [52]. Then, we calculate the concentration of COD in the wastewater (ρ_1), which can be found in Appendix C. COD discharge data is not given for agriculture in the Inner Mongolia Statistical Yearbook (2008); so, we adopt the COD discharge coefficients from Guan and Hubacek [57].

The General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China [73] has promulgated industrial wastewater discharge standards (referred to as the standard thereafter), which classify the contents of COD into three grades (See Table S1 below).

Table S1: Industrial wastewater discharge standard for COD content (grams per cubic metre)

Industry	**Grade I**	**Grade II**	**Grade III**
Beet sugar manufacturing, fatty acid synthesis, wet fibreboard processing, dye manufacturing, organophosphorus pesticides industry	100	200	1000
Monosodium glutamate, ethanol, medicines, medicines, biochemistry, fur industry, pulp purification industry	100	300	1000
Petroleum refinery	60	120	150
Secondary wastewater treatment plant	60	120	Not available
Other wastewater discharge	100	150	500

Source: [73]

The concentration of COD in wastewater needs to achieve the concentration shown in Grade I industrial wastewater discharge standard (regarded as the standard concentration of COD, ρ_2, in this study) in Appendix D.

As shown in Appendix D, the concentration of COD in wastewater for most industries is higher than the Grade I industrial wastewater discharge standard. Grade I industrial wastewater discharge standard is adopted due to the following reasons:

1) Industries that fulfil the requirements of Grade II are only allowed to discharge wastewater to Class IV or Class V water bodies. The water quality of Class IV and Class V is considered as a poor quality of water resource, which are only available for agricultural purposes. Thus, higher standard should be used.

2) The Inner Mongolia Statistical Yearbook [52] provides COD discharge data as COD removal and COD discharge. We assume that the COD discharge data are derived after the removal of COD content in secondary wastewater treatment plants. Our assumption is based on two reasons: firstly, the COD removal figures are an order of magnitude higher than COD discharge figures; secondly, primary wastewater treatment plants use physical methods to remove tangible waste in the water body, which cannot remove COD content. Hence, Grade III in the wastewater standard is not considered in this study.

3) The standard is stipulated in 1996, which needs to be revised because of the improvement of wastewater treatment technology in the past decade.

Hence, in order to achieve the Grade I standard, additional water (estimated by $v_2 - v_1$) is required to dilute the COD concentration.

Appendix D: COD discharge and COD discharge standard by sectors

Economic Sectors	**Wastewater discharge**	**COD discharge**	**Average COD level**	**COD discharge standard (Grade I)**
Unit	**10,000 m^3**	**tonne**	**g/m^3**	**g/m^3**
Agriculture	8807.46	25541.64	290.000	100
Coal Mining & Processing	2829.56	4038.91	142.740	100
Petroleum & Natural Gas Pumped	1.70	0.09	5.318	60
Mining & Dressing of Ferrous Metals	240.42	107.04	44.520	100

Mining & Dressing of Non-ferrous Metals	2092.28	18988.36	907.545	100
Mining & Dressing of Non-metal Minerals	14.62	65.49	447.910	100
Mining of Other Mineral	0.00	0.00	0.000	100
Processing of Agricultural Side-Line Food	1605.55	12635.80	787.006	100
Manufacturing of Food	1933.61	10653.12	550.946	100
Manufacturing of Beverages	1241.40	13488.52	1086.561	100
Tobacco Products	5.88	18.04	306.718	100
Textile Industry	303.44	2254.47	742.962	100
Textile, Clothes, Shoes & Hats	34.20	84.67	247.533	100
Leather, Furs, Down & Related Products	23.82	82.68	347.143	100
Timber Processing, Bamboo, Cane	330.15	428.49	129.789	100
Palm Fibre & Straw Products	0.00	0.00	0.000	100
Paper-making & Paper Products	3011.23	49981.95	1659.851	100
Printing & Record Pressing	0.00	0.00	0.000	100
Petroleum Processing, Coke Products & Processing of Nuclear Fuel	141.77	98.12	69.211	100
Chemical Materials & Products	1464.47	2903.29	198.249	100
Manufacturing of	500.17	1766.53	353.188	100

Medicine				
Plastic Products	0.00	0.00	0.000	100
Non-metal Mineral Products	207.08	120.07	57.982	100
Smelting & Pressing of Ferrous Metals	2855.72	1777.99	62.261	100
Smelting & Pressing of Non-ferrous Metals	303.18	213.38	70.382	100
Metal Products	0.60	1.12	186.291	100
General-Purpose Equipment	8.19	23.35	285.076	100
Special Equipment	155.96	116.87	74.938	100
Transported Equipment	13.88	10.81	77.871	100
Electric Equipment & Machinery	8.48	5.24	61.765	100
Manufacturing of Telecoms, Computer	7.86	10.11	128.633	100
Instruments, Meters, Cultural	0.00	0.00	0.000	100
Production & Supply of Electric Power	3516.72	2029.68	57.715	100
Production & Supply of Gas	2.92	43.42	1486.986	100
Production & Supply of Water	234.73	280.88	119.659	100
Housing & Civil Construction	0.00	0.00	0.000	100
Railway Transport	0.00	0.00	0.000	100
Other Sectors	120.03	515.52	429.503	100
Total	**32017.07**	**148285.66**	**463.15**	

Source: Wastewater discharge data and COD discharge data are from [56]; COD discharge standard are from [73].