Supplementary Information

Life cycle energy consumption analysis and green manufacture evolution for papermaking in China

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1. Production pathways of major paper types in this study

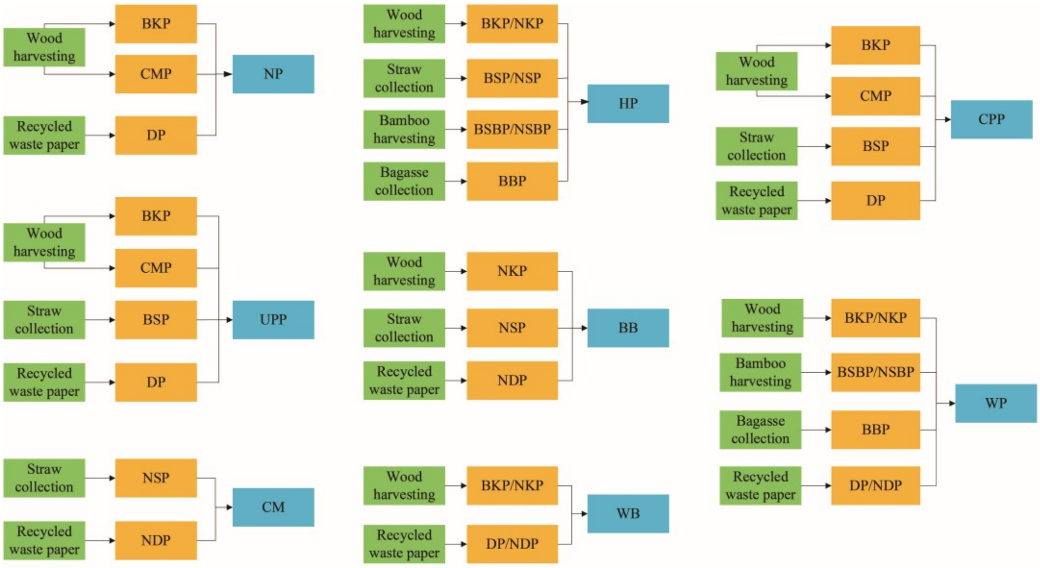

Fig. S1. Production pathways of major paper types

2. The paper production efficiency

The data in Table S1 represent $m_{pu,i}$ in calculation methods. 1 ton of air-dried pulp contains 0.9 tons of absolutely dry pulp, the amount of dry pulp for producing 1 ton of paper is mostly less than 1 ton due to the addition of fillers. Tissue paper needs the least amount of fillers and is relatively easy to have broken paper, so it consumes the most amount of pulp.

Table S1. The amount of pulp for various paper types[1]

Paper	**The amount of pulp** (unit: ADt/t paper)
NP	1.02-1.05
UPP	0.96-1.00
TP	1.05-1.30
WB	1.00-1.05
BB	1.00-1.05
CM	1.05-1.10
CPP	1.00-1.05
WB	0.92-1.05

The data in Table S2 represent $Y_{pu,m}$ in calculation method, the chemical process part in chemistry mechanical pulp and recycled paper pulp is mild, so their pulp yield is high.

Table S2. The pulp yield of various raw materials[2]

Raw material	Pulping method	Pulp yield
Wood	Chemistry	45 ~ 50 %
Wood	Chemistry mechanical	85 ~ 90 %
Rice straw	Chemistry	34 ~ 38 %
Wheat straw	Chemistry	41 ~ 50 %
Corn straw	Chemistry	~ 51 %
Bamboo	Chemistry	46 ~ 52 %
Bagasse	Chemistry	~ 50 %
Recycled paper	Deinked pulping	60 ~ 78 %

3. Chemicals consumption in pulp production process and the energy demand for chemicals production

Table 3a ~ 3e review the types and amount of pulping chemicals, which correspond to m_{c1} in calculation methods. The data in Table 3f are the amount of papermaking chemicals and fillers which correspond to m_{c2}. Table S4 is the production energy consumption, which represent EC_{c1} and EC_{c2}.

Table S3a. Chemicals consumption per unit of virgin pulp[1]

(unit: kg/ADt)

	NaOH	Na_2S	Cl_2
BKP*	18.75	6	87.5
NKP	16.25	4.5	0
BSP	58	8.7	65
NSP	29	2.9	0
BSBP	37.5	7.5	75
NSBP	32.5	6.5	0
BBP	53	4.4	60
BRP	33.1	6.6	55

*Chemicals consumption of CMP is about 60% of BKP[3]

Table S3b. Chemicals consumption per unit of deinked pulp[4]

(unit: kg/ADt)

	NaOH	**Na_2SiO_3**	**H_2O_2**
DP*	49	34	78

Table S3c. Chemicals consumption per unit of BKP (ECF)[5]

(unit: kg/ADt)

	CH_3OH	**H_2O_2**	**H_2SO_4**	**$NaClO_3$**	**NaOH**
BKP (ECF)	2.78	18.06	25.89	31.61	33.7

Table S3d. Chemicals consumption per unit of BKP (TCF)[6]

(unit: kg/ADt)

	O_2	**H_2O_2**	**NaOH**	**H_2SO_4**	**Na_2SO_4**	**EDTA**	**H_2**
BKP (TCF)	27	23	14.6	10.7	7.3	3	1.9

Table S3e. Chemicals consumption per unit of BSP[7]

(unit: kg/ADt)

	$CaCO_3$	**Urea**	**NaOH**	**ClO_2**	**Cl_2**	**H_2O_2**
Company A	4.36	0.36	40	50	-	40
Company B	4.28	5.61	75.84	-	120	48

Table S3f. Chemicals consumption per unit of paper[1]

(unit: kg/t paper)

	Rosin	**$Al_2(SO_4)_3$**	**Fillers**
NP	-	-	40
UPP	7.5	30	165
TP	5.2	-	-
WB	3.5	15	35
BB	6	20	-
CM	2.5	11.5	-
CPP	9	35	90
WP	5	16	-

Table S4. Primary energy demand for chemicals production[8]

	PED (unit: MJ/kg)
NaOH	32.07
$NaClO_3$	75.2
NaCl	2.18
H_2O_2	46
O_2	4.6
H_2SO_4	5.36
Na_2SiO_3	16
Cl_2	25.3
CaO	7.77
Na_2SO_4	33.78
H_2	165.66
EDTA	3.2
CH_3OH	33.5
$CaCO_3$	2.13
Urea	37.8
Al_2O_3	24.1
Kaolin	3.53
MgO	532
ClO_2	145
Starch	32.2
Rosin	3.4
$Al_2(SO_4)_3$	11.79
Na_2S	30

4. The paper production efficiency energy consumption

Table S5 and S6 are the average production energy consumption of main products in papermaking industry in China from 2000 to 2020, corresponding to EU_i and EA_i.

Table S5. Energy consumption of various types of pulp from 2000 to 2020 (unit: GJ/ADt)

	2000	**2005**	**2010**	**2015**	**2020**
BKP	20.60	18.27	14.95	12.29	11.13
NKP	14.71	13.05	10.68	8.78	7.95
CMP	22.07	19.58	16.02	13.17	11.93
BSBP	24.52	21.76	17.80	14.64	13.25
NSBP	17.17	15.23	12.46	10.24	9.28
BSP	25.01	22.19	18.16	14.93	13.52
NSP	21.58	19.14	15.66	12.88	11.66

BBP	26.49	23.50	19.22	15.81	14.31
DP	10.30	9.14	7.48	6.15	5.57
NDP	4.17	3.70	3.03	2.49	2.25

Table S6. Energy consumption of various types of paper from 2000 to 2020 (unit: GJ/t paper)

	2000	**2005**	**2010**	**2015**	**2020**
NP	16.95	15.13	12.39	9.66	8.75
UPP	21.57	19.25	15.77	12.29	11.13
CPP	23.11	20.63	16.90	13.17	11.93
TP	29.79	26.59	21.78	16.98	15.38
WB	16.95	15.13	12.39	9.66	8.75
BB	16.44	14.67	12.02	9.37	8.48
CM	16.95	15.13	12.39	9.66	8.75
WP	23.63	21.09	17.28	13.46	12.19

5. Full calculations for life cycle energy consumption of paper productions: Taking tissue paper as an example

The tissue paper producing by bleached kraft pulp is taken as an example to show how to obtain the results in Fig. 8 in the main text. The pulping yield of bleached kraft pulp is 45% (see Table S2, lower bound for bleached pulp, upper bound for natural pulp). It takes about 1.175 tons of air-dried pulp (ADt) to produce 1 ton (t) of tissue paper (see Table S1). The energy consumption per unit of wood collection has been obtained and its value is 376.66 kJ per kg (kJ/kg) (see Fig. 4 in the main text). So the energy consumption at the wood collection stage is 0.984 GJ per one ton of tissue paper (GJ/t TP) and the calculation method is based on equation (2) in the main text, as shown in equation (S1).

$$\boldsymbol{EM_i = m_{pu,i} \times \frac{\sum_e (M_e \times ELC_e)}{Y_{pu,m}}} \qquad \text{(S1)}$$

$$\boldsymbol{= 1.175 \times \frac{376.66}{0.45 \times 1000} = 0.984 \ \ (\text{GJ/t TP})}$$

The transportation materials in this pathway include wood, bleached kraft pulp board and coal, the calculation method is shown in equations (5) ~ (8) in the main text. The transportation mode of wood is assumed as 200 km of highway road transportation (short distance),[2] its energy intensity is 1363 kilojoule/(ton·kilometer) (kJ/(t·km)) (See Fig. 7 in the main text) and diesel consumption accounts for 68% and the rest is gasoline. The life cycle energy consumption of diesel and gasoline is 1.271 and 1.282 (See Fig. 3 in the main text). According to the equation (6) in the main text, the energy consumption at the wood transportation stage is about 0.907 GJ/t TP, as shown in equation (S2):

$$\boldsymbol{EFT_i = \frac{m_{pu,i}}{Y_{pu,m}} \times E_s \times \sum_e \left(ELC_e \times R_{s,e}\right) \times D_m} \tag{S2}$$

$$= \boldsymbol{\frac{1.175}{0.45} \times 1362 \times (0.68 \times 1.271 + 0.32 \times 1.282) \times \frac{200}{1000000} = 0.907 \ \ (GJ/t\ TP)}$$

It is assumed that the transportation of pulp board is 500 km of highway road transportation (long distance), its energy intensity is 1200 kJ/(t·km) (See Fig. 7 in the main text) and the energy types is the same as the short-distance road transportation. According to the equation (7) in the main text, the energy consumption at the pulp board transportation stage is about 0.900 GJ/t TP, as shown in equation (S3):

$$\boldsymbol{EUT_i = m_{pu,i} \times E_l \times \sum_e \left(ELC_e \times R_{l,e}\right) \times D_u} \tag{S3}$$

$$\boldsymbol{= 1.175 \times 1200 \times (0.68 \times 1.271 + 0.32 \times 1.282) \times \frac{500}{1000000}}$$

$$\boldsymbol{= 0.900 \ \ (GJ/t\ TP)}$$

The average transportation distances for coal in China are 1000 km by railway,[14] its energy intensity is 240 kJ/(t·km) (see Fig. 7 in the main text) and diesel consumption accounts for 55% and electricity consumption accounts for 45%. The life cycle energy consumption of electricity is 2.934 (see Fig. 3 in the main text). The production energy consumption per unit of bleached kraft pulp and tissue paper is 587.989 kg raw coal and 811.984 kg raw coal (1 kg raw coal=20908 kJ) (see Table S5 and S6), the energy consumption at the coal transportation stage is 0.728 GJ/t TP according to equation (8), as shown in equation (S4):

$$\boldsymbol{ECT_i = \left(m_{pu,i} \times EU_i \times E_r \times D_{coal} + EA_i \times E_r \times D_{coal}\right) \times \sum_e \left(ELC_e \times R_{r,e}\right)} \quad \text{(S4)}$$

$$\boldsymbol{= (1.175 \times 587.989 \times 240 \times 1000 + 811.984 \times 240 \times 1000) \times (0.55 \times 1.271 + 0.45 \times 2.924)/10^9 = 0.728} \ \textbf{(GJ/t TP)}$$

To sum up, the total transportation energy consumption is 2.535 GJ/t TP in this pathway, as shown in equation (S5).

$$\boldsymbol{ET_i = EFT_i + EUT_i + ECT_i} \quad \text{(S5)}$$

$$\boldsymbol{= 0.907 + 0.900 + 0.728 = 2.535} \ \textbf{(GJ/t TP)}$$

The production energy consumption of chemicals for producing bleached kraft pulp and tissue paper is 2.830 GJ/ADt and 0.037 GJ/t TP (see Table 1 and 2 in the main text), according to the equation (3), the energy consumption at the chemical production stage is 3.362 GJ/t TP, as shown in equation (S6).

$$\boldsymbol{EC_i = m_{pu,i} \times \sum_{c1}(m_{c1} \times EC_{c1}) + \sum_{c2}(m_{c2} \times EC_{c2})} \quad \text{(S6)}$$

$$\boldsymbol{= 1.175 \times 2.830 + 0.037 = 3.362} \ \textbf{(GJ/t TP)}$$

The production energy consumption per unit of bleached kraft pulp and tissue paper is 12.29 GJ/AD and 16.98 GJ/t paper (See Table S5 and S6). The life cycle energy consumption of coal is 1.089 (See Fig. 3 in the main text). According to the equation

(4), the total energy consumption at the pulp and papermaking stages is 34.119 GJ/t TP, as shown in equation (S7).

$$\boldsymbol{EUA_i = (m_{pu,i} \times EU_i + EA_i) \times ELC_{coal}} \quad \text{(S7)}$$

$$\boldsymbol{= (1.175 \times 12.29 + 16.89) \times 1.089 = 34.119} \ \ \textbf{(GJ/t TP)}$$

In summary, when 1 ton of tissue paper using bleached kraft pulp is produced, the total life cycle energy consumption is about 41 GJ, as shown in Table S7.

Table S7. Life cycle energy consumption in each stage for the production of tissue paper

Life cycle stages	Energy consumption (GJ/t TP)
Raw material collection	0.907
Transportation	2.535
Chemical production	3.362
Pulping	15.726
Papermaking	18.393
Total	40.923

6. Data of the GHG emissions

The GHG emission factors of fossil fuels and biomass will not change much over time, as shown in Table S8 (ECL_e in calculation methods). The GHG emission factors of steam and electricity will decrease with the improvement of energy structure and efficiency. Therefore, we obtain the GHG emission factors for various power generation technologies and the efficiency of heat production and power generation, as shown in Table S9. The future data is obtained by comparing with the current advanced level globally.[9] Finally, according to the prediction of power structure by IEA, the GHG emission factors of steam and electricity are shown in Fig. S3, these data is used to calculate and predict the GHG emissions in Fig. 13 in the main text.

Table S8. GHG emission factors for part of energy types[10, 11]

	GHG emission factors (unit: g CO_2 eq/MJ)
Coal	102.8
Natural gas	56.6
Fuel oil	75.8
Biomass	108.5

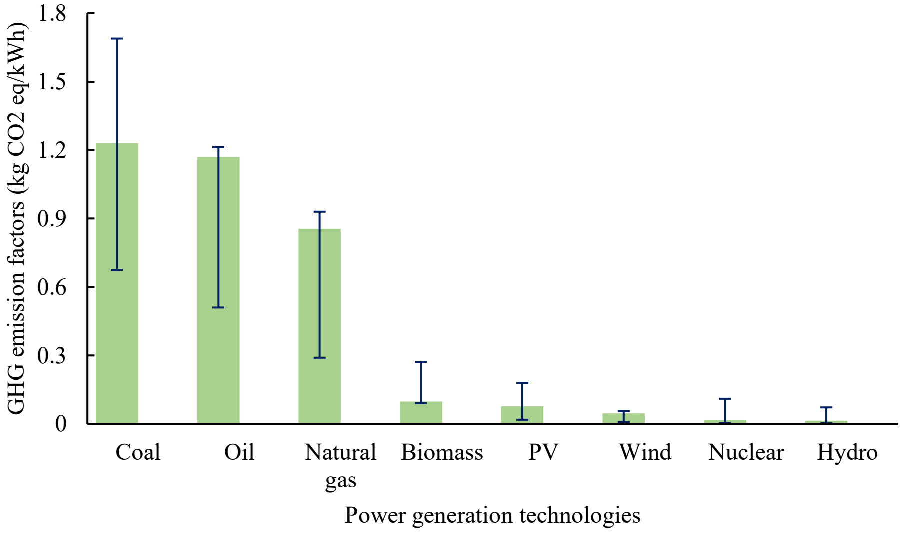

Fig. S2. GHG emission factors for various power generation technologies[12-15]

Table. S9. The efficiency of heat production and power generation

	2000	**2005**	**2010**	**2015**	**2020**
Coal-fired boiler efficiency[16]	-	-	65%	70.0%	75.0%
Power generation and heating efficiency in power plant[17]	37.80%	39.0%	42.0%	44.2%	-
Energy consumption per unit power generation in thermal power plant (unit: gce/kWh)[18]	392	370	333	315	300

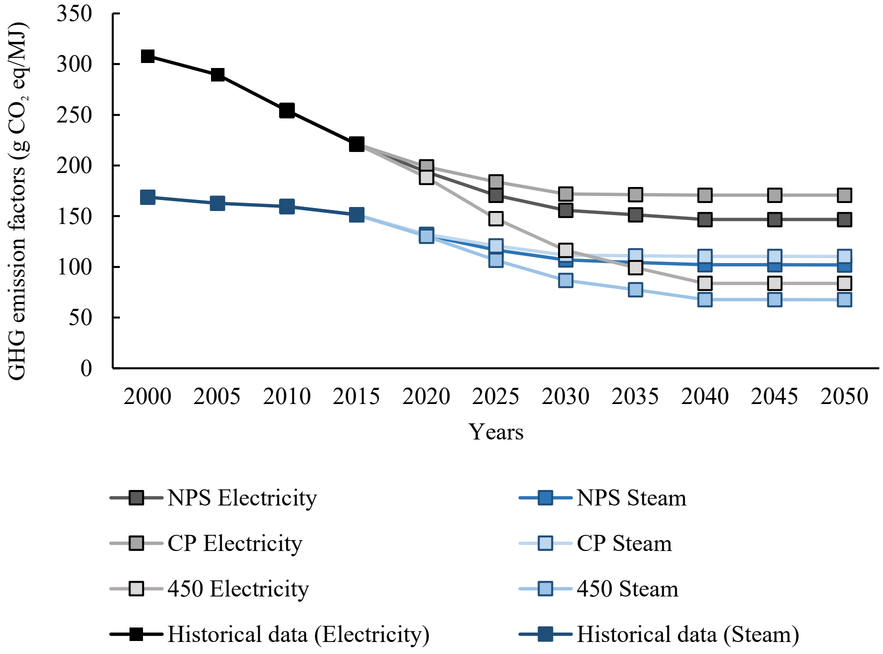

Fig. S3. GHG emission factors of steam and electricity from 2000 to 2050

7. Energy consumption of wood production processes

The data in Table S10 represent M_e in calculation methods.

Table. S10. Energy consumption of wood production processes[2]

Step	Method	Energy type	Energy consumption
Logging	chain saw	gasoline	0.163 L/m^3
Skidding	tractor	diesel	0.588 L/m^3
	cableway	diesel	0.496 L/m^3
Loading	winch machine	diesel	0.118 L/m^3
Transport	diesel vehicles	diesel	0.06 L/(m^3*km)
Timber yard	storage & machining	electricity	1.315 kW*h/m^3

8. GHG emissions structure under different scenarios

Fig. S4 shows the GHG emission structure under 'ECS+450+CCS' scenario in Fig. 13 in the main text. With the increase of purchased heat and electricity, the proportion of coal and biomass consumed by self-equipped thermal power plants will drop significantly. However, the energy structure which is able to produce heat limit the decrease of emission factor of heat and it will gradually take the largest share of emissions. The operation of CCS technology in thermal power plants can significantly reduce GHG emissions and eventually achieve the emission mitigation target.

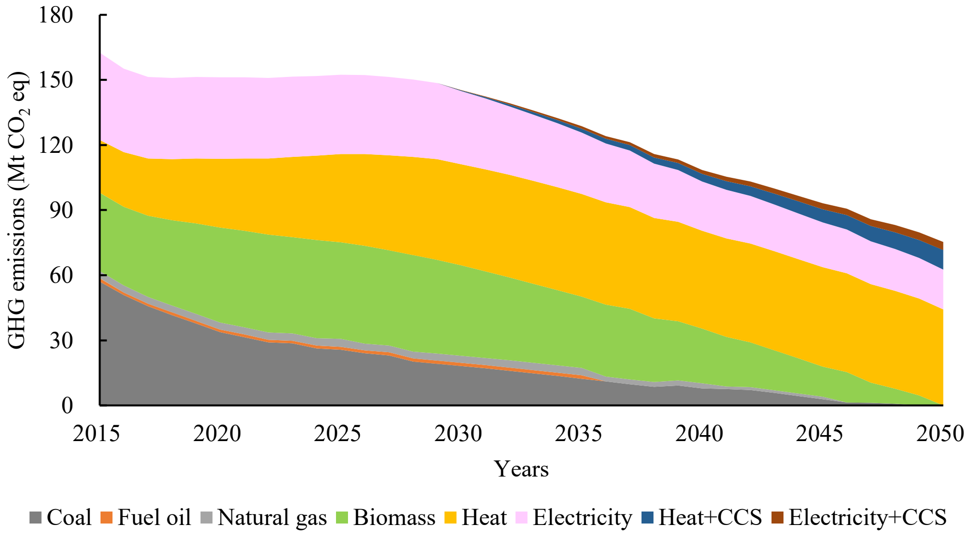

Fig. S4. GHG emissions structure under the scenario for achieving mitigation target

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