Chapter 20
Environmental Performance of Coal Power Generation in China

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20.1 Introduction

Economic growth requires a continuous flow of energy placing a huge burden on the still untapped energy resources. China is a major user of coal for power generation (72.2 % out of a total installed power capacity of 9.6 × 108 kW as of September 2010, and still increasing) owing to its large indigenous reserves (CEC 2011). In 2010, China consumed coal equivalent to about 1.71 billion t of oil accounting for about 48 % of the total coal use worldwide, and the proven reserves of Chinese oil and natural gas are relatively small (respectively, 4.3 and 0.1 billion toe; BP 2011), and hence its reliance on coal so intensively (WPE 2012). The lower cost of coal is a major attraction for reliance on it compared to oil and gas. China has embarked on a massive multiple coal power plant construction, despite warnings by the Energy Watch Group (Zittel et al. 2007) that China's coal will peak out by 2020. In recent years, massive economic development in China and high energy prices have accelerated the use of coal with the gradual replacement of small coal-fired power units (less than 200 MW) by big and supercritical power-generating units (600 MW or more).

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In 2009, the worldwide CO_2 emissions were about 28.9 Gt, of which 43.2% emanated from coal, 36.8% from oil, and 19.9% from natural gas (IEA 2011), which in 1990 were 39.7, 42.1 and 18.2%, respectively, showing the role of coal in CO_2 emission increase. Compared to 1990, CO_2 emissions in 2009 were 2.97 times higher. The share of 2009 CO_2 emissions from China was 83.6% from coal, 13.9% from oil and 2.4% from natural gas. The generation of 1 kWh of electricity from coal/peat releases, by world averages of 2007–2009, about 901 g of CO_2 emissions, 666 g by oil and 390 g by natural gas, which in China were 898, 572, 422 g CO_2/kWh, respectively, showing less than world average levels in coal and oil use, but higher in natural gas use.

Most studies on the generation of electricity from coal focus on energy conversion efficiency and, from an environmental point of view, on the need to limit the concentration of pollutants released. Little attention was paid to the relationship between energy conservation and environmental problems, and even lesser attention to the relationship between the sustainability of the economy and the environmental quality of the fossil resource. An integrated approach is needed to evaluate the process from both points of view complementing each other, namely, a "user-side" assessment that looks at the final efficiency indicators (energy delivered per unit of energy input and emissions per unit of energy delivered) and a "donor-side" assessment that considers the role of nature in providing resources as an important component of sustainability. To achieve such integration we have investigated the production of coal-fired electricity in a modern coal power plant in China by combining the accounting methods of energy, carbon and emergy (Odum 1996). The procedure involves a set of performance and sustainability indicators that can be used for evaluation and comparison of coal power plants. CO_2 emissions from coal combustion were calculated and used to assess the environmental costs of their diffusion employing emergy method developed by Ulgiati and Brown (2002). The emissions were also used to assess the green plantation area needed for diffusion by photosynthesis. Finally, an emergy-based indicator, the *Emergy Sustainability Index* (ESI), was used to place an additional sustainability constraint, by requiring the ESI of the plant to be not less than the ESI of the Chinese economy as a whole (Bo and Ulgiati 2012) to consider it as an actual improvement.

20.2 Methods

20.2.1 Description of Plant under Evaluation

The plant under evaluation is a 5-billion yuan RMB (US$ 0.76 billion, at an exchange rate of US$/RMB Yuan was 1:6.56; Bo and Ulgiati 2012) 2 × 600 MW supercritical power generation unit under construction in Guangdong (China) using the Chinese Shenfu bituminous coal. The plant uses electrostatic precipitators to capture and remove coal ash to use as additive material in downstream cement production. Gas after dedusting is sent to desulfurization devices based on limestone–gypsum wet flue gas process to yield a byproduct, calcium sulfate dihydrate (plaster), which is used as construction material (Guangdong Electric Power Design Institute 2004).

Coal consumption is estimated at 2.53 million t/year. The coal LHV (equal to HHV minus the heat loss due to water evaporation) is 21.80 MJ/kg. Therefore, the plant receives 5.52E+16 J/year as input energy.

20.2.2 The Emergy Accounting

Odum (1988, 1996) introduced the concept of emergy as an expansion of the embodied energy concept to include time and quality. *Unit emergy value* (UEV) is used for the conversion of the different flows into emergy units with reference, to the biosphere emergy baseline of 15.83E+24 seJ/year (Odum et al. 2000; Brown and Ulgiati 2010). Such conversion, the core of the emergy accounting approach, is done by using the following emergy equation:

$$E_m = \sum f_i * UEV_i \qquad i = 1, \ldots, n \tag{20.1}$$

where E_m is the total solar emergy supporting the system, f_i, the ith input flow of matter or energy, and UEV_i is the *unit emergy value* of the i^{th} flow (from literature or as calculated in this work); the calculation procedures according to Eq. (20.1) are generally grouped in a summary table. Performance indicators are calculated based on the fractions of renewable, nonrenewable, local and imported input emergy flows (Brown 2010), among which:

- *Emergy yield ratio* (EYR), is a measure of the ability of the process to exploit local resources thanks to investments from outside; *EYR*=U/F=(R+N+F+S)/(F+S)
- *Environmental loading ratio* (ELR), is a measure of the pressure of local and imported nonrenewable investments on local renewable sources; *ELR*=(N+F+S)/R
- *Emergy sustainability index* (ESI), is calculated as *EYR*/*ELR*, an aggregated measure of benefit and environmental sustainability: *ESI*=*EYR*/*ELR*
- *Empower density* (ED), is a measure of the emergy investment per unit area and year; *ED*=U/Area=(R+N+F+S)/Area
- %REN is the fraction of emergy use that is renewable; %REN=R/U=R/(R+N+F+S)

Further details on the emergy method and emergy-based indicators can be found in the published literature (Brown 2010; Brown and Ulgiati 2004; Ulgiati and Brown 2012). Recent studies that apply the emergy accounting method specifically to power plants are also available which deal with eco-integrated production parks (Wang et al. 2006), electricity generation at national level (Häyhä et al. 2011), power generation from waste biomass(Buonocore et al. 2012), among others, and can usefully serve as reference for further improvement.

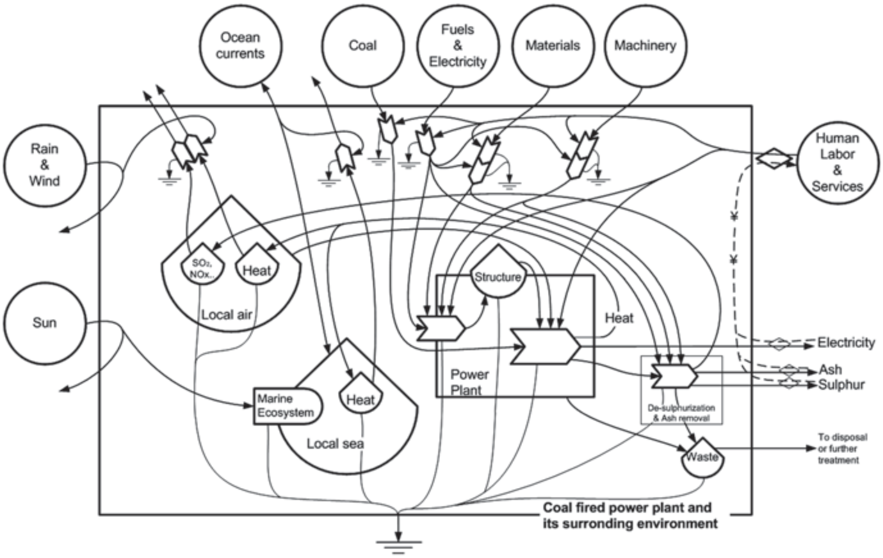

Fig. 20.1 Systems diagram of a coal-fired power plant showing renewable and nonrenewable input flows, components and subprocesses within the boundary

The systems diagram of the investigated coal-fired plant is shown in Fig. 20.1 with the main input and output flows, components and processes identified. Input flows are ordered from left to right, clockwise, in order of increasing UEV. Locally renewable flows enter from the left, while products exit to the right. The larger frame identifies the system's boundary, placed around the plant including extra land around it, directly accommodating the plant's facilities or indirectly as buffer land.

All matter and energy pathways flow into the system, except sunshine, wind and rain, a fraction of which leaves the area due to albedo, partial capture and evapotranspiration, so oceanic currents are drawn as both inflowing and outflowing the area. Heat and chemicals released by the power plant are carried and dispersed by these renewable driving forces.

Coal can either be a local resource or imported (as in Fig. 20.1), while all the other flows are considered imported when they are from outside the boundary. Coal being *local* means that the plant is located not far from the coal mine. Coal *imported* means that some transport costs must be included. The choice of coal, either local or imported, affects the indicators in many ways. If local, the EYR and ESI increase, while the opposite is true if it is imported. The sustainability constraint, $ESI_{\text{plant}} \geq ESI_{\text{economy}}$ (ESI_{economy} means chinese national economy value, $ESI_{\text{economy}} = 0.47$ (Bo and Ulgiati 2012)), influences the demand for green belt (buffer land). In fact, a larger buffer land captures more renewable emergy, R, decreases the loading ratio ELR and increases the ESI_{plant}, while influencing the other emergy indicators. Of course, energy and carbon indicators are not influenced by such choices.

20.2.3 Carbon Accounting

Fossil fuel-based activities (transportation, electricity generation, and space heating) are among the most important contributors to CO_2 emissions. Their dilution in the atmosphere is not a solution as their contribution to global warming does not depend on their local concentration, but instead by the total quantum released. We assume that CO_2 will be diffused through photosynthesis. As a consequence, we calculate the land required for CO_2 diffusion building a buffer land to assess the land required.

We also calculate the primary heat and non-CO_2 emissions (NO_x, SO_x), on an annual basis; then, we estimate the volume of air or water required for cooling or diluting to the biosphere background level (or to the extent the law demands) by dividing the total emission by this threshold value. The volumes of air or water are multiplied by their average density and converted to mass units; then their kinetic or chemical energies are calculated and finally converted to emergy by employing suitable UEVs from the literature (Ulgiati and Brown 2002).

20.3 Results and Discussion

20.3.1 Results

We have calculated the emergy indicators with the assumption that coal is local (plant site close to the mine), that ash and sulfur are extracted and sold as by-products, and that residual emissions are diluted by wind. Additional emergy flows for de-dusting and de-sulfurization processes as well as for the emergy value of ecosystem services are considered. The need for larger area for buffer land for total diffusion of CO_2 via photosynthesis and for ESI-based sustainability constraint was also calculated.

Equation 20.1 is applied to the process with the inventory of input energy and matter flows, and all input flows in Table 20.1 were derived from official statistical and environmental databases (CEC 2011; WPE 2012) and integrated employing calculations described in Sect. 2.1. Items 1–5 are material and energy flows related to plant construction, and all inputs have been divided by 30, the years of anticipated lifetime of the plant. Item 6 is the flow of labor and services (indirect labor in the supply chain) needed for construction, converted to emergy by means of emergy per capita and emergy/RMB ratios of China (Bo and Ulgiati 2012). Items 7–15 are the main annual input flows into plant operation including labor and services. In particular, items 9–11 deal with ecosystem services for heat and chemical emission diffusion will be discussed later.

Items 16–18 and items 19–23 are additional inputs to ash and sulfur removal, respectively. Items 24–26 refer to electricity, ash and sulfur product flows. The total emergy for plant construction, power operations, removal of ash and sulfur is

Table 20.1 Emergy accounting of coal-fired electricity production in China with ash and sulfur removal. (Data on annual basis; 1200 MW power plant, situated in Guang Dong (China))

No.	Item	Unit/year	Raw amount	Solar UEV (seJ/unit)	Ref. for UEV	Solar emergy (seJ)
Plant construction phase (all input flows divided by estimated plant lifetime, 30 years)						
1	Concrete	g	1.62E+10	8.53E+08	Brown and Buranakarn 2003	1.38E+19
2	Iron and steel for structure	g	2.17E+09	4.65E+09	Brown and Buranakarn 2003	1.01E+19
3	Insulating materials (plastic and rock wool)	g	1.00E+07	9.83E+09	Brown and Buranakarn 2003	9.83E+16
4	Copper electric wires	g	9.35E+07	9.80E+10	Cohen et al. 2006	9.16E+18
5	Petroleum-derived fuels and lube oils	g	8.69E+13	1.11E+05	Odum 1996	9.64E+18
6	Labor and services for the whole plant construction	RMB	1.67E+08	9.95E+11	Bo and Ulgiati 2012	1.66E+20
Plant operation phase						
Locally available environmental inputs						
7	Solar radiation	J	6.26E+19	1.00E+00	Odum 1996	6.26E+19
8	Rain water	J	2.80E+16	3.05E+04	Odum 1996	8.55E+20
9	Cooling service at condenser (sea water)	J	2.84E+16	5.20E+03	Odum 1996	1.48E+20
Indirect environmental inputs from outside the area						
10	Cooling service at chimney (heat dilution by wind)	J	4.75E+12	2.52E+03	Odum 1996	1.20E+16
11	Dispersal of released chemicals (dilution by the wind)	J	2.03E+17	2.52E+03	Odum 1996	5.12E+20
Nonrenewable inputs						
12	Coal	J	5.52E+16	6.63E+04	Brown et al. 2011	3.66E+21
Labor and services for operational phase						
13	Labor					
	Graduated	Years	6.00E+01	6.57E+16	Bo and Ulgiati 2012	3.94E+18

Table 20.1 (continued)

No.	Item	Unit/year	Raw amount	Solar UEV (seJ/unit)	Ref. for UEV	Solar emergy (seJ)
	Technical and administrative	Years	4.00E+01	4.38E+16	Bo and Ulgiati 2012	1.75E+18
	Unskilled labor	Years	4.00E+01	2.19E+16	Bo and Ulgiati 2012	8.76E+17
14	Labor for plant maintenance	Years	1.00E+02	4.38E+16	Bo and Ulgiati 2012	4.38E+18
15	Services for fuel supply	RMB	1.97E+09	9.95E+11	Bo and Ulgiati 2012	1.96E+21
De-dusting (ash removal) after combustion						
16	Electricity consumption (from plant)	J	3.25E+12	3.22E+05	This work, result of calculation	1.05E+18
17	Steel for structure	g	6.48E+09	4.65E+09	Brown and Buranakarn 2003	3.02E+19
18	Services	RMB	5.17E+05	9.95E+11	Bo and Ulgiati 2012	5.15E+17
Desulfurization (removal of sulfur from 0.41 to 0.041 % for conversion to plaster)						
19	Limestone	g	3.60E+10	9.50E+09	Odum 2000	3.42E+20
20	Electricity consumption (from plant)	J	1.85E+14	3.22E+05	[6]	5.96E+19
21	Steel for structure	g	1.97E+08	4.65E+09	Brown and Buranakarn 2003	9.15E+17
22	Water (from underground reservoir)	J	8.25E+11	5.00E+04	Buenfil 2001	4.13E+16
23	Services	RMB	3.30E+06	9.95E+11	Bo and Ulgiati 2012	3.28E+18
Net electricity production						
24a	Annual net electricity production (with L&S)	J	2.36E+16	3.22E+05	This work, result of calculation	7.58E+21
24b	Annual net electricity production (without L&S)	J	2.36E+16	2.28E+05	This work, result of calculation	5.38E+21
25a	Ash-to-cement production (with L&S)	g	3.42E+11	2.31E+09	This work, result of calculation	7.91E+20
25b	Ash-to-cement production (without L&S)	g	3.42E+11	1.54E+09	This work, result of calculation	5.25E+20
26a	Sulfur-to-plaster production (with L&S)	g	5.58E+10	9.50E+09	This work, result of calculation	5.30E+20
26b	Sulfur-to-plaster production (without L&S)	g	5.58E+10	8.66E+09	This work, result of calculation	4.83E+20

Table 20.2 Energy and carbon performance indices (based on Table 20.1)

Total net electrical energy produced per year	2.36E+16	J/year
Total gross energy invested per year (fuels included)	5.82E+16	J/year
CO_2 released	5.62E+12	g CO_2/year
C released = (12/44) × total CO_2 mass	1.53E+12	g C/year
Dry biomass equivalent to photosynthetic diffusion of CO_2 (assuming C equal to 0.45 % of dry biomass)	3.40E+12	g dry biomass/year
NPP (average) in the area	3.00	T NPP (d.m.)/ha
Buffer area/green belt/set-aside area needed to nullify CO_2 emissions	1.13E+06	Ha
CO_2 released/electricity produced	857.71	g CO_2/kWh
Energy ratio (out/in)	0.41	

assigned to electricity, as these are necessary inputs to the final net electricity output (gross electricity generated less electricity used for removal of ash and sulfur). The calculated UEVs are therefore 3.22E+05 and 2.28E+05 seJ/J, with and without L&S, respectively. Instead, the emergy of ash and sulfur product flows was calculated as the emergy for removal processes plus a fraction of the total operational emergy proportional to the amount of ash and sulfur in coal. These smaller values are used for the calculation of ash and sulfur UEVs with and without L&S.

After calculating the CO_2 emissions from coal combustion as per the procedure, the biomass corresponding to its full photosynthetic diffusion is calculated. Based on the average value of *net primary production* (NPP), the area needed for buffer land is estimated. Later, the CO_2 emissions per kWh and the energy output/input ratio are calculated. The values of energy and carbon performance indices in Table 20.2 are based on a regular 2 × 600 MW power station and the total calculated output is 2.36E+16 J/year. CO_2 emissions also include emissions from machinery production chain, coal extraction, refinery and supply chain.

A comparison of results is shown in Tables 20.3, 20.4, 20.5. It is assumed that the residual heat and chemical emissions are fully diluted by the wind; therefore the emergy of wind-based ecosystem services is also included in the calculation of indicators. Such an assumption is not significant, but imposes restrictions on the process of power generation. Generally, other sources of combustion are also concentrated in the same area and the facilities available in the area are not sufficient to abate or dilute heat and emissions. In fact, if the ecosystem supports one process, it can no support other needs (e.g., further cooling of another source of heat emission), which places a limitation on the number of emission sources that it can handle in a given area. Therefore, only a small number of high-emission processes are located in a region, not to overload its carrying capacity and prevent their breakdown. Once the emergy of the buffer land is known, the number of manageable pollution sources can be easily calculated. In this study, we will, however, consider these additional emissions to be negligible compared to the plant.

The data in the tables suggests that some efforts be made to remove ash and sulfur and recycle, and enable emergy to incorporate it too. Table 20.4 also consid-

Table 20.3 Indicators of coal-fired electricity generation in China using locally available coal, ash and sulfur removed, and non-C emissions diluted by wind

Total emergy, U (seJ $year^{-1}$)	with L&S	6.87E+21
	without L&S	4.73E+21
UEV (seJ J^{-1})	with L&S	2.92E+05
	without L&S	1.98E+05
EYR		2.24
ELR		45.46
ESI=EYR/ELR		0.05
ED (seJ m^{-2} $year^{-1}$)		7.69E+15
Radius of buffer land for photosynthetic CO_2 diffusion (km)		0.38
CO_2 emissions (g kWh^{-1})		857.71

Table 20.4 Indicators of coal-fired electricity generation in China with coal as a local resource, ash and sulfur removed, CO_2 uptake via photosynthesis and non-C emissions diluted by wind

Total emergy, U (seJ $year^{-1}$)	with L&S	7.58E+21
	without L&S	5.44E+21
UEV (seJ J^{-1})	with L&S	3.22E+05
	without L&S	2.31E+05
EYR		2.47
ELR		7.87
ESI=EYR/ELR		0.31
ED (seJ m^{-2} $year^{-1}$)		6.68E+11
Radius of buffer land for photosynthetic CO_2 diffusion (km)		60.10
CO_2 emissions (g kWh^{-1})		857.71

ers that CO_2 is absorbed by photosynthesis (and some land needs to be identified to grow wood plantation which will absorb CO_2 until the trees reach their optimal size coinciding with the lifetime of the plant, i.e., 30 years). The buffer land developed will lower the plant's discharges into the atmosphere and will provide more solar energy to the system improving the R factor in the calculation of indicators. The other is the assumption that $ESI_{plant} \geq ESI_{economy}$, i.e., the plant's operation should not affect the sustainability of the country's economy. However, such an assumption involves more land allocation to the plant for a higher R input and consequently a lower ELR. Table 20.3 represents the process as it stands, that is, electricity production is supported by the emergy of fuel, machinery and labor, ash and sulfur are removed by means of technological devices and residual emissions are diluted by wind. In this basic case, only 44.7 ha are allocated to the plant, i.e., the real area where the plant is located. Tables 20.4 and 20.5 depict two scenarios in which sufficient land is allocated to the units to meet two different sustainability constraints.

Table 20.5 shows that the total emergy, U, increases (as more renewable emergy R is received) along with UEV, with and without the inclusion of the emergy value of labor and services. The EYR increases very little, while ELR is very high in

Table 20.5 Indicators of coal-fired electricity generation in China with coal as a local resource, ash and sulfur removed, non-C emissions diluted by wind and emergy-based sustainability constraint ($ESI_{plant} \geq ESI_{economy}$)

Total emergy, U (seJ year^{-1})	with L&S	7.86E+21
	without L&S	5.71E+21
UEV (seJ J^{-1})	with L&S	3.33E+05
	without L&S	2.42E+05
EYR		2.59
ELR		5.51
ESI=EYR/ELR		0.47
ED (seJ m^{-2} year^{-1})		4.91E+11
Radius of buffer land (km) for $ESI_{plant} \geq ESI_{economy}$		71.83
CO_2 (g Kwh^{-1})		857.71

the basic case and drops in the two sustainability constraint scenarios. The ESI increases as a consequence of assumptions: in the basic case, it is very low, while as per Table 20.5, it equals the country's sustainability index. Since more land is allocated to the process to develop greenery for CO_2 absorption, and even more is needed for the implementation of the ESI-based sustainability constraint, the *empower density* (ED), drops from the basic case (Table 20.3) to the more sustainable cases of Tables 20.4 and 20.5.

More land is needed to build a circular ring around a plant free of any combustible material sources (as in the case of Table 20.4) or any other development (as in the case of Table 20.5). Therefore, the radius around the plant expands from 0.38 km (the real case, Table 20.3) to 60.10 and 71.83 km, respectively, as in cases suggested in Tables 20.4 and 20.5 (virtual land allocation).

Finally, all tables show that 858 g of CO_2/kWh is released by the plant, irrespective of the buffering assumption.

20.3.2 Discussion

First of all, is it right to consider the investigated plant to be representative of electricity generation in China? The likely answer is yes. As coal supports 72 % of total Chinese electricity generation and the plant energy and carbon performance shown in Table 20.2 are very similar to the average values available in China (WCA 2010; IEA 2010).

Important components of plant sustainability are the investment for construction of the plant and operation, emission levels, and their cost of dispersal. The investment in construction, quantified in emergy terms, is not significant as it has a lifetime of over 30 years translating into a small percentage of total emergy use, U. On the contrary, the operational phase is highly expensive in annual emergy cost of fuel and for the removal of ash and sulfur. This clearly leads to low sustainability of the basic model (Table 20.3). Using nonrenewable material and energy inputs makes it sustainable and reduces environmental burden. The CO_2 released can be absorbed by dedicated tree plantations in land set aside for the purpose. Considering that there are a large number of coal-fired power plants in China, it is unlikely that this will be a suitable solution in the long run, but could become at least a partial solution during the much-needed transition to carbon-free power. It is to be noted that, as a consequence of larger area of land diverted for tree plantation to minimize the carbon footprint, some emergy indicators become larger (U and UEV, increase in demand for environmental support).

There is an assumption that the power plant operations do not affect the country's economy (i.e., do not contribute to lower its average sustainability measured in emergy terms, $ESI_{plant} \geq ESI_{economy}$) but it is to be understood as a limiting factor. It means that no matter what the CO_2 diffusion is, the balance of different emergy flows that support the plant (locally renewable, nonrenewable, imported, and labor and services) must be better or equal to the native ones. The underlying principle (Brown and Ulgiati 2001) is that each area has a limited carrying capacity for investments, beyond which the global environmental integrity and dynamics is altered and sustainability declines. The real problem is that the need for additional land for plantations is much higher. In the scenario investigated (Table 20.5) the emergy-based sustainability constraint would require 2.8 times higher land than the one required by simple CO_2 diffusion model.

Our results, however, identify two major alternatives that might help the transition towards renewable energy: increasing CO_2 capture owing to afforestation of fallow lands and increasing additional product production like those of heat, chemicals, construction materials, apart from electricity, out of power plant operations. In addition to achieving better environment, an integrated network generates additional products that save the energy required for their production in specifically dedicated processes (not accounted for as a saving in the present study) (Ulgiati et al. 2007).

20.4 Concluding Remarks

A 2×600 MW coal-fired power-generating station in Guangdong, China, which represents the most recent supercritical power generation plants in China, was investigated using an integrated approach based on energy, emergy and carbon accounting. To reduce carbon emissions and use the ESI a buffer land, respectively, is required to be set aside to diffuse CO_2 emissions (lower estimate) and balance plant unsustainability (higher estimate). Such huge tracts of land are unlikely to be available. Consequently, carbon-based energy patterns are not a sustainable strategy. Setting the land aside might provide a temporary solution, but more effectively the removal of ash and sulfur and their use in other processes as well as the use of cogenerated heat decrease the need for environmental solutions thus increasing the sustainability of the plant and the processes that use its cogenerated products. Thus, we recommend integrated ecofriendly industrial networks as an alternative solution to sustainable and carbon-free energy. However, the outcome of our study places a limit on the number of fossil-fired power plants that are acceptable to the people and sustainable in China despite coal being a cheap and domestically available resource.

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