Supplementary Data

S1 Main calculation model formulas

S1.1 Grey Markov model

The formula for calculating the total amount of crop residue output is:

$$S = \sum_{j} \hat{S}_j \times D_j , \qquad (1)$$

where j = 1–10, representing 10 types of crops: rice, wheat, corn, other cereals, beans, tubers, oil-bearing crops (including peanuts, sesame and rapeseeds), cotton, fiber crops, sugar crops . S represents the total amount of crop residue output expressed in tons per year. S_j represents the net production of a particular type of crops. D_j represents the ratio of crop to crop residues, which can be obtained from the MOA/DOE report.

The formulae used for the Grey-Markov model are as follows:

$$X_{(1)}^{\frac{1}{m}}(t+1) = (X_{(0)}^{\frac{1}{m}}(1) - \mu / a)e^{-at} + \mu / a , \qquad (2)$$

$$X_{(0)}\left(t+1\right) = X_{(1)}\left(t+1\right) - X_{(1)}\left(t\right) , \qquad (3)$$

$$\hat{S}_j\left(t\right) = X_{j(0)}\left(t+1\right) , \qquad (4)$$

$$\Delta_{ij} = [A_{ij}, B_{ij}], \qquad (5)$$

$$A_{ij} = \hat{S}_j\left(t\right) + a_{ij}\bar{S}_j , \qquad (6)$$

$$B_{ij} = \hat{S}_j\left(t\right) + b_{ij}\bar{S}_j , \qquad (7)$$

where Δ_i (i = 1949, 1950,…, 2010) represents the output state of crop j in year i. $\hat{S}_j$ represents the change in crop net production. a_{ij} and b_{ij} are translation constants. $\bar{S}_j$ represents the average net production of crop j. With the classification of Δ_i performed using the Mathematics software package, the state transfer probability matrix from the Markov model is used to simulate crop net production from 2011 to 2030.

S1.2 Module for calculating the potential of crop residue recycling

The calculation formula is as follows:

$$\mathrm{SRP}_t = \sum_l \mathrm{S}_{l,t} = \sum_l \sum_k \mathrm{S}_{l,k,t} = \sum_l \sum_k (\mathrm{po}_{l,k,t} / \mathrm{TI}_{l,k,t}), \qquad (8)$$

in which SRP_t represents the potential of CRRC for year t, expressed in million tons. $\mathrm{S}_{l,t}$ represents the potential of crop residue recycling by product l in year t, expressed in million tons. $\mathrm{S}_{l,k,t}$ represents the potential of crop residue recycling by technology k for product l in year t, expressed in million tons. $\mathrm{po}_{l,k,t}$ represents the output of product l. $\mathrm{TI}_{l,k,t}$ represents the transform index of technology k for product l in year t, expressed in kWh t^{-1}, m^3 t^{-1}, t t^{-1}, where the transform index (TI) reflects the system’s efficiency affected by different equipment used to implement the technology.

S1.3 Technology selection module

The target variable (TV) calculation is as follows:

$$\max \mathrm{TV}_t = \begin{pmatrix} \sum_l \sum_k \mathrm{IV}_{l,k,t} \left(\frac{\mathrm{po}_{l,k,t_0}}{\mathrm{TI}_{l,k,t_0}} + \frac{\mathrm{IV}_{l,k,t}}{\sum_l \sum_k \mathrm{IV}_{l,k,t}} \left(\sum_l \sum_k \frac{\mathrm{po}_{l,k,t}}{\mathrm{TI}_{l,k,t}} - \sum_l \sum_k \frac{\mathrm{po}_{l,k,t_0}}{\mathrm{TI}_{l,k,t_0}} \right) \right) & (\mathrm{CUR}_t < 100\%) \\ \sum_l \sum_k \mathrm{IV}_{l,k,t} \left(\frac{\mathrm{IV}_{l,k,t}}{\sum_l \sum_k \mathrm{IV}_{l,k,t}} \times \frac{\mathrm{po}_{l,k,t}}{\mathrm{TI}_{l,k,t}} \right) & (\mathrm{CUR}_t = 100\%) \end{pmatrix},$$

(9)

$$\mathrm{PR}_{l,k,t} = \frac{\mathrm{IV}_{l,k,t}}{\sum_l \sum_k \mathrm{IV}_{l,k,t}}, \qquad (10)$$

TV_t represents the total practical net economic benefit from technologies in year t. $PR_{l,k,t}$ represents the popularization rate of technology k in producing product l in year t, expressed as a percentage. $po_{l,k,t}$ and $po_{l,k,t0}$ represent the output of product l by technology k in year t and the base year t_0.

If the independent variables (IV) as the net economic average benefit of a technology (IV_{neb}), the assessment uses a cost-benefit analysis to estimate the likely market penetration of different crop residue recycling technologies. The calculation formula of IV is as follows:

$$\mathrm{IV}_{l,k,t} = \frac{\mathrm{AB}_{l,k.t}}{\mathrm{TI}_{l,k.t}} = \frac{\mathrm{AR}_{l,k.t} - \mathrm{AC}_{l,k.t}}{\mathrm{TI}_{l,k.t}} = \frac{(\mathrm{Sub}_{l,k,t} + \mathrm{P}_{l,k,t})\mathrm{po}_{l,k,t} - \sum_n \mathrm{C}_{n,l,k,t} / \mathrm{po}_{l,k,t}}{\mathrm{TI}_{l,k.t}}, \qquad (11)$$

in which $AB_{l,k,t}$, $AR_{l,k,t}$, and $AC_{l,k,t}$ represents the average benefit, average revenue and average cost for producing one unit of product l by technology k in year t. $P_{l,k,t}$ represents the price per unit of product l produced by technology k in year t. $Sub_{l,k,t}$ represents the subsidy per unit of product l from the government for technology k in year t. $C_{n,l,k,t}$ represents the total cost to produce product l using technology k in year t, including committed capacity costs, fuel costs, haul costs, labor costs, maintenance costs, main material costs, and management costs.

If resources (energy or materials) are saved by a technology (IV_{rs}), crop residues recycling technologies can be used as a substitute for traditional materials for producing certain products. The extent of substitution depends on parameters such as the rate of power generation and thermal efficiency when crop residues are used to replace fossil fuels to produce power or heat. The calculation formula of IV for this purpose is as follows. When crop residues are used as energy resources for heat supply:

$$\mathrm{IV}_{l,k,t} = \mathrm{TI}_{l,k.t}\,\frac{\mathrm{Q}_k \times \eta_k}{\mathrm{Q}_{fk} \times \eta_{fk}}, \qquad (12)$$

where Q_k and Q_{fk} represent the heat content of crop residues and fossil fuel, expressed in kJ m^{-3} or kJ kg^{-1}; η_k and η_{fk} represents the thermal efficiency of crop residues and fossil fuel, expressed as percentages. When crop residues are used as energy resources for power generation:

$$\mathrm{IV}_{l,k,t} = \frac{\mathrm{p}_{k,t}}{\mathrm{p}_{fk,t}}, \qquad (13)$$

where $p_{k,t}$ and $p_{fk,t}$ represents the rate of power generation of crop residues and fossil fuels, expressed in kWh kg^{-1}. When crop residues are used as forage, manure or industrial raw materials to replace dry grass, chemical fertilizers, waste paper or wood, the format of the calculation formula for IV is the same as the above equation. However, $p_{k,t}$ and $p_{fk,t}$ will respectively represent the nutritive value, fertilizer efficiency or paper production efficiency of crop residues and its substitution.

S1.4 Constraints

Crop residue recycling constraints: the amount of crop residues recycled by the 20 alternative technologies is the total amount of crop residues that are recycled for each year.

$$\sum_{l}\sum_{k}\mathrm{S}_{l,k,t} = \mathrm{S}_t \times \mathrm{CUR}_t, \qquad (14)$$

Technological progress constraints: the potential of each utilization purpose for each year should be more than that for the base year;

$$\mathrm{S}_{l,t} > \mathrm{S}_{l,t_0}, \qquad (15)$$

the potential for each technology should be less than the total potential of all technologies;

$$\frac{\mathrm{IV}_{l,k,t}}{\sum_l \sum_k \mathrm{IV}_{l,k,t}} < 1, \qquad (16)$$

the net benefits of all technologies should be above zero;

$$\sum_l \sum_k \mathrm{IV}_{l,k,t} > 0, \qquad (17)$$

if the net benefit of some technology is above zero, the amount of crop residues recycled by this technology should be monotone increasing, otherwise the amount should be monotone decreasing.

$$\frac{\mathrm{po}_{l,k,t+1}}{\mathrm{TI}_{l,k,t+1}} > \frac{\mathrm{po}_{l,k,t}}{\mathrm{TI}_{l,k,t}} > \frac{\mathrm{po}_{l,k,t_0}}{\mathrm{TI}_{l,k,t_0}}, \qquad (18)$$

when $\min\left(\mathrm{IV}_{neb,l,k,t}, \mathrm{IV}_{rs,l,k,t}\right) > 0$ and $\mathrm{IV}_{r,l,k,t} \neq \min\left(\mathrm{IV}_{r,l,k,t}\right)$;

$$\frac{\mathrm{po}_{l,k,t+1}}{\mathrm{TI}_{l,k,t+1}} < \frac{\mathrm{po}_{l,k,t}}{\mathrm{TI}_{l,k,t}} < \frac{\mathrm{po}_{l,k,t_0}}{\mathrm{TI}_{l,k,t_0}}, \qquad (19)$$

when $\min\left(\mathrm{IV}_{neb,l,k,t}, \mathrm{IV}_{rs,l,k,t}\right) < 0$ or $\mathrm{IV}_{r,l,k,t} = \min\left(\mathrm{IV}_{r,l,k,t}\right)$. $\mathrm{IV}_{\mathrm{neb},l,k,t}$, $\mathrm{IV}_{\mathrm{rs},l,k,t}$ represent $\mathrm{IV}_{r,l,k,t}$ for the different targets (r = neb, rs. “neb” means “net economic average benefit”; “rs” means “resources (energy or materials) saved”).

S2 Main model results and intermediate results

The results indicate that the output of crop residue will continue to increase, with available amounts expected to reach 1062 million tons by 2030, where corn, rice, and wheat will account for 76% of total crop residue. In the field of recycling potential, our study has drawn the following conclusions. 1) The amount of crop residue recycled is expected to reach 956 million tons by 2030. 2) Forage production is simulated to remain the main recycling approach, accounting for 40% of the total amount of recycled crop residue in 2030. 3) The amount used for power generation will increase significantly, and is expected to reach 22% in 2030. 4) The average worth of crop residue is expected to be 138 CNY per ton by 2030, and the net benefit to power generation and heat generation is expected to increase by approximately 7-fold. Prioritized alternative technologies can also be obtained through the model.

The benefits of the technologies on the top of the priority list (liquefaction, amination, silo, CSP, MDLA, MSS, solidification, SPCP and CRF) are expected to increase their market share to more than 85%. The relatively high price of traditional energy resources, such as coal and oil, increases the advantages of co-firing straw power and bio-coal. According to our study, decision makers can prioritize various crop residue recycling technologies. In some cases, in regions where production and living levels are constrained, economic incentives such as subsidies or tax incentives should be provided to achieve sustainable goals.

Table S1 Net production of ten types of crops from 1949 to 2010 in China (10000 tons) [a)]

	rice	wheat	corn	beans and other cereal	tubers	oil-bearing crops	cotton	fiber crops	sugar cane
Dj	1.0	1.0	2.0	1.5	1.0	2.0	3.0	2.0	0.1
1949	4865	1381	1242	1964	985	256	44	4	283
1950	5510	1450	1389	2462	1239	297	69	8	338
1951	6056	1723	1381	2557	1400	362	103	25	499
1952	6843	1813	1685	3215	1633	419	130	31	760
1953	7127	1828	1669	3145	1666	386	118	14	771
1954	7085	2334	1714	2733	1698	431	107	14	958
1955	7803	2297	2032	2942	1890	483	152	26	971
1956	8248	2480	2305	2524	2185	509	145	26	1030
1957	8678	2364	2144	2626	2192	420	164	30	1189

1958	8085	2259	2312	2159	3273	477	197	27	1563
1959	6937	2218	1665	2136	2382	410	171	23	1215
1960	5973	2217	1603	1456	2035	194	106	20	986
1961	5364	1425	1549	1721	2173	181	80	12	507
1962	6299	1667	1626	1789	2345	200	75	13	378
1963	7377	1848	2058	1978	2139	246	120	20	832
1964	8300	2084	2269	2138	2013	337	166	24	1347
1965	8772	2522	2366	1947	1986	363	210	28	1538
1966	9539	2528	2843	2441	2253	392	234	35	1404
1967	9369	2849	2741	2539	2243	399	235	40	1524
1968	9453	2746	2503	2434	2229	343	235	40	1250
1969	9507	2729	2492	2364	2412	333	208	34	1288
1970	10999	2919	3303	2725	2668	377	228	34	1556
1971	11521	3258	3585	2510	2507	411	211	30	1526
1972	11336	3599	3210	2043	2452	412	196	38	1874
1973	12174	3523	3863	2719	3156	419	256	56	1964
1974	12391	4087	4292	2588	2824	441	246	63	1872
1975	12556	4531	4722	2517	2857	452	238	70	1914
1976	12581	5039	4816	2091	2666	401	206	73	1956
1977	12857	4108	4939	2108	2967	402	205	86	2021
1978	13693	5384	5595	2220	3174	522	217	135	2382
1979	14375	6273	6004	2122	2846	644	221	136	2461
1980	13991	5521	6260	2017	2873	769	271	144	2911
1981	14396	5964	5921	2175	2597	1021	297	158	3603
1982	16160	6874	6056	2260	2705	1182	360	124	4359
1983	16887	8139	6821	2566	2925	1055	464	125	4032
1984	17826	8782	7341	2445	2848	1191	626	179	4780
1985	16857	8581	6383	2209	2604	1578	415	445	6047
1986	17222	9004	7086	2153	2534	1474	354	193	5853

1987	17442	8777	7982	2215	2822	1528	425	208	5550
1988	16911	8534	7735	2165	2697	1320	415	181	6187
1989	18013	9081	7893	1842	2730	1295	379	112	5804
1990	18933	9823	9682	2126	2743	1613	451	110	7215
1991	18381	9595	9877	2960	2716	1638	374	88	8419
1992	18622	10159	9538	3103	2844	1641	434	94	8808
1993	17751	10639	10270	3808	3181	1804	477	96	7624
1994	17593	9930	9928	4034	3025	1990	420	75	7345
1995	18523	10221	11199	3457	3263	2250	477	90	7940
1996	19510	11057	12747	3603	3536	2211	420	80	8360
1997	20074	12329	10431	3392	3192	2157	460	75	9387
1998	19871	10973	13295	3486	3604	2314	450	50	9790
1999	19849	11388	12809	3153	3641	2601	383	47	8334
2000	18791	9964	10600	3178	3685	2663	442	53	7635
2001	17758	9387	11409	3147	3563	2655	532	68	8655
2002	17454	9029	12131	3426	3666	2627	492	96	10293
2003	16066	8649	11583	3259	3513	2543	486	85	9642
2004	17909	9195	13029	3257	3558	2823	632	107	9571
2005	18059	9745	13937	3194	3469	2802	571	111	9452
2006	18172	10847	15160	3113	2701	2452	753	89	10460
2007	18603	10930	15230	2742	2808	2416	762	73	12188
2008	19190	11246	16591	3119	2980	2698	749	63	13419
2009	19510	11512	16397	2922	2996	2899	638	39	12277
2010	19576	11518	17725	3013	3114	2931	596	32	12009

Note: a) The data sources: China Statistical Yearbooks (1950–2011), National Statistics Bureau of China

Table S2 Straw and food outputs from 1949 to 2030 in China (10000 tons)

	straw	food		straw	food		straw	food		straw	food
1949	13333	11020	1970	28873	24775	1991	60302	54048	2011	77269	66819
1950	15505	12754	1971	29829	25529	1992	61008	55243	2012	78600	67930
1951	16859	14081	1972	28471	25122	1993	63816	55650	2013	78881	69197
1952	19786	16498	1973	32460	28074	1994	62579	54340	2014	78620	68620
1953	19880	16710	1974	33575	28741	1995	66493	57419	2015	79352	67798
1954	19923	17060	1975	34973	29787	1996	71680	61525	2016	81741	69232
1955	21986	18570	1976	34670	29756	1997	68327	61496	2017	78235	67422
1956	22865	19426	1977	34593	29607	1998	73324	63834	2018	83669	71118
1957	22912	19777	1978	38974	33322	1999	72502	62204	2019	87011	73990
1958	23181	20325	1979	41154	35082	2000	65927	57010	2020	88579	75855
1959	19526	17134	1980	40861	34757	2001	66155	57175	2021	89766	78112
1960	16420	14570	1981	41671	36132	2002	67500	59213	2022	90217	79063
1961	15294	13000	1982	45369	40080	2003	63961	55826	2023	93816	82205
1962	16909	14379	1983	49597	43014	2004	70319	60080	2024	94733	83490
1963	19382	16598	1984	52902	46018	2005	72420	61338	2025	97805	85342
1964	21449	18654	1985	50017	45119	2006	73880	63797	2026	96843	84325
1965	22442	19704	1986	51143	45873	2007	77163	66230	2027	94024	83258
1966	25294	21634	1987	53630	46949	2008	71797	64619	2028	96933	85187
1967	25407	21899	1988	51725	46145	2009	74966	65263	2029	104269	87135
1968	24601	21193	1989	52904	47149	2010	73550	63103	2030	106245	89457
1969	24597	21333	1990	59573	52696						

Table S3 Simulation of crop residues utilization for different purposes (million tons)

	heat	power	forage	manure	IRM[a]		heat	power	forage	manure	IRM
1981	105		42	17	5	2006	101	1	2340	125	21
1982	109		49	18	5	2007	116	2	248	126	22
1983	118		53	19	6	2008	95	4	247	127	13
1984	125		55	22	7	2009	100	9	255	128	24
1985	134		61	23	7	2010	102	20	253	129	11
1986	140		68	22	8	2011	104	33	259	130	21
1987	148		74	25	8	2012	106	45	259	131	21
1988	163		82	26	10	2013	103	55	267	122	26
1989	165		84	24	12	2014	105	66	274	113	23
1990	170		92	22	14	2015	103	75	281	114	22
1991	176		107	22	15	2016	95	83	308	115	21
1992	196		114	22	16	2017	81	91	315	107	12
1993	188		120	23	19	2018	92	98	321	118	23
1994	183		125	24	20	2019	116	104	327	119	20
1995	178		131	24	22	2020	120	108	333	121	27
1996	171		152	25	22	2021	123	112	338	126	28
1997	158		167	26	23	2022	129	115	344	133	17
1998	129		174	26	23	2023	136	119	348	145	31
1999	126		185	27	22	2024	138	122	354	146	37
2000	115		192	46	21	2025	137	143	357	148	46
2001	99		198	81	22	2026	138	145	361	150	38
2002	85		204	89	18	2027	141	146	365	151	12
2003	86		192	93	20	2028	144	168	369	153	17
2004	77		203	103	21	2029	150	199	382	155	32
2005	82		226	117	21	2030	157	211	385	157	30

Note: a) IRM: industrial raw material production

Table S4 Simulation of potential and net benefits of crop residues recycled by different technologies and sensitivity analysis in 2020 and 2030

	potential simulation		net benefits simulation and sensitivity analysis					
	2020 /(10^6 t)	2030 /(10^6 t)	2020/(10^6 CNY)	0.9C[a)]/%	1.1C[b)]/%	2030/(10^6 CNY)	0.9C[a]/%	1.1C[b)]/%
liquefaction	62	100	19.01	3.36	–3.80	31.05	3.36	–3.80
amination	103	187	12.15	9.96	–9.96	16.76	10.02	–10.02
silo	156	102	7.49	10.01	–10.01	4.90	10.00	–10.00
CSP	57	111	8.61	5.23	–5.34	22.07	5.17	–5.44
MDLA	54	69	9.99	10.01	–10.01	12.70	10.00	–10.00
MSS	74	83	3.70	10.00	–10.00	4.15	9.88	–9.88
solidification	30	55	4.50	10.00	–10.00	8.25	9.94	–9.94
SPCP	31	60	2.54	72.05	–52.36	4.92	76.83	–46.34
CRF	50	65	8.75	9.94	–9.94	11.38	10.02	–10.02
SGP	16	32	0.70	84.29	–47.14	1.38	89.86	–40.58
OPRF	14	18	0.62	9.68	–9.68	0.81	9.88	–9.88
SGH	4	10	0.16	281.25	–18.75	0.38	297.37	–10.53
SCM	12	18	6.60	10.00	–10.00	7.90	10.00	–10.00
BH	8	15	0.83	6.02	–7.23	1.48	6.08	–6.76
BCH	2	4	0.02	300.00	–100.00	0.03	300.00	–100.00
BP	4	7	0.04	0.00	0.00	0.07	14.29	–14.29
MDRF	3	6	0.01	0.00	0.00	0.02	0.00	0.00
SK	9	12	3.15	9.84	–9.84	4.20	9.84	–9.84
SCH	13	3	0.04	0.00	0.00	0.01	0.00	0.00
SP	6	0	1.20	10.00	–10.00	0.00	0.00	0.00

Notes: a) The data represent that the changes of the net benefits of different technologies when the average cost per unit crop residues decrease by 10%; b) the data represent that the changes of the net benefits of different technologies when the average cost per unit crop residues increase by 10%.

Table S5 Alternative technologies[1–4]

alternative uses	technologies	cases
power generation	straw pure combustion power generation (SPCP)	the SPCP plant in Shan county, Shandong Province
	co-firing straw power generation (CSP)	Shi Li Quan power plant in Shandong Province
	straw gasification power generation (SGP)	MW-scale straw gasification power generation systems
	biogas power generation (BP)	the BP plant in Zibo, Shandong Province
heat generation	stove combustion heat generation (SCH)	the household stoves in rural areas
	boiler combustion heat generation (BCH)	the straw boilers in rural areas
	straw gasification heat generation (SGH)	the biomass gasification pilot projects for gas supplying system in rural areas
	biogas heat generation (BH)	biogas production pilot demonstration projects in 11 provinces
	solidifications	the demonstration project in Huaian, Jiangsu Province
	liquefaction	the project of ethanol production with straw in Nanyang, Henan Province
manure production	mechanization returning to field (MDRF)	the projects in Jiangsu Province
	overlay planting returning to field (OPRF)	the projects in Changzhi, Shanxi Province
	composting returning to field (CRF)	the projects in Hebei Province
	manure digested by livestock and ashes (MDLA)	the projects in Shandong Province
forage production	silo	the cattle and sheep breeding base in Shandong Province
	amination	the cattle and sheep breeding base in Shandong Province
	microbial straw silage (MSS)	the cattle and sheep breeding base in Shandong Province
industrial	straw pulp (SP)	the Quanlin project in Jinan, Shandong Province
raw material (IRM)	cultivation of edible mushrooms with straw (SCM)	the projects in Lianyungang, Jiangsu Province
production	straw knitting (SK)	the projects in Shandong Province and Sichuan Province

S3 Alternative technologies appendix

The CRRC model selected 20 crop residue recycling technologies for analysis, which are further divided into five classes as shown in Table S5.

S3.1 Power generation technologies

S3.1.1 Straw pure combustion power (SPCP) generation technology

A combustion power plant collects straw and sends it into a particular steam boiler, which drives dynamo to produce electricity. In 2006, the first straw combustion power plant in China was operated in Shan county, Shandong province. The plants burn 0.18 to 0.22 million tons of straw a year. The investment cost to build a straw combustion power plant can be 10000 CNY kW^{-1}, as key technologies are imported from Denmark. By 2015, there are expected to be 55 power plants, with 120 expected by 2020. The electricity generated by these plants will reach 7000 million kWh and 15200 million kWh respectively.

S3.1.2 Co-firing straw power generation technology

Co-firing combustion technology uses straw together with coal as fuel in coal-fired power plants. After technological improvements to the 140 MW power generation system in 2005, the Shi Li Quan power plant in Shandong Province became the first co-firing straw power plant, burning 10 tons of straw every year. Co-firing straw in a gas flame enables a high burning rate as well as high combustion efficiency. However, these plants are only subsidized with 0.25 CNY kWh^{-1} from the government unless the proportion of conventional energy exceeds 80% of the total quality of heat.

S3.1.3 Straw gasification power generation technology

Research and development of biomass gasification-power generation technology began in the 1960s, characterized by a 60 kW rice hull gasification and power generation system. Different scales of straw gasification power generation systems with circulating fluidized beds for different kinds of crop residues have been developed after 1987. Besides a 200 kW gasification generator set, demonstration units of 600 and 800 kW have also been built and successfully operated. In recent years, a study on MW-scale biomass gasification power generation (BGPG) system was carried out, with the aim of developing a mid-scale application of biomass technology. In 1998, a 1 MW BGPG system with a circulating fluidized bed gasifier was developed by the Guangzhou Institute of Energy Conversion. Currently, a 2000 kW straw gasification power generation system has been built, costing under 3500 CNY kW^{-1} and with a power generation cost between 0.2 and 0.3 CNY kWh^{-1}.

S3.1.4 Biogas power (BP) generation technology

Since the mid-1980s, farmers in China began to build self-funded biogas digesters with a small proportion of collective subsidy. Development of biogas generation technology with crop residue as the main raw material is only in an early stage.

S3.2 Heat generation technologies

S3.2.1 Stove combustion heat (SCH) generation technology

China’s biomass stoves are used for cooking and heating. The large-scale use of inefficient bio-fuel stoves for cooking and heating in the rural areas of China can cause ecological and environmental problems [5]. In 1982, the Chinese government encouraged the diffusion of improved biomass stoves. From 1982 to 1994, these improved biomass stoves had been used by 144 million households, with 62% of the Chinese market penetrated [6]. After the diffusion program, the thermal efficiency of old stoves, which ranged from 10% to 12%, increased to greater than 20%–25%. However, this thermal efficiency is still low compared with other heat generation technologies available using crop residue.

S3.2.2 Boiler combustion heat (BCH) generation technology

Boiler combustion uses modernized boiler technology and is fit for large-scale utilization of biomass. Compared with stove combustion, boiler combustion has a combustion efficiency of 60%–80%. The cost of heat supply in rural areas will decrease owing to the scaling effect if household stoves are replaced by these central heating projects.

S3.2.3 Straw gasification heat (SGH) generation technology

Since 1995, the NDRC jointly with other administrative departments has arranged special funds to support the construction and management of biomass gasification pilot projects for supplying gas systems to rural areas. This is expected to boost the popularization of this technology. Over the past decade, there has been significant progress in the development of gasification technology in China. Many types of biomass gasification processes have been developed by treating different materials. The first generation of this technology is the up-draft fixed bed gasifier for boiler fuel, with gasification efficiency over 75% and maximum energy output of about 10 million kJ h^{-1}. The second generation is the down-draft fixed bed gasifier for supplying domestic cooking gas and wood drying process in factories, with gasification efficiency around 75% and maximum energy output of 4 million kJ h^{-1}. The most recent development is the circulating fluidized bed gasifier for fuel boiler or electricity generation, with efficiency of 75% but with a maximum energy output available to be increased to 40 million kJ h^{-1} [7]. Currently, only the boiler heating and power generation projects are of appropriate scale to be economically viable because of constraints including pollution issues, competitiveness with electricity generated by conventional fuel, and the problem of transmitting the electricity into the local electric grid.

S3.2.4 Biogas heat (BH) generation technology

Biogas technology is an applied eco-agricultural technology, by which methane can be obtained by mixing crop residues, human wastes and animal dung and organic wastes in certain proportions under anaerobic conditions. However, prior to 2004, crop residue had been used as a supplementary material for biogas production. Despite 10.8 million household biogas digesters being used by the end of 2005, there were only about 0.2 million tons of crop residues devoted to producing biogas. The Ministry of Agriculture has since organized related research institutions to develop the technology for crop residue biogas production and has constructed hundreds of pilot demonstration projects across 11 provinces in China. These household biogas projects and biogas central supply projects have achieved remarkable success [8].

S3.2.5 Solidification technology

Crop residue solidification technology changes the briquette production of crop residue into molding charcoal or bio-coal at higher pressure. This mode of crop residue utilization improves energy efficiency by 40%. Crop residue carbonization and bio-coal have extensive applications for energy production and are convenient for large-scale transportation and storage. Until recently, key equipment was not able to meet the needs of commercialization and large-scale promotion in China because such equipment had high energy consumption, low reliability and inferior applicability, as well as high cost of pre-processing [9]. According to the goals mentioned in the report of Middle- and Long-Term Program of Renewable Energy Development, the production of biomass solid fuel is expected to reach 50 million tons in 2020, which indicates that crop residue solidification technology will become one of the main approaches to crop residue utilization within 10–20 years.

S3.2.6 Liquefaction technology

The Chinese corn-ethanol program appears to be following in the footsteps of the program that has been in place in the United States since the 1970s. Around 1990, China started the development and research on hydrolysis technology to produce ethanol. Progress has been made in ethanol production with crop residue instead of corn technology, and the first large-scale fibrous ethanol production line with a production capacity of 5000 tons has been established.

S3.3 Manure production technologies

Crop residue can be returned to the fields to improve soil organic matter, benefitting succeeding crops. It is an important part of manure production using biomass in rural China. Four types of this crop return are mentioned in this study. Currently, direct returning of crop residue to the fields is still practiced, through either turning the crop stubble over into the soil or spilling the crop residues into pieces by special machines. Besides these direct returns, indirect returning to the fields is also popular in China, including using organic fertilizers after fermentation, manure digested by livestock and ashes.

S3.3.1 Mechanization returning to field (MDRF)

Mechanized returning to field means to spill the crop residues into 10-cm-length pieces by special machines and turn them over into the soil. This method saves labor and work, and is also highly efficient. However, owing to high cost and energy consumption, the speed of this technology is low, with just 40 million tons of crop residue used by this technology.

S3.3.2 Overlay planting returning to field (OPRF) technology

As opposed to mechanization returning to field, overlay planting returning to field technology means to cover the soil with pieces or the whole stalk of crop residue directly, which decreases moisture evaporation in the soil and aids in moisture conservation. In 2010, about 8 million tons of crop residue was used in this way.

S3.3.3 Composting returning to field (CRF) technology

Crop residue composting is an effective way to store organic fertilizer. In 2010, more than 20 million tons of crop residue was used by this technology. Composting can be classified as common composting or high-temperature composting. In China, common composting is most commonly used but for long-term methods, high temperature composting can play a leading role.

S3.3.4 Manure digested by livestock and ashes (MDLA) technology

Manure digested by livestock and ashes technology means to feed livestock with crop residue as forage to provide nutrients by livestock feces as manure for the soil. More than 50 million tons of crop residues were used by this technology in 2010.

S3.4 Forage production technologies

S3.4.1 Silo technology

Since 1950, silo technology that changes crop residue into feed for domestic animals has been popularized. Prior to 1950, crop residue was mainly used as a fuel source for households, instead of firewood. With cheap prices and broad sources, the amount of crop residue used by this technology increased from 18.29 million tons in 1986 to about 160 million tons in 2010.

S3.4.2 Amination technology

Early in 1989, the Ministry of Agriculture ranked crop residues amination technology as one of 10 important practical technologies for promotion. With support from the government, amination crop residue increased from 1.83 million tons in 1989 to about 40 million tons in 2010. The cost of amination technology is 0.26 CNY kg^{-1}, which is higher than that of silo technology but is also more beneficial. Subsequently, amination technology has been rapidly developed over recent years.

S3.4.3 Microbial straw silage (MSS) technology

Microbial straw silage technology is a new technology with a processing cost of 0.04 CNY kg^{-1}. In 2010, about 18 million tons of straw were fermented by this technology.

S3.5 Industrial raw material (IRM) production technologies

For industrial purposes, crop residue is mainly used for papermaking, knitting or culture medium. Currently, papermaking pulp from straw has replaced pulp from waste paper. In China, straw pulp technology causes significant pollution and has high energy consumption.

Straw knitting has developed quickly in recent years because of obvious economic benefit. Products from straw knitting technology have been mainly exported by some provinces in China such as Shandong Province and Sichuan Province. About 1.6 million tons of straw has been used for knitting in 2010.

The cultivation of edible mushrooms with straw is a value-added process that converts these materials, which are otherwise considered as waste, into human food. This represents an efficient biologic method by which these residues can be recycled. About 1.8 million tons of straw have been used in Jiangsu Province.

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