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# 1 The Energy and Water Nexus in Chinese Electricity 2 Production: A Hybrid Life Cycle Analysis

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10 *Keywords:* Electricity generation technologies, hybrid life-cycle analysis, CO<sub>2</sub> emissions, water  
11 scarcity, China

12

## 13 **Abstract**

14 Between 2000 and 2010, China's electricity production had increased threefold and accounted  
15 for 50% of domestic and 12% of global CO<sub>2</sub> emissions in 2010. Substantial changes in the  
16 electricity fuel mix are urgently required to meet China's carbon intensity target of reducing CO<sub>2</sub>  
17 emissions by 40% - 45% by 2020. Moreover, electricity production is the second largest  
18 consumer of water in China, but water requirements vary significantly between different  
19 electricity generation technologies. By integrating process-based life-cycle analysis (LCA) and

20 input-output analysis (IOA) and through tracking national supply chains, we have provided a  
21 detailed account of total life-cycle carbon emissions (in g/kWh) and water consumption (in  
22 liter/kWh) for eight electricity generation technologies – (pulverized) coal, gas, oil, hydro,  
23 nuclear, wind, solar photovoltaic, and biomass. We have demonstrated that a shift to low carbon  
24 renewable electricity generation technologies, i.e. wind, could potentially save more than 79%  
25 of total life-cycle CO<sub>2</sub> emissions and more than 50% water consumption per kWh electricity  
26 generation. Not only a reduction of coal use in China’s electricity fuel mix can help mitigate  
27 climate change, but it also alleviates water stress. For example, if the projected wind farms are  
28 built by 2020, Inner Mongolia, one of the water scarce northern provinces, would annually save  
29 179 MT CO<sub>2</sub> (i.e. 44% of Inner Mongolia’s total CO<sub>2</sub> emissions in 2008) and 418 million m<sup>3</sup>  
30 (Mm<sup>3</sup>) water (18% of its industrial water use in 2008) compared with the same amount of  
31 electricity produced from coal.

## 32 **1. Introduction**

33 China was a major player in the Copenhagen Accord [1] which was developed at the  
34 Copenhagen climate summit in December 2009. As a signatory of the Accord, China agreed to  
35 reduce its carbon dioxide (CO<sub>2</sub>) emissions per unit of Gross Domestic Product (GDP) by 40% -  
36 45% by 2020 from 2005 levels and increase the share of non-fossil fuels in primary energy  
37 consumption to around 15% [2]. The targets that China has set are of major consequence and, if  
38 met, will make a significant contribution to international CO<sub>2</sub> mitigation efforts and a shift  
39 toward sustainable, renewable energy sources at the national scale. A continuation of China’s  
40 historic trend of declining carbon intensity since 1980 would seem to be sufficient to enable  
41 China to exceed its target range. However, this does not mean that achieving the target is easy,  
42 nor that the policies are sustainable. For example, the declining trend was reversed during 2003

43 and 2004, and further progress will not be sustained without strong Chinese government policy  
44 interventions. Even so, purely on the basis of meeting 15% of its primary energy requirements  
45 from non-fossil fuels, large investments in a transformed energy system with substantial changes  
46 in the fuel mix is a precondition for achieving this target. For example, according to a  
47 government report, China's spending to develop renewable energy may total US\$294 billion (1.8  
48 trillion yuan) in the five years through 2015 as part of the nation's efforts to counter climate  
49 change [3].

50 Several studies [4-7] can be found in the literature which examined the status, outlook and  
51 projection of China's energy sector. However, it is essential to examine the feasibility of the  
52 energy targets and more importantly, their implications and trade-offs (such as increasing water  
53 requirements). These trade-offs need to span the whole life-cycle of the respective technology as  
54 a new low-carbon energy system can reduce direct carbon emissions from the energy generation  
55 itself, but building a new energy system itself can be energy-intensive because upstream (i.e.  
56 indirect) emissions related to such capital investments can be significant [8]. Hence, there is a  
57 need for assessing life-cycle CO<sub>2</sub> emissions (both direct and indirect) of electricity production,  
58 particularly of the so-called low carbon energy generation technologies (e.g. nuclear, hydro,  
59 wind and solar photovoltaic (PV)) which can cause substantial CO<sub>2</sub> emissions in upstream  
60 production processes compared to fossil fuel based energy technologies. Total life-cycle CO<sub>2</sub>  
61 emissions refer to the direct and indirect CO<sub>2</sub> emissions per kWh over the lifetime of an energy  
62 generation technology; this includes CO<sub>2</sub> emissions during transportation of fuels, transmission  
63 of electricity, construction and operation of power plants, grid-connection and decommissioning of  
64 power plants. Direct CO<sub>2</sub> emissions are emissions released during the electricity production  
65 process while indirect CO<sub>2</sub> emissions result in upstream production processes (i.e. the previous

66 production stages; e.g. CO<sub>2</sub> emissions released from manufacturing of electricity production  
67 technologies and associated inputs as well as their respective inputs).

68 The electricity sector is not only the major contributor to CO<sub>2</sub> emissions, but also one of the  
69 largest water consumers in China apart from agriculture [9]. Thus, the electricity sector can be a  
70 contributor to water scarcity which has already occurred in many parts of the country, in  
71 particular in Northern China [10]. As life-cycle water requirements for different types of  
72 electricity generation technology vary significantly, the choice of water-intensive power  
73 generation plants either exacerbates the problem of water supply in water scarce regions or  
74 constrains the efficiency of operating water-intensive power plants during water-shortage periods  
75 [11]. As argued by Cooper and Sehike [12], climate change mitigation efforts may have the risk  
76 of creating negative impacts on other aspects of environmental sustainability if such efforts  
77 become too focused on emission reduction. The energy water nexus has recently attracted lots of  
78 attention investigating the link of energy production and water consumption [13-15]. Hence,  
79 besides CO<sub>2</sub> emissions, there is also an urgent need for assessing direct and indirect water  
80 consumption from different electricity generation technologies.

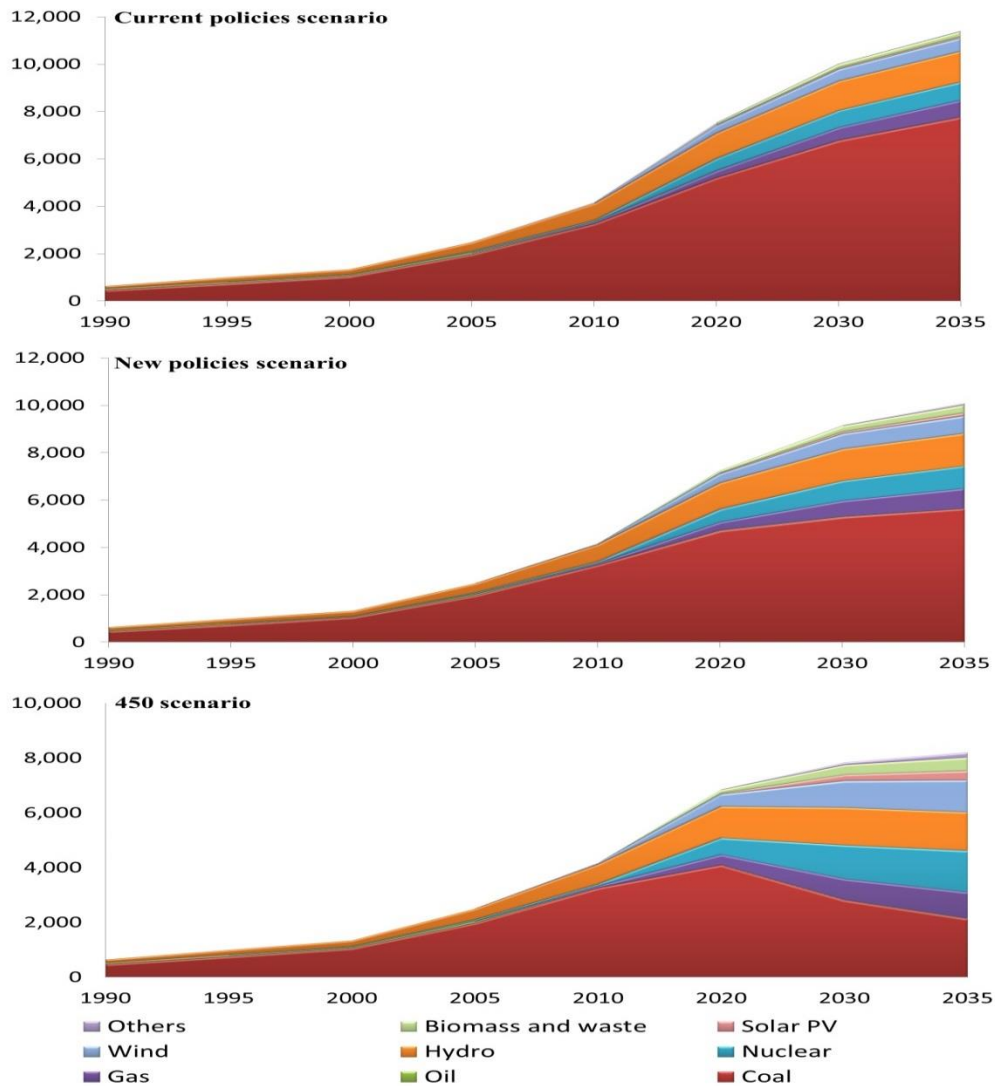
81 Our research investigates whether low carbon electricity generation technologies really help  
82 mitigate CO<sub>2</sub> emissions and reduce water stress on existing water resources. In this study, we  
83 apply an integrated hybrid LCA approach to eight different electricity generation technologies in  
84 China to calculate their total life-cycle CO<sub>2</sub> emissions and water consumption throughout  
85 national supply chains. The selected electricity generation technologies are coal, gas, oil, hydro,  
86 nuclear, wind, solar PV and biomass that together contribute almost 100% of total electricity  
87 production in China. This is the first study to comprehensively examine the connection between

88 embodied CO<sub>2</sub> emissions and water consumption for all major electricity generation technologies  
89 in China.

## 90 **2. Electricity generation in China**

91 China's electricity generation has substantially increased by 7.6 times over the last two decades  
92 (from 650 terawatt hours (TWh) in 1990 to 4,940 TWh in 2012 [16]. Coal contributes  
93 approximately 80% to China's electricity generation followed by hydropower, accounting for  
94 17% of the total electricity production. Increased concerns over climate change, national energy  
95 security and energy-related environmental repercussions in recent years have prompted the  
96 Chinese government to consider the transition to a low carbon electricity system [17-20].  
97 Subsequently, a number of high level energy plans based on substantial increases in the shares of  
98 nuclear power, wind power and other low carbon emission power generation technologies have  
99 been introduced and implemented by the Chinese government (e.g. the Mid-Long Term Nuclear  
100 Development Plan [21] and the Mid-Long Term Renewable Energy Development Plan [22]).  
101 Two aspects are frequently addressed in the Chinese energy policies, namely, energy efficiency  
102 improvement and energy structure diversification. For instance, the Eleventh Five Year Plan  
103 (between 2006 and 2010) stated an energy efficiency improvement target of 20% by 2010  
104 compared to the 2005 baseline [23]. In 2006, the first Renewable Energy Law was promulgated  
105 to legitimate and stimulate the development of renewable energy technology. The national  
106 strategy to climate change mitigation and adaptation was published in 2008 by the Central  
107 Government. The strategy developed the targets and plans in order to combat climate change and  
108 at the same time to diversify the energy structure and improve energy efficiency [24]. In 2009,  
109 the target of reducing the CO<sub>2</sub> emissions by 40-45% per unit of Gross Domestic Product (GDP)  
110 in 2020 compared with the 2005 baseline was delivered by President Hu Jintao [25]. In addition,

111 energy efficiency standards on lighting, building construction and house appliances either have  
112 been introduced or are being drafted by the Chinese government [26]. The 12th Five Year Plan  
113 on Energy Development (between 2011 and 2015) proposed dual targets on energy intensity  
114 reduction (16% compared to the 2010 baseline) and total energy consumption by 2015 (capped at  
115 4 billion tons of coal equivalent compared to 3.25 billion tons in 2010) [27]. Although the shares  
116 of nuclear power and wind power in China's total electricity production are still insignificant,  
117 these energy generation technologies have enjoyed substantial growth over the last few years.  
118 For example, wind power generation has increased more than 17-fold from 2.8 TWh in 2006 to  
119 49.4 TWh in 2010. Development of nuclear energy showed a similar trend. According to the  
120 World Nuclear Association [28], China has 15 nuclear power reactors in operation, 26 new  
121 nuclear reactors (out of a total of 60 reactors worldwide) are currently being constructed in China  
122 and most reactors have had their generating capacity of more than 1 Gigawatt (GW). Figure 1  
123 depicts past and future trends of China's primary electricity production by source from 1990 to  
124 2035, based on information provided by the International Energy Agency (IEA).



125  
126 **Figure 1.** The historical and future trends of China’s primary electricity generation by source  
127 from 1990 to 2035, based on the International Energy Agency (IEA) scenario projections (in  
128 TWh).

129 *Source:* Data for the historical primary electricity production (1990-2010) are collected from the  
130 IEA Statistics & Balances and the future projections (for 2020, 2030 and 2035) are based on IEA  
131 World Energy Outlook 2011[29].

132 According to the IEA’s “current policies scenario”, China’s electricity generation from coal is  
133 projected to continue its rapid growth by 2035, and there is also an increasing trend of electricity  
134 generated from coal by 2035 based on the “new policies scenario” but with much lower growth  
135 rates [29]. In the IEA’s “450 scenario”, coal-based electricity production is expected to decline  
136 by 2020 due to a slowdown of electricity consumption (e.g. improvement of energy efficiency



137 and slowdown of population growth) and heavy promotion of renewable energy to limit the long-  
138 term increase in the global mean temperature to two degrees Celsius (2°C) above pre-industrial  
139 levels has been criticized as an already elusive target. In addition to that, approximately 900 MW  
140 of coal-fired power generation units planned to be installed in China every week in 2010 [30].  
141 Considering the average lifespan of Chinese coal-fired power plants of around 40 years, the  
142 targets of IEA's "450 scenario" will not be attainable without aggressive government policies on  
143 carbon emission restrictions and extensive investments in alternative energy technologies. Also,  
144 thermal power generation technologies, such as coal-fired plants, require large volumes of  
145 freshwater which has significant implications on local water resources. However, these problems  
146 are often overlooked in the Chinese national energy plans [31]. Without assessing the life-cycle  
147 impacts, it makes the net carbon effects uncertain, in particular the unintended consequences on  
148 water consumption of each energy production technology.

### 149 **3. Materials and Methods**

150 LCA is one of the most widely used methods for quantifying the environmental impacts of a  
151 given product throughout its entire life cycle [32, 33]. There are three methodological variants of  
152 LCA: Process Life Cycle Analysis (PLCA), Input-Output based Life Cycle Analysis (IO-LCA)  
153 analysis and hybrid LCA. PLCA has often been employed to establish the indirect environmental  
154 impacts associated with production processes. However, this method can lead to significant  
155 truncation errors in the calculations due to an artificial cut-off when defining the system  
156 boundaries [34, 35]. The limitation of PLCA has led to the use of a combined IO and LCA  
157 analysis. Whereas LCA is a bottom-up approach based on individual processes, input-output  
158 analysis is a top-down approach, which represents monetary flows between sectors and is able to  
159 capture environmental flows between economic sectors by transforming monetary flows to

160 physical flows [33, 35]. The advantage of IO-LCA is the completeness of system boundaries  
161 since the entire economic activities of a nation state or the global economy are represented.  
162 However, the shortcomings of this method include aggregation and allocation errors [32, 33, 35,  
163 36]. Combining the strengths of PLCA and IO-LCA, hybrid analysis methods for LCA have  
164 successfully been applied in numerous studies [37-39]. In this study, we applied the integrated  
165 hybrid LCA developed by Suh and Huppes [33], which integrate process-based LCA and the IO-  
166 LCA methods.

### 167 3.1 Process-based LCA

168 An initial approach to completing a LCA is a process-based LCA method. Process-based LCA  
169 calculates the amount of commodities required to produce a certain functional unit (1 kWh  
170 electricity in this study). Life Cycle Inventory (LCI) is the data collection phase of an LCA,  
171 involving the compilation and quantification of inputs and outputs for a given product system  
172 throughout its life cycle [40]. Heijungs [41] first introduced the matrix inversion method to LCI  
173 computation [33]. In Heijungs's study, an inventory problem is solved by a system of linear  
174 equations, which can be denoted by a  $m \times n$  matrix with  $m$  commodities and  $n$  processes. We  
175 define  $A_{cp} = a_{ij}$  as LCA technology matrix, which shows inflows (recorded as negative values)  
176 and outflows (recorded as positive values) of commodity  $i$  of process  $j$  for a certain duration of  
177 process operation [42]. The assumption is that processes at stake are being operated under a  
178 steady-state condition, which means the selection of a specific temporal window for each process  
179 does not change their efficiency [33]. For convenience, a column vector  $S$  is used as scaling  
180 factor [42], which indicates the required factor of scaling each process to produce the required  
181 net output of the system. Therefore, commodity net output of the systems  $f_p$  is given by

$$182 \quad \mathbf{A}_{cp} * \mathbf{S} = \mathbf{f}_p \quad (1)$$

183 Equation (1) shows that the amount of a commodity delivered to a consumer outside the system  
184 is equal to the amount of commodities produced minus the amount used within the system.  
185 Therefore, the Equation (1) can be re-arranged to calculate the scaling factor (supplementary  
186 Equation 2)

187 
$$\mathbf{S} = \mathbf{A}_{cp}^{-1} * \mathbf{f}_p \quad (2)$$

188 To calculate the emissions and water consumption, we define a vector  $E_p = e_j$  which contains  
189 element  $e_j$  that shows CO<sub>2</sub> emissions or water consumption incurred by process  $j$  during the  
190 operation that  $a_j$  is specified for, where  $a_j$  is a vector of inputs and output by process  $j$ . The total  
191 direct and indirect carbon emissions and water consumption required by the system to deliver a  
192 commodity is calculated by

193 
$$\mathbf{G}_p = \mathbf{E}_p * \mathbf{A}_{cp}^{-1} * \mathbf{f}_p \quad (3)$$

194 Where  $G_p$  is a vector of the total direct and indirect carbon emissions, and  $f_p$  is a vector that is  
195 defined as the functional unit of the system.

### 196 3.2 IO-based LCA

197 All the processes in an economy are directly or indirectly linked with each other. However,  
198 process-based LCA is always truncated to a certain degree as the system boundary is not  
199 complete and where the upstream emissions are not captured. Thus, to deal with this system  
200 boundary problem, many researchers have used IOA to conduct LCAs, as IOA has the advantage  
201 of depicting the entire national economy including all processes (at an aggregate level) [43-46].

202 IOA originally developed by Leontief describes how sectors are inter-related through producing  
203 and consuming intermediate economic outputs that are represented by monetary transaction  
204 flows between economic sectors, which can be transformed to physical flows such as carbon  
205 emissions under the assumption that all outputs of a sector are produced with the same physical  
206 flow intensity [47]. In an input-output (IO) model, it is assumed that each industry consumes  
207 outputs of various other industries in fixed ratios in order to produce its own unique and distinct  
208 output [33, 47].

209 Based on this assumption, we define a  $n \times n$  matrix,  $A_{ss}$ , of which each column of  $A_{ss}$  shows  
210 domestic and imported intermediate economic outputs in monetary values which are required to  
211 produce one unit of monetary output of another sector;  $s$  represents economic sector. We define  $x$   
212 as the total economic output where  $x$  is equal to the summation of the economic outputs

213 consumed by intermediate economic sectors final consumers (e.g. household, government,  
214 capital investment and export). For the economy as a whole, the IO model can be shown by

$$215 \quad \mathbf{x} = \mathbf{A}_{ss} * \mathbf{x} + \mathbf{f}_{IO} \quad (4)$$

216 where  $f_{IO}$  denotes final demand. The total economic output  $x$  required to satisfy final demand is  
217 calculated by

$$218 \quad \mathbf{x} = (\mathbf{I} - \mathbf{A}_{ss})^{-1} \mathbf{f}_{IO} \quad (5)$$

219 where  $I$  denotes the  $n \times n$  identity matrix.

220 The total direct and indirect emissions by domestic and import sectors to deliver a certain  
221 amount of economic output can be calculated by the environmentally extended input-output  
222 (EIO) model which assumes that the amount of emissions generated by a sector are proportional  
223 to the amount of output of the sector, thus the emissions per unit of sectoral output are fixed.  $E_{IO}$ ,  
224 is defined as a vector which shows the amount of CO<sub>2</sub> emissions or water consumption incurred  
225 to produce one monetary unit output of each economic sector. Therefore, the total direct and  
226 indirect emissions and water consumption are calculated by

$$227 \quad \mathbf{G}_{IO} = \mathbf{E}_{IO} * (\mathbf{I} - \mathbf{A}_{ss})^{-1} * \mathbf{f}_{IO} \quad (6)$$

228 where  $G_{IO}$  is the total domestic direct and indirect CO<sub>2</sub> emissions and water consumption, and  $f_{IO}$   
229 is a vector that shows the net economic outputs of the system.

### 230 3.3 Integrated Hybrid LCA

231 In process-based life-cycle approaches, a boundary is drawn around the main inputs and their  
232 production processes. Integrating the bottom-up process analysis into a top-down IOA accounts  
233 for interactions between the energy sector(s) and the rest of the economy more comprehensively  
234 [38, 39]. The environmental impacts of a unit production of electricity include all impacts along  
235 the entire supply chain such as impacts from extraction of materials, transportation,  
236 manufacturing, construction, installation, operation and maintenance, distribution and

237 transformation, and dismantling and disposal. In this study, we construct an integrated hybrid  
 238 analysis framework to calculate the embodied CO<sub>2</sub> emissions and water consumption for eight  
 239 electricity generation technologies in China. In this framework, the IO table is interconnected  
 240 with the matrix representation of the physical production system at upstream and downstream  
 241 cut-offs.

242 The general formula of the integrated hybrid model is depicted in Equation (7).

$$243 \quad \mathbf{G}_{HL} = \begin{bmatrix} \widehat{\mathbf{E}}_p & \mathbf{0} \\ \mathbf{0} & \widehat{\mathbf{E}}_{IO} \end{bmatrix} \begin{bmatrix} \mathbf{A}_p & -\mathbf{C}_d \\ -\mathbf{C}_u & \mathbf{I} - \mathbf{A}_{IO} \end{bmatrix}^{-1} \begin{bmatrix} \mathbf{f}_p \\ \mathbf{0} \end{bmatrix} \quad (7)$$

244 Where  $G_{HL}$  denotes total life-cycle emissions;  $E_p$  denotes a diagonal of environmental vector of  
 245 processes;  $E_{IO}$  is a diagonal environmental vector of input-output sectors;  $A_p$  refers to the full  
 246 process matrix with 3,931 products by 3,931 processes;  $A_{IO}$  is a matrix of technical coefficients  
 247 of the latest Chinese input-output table in 2007; Matrix  $C_u$  denotes upstream cut-off flows to the  
 248 LCA system, linked with the relevant economic sector in IO table, and matrix  $C_d$  represents  
 249 downstream cut-off flows to the IO system from the LCA system and under certain assumptions,  
 250  $C_d$  can be set to zero [48];  $f_p$  is functional unit in kWh. Each element of  $C_u$  has a unit of monetary  
 251 value per functional unit and each element of  $C_d$  is in a unit of physical unit per monetary value.  
 252 The integrated hybrid LCA can model the full interactions between individual processes and  
 253 industries in a coherent way.

### 254 3.4 Water Stress Index

255 Water is a regional issue. There is a well-known regional disparity of water resources in China:  
 256 the water abundant South vs. water scarce North. In this study, we use a water stress index (WSI)  
 257 to identify water scarcity at provincial level. WSI is commonly defined as the ratio of total

258 annual freshwater withdrawal to hydrological availability[49]. Pfister *et al.* (2009) advanced the  
259 water stress concept to calculate a WSI, ranging from 0 (no stress) to 1 (maximum stress) (see  
260 Pfister *et al.* (2009) [50] for the detailed descriptions of the index). The WSI is used in a number  
261 of water studies [51, 52] following the draft ISO 14046 standard [53]. Other indicators for  
262 assessing water scarcity do exist [54], but they have lower spatial resolution. In this study, we  
263 applied Pfister *et al.*'s method to calculate WSI for each province in China. The WSI was  
264 initially obtained at 10 km grid cell and we computed the provincial WSI from the average value  
265 of the grids within the provincial boundary.

## 266 3.5 Data

### 267 3.5.1 Process data

268 The 2009 Ecoinvent database version 2.1 was used to construct the process analysis LCI  
269 (<http://www.ecoinvent.org>). The Ecoinvent database contains LCI data of about 4000 processes,  
270 products and services. The process matrix contains 3,931 processes and 3,945 products. In the  
271 2009 database, 14 products that had no correspondence with any process were removed from the  
272 original matrix to derive a 3,931 by 3,931 dimensional process matrix. The process matrix is  
273 referred to as  $A_p$  in Equation 1. This database includes China's electricity generation data for  
274 coal, nuclear and biomass. The calculation of power generated from coal was based on two  
275 reference plants with 100 MW and 500 MW, which have a share of 10% and 90%, respectively.  
276 Power from nuclear was based on a nuclear power plant with a 1,000 MW pressure water  
277 reactor. Energy from biomass was based on a co-generation unit with a capacity of 6400 kW and  
278 by burning sweet sorghum stems. In terms of wind power, 6,469 wind turbines were installed in  
279 China by the end of 2007, with the total generation capacity of 5.9 GW and an average wind

280 turbine size of 912 kW [55]. Therefore, a similar size of wind turbines with 800 kW is chosen  
281 given that onshore wind farms are seen as having the largest potential in China. In addition, there  
282 is no process data for electricity generation from oil, natural gas, hydro, and photovoltaic power  
283 plants. In this study, we use the best available LCA data in Ecoinvent to represent electricity  
284 generation technologies in China. For natural gas, there are two sizes of power plants in the  
285 Ecoinvent database, 100 MW and 300 MW, respectively. In this study, we select the 300 MW  
286 natural gas power plants, because the recently installed natural gas power plants were relatively  
287 large (more than 1000 MW). There is only one oil power plant (550 MW) in Ecoinvent database  
288 [56], which is selected in this study. For hydro power electricity, there is only a mix of run-of-  
289 river power plants in Europe available in the database. Electricity from solar photovoltaic (PV)  
290 power plant is 3 kW based on electricity production with grid-connected PV power plants  
291 mounted on buildings with slanted roof in Switzerland.

### 292 *3.5.2 IO data*

293 The National 2007 IO table for China is used in this study. The IO table was collected from the  
294 National Statistical Bureau of China [57]. The Chinese IO table for 2007 contains 135 economic  
295 sectors, is the latest IO table published by the Chinese government.

### 296 *3.5.3 Upstream requirement matrix*

297 The upstream requirement matrix refers to  $C_u$  matrix in Equation 1. To construct this matrix, we  
298 followed the procedure described in Wiedmann et al. [38] with China-specific data: First, we  
299 create a concordance matrix between Ecoinvent processes and IO sectors. The concordance  
300 matrix was set up with 135 rows representing all sectors in the IO table and 3,931 columns  
301 representing processes in the process matrix. Matching processes and sectors are indicated by

302 ones in the matrix; otherwise, cells are marked as zeros. Second, we established unit prices for  
303 Ecoinvent processes. The unit prices of products were assigned based on China Price Yearbook.  
304 Third, we created a technical coefficient matrix matching the process matrix. We used the  
305 concordance matrix to populate columns of the designated upstream requirement matrix  $C_u$  with  
306 technical coefficients from the national IO table. Technical coefficients  $a_{ij}$  from the IO table were  
307 placed into cell  $a_{ik}$  of the matrix where  $i$  is an economic sector and  $j$  is the economic sectors  
308 matching product/process  $k$ . Fourth, we multiplied columns of the matrix from step 3 by the unit  
309 price  $p_k$  of the corresponding Ecoinvent products to yield price-weighted coefficients. Fifth,  
310 those upstream inputs in matrix  $C_u$  were removed to avoid double-counting. It is due to the fact  
311 that they have already been included in the process matrix.

#### 312 *3.5.4 Environmental data*

313 The Ecoinvent database contains environmental data, such as CO<sub>2</sub> emission and water  
314 consumption, for Ecoinvent processes [57]. We directly adopted the CO<sub>2</sub> emission data from the  
315 Ecoinvent database for our calculation. However, the water data in the Ecoinvent database refers  
316 to water withdrawal data and there is no water consumption data. According to China  
317 Environmental Yearbook 2007 [58], we adopted the assumption of a 30% conversion rate from  
318 water withdrawal to water consumption for all industrial processes. Direct water consumption  
319 per kWh for hydropower plants based on evaporation is determined based on US Department of  
320 Energy (2006) [59] due to lack of the data in China.. CO<sub>2</sub> emission intensities for input-output  
321 sectors were calculated by dividing the sectoral emissions by sectoral economic output. Sectoral  
322 CO<sub>2</sub> emissions were calculated from combustion of fuels and industrial processes using the  
323 Intergovernmental Panel on Climate Change (IPCC) reference approach [60]. Fossil fuels



324 combustion data at sectoral level were collected from China Energy Statistical Yearbook 2008.  
325 Sectoral water withdrawal data were collected from China Economic Census Yearbook 2008.

### 326 3.6 Data uncertainty

327 There are data uncertainties that need to be mentioned in this study. First, the IO table used in  
328 this study is in 135x135 sectors. Despite this great level of detail, there are still many dissimilar  
329 commodities aggregated into the same category and assumed identical with regards to production  
330 inputs. However, it provides a comprehensive framework and complete system boundaries to  
331 capture the upstream emissions and water consumption. The IO table used in this study is the  
332 most recent and detailed at present. Second, the LCA data for electricity generation from the  
333 Ecoinvent database are based on the power plant constructed in the past, which might not reflect  
334 current technology, in terms of size and efficiency. However, it is the best data available. Third,  
335 the Ecoinvent database only contains LCA data of electricity generation from coal, nuclear and  
336 biomass power for China. Therefore, we use the LCA data available from Ecoinvent for other  
337 countries to represent electricity generation technologies of natural gas, oil, wind, hydro, and  
338 solar in China. This may lead to an increase in uncertainty. To best present Chinese technology,  
339 electricity inputs for all production process in the process matrix was replaced by the Chinese  
340 electricity production mix due to the fact that electricity is the essential input to the production of  
341 most goods and is crucial in term of both CO<sub>2</sub> emissions and water consumption. Therefore, all  
342 the electricity consumed in the processes reflects electricity generation in China.

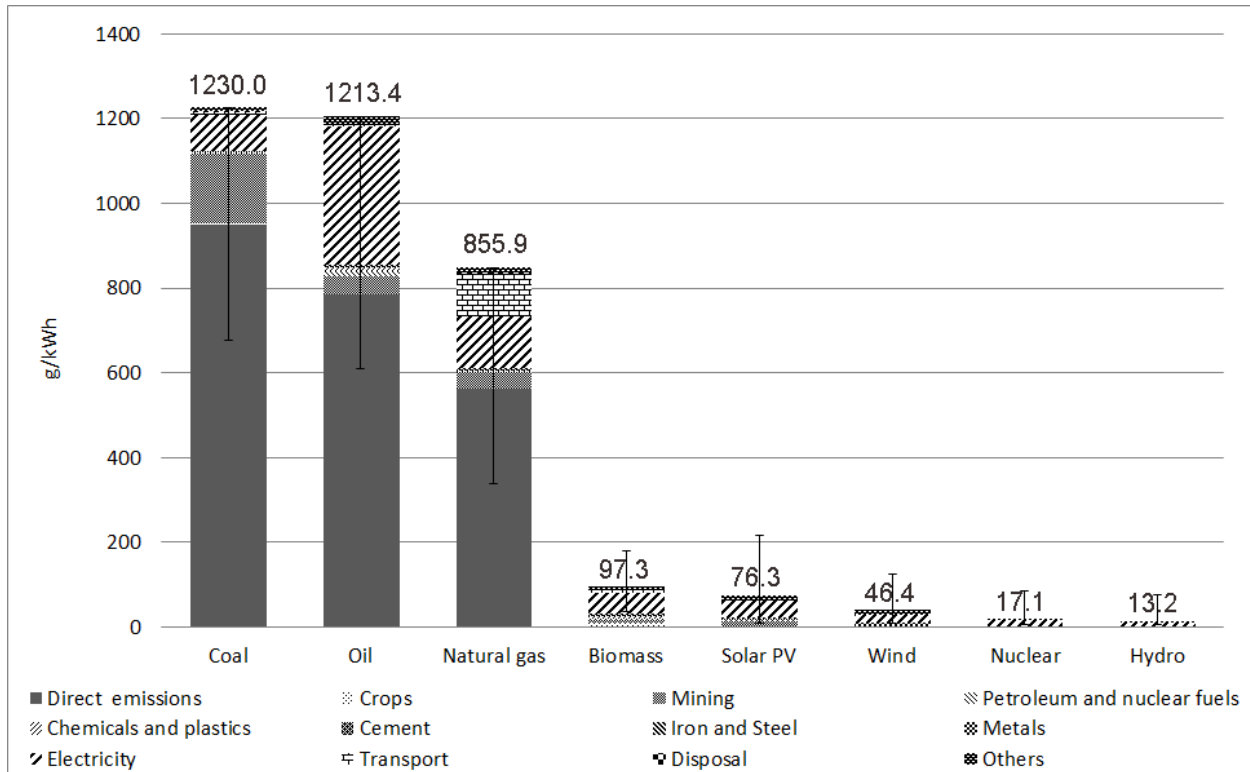
343 To assess the uncertainty range of the results from this study, we collected the life-cycle CO<sub>2</sub>  
344 emissions and water consumption for different electricity generation technologies from various

345 studies in the literature. Based on this, we created error bars on the top of our results to show the  
346 differences between our findings and other studies in the literature.

## 347 **4. Results**

### 348 4.1 Total Life-cycle CO<sub>2</sub> Emissions

349 Life-cycle CO<sub>2</sub> emissions of electricity produced by different energy generation technologies,  
350 which are ranked in high-to-low order, are presented in Figure 2. In addition, an error bar for  
351 each generation technology is shown in the figure based on the results from previous studies .  
352 Our results show that the total life-cycle CO<sub>2</sub> emissions from fossil fuel based electricity  
353 production are significantly higher than the total life-cycle CO<sub>2</sub> emissions from renewable  
354 energy, particularly due to the lower emissions during the operation of the power plant (shown as  
355 direct emissions). Electricity generated from (pulverized) coal produces the highest amount of  
356 CO<sub>2</sub> emissions per kWh (1,230.0 grams per kilowatt-hour (g/kWh), followed by oil based  
357 electricity generation (1,213.4 g/kWh) and natural gas (855.9 g/kWh, which is about 30% lower  
358 than the emissions from coal and oil). Switching electricity generation from fossil fuels to  
359 renewable energy sources could reduce the total life-cycle CO<sub>2</sub> emissions by more than 79% in  
360 emissions per kWh. For instance, emissions from electricity produced by hydro power, wind,  
361 solar PV and biomass are within a range of 13.2 g/kWh to 97.3 g/kWh. Hydro (13.2 g/kWh) has  
362 the lowest total emissions while nuclear power takes second lowest place (17.1 g/kWh).



363

364 **Figure 2.** The total life-cycle CO<sub>2</sub> emission of eight electricity generation technologies in China  
 365 from 2000 – 2010 (in g/kWh). Note: 1 kWh is used as the functional unit to compare different  
 366 electricity generation technologies. Note: the error bars are based on the results from the  
 367 literature; for example, coal [61-67], oil [64, 68-70], natural gas [8, 66, 71], biomass [63, 72-75],  
 368 solar PV [64, 76-87], wind [38, 43, 44, 64, 67, 88-98], nuclear [67, 98-106] , and hydro [64, 107-  
 369 111] ( A full list of the literature used in this study can be found in appendices)  
 370

371 Sources of emissions vary substantially across different types of energy production technologies.

372 For coal-based electricity production, about 78% of emissions have resulted from coal  
 373 combustion while indirect emissions are caused by fuel combustion in mining and electricity  
 374 generation for own consumption, which account for 13% and 7% of total emissions, respectively.

375 For oil based electricity production, the share of the direct life-cycle emissions during the  
 376 electricity production processes is about 65%, which is lower than coal based power generation.

377 Among the eight electricity generation technologies, electricity generated by natural gas has a  
 378 relatively large share (12% of total emissions) of transport-related emissions due to large

379 volumes of natural gas burned in compressor stations which help the transport of natural gas  
380 from extraction sites to power plants. Non-fossil fuel based electricity technologies have much  
381 lower total carbon emissions and even their indirect emissions from upstream processes are  
382 much lower. The higher indirect emissions of fossil fuel based electricity generation are mainly  
383 due to the large emissions from mining and the demand of electricity during mining and  
384 operation of the power plant. However, non-fossil fuel based technologies require less inputs for  
385 mining and operation, thus tend to have lower indirect emissions as well. For non-fossil fuel  
386 based technologies, upstream processes play a major role in contributing to the total life-cycle  
387 CO<sub>2</sub> emissions. For instance, in the case of wind power generated electricity, electricity  
388 consumption during upstream production processes contributes 43% of the total life-cycle CO<sub>2</sub>  
389 emissions, while steel, cement, and chemicals and plastics contribute 12%, 5%, and 3%,  
390 respectively. In the case of hydropower, cement contributes 24% of total life-cycle CO<sub>2</sub>  
391 emissions.

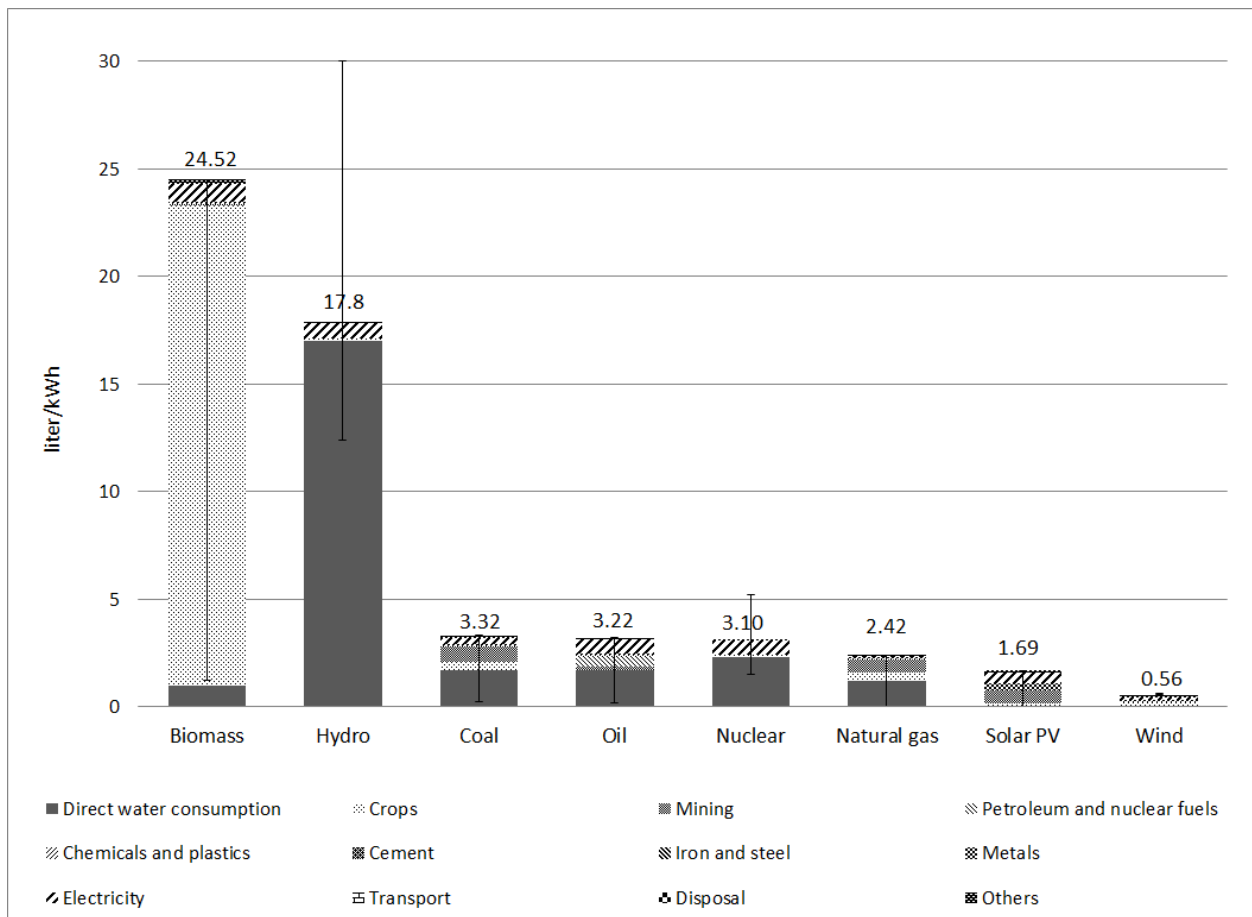
392 In this study, CO<sub>2</sub> emissions per kWh for fossil fuel based electricity generation technologies  
393 such as coal, oil, and natural gas are higher than the results from other studies (See error bars in  
394 Figure 2). Three factors may explain these differences: First, most LCA studies for fossil fuel  
395 based power generation use the process-based LCA approach [e.g. 61, 62, 63-66, 68, 71], which  
396 mainly captures direct emissions during the production processes and some emissions from  
397 upstream production depending on the system boundary. For example, in Odeh's study on LCA  
398 of UK's coal fired power plants, direct emissions from coal combustion accounted for 89% of  
399 the total life-cycle CO<sub>2</sub> emissions compared with 78% in this study..The main reason is that our  
400 study uses a hybrid LCA with a more complete system boundary (i.e. the entire national supply  
401 chains) capturing both emissions from power plant operations and upstream production (See Suh

402 and Huppés (2005) [33] and Wiedmann (2011) [38] for details). In fact, the direct emissions  
403 from fossil fuel based technologies in this study are fairly close to the emissions presented in the  
404 literature based on process-based LCA as shown in Figure 2, such as coal (950 g/kWh vs. 902  
405 g/kWh in average), oil (790 g/kWh vs. 772 g/kWh), and natural gas (560 g/kWh vs. 450g/kWh).  
406 Therefore, the differences are mainly due to the indirect emissions. Second, a high percentage of  
407 fossil fuels in China's fuel mix lead to a large amount of indirect emissions caused upstream.  
408 This is also reflected in the results from this study that indirect emissions account for more than  
409 20% of the total life-cycle emissions for fossil fuel based generation technologies, mainly from  
410 electricity input, transportation, mining, iron and steel. However, other studies focused on the  
411 UK [8, 112], US [62, 63], Japan [64], and other countries[65, 66], are with better fuel mix and  
412 thus lower upstream CO<sub>2</sub> emissions. Third, most LCA studies in the literature focused on  
413 developed countries which may have much higher energy efficiency in their electricity  
414 generation sector. Thus, their CO<sub>2</sub> emissions per unit of electricity are lower than China's.

#### 415 4.2 Total Life-cycle Water Consumption

416 Electricity generation requires huge amounts of water, which can put substantial pressures on  
417 water resources and ecosystems, and is particularly important in water scarce regions such as  
418 North China. Figure 3 depicts the total life-cycle water requirements for the eight electricity  
419 generation technologies. Total life-cycle water consumption is referred to as the net amount of  
420 water (i.e. water withdrawal minus water discharge) consumed along the supply chain to produce  
421 1 kWh of electricity. The findings show that biomass power generation ranks first (24.52  
422 liter/kWh); and crop production accounts for 95% of its total water consumption. Hydropower  
423 ranks second (17.8 liter/kWh) in terms of total life-cycle water requirements; water evaporation  
424 in reservoirs accounts for most of its water consumption. Thermoelectric production technologies

425 such as coal, oil, natural gas and nuclear are at a similar range, with total life-cycle water  
 426 requirements between 2.42 liter/kWh and 3.32 liter/kWh, of the total. While electricity from  
 427 solar PV generation requires about half the water (1.69 liter/kWh) per unit of electricity output  
 428 compared with thermoelectric energy production; wind power consumes the least amount of  
 429 water (0.56 liter/kWh) among all investigated electricity generation technologies.



430

431 **Figure 3.** Total life-cycle water requirements for the eight major electricity generation  
 432 technologies in China (in liter/kWh). Note: the error bars are based on the results from the  
 433 literature: .for thermal electric [113, 114], coal [115, 116], natural gas [115, 116], solar PV [59],  
 434 and wind [44]. (A full list of the literature used in this study can be found in appendices)

435 Figure 3 also shows that in thermoelectric-based energy generation technologies (e.g. coal, oil,  
 436 natural gas and nuclear power), direct water consumption attributes 50% to 74% of the total life-  
 437 cycle water requirements. For solar PV and wind power, electricity production requires most

438 water for supporting upstream processes. For example, mining, electricity, and metals accounts  
439 for 35%, 31%, and 17% of life-cycle water consumption, respectively, for solar PV, and wind  
440 powered electricity requires water from agriculture (40%), electricity (21%) and metals (5%).

441 Figure 3 shows that the uncertainties of LCA water consumption are extremely large for biomass  
442 due to differing climatic conditions and fossil fuels, . mainly due to differences in cooling  
443 technologies. For example, power plants with air cooling systems may potentially require up to  
444 50% less total life-cycle water inputs compared to once-through and recirculating systems [59].  
445 However, air cooling systems are still not commonly used in China. Although air cooling may  
446 significantly reduce direct water consumption for thermal power plants, their indirect water  
447 consumption for inputs such as mining and coal washing, is still significantly larger than for  
448 wind electricity. For example, the indirect water consumption of electricity from coal is 1.6  
449 liter/kWh, which is almost three times the total life-cycle water consumption from wind power.  
450 There are also large differences in total water consumption of electricity from biomass between  
451 this study and studies in literature. This is mainly due to the systems boundary cut-off, as other  
452 studies only took direct water consumption into account while indirect water consumption, such  
453 as water consumption in agricultural production, was neglected. For wind power, our calculation  
454 is slightly lower than the finding from Li *et al.* (2012) [44], which may be due to using different  
455 methods. Li *et al.* (2012) applied an IO-based LCA, while this study used an integrated hybrid  
456 LCA approach.

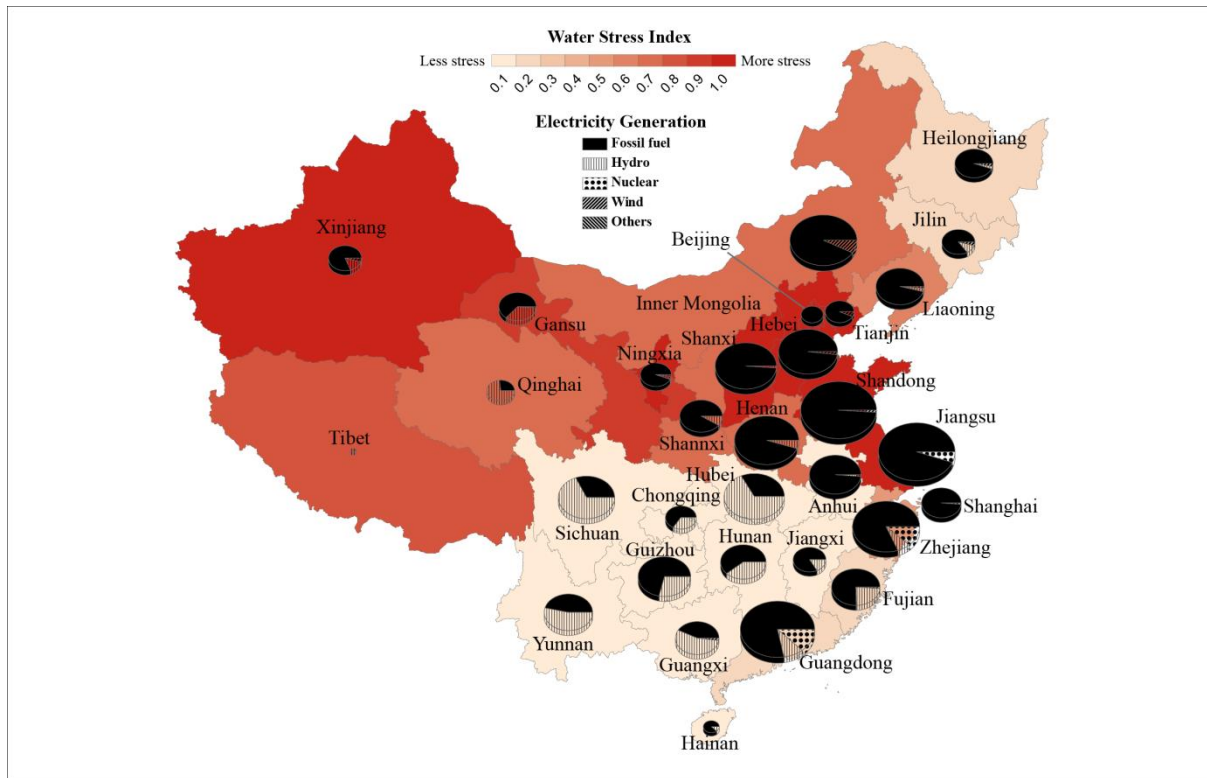
## 457 **5. Discussion**

458 Coal is by far the dominant energy source in China's electricity fuel mix because of its low costs.  
459 On the other hand, among all energy generation technologies, coal-fired electricity not only

460 ranks highest for total life-cycle CO<sub>2</sub> emissions with 1230 g/kWh, but also requires 3.32 liters of  
461 water during the entire life-cycle to generate 1 kWh of electricity potentially exerting  
462 considerable pressure on water resources particularly in water scarce areas of China.

463 Figure 4 shows China's regional fuel mix in electricity generation and WSI. Fossil fuel based  
464 electricity (i.e. to 97% based on coal) accounts for more than 90% of the power supply in most  
465 regions of North China where water is also of limited supply. Additionally, for coal-fired  
466 electricity generation, direct water consumption ranks the highest and accounts for 52% of its  
467 total life-cycle water consumption, making it a significant stressor on local water resources in  
468 addition to agricultural water consumption; its effects are particularly important to highly water  
469 stressed areas such as Inner Mongolia and Shanxi, with electricity mainly generated by coal-fired  
470 plants. A significant share (more than 35%) of total electricity generation gets exported to  
471 surrounding regions, such as Beijing, Hebei, and Liaoning. Hence, reducing coal-fired electricity  
472 generation or switching to air cooling system can mitigate water stress in these electricity  
473 exporting regions.





474

475 **Figure 4.** China’s regional electricity fuel mix and degree of water stress in 2010. The size of  
 476 the pie chart reflects the amount of electricity production. Background colors of the map show  
 477 WSI ranging from severe water stress regions in red color to less water stress in pink color.

478 This study shows that wind power electricity generation can potentially save more than 79% life-  
 479 cycle CO<sub>2</sub> emissions and potentially consume up to 83% less water than fossil-fuel based  
 480 electricity such as coal. Despite very high uncertainties of water consumption of thermal power  
 481 plants due to differences in cooling technologies, one can conclude that it is particularly  
 482 important to water stressed areas in China such as North China to reap the dual benefits of lower  
 483 carbon emissions and water consumption by switching from traditional, fossil-fuel based to  
 484 renewable electricity generation. There is ample potential for producing renewables in many  
 485 parts of china. For example, a report by the Global Wind Energy Council (GWEC) [117]  
 486 concluded that the technically exploitable capacity of wind energy is around 600 – 1,000  
 487 gigawatts on land in China, which is enough to allow wind playing a major part in China’s future  
 488 energy mix. These wind resources are largely available in northern China where water is scarce.

489 Thus, there is a huge potential for the northern provinces such as Inner Mongolia, Ningxia,  
490 Shanxi, Hebei, Gansu, and Xinjiang to develop wind power. Based on China's wind power  
491 development plans [118], our calculations show that by 2020 Inner Mongolia could potentially  
492 save annually up to 179 MT CO<sub>2</sub> (i.e. 44% of Inner Mongolia's total CO<sub>2</sub> emissions in 2008) and  
493 418 million m<sup>3</sup> (Mm<sup>3</sup>) water (18% of its industrial water use) for water and carbon savings in  
494 other provinces).

495 As shown in our findings, solar PV is another technology that has the potential for significantly  
496 reduced total life-cycle CO<sub>2</sub> emissions per unit of electricity production. Nonetheless, solar PV  
497 does not have the same advantage as wind power to reduce water consumption. Also, there are  
498 many other issues that need to be addressed before solar PV can play a major role in China's  
499 future electricity fuel mix. These issues include a shortage of the supply of silicon material,  
500 rising cost of raw materials, low efficiency and environmental issues such as pollution (i.e.  
501 acidic and alkaline waste water and heavy metal waste residues) [119].

502 Carbon capture and storage (CCS) has been a very prominent subject in the climate debate over  
503 the last few years[120]. Odeh and Cockerill (2008) showed that pulverized coal with CCS could  
504 lead to a 72% of CO<sub>2</sub> emission reduction [8]. However, it is an energy intensive process which  
505 may reduce the overall efficiency of the power plant [8]. Furthermore, there are issues of  
506 financing adequate transport infrastructure and permanent storage [121]. Although CCS can help  
507 to reduce CO<sub>2</sub> emissions, it consumes more water per kWh electricity due to the decline in  
508 efficiency of the power plant CCS causes. Therefore, it is vital to take water consumption and  
509 other factors into account when developing CCS.

510 As shown in Figure 4, hydro power plays a significant role in electricity production in the south  
511 and south-west of China because of abundant water resources in these regions. For example,  
512 hydro power electricity contributes more than half to total electricity production in Hubei,  
513 Yunnan, and Sichuan. There are a number of environmental issues associated with hydropower  
514 plants [122, 123], as well as social issues [124], which could further be exacerbated through  
515 extensive large-scale projects. Many studies emphasized that “small” hydropower is a source of  
516 clean energy with little or no adverse environmental impacts [125, 126]. However, an extensive  
517 use of this technology may lead to higher environmental degradation than that caused by large  
518 hydropower [127].

519 Nuclear power has also much lower CO<sub>2</sub> emissions per kWh than fossil-fuel based energy  
520 generation technologies. However, nuclear power plants generally require large water inputs for  
521 cooling processes, which is reflected in their site locations such as the coastal regions  
522 Guangdong and Zhejiang and to a lesser extent in Jiangsu (see Figure 4). Therefore, the  
523 development of nuclear energy in China is not sustainable in terms of water consumption,  
524 particularly if a large number of nuclear power plants are deployed in inland or North China.  
525 Moreover, disposal and storage of nuclear waste and potential hazards have been criticized for  
526 decades [128]. With less than 1% of the global uranium reserves located in China[129], the over-  
527 dependence on nuclear power would compromise national energy security, which is inconsistent  
528 with the principle of safeguarding energy security stated in China’s Mid-Long Term  
529 Development Plan for Nuclear Power[21].

530 Failure to incorporate both water and climate implications of energy policies can potentially lead  
531 to serious and unexpected side effects such as water scarcity. Increasing the share of renewable  
532 energy in China’s electricity fuel mix could not only curb CO<sub>2</sub> emissions, but also reduce the

533 pressure on the local environment especially in already water scarce regions. Therefore, water  
534 availability should play a much larger role in China's energy plan than it currently does. Even if  
535 non-coal energy generation technology were significantly more expensive than coal-based  
536 technology, renewables might be more cost-effective when considering lower impacts on local  
537 water resources, in particular in water scarce areas such as in north and north-east China.

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831

## 832 **Appendices**

833 **Table A1:** Coal, Oil and Natural Gas. Life-cycle emissions of electricity from coal are between  
834 676 g-CO<sub>2</sub>-e/kWh and 1042 g-CO<sub>2</sub>-e/kWh with an average of 902 g-CO<sub>2</sub>-e/kWh across the

835 world. Natural gas combined cycle (NGCC) power plants cause an average of 450 g-CO<sub>2</sub>-e/kWh  
 836 across the world in the range of 337 to 499 g-CO<sub>2</sub>-e/kWh. The world average of life-cycle  
 837 emissions for electricity generation from oil is about 772 g-CO<sub>2</sub>-e/kWh in the range of 608 and  
 838 932.

| Power plant                                  | Location    | Study | Gross output<br>MW | Capacity<br>factor | Life time | g-CO <sub>2</sub> /kWh |
|--|-------------|-------|--------------------|--------------------|-----------|------------------------|
| Coal   | US          | [62]  | 360                | 60                 | 30        | 1042                   |
| Coal   | US          | [63]  | 600                | -                  | -         | 847                    |
| Coal   | US          | [67]  | 1000               | 75%                | 40        | 974                    |
| Coal   | Japan       | [64]  | 1000               | 70%                | 30        | 975.2                  |
| Coal   | Germany     | [66]  | 700                | -                  | -         | 676                    |
| Coal   | UK          | [61]  | 660                | -                  | 30        | 990                    |
| Coal   | UK          | [8]   | 453                | 75%                | -         | 879                    |
| Coal   | Netherlands | [65]  | 600                | -                  | 30        | 837                    |
| Oil  | Japan       | [70]  | 1000               | -                  | -         | 755.7                  |
| Oil – existing<br>peak load power<br>station | UK          | [68]  | 527.9              | -                  | -         | 823                    |
| Oil - Combined<br>cycle base load<br>plant   | UK          | [68]  | 527.9              | -                  | -         | 608                    |
| Oil  | Singapore   | [69]  | 250                | 70%                | 25        | 932                    |
| Oil  | Japan       | [64]  | 1000               | 70%                | 30        | 742.1                  |
| NGCC   | US          | [80]  | 620                | -                  | -         | 466                    |
| NGCC   | US          | [63]  | 600                | -                  | -         | 499                    |
| NGCC   | Germany     | [66]  | 700                | -                  | -         | 337                    |
| NGCC   | UK          | [8]   | 500                | 75%                | 30        | 488                    |
| NGCC   | Norway      | [71]  | 400                | -                  | 25        | 459                    |

839 Note: IGCC = coal-based integrated gasification combined cycle; NGCC = natural gas combined cycle.

840

841 **Table A2:** Nuclear. The average life-cycle emissions for LWR, PWR and BWR are 28.35 g-  
 842 CO<sub>2</sub>/kWh, 16.69 g-CO<sub>2</sub>/kWh and 19.39 g-CO<sub>2</sub>/kWh, respectively.

| Power plant | Location | Study | Gross output<br>MW | Load factor | Life<br>time | g-CO <sub>2</sub> /kWh |
|-------------|----------|-------|--------------------|-------------|--------------|------------------------|
| PWR         | Japan    | [106] | 1000               | -           | 30           | 34                     |
| LWR         | Germany  | [104] | 1300               | 77.6        | 20           | 5                      |
| LWR         | Germany  | [104] | 1300               | 77.6        | 20           | 21                     |
| LWR         | Germany  | [104] | 1300               | 77.6        | 20           | 28                     |
| LWR         | Germany  | [104] | 1300               | 77.6        | 20           | 84                     |
| BWR         | Japan    | [103] | 1000               | 70          | 30           | 21.6                   |
| BWR         | Japan    | [103] | 1000               | 70          | 30           | 26.4                   |

|     |             |       |      |      |    |       |
|-----|-------------|-------|------|------|----|-------|
| BWR | Japan       | [103] | 1000 | 70   | 30 | 37    |
| PWR | Japan       | [103] | 1000 | 70   | 30 | 24.7  |
| PWR | Japan       | [103] | 1000 | 70   | 30 | 31.4  |
| PWR | Belgium     | [98]  | 1000 | 86.8 | 40 | 1.8   |
| PWR | Belgium     | [98]  | 1000 | 86.8 | 40 | 4     |
| PWR | US          | [67]  | 1000 | 75   | 40 | 15    |
| LWR | Switzerland | [105] | 1000 | 70   | 40 | 8.88  |
| LWR | Switzerland | [105] | 1000 | 70   | 40 | 8.92  |
| BWR | Japan       | [105] | 1000 | 75   | 30 | 8.93  |
| BWR | Japan       | [105] | 1000 | 75   | 30 | 10.18 |
| BWR | Japan       | [105] | 1000 | 75   | 30 | 19.41 |
| BWR | Japan       | [105] | 1000 | 75   | 30 | 20.93 |
| PWR | France      | [101] | 1000 | 81.4 | 40 | 5.95  |
| BWR | Germany     | [101] | 1000 | 81.4 | 40 | 10.7  |
| AGR | UK          | [99]  | 1250 | -    | 34 | 5.05  |
| AGR | UK          | [100] | 1250 | -    | 34 | 6.85* |
| LWR | US          | [102] | 1000 | 85   | 40 | 17    |
| LWR | US          | [102] | 1000 | 85   | 40 | 54    |

843 Note: AGR = Advanced gas-cooled reactor; LWR = Light Water Reactor; HWR = Heavy Water  
844 Reactor; PWR = Pressurised Water Reactor; BWR = Boiling Water Reactor; \*for future  
845 projection.

846 **Table A3:** Hydropower. Small hydro power plants have smaller emission factors of about 40 g-  
847 CO<sub>2</sub>-e/kWh on average, while large hydro tends to have much lower emission intensity.

| Power plant | Location | Study | Gross output<br>kW | Life time | g-CO <sub>2</sub> /kWh |
|-------------|----------|-------|--------------------|-----------|------------------------|
| Small Hydro | Japan    | [64]  | 10000              | 30        | 11.3                   |
| Small Hydro | Japan    | [107] | 10000              | 30        | 18                     |
| Small Hydro | Japan    | [108] | 10000              | 30        | 17.6                   |
| Small Hydro | India    | [109] | 50                 | 30        | 74.88                  |
| Small Hydro | India    | [109] | 100                | 30        | 55.42                  |
| Small Hydro | India    | [110] | 3000               | 30        | 35.29                  |
| Small Hydro | India    | [110] | 250                | 30        | 35.35                  |
| Small Hydro | India    | [110] | 1000               | 30        | 42.95                  |
| Small Hydro | India    | [110] | 400                | 30        | 33.87                  |
| Small Hydro | India    | [110] | 2000               | 30        | 31.2                   |
| Small Hydro | India    | [110] | 1000               | 30        | 62.4                   |
| Large Hydro | Sweden   | [111] | -                  | -         | 6                      |

848

849 **Table A4:** Wind. The global average emission factor of onshore wind power plants is about 30  
850 g-CO<sub>2</sub>-e/kWh.

| Power plant | Location | Study | Power rate<br>kW | Capacity<br>factor | Life time | g-CO <sub>2</sub> /kWh |
|-------------|----------|-------|------------------|--------------------|-----------|------------------------|
| Wind        | Japan    | [96]  | 100              | 31.5%              | 20        | 71.7                   |

|          |             |      |         |       |    |             |
|----------|-------------|------|---------|-------|----|-------------|
| Wind     | Japan       | [97] | 100     | 31.5% | 20 | 95.6        |
| Wind     | Japan       | [95] | 100     | 40%   | 20 | 123.7       |
| Wind     | UK          | [93] | 6600    | -     | 20 | 25          |
| Wind     | Argentina   | [90] | 2.5     | 22%   | 20 | 42          |
| Wind     | US          | [67] | 25      | 24%   | 25 | 15          |
| Onshore  | Demark      | [94] | 500     | 25.1% | 20 | 9.7         |
| Offshore | Demark      | [94] | 500     | 28.5% | 20 | 16.5        |
| Wind     | Belgium     | [98] | 600     | 34.2  | 20 | 7.9 - 9.2   |
| Wind     | Japan       | [91] | 100     | 34.8% | 25 | 39.4        |
| Wind     | Japan       | [64] | 300/400 | 20%   | 30 | 20.3 - 29.5 |
| Wind     | Canada      | [89] | 500     | -     | 20 | 40.6        |
| Onshore  | Germany     | [43] | 500     | -     | 20 | 45 – 77     |
| wind     |             |      |         |       |    |             |
| Onshore  | Brazil      | [43] | 500     | -     | 20 | 26          |
| wind     |             |      |         |       |    |             |
| Onshore  | Germany     | [92] | 1500    | -     | -  | 11          |
| Offshore | Germany     | [92] | 2500    | -     | -  | 9           |
| Onshore  | Switzerland | [88] | 800     | -     | 20 | 11          |
| wind     |             |      |         |       |    |             |
| Offshore | Switzerland | [88] | 2000    | -     | 20 | 13          |
| wind     |             |      |         |       |    |             |
| Offshore | UK          | [38] | 2000    | 30%   | 20 | 30.2        |
| On shore | China       | [44] | 800     | 30%   | 20 | 69.9        |

851

852 **Table A5:** Solar PV. Life-cycle emissions are quite variable between 9.4 and 217 g-CO<sub>2</sub>-e/kWh,

853 depending on whether a binary or open cycle plant is used, and on whether new geothermal vents

854 are created during field exploration. A global average of mixed solar power has an emission

855 factor of 63.91 g-CO<sub>2</sub>-e/kWh.

| Type of cell                           | Location    | Study | Power rating<br>kW | Life time | g-CO <sub>2</sub> /kWh |
|--|-------------|-------|--------------------|-----------|------------------------|
| Amorphous solar PV                     | Netherlands | [81]  | 30m <sup>2</sup>   | 20        | 47                     |
| Mono-crystalline solar PV              | Japan       | [78]  | 3                  | 20        | 91                     |
| Amorphous solar PV                     | Netherlands | [76]  | 3300               | -         | 50                     |
| Nano-crystalline dye sensitized system | Sweden      | [77]  | -                  | 20        | 19 - 47                |
| Mono-crystalline solar PV              | India       | [79]  | 0.035              | 20        | 64.8                   |
| Poly-crystalline solar PV              | China       | [83]  | 100                | 30        | 12                     |
| Poly-crystalline solar PV              | Japan       | [64]  | 3                  | 30        | 53.4                   |
| Poly-crystalline solar                 | Greece      | [87]  | 3                  | -         | 104                    |

|                           |           |      |      |    |      |
|---------------------------|-----------|------|------|----|------|
| PV                        |           |      |      |    |      |
| Mono-crystalline solar PV | Singapore | [84] | 2.7  | 25 | 217  |
| Mono-crystalline solar PV | Singapore | [84] | 2.7  | 25 | 165  |
| Mono-crystalline solar PV | UK        | [85] | 14.4 | 30 | 44   |
| Amorphous solar PV        | US        | [80] | 8    | 30 | 39   |
| Amorphous solar PV        | China     | [82] | 100  | 30 | 15.6 |
| Amorphous solar PV        | US        | [86] | 33   | 20 | 34.3 |
| Poly-crystalline solar PV | China     | [82] | 100  | 30 | 9.4  |
| Poly-crystalline solar PV | China     | [82] | 100  | 30 | 12.1 |

856

857 **Table A6:** Biomass. The average emission factor of biomass is about 80 g-CO<sub>2</sub>-e/kWh, in the  
858 range between 35 g-CO<sub>2</sub>-e/kWh and 178 g-CO<sub>2</sub>-e/kWh.

| Power plant  | Location | Study | Gross output<br>MW | g-CO <sub>2</sub> /kWh |
|--|----------|-------|--------------------|------------------------|
| 90% hard coal and<br>10% straw   | Germany  | [74]  | 509                | 37                     |
| 90% hard coal and<br>10% wood  |          |       |                    | 35                     |
| Coal system +<br>biomass co-firing<br>and CO <sub>2</sub><br>sequestration | US       | [63]  | 457                | 43                     |
| IBGCC + CO <sub>2</sub><br>removal (chemical<br>absorption)                | -        | [72]  | 204.5              | 178                    |
| Biogas cogeneration  | Austria  | [73]  | 0.08               | 78                     |
| IGCC   | -        | [75]  | 1 MWh              | 110                    |

859

860 **Table A7:** Water consumption per unit of electricity generation from different energy  
861 technologies.

| Power plant    | Location  | Study | Gross output<br>MW | liter/kWh |
|----------------|-----------|-------|--------------------|-----------|
| Thermoelectric | Global    | [113] | -                  | 1.5       |
| Thermoelectric | U.S.      | [114] | -                  | 1.8       |
| Coal           | Australia | [116] | -                  | 2.0-2.2   |
| Coal           | U.S.      | [115] | -                  | 1.8       |

|             |           |       |      |     |
|-------------|-----------|-------|------|-----|
| Natural Gas | U.S.      | [115] | -    | 0.8 |
| Natural Gas | Australia | [116] | -    | 1.2 |
| Wind        | China     | [44]  | 800k | 0.6 |
| Solar       | U.S.      | [59]  | -    | 1.5 |

862

863