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Supplementary Material for Modeling water-energy-food nexus to understand trade-offs between energy and agriculture under limited water availability

Junlian Gao [1,2,*], Xiangyang Xu [1,2], Guiying Cao [3], Yurii M. Ermoliev [3], Tatiana Y. Ermolieva [3], and Elena A. Rovenskaya [3,4]

1 Management School, China University of Mining and Technology (Beijing), Beijing 100083, China; xxy@cumtb.edu.cn
2 Resources and Environment Policy Research Center, China University of Mining and Technology (Beijing), Beijing 100083, China
3 International Institute for Applied Systems Analysis, Schlossplatz 1, A-2361 Laxenburg, Austria; Cao@iiasa.ac.at (G.C.); ermoliev@iiasa.ac.at (Y.M.E.); ermol@iiasa.ac.at (T.Y.E.); rovenska@iiasa.ac.at (E.A.R.)
4 Faculty of Computational Mathematics and Cybernetics, Lomonosov Moscow State University, Leninskie Gory, 1(52), GSP-1, Moscow 119991, Russia
* Correspondence: gao@iiasa.ac.at; Tel.: +86-152-1057-4472

The supplementary material presents the formal description of the regional spatially-detailed cost-minimizing model for coal and agricultural production planning under scarce natural resources and food, energy, water security targets. The document also includes the description of all parameters calibrated for the model, e.g. the calculation of the area occupied by gangue, as well as the data used in the case study of Shanxi province.

1. Water availability across Shanxi Province in 1994-2012

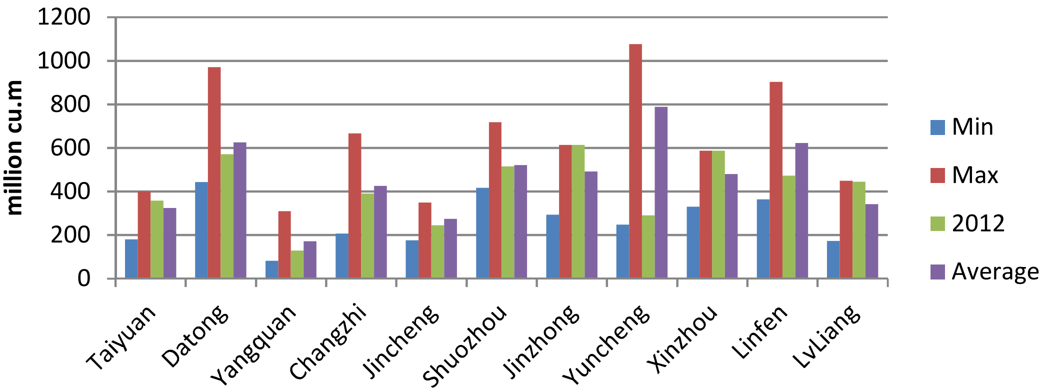

Figure S1. The minimum, maximum, the 2012 year, and the average water availibitiy by regions, Shanxi, from 1994 to 2012.

2. Technologies profile for the four water availability scenarios in Shuozhou city

Table S1. Coal technologies in Shuozhou under four water scenarios unit：Million tons.

Stages	Technologies	Scenarios			
		BAUWA	AWA	LWA	HWA
Exploitation	Underground	220.00	106.82	31.22	200.00
	Opencast	20.00	20.00	20.00	20.00
	Total	220.00	126.82	51.22	220.00
Processing	Wet	220.00	126.82	31.22	185.60

	Dry	0.00	0.00	0.00	20.00
	No Wash	0.00	0.00	20.00	14.40
	Total	220.00	126.82	51.22	220.00
	Electricity_one_through_Subcritical	0.00	0.00	0.00	0.00
	Electricity_one_through_Supercritical	0.00	0.00	0.00	0.00
	Electricity_closed_Subcritical	0.00	0.00	0.00	0.00
	Electricity_closed_Supercritical	0.00	30.86	0.00	0.00
	Electricity_closed_IGCC	0.00	0.00	0.00	0.00
	Electricity_air_cooled	0.00	0.00	31.22	0.00
	Electricity_hybrid	0.00	0.00	0.00	0.00
Conversion	Electricity_Total	0.00	30.86	31.22	22.8
	Coke	0.00	0.00	9.26	24
	Gasification	0.00	0.00	0.00	20.00
	Chemical	0.00	0.00	0.00	0.00
	Liquefaction	0.00	0.00	0.00	14.40
	Direct-utilization	1.10	1.10	1.10	1.10
	Export	218.90	94.86	8.90	157.70
	Total	220.00	126.82	51.22	220.00

3. Detailed mathematical description of the model

Indices

The model accounts for various coal mining, processing and conversion technologies, as well as for different types of crops in a number of locations within a region under investigation. We consider the existing technologies as well as those, which are only at the beginning of implementation or even in the research stage, for example, various carbon capturing technologies. Index i is used to denote the type of coal, which is a combination of the coal class, the extraction (underground room-and pillar or long wall mining, surface strip or auger mining, etc.) and the processing (washing, cleaning, purification, enrichment) technologies, for example, lignite class, longwall mining, and wet washing. By t we denote a coal conversion technology resulting in end-use product (electricity, coke, heat, gasification and liquefaction). Import and export can also be considered as a way of conversion. Index k is used to represent different types of crops (corn, wheat, soybean etc.). Index d defines the end-use product such as electricity, gas, oil, coke, etc.

Indexes j and m are used to denote different locations within the case study region. The model can operate at different resolutions. Depending on the chosen resolution, these indices refer to a county, a city, or a smaller geographical unit. In the studies, the analysis is carried out at the spatial resolution of 11 prefectural cities in Shanxi province.

Main variables and goal function

In the model, variables x_{ijmt} denote the amount of coal (in tons) of type i produced in location j, transported to location m and utilized by technology t. Variables y_{kjm} denote the amount of crop k of type (in tons) produced in location j and exported to location m. A social planner chooses how much of coal i and agricultural commodity k to produce in location l, so that the total cost of coal and agricultural production, transportation, conversion is minimized and constraints on natural resource utilization, environmental pollution, food security, energy (coal end-product) demand are fulfilled. The goal function is formulated as follows:

$$\min_{x,y} \sum_{i,j,k,m,t}\left[c_{ij}^{CP} x_{ijmt} + c_{ij}^{CT} x_{ijmt} + c_{ij}^{CC} x_{ijmt} + c_{kj}^{AP} y_{kjm} + c_{kj}^{AT} y_{kjm}\right] (1)$$

where c_{ij}^{CP} stands for the production cost of a unit (ton) of coal of type i in location j, c_{ijm}^{CT} stands for the transportation cost of a unit of coal i from location j to location m, c_{ijt}^{CC} defines the conversion costs of a unit of coal i by technology t in location j, c_{kj}^{AP} are costs associated with production of a unit (ton) agricultural commodity k in location j, c_{kjm}^{AT} stands for the transportation cost of a unit of the agricultural commodity k from location j to location m. By x and y we mean the sets of all x_{ijmt} and y_{kjm} correspondingly.

Resource and security constraints

Land constraints

In China about 40% of the total farmland area overlap with coal reserves. The model incorporates two main farmland disturbances from coal mining - land subsidence and gangue (waste) deposits which is left as a result of separating coal from other materials, both leading to deterioration of land. A number of researches have estimated the land subsidence rate due to coal mining.[2] The character of the subsidence depends on the disposition of mined strata and also on the mining process in place. For example, if backfill mining is applied, the land subsidence can be prevented or controlled as voids are filled with the low-cost solid materials, coming, e.g., from tailings. Using gangue for filling in the voids helps decrease the area occupied with the waste deposits. Subsided land can be recovered by reclamation programs; however it can take long time. Therefore, in our model we divide the farmland into three types: the land used for agriculture, subsided land and the land occupied by the gangue. We impose a land constraint prescribing that the total land used for agriculture, the land which subsides due to coal mining and the land occupied with waste deposits cannot exceed the total farmland in each location. Thus, the constraint is formulated as follows:

$$\sum_{k,m} l_{kj}^{A} y_{kjm} + \sum_{i,m,t} (1-r_{ij})\Delta l_j l_{ij}^{S} x_{ijmt} + g\sum_{i,m,t} x_{ijmt} \le L_j \quad (2)$$

where l_{kj}^{A} stands for the area of farmland required for production of a unit of crop k in location j, l_{ij}^{S} is the area of land that subsides as a result of coal mining of a unit of coal of type i in location j, Δl_j denotes the fraction of the farmland overlapped with the coal filed in the location j, r_{ij} stands for the land reclamation rate (or efficiency rate) for coal i in location j. Coefficient g stands for the coefficient of the gangue[1] occupied area resulting from the production of a unit of coal i in location j. L_j is the farmland constraint in the location j.

Food security constraints

We assume that the region under investigation aims to produce enough food to provide a required amount of calories (nutrition norms) to its population, i.e., ensure the food security. Domestic production can be supplemented by imports depending on the import costs, which can be higher than the costs of domestic production. Thus we impose a constraint on the minimal required level of commodity k in location m as follows

$$\sum_{j} y_{kjm} \ge D_{km}^{A} \quad (3)$$

where the right-hand side D_{km}^{A} defines the demand for agricultural commodity k in location m This constraint requires accounting for transportation costs in the goal function (1) among locations having shortages and overproduction. Note that D_{km}^{A} can be measured in terms of the minimum amount of daily calories per capita suggested by the World Health Organization (WHO) accounting for the size, age, sex, physical activity, climate, and other factors.

Energy security constraints

Our model is driven by an exogenous demand for the final energy (electricity) converted from coal. Apart from electricity, the model includes the demand for such end-products of coal as heat, coke, gas, and oil. The demand scenarios at national or subnational levels can come from aggregate models. The conversion efficiency depends on the conversion technologies. Energy security constraint is responsible for fulfilling the demand for the end-products from coal. It is introduced as follows:

$$\sum_{m,t} \alpha_{ijt}^{d} x_{ijmt} \geq D_j^d \quad (4)$$

where α_{ijt}^{d} denotes conversion efficiency of coal type i in location j by technology t, end-products are denoted by d, and D_j^d defines the demand for end-use product d.

Water security constraints

Since water plays a key role in coal production and at the same time it is essential for agriculture and for the daily use of regional residents, we impose a constraint on the total water consumed by coal extraction, processing and conversion as well as by the crops irrigation in each location j:

$$\sum_{i,m,t} w_{ij}^{P} x_{imlt} + \sum_{i,m,t} w_{ij}^{d} x_{ijmt} + \sum_{k,m} w_{kj}^{c} y_{kmj} \leq W_j \quad (5)$$

where w_{ij}^{P} defines the amount of water required to produce a unit of coal i in location j, w_{ij}^{d} is the amount of water required to convert a unite of coal i in location j, w_{kj}^{c} is the amount of water required to irrigate a unit of crop *k* in location *j*, and W_j defines the water availability for the industry and agriculture sectors in location *j*. Note that constraints on water use could also be introduced in the model separately for coal production (mining) and coal conversion.

Environmental Security

The environmental security considerations are introduced in the model in the form of emissions constraints, in particular, on the emissions from coal conversion, of which SO_2 and CO_2 are the most important pollutants. In the model we include technologies, which are able to reduce SO_2 and CO_2 emissions, however, at the cost of some additional water consumption.

The coal-based power plants are the main source of SO_2 emission in China, as SO_2 is generated during the combustion of coal.[3] In the future, due to the air emission standards coming into force, both new and existing coal-based plants will be required to install a Flue Gas Desulfurization (FGD) system in China. A wide range of commercial FGD processes are available to remove SO_2 from the flue gas. By far, wet scrubbing system is the most common one with 80% of the global installed capacity. However the FGD systems require a lot of water and their introduction will increase water needs for coal-based power plants too.[4] Thus, we impose a SO_2 emission constraint associated with the coal conversion in location j, which sets up an upper limit for SO_2 to be emitted in the location as follows:

$$\sum_{i,m,t} e_{ijt}^{SO2,d} x_{ijmt} \leq E_j^{So_2} \quad (6)$$

where $e_{ijt}^{SO2,d}$ is the SO_2 emission rate from coal i in location j by technology t converted into the end-use product d; E_j^{SO2} defines SO_2 emission cap in location j.

Apart from SO_2, coal-based power plants are the largest contributors to the atmospheric CO_2 concentrations. According to the IEA estimates, CO_2 resulting from coal-based power plants accounts for 45% of the total GHG emissions from fossil energy in China.[5] In order to decrease CO_2, China needs to considerably reduce the coal demand and supplement coal mining with carbon capture and storage (CCS) technologies. The timing and rate of this process will depend on the stringency of the near-term climate policy and will have important implications for the stranding of coal power plant capacity without CCS. [6]China will require commercial deployment of the CCS technology to begin in the next few years. The importance of CCS is expected to grow between 2020 and 2030.[7] However the CCS systems require additional cooling involving water. Introduction of the CCS systems, such as the wet cooling tower, doubles the water use at coal-based plants.[8] Given that, the water pressure in coal-producing regions in China is expected to become even stronger. In our model we impose a CO_2 emission constraint associated with the coal conversion by setting an upper limit for the CO_2 emissions as follows:

$$\sum_{i,m,t} e_{ijt}^{CO2,d} x_{ijmt} \leq E_j^{co_2} \quad (7)$$

where $e_{ijt}^{CO2,d}$ is CO_2 emission rate from conversion of coal i in location j by technology t converted into the end-use product d ; E_j^{CO2} defines CO_2 emission cap in location j .

Coal productive capacity

The amount of coal produced in each location is constrained by the coal productive capacity of that location. Coal productive capacity is the maximum amount of coal that can be produced annually depending on geological conditions, mining technology and equipment. According to the Regulation of State Safety Work Administration, for the sake of safety, mining companies are forbidden to produce above the productive capacity which is registered in coal production license.[9] We impose the following constraint

$$\sum_{i,m,t} x_{ijmt} \leq C_j^c \quad (8)$$

where C_j^c stands for the coal productive capacity in location j .

Coal purification and enrichment processes: dry and wet cleaning

Washing coal is a promising way of increasing its efficiency and utilization – it increases the coal quality as well as serves environmental protection. Washing helps remove the waste materials from coal. Also it makes the transportation cost lower. In China, the washing rate of raw coal is relatively low compared with, for example, the one in the USA and Australia. However, recently the Government has acknowledged the importance of washing coal in the energy development 12th Five-year Plan requiring the washing rate to increase up to 65% by 2015. In our model we impose a limit for the washing rate in each location j as follows

$$\sum_{m,t} x_{ojmt} \leq w \sum_{i,m,t} x_{ijmt} \quad (9)$$

where w is the washing rate of raw coal, and index o represents the type of coal without washing.

4. Model Calibration

We calibrate the model using relevant data from the year 2012. In the case study, we distinguish 11 major coal and crop production locations corresponding to the prefecture-level cities, i.e. Taiyuan, Datong, Changzhi, Jincheng, Jinzhong, Linfen, Lüliang, Shuozhou, Xinzhou, Yangquan, and Yuncheng.

In 2012, there was no absolute value control on GHG, as well as sulfur dioxide, nitrogen oxides in Shanxi, therefore in 2012 we assume no constraints on emissions.

Agricultural land use is constraint by the available farmland in each location in 2012.

Calculation of the Area Occupied by Gangue

In processing of coal, gangue comes from two stages of the process. On the stage of coal mining, gangue is extracted together with coal and is called extraction gangue. In Shanxi, the rate of extraction gangue (EGe) is 10%-15% of the coal production. On the second stage, gangue comes from coal preparation. The rate of coal preparation gangue (EG_P) is 15%-20% of the coal [10]According to the 12th Five-year Plan of the coal industry development, the rate of coal preparation gangue (R_P) should be about 65% of the processed coal at the end of 2015. The gangue output, GP_{ijt} in location j from coal of type i and technology t is calculated as follows

$$GP_{ijt} = \sum_m x_{ijmt}(1-R_P)EG_e + x_{ijmt}R_P EG_P = \sum_m x_{ijmt}(1-65\%)EG_e + x_{ijmt}65\%15\% = \sum_m 0.1325x_{ijmt} \quad (10)$$

In 2010, the rate of gangue utilization was about 61.4%. [11]The area occupied by the gangue pile (GL) is calculated as $GL = \left(\frac{1}{\tan B * \tan P} + \frac{3.14}{\tan^2 P}\right)H^2$, where H is the height of the gangue pile, which can be calculated as $H = \sqrt[3]{\frac{6\tan^2 P * \tan B}{2\tan P + 3.14\tan B}} * V$, *V* is the volume of the gangue pile, *B* is the angle of the waste dump, the value is 16°.[11] P is the repose angle of the waste dump with the value of 40°, the coefficient of 1.6t / m[3]

$$GP_{ijt} = \left(\frac{1}{\tan B * \tan P} + \frac{3.14}{\tan^2 P}\right)\left(\sqrt[3]{\frac{6\tan^2 P * \tan B}{2\tan P + 3.14\tan B}} * \frac{GL_{ijt}}{1.6}\right)^2 = 3.67 * 10^{-4}\left(GL_{ijt}\right)^2 \quad (11)$$

We assume the average weight of a gangue pile is about 100t, the coefficient of occupied area from the gangue is 0.0367 which is close to the field data 0.04 in Shanxi. [11] Finally, the coefficient of the area occupied by coal is calculated as 0.0367*0.1325≈0.0049

Data for Shanxi Province.

Table S2 is the data of the sown area of the crops in Shanxi, which is used for L_j in formula (2).[12] Table S3 is the yields of the crops in Shanxi.[13] The data in Table S1 divided by the data in Table S2, we get the data for l_{kj}^A in formula (2). Table S4 is the data of water availability in each city.[13] Table S5 is the data of proportion of water withdrawals by industry and agriculture sectors over the total water availability in 2012. [13] We get W_j in formula (5) by multiply the data from Table S4 and Table S5. Table S6 is the data of coal production in Shanxi, which is used for C_j^c in formula (8). [13] Table S7 is the data of the coal field area in Shanxi, which used for l_{ij}^S in formula (2). [13] Table S8 is the data of water withdrawals of different technologies in the coal industry, which is used for w_{ij}^P and w_{ij}^d in formula (5). [14-20] Table S9 is the data of Water withdrawals by crops in Shanxi, which is used for w_{kj}^c in formula (5). [21-23] Table S10 is the data of distance between major cities in Shanxi, which used for c_{ijm}^{CT} and c_{kjm}^{AT} in the formula (1).[13]Table S11 is the data of efficiency of conversion technologies, which is used for α_{ijt}^d in formula (4).[13] Table S12 is the data of demand for coal end-use products energy, which is used for D_j^d in the formula (4).[13] Table S13 is the data of demand for crops, which is used for D_{km}^A in formula(3).[13] The washing rate of raw coal is not lower than 60%, the target is set as of 2012 year, which is use for w in formula 10.

Table S2. Sown area of major farm crops in Shanxi (2012) unit: km^{2}.

	Wheat	Corn	Millet	Sorghum	Oats	Buckwheat	Bean	Potato
Taiyuan	8	555	64	13	6	13	46	70
Datong	0	1,619	180	20	89	54	124	274
Yangquan	1	478	45	0	0	0	8	19
Changzhi	142	2,045	127	13	3	3	59	103
Jincheng	617	855	77	4	0	0	374	27
Shuozhou	1	1,447	80	17	141	128	107	328
Jinzhong	202	2,101	129	31	1	15	182	68
Yuncheng	3,434	2,758	14	9	0	0	128	3
Xinzhou	2	2,475	279	17	193	4	243	521
Lingfen	2,357	2,136	163	9	3	8	116	69
Lvliang	71	1,609	382	63	32	13	531	450

Table S3. Output of major farm crops in Shanxi (2012) unit: ton.

	Wheat	Corn	Millet	Sorghum	Oats	Buckwheat	bean	Potato
Taiyuan	4,650	213,782	9,565	7,184	600	1,709	5,705	9,674
Datong	0	754,508	35,075	6,277	9,035	6,425	13,900	59,210
Yangquan	615	261,148	9,759	6	0	4	1,470	4,753
Changzhi	51,920	1,123,154	41,091	6,591	209	220	11,856	43,832
Jincheng	201,481	568,509	27,543	1,936	0	0	77,130	14,053
Shuozhou	424	870,431	19,254	5,300	14,304	12,431	9,970	73,160
Jinzhong	81,534	1,183,707	35,032	15,214	156	1,449	34,499	21,830
Yuncheng	1,041,930	1,208,948	3,084	3,387	0	0	11,619	1,690
Xinzhou	869	1,261,526	78,676	7,253	33,107	615	36,075	143,764
Lingfen	733,160	1,108,236	43,331	2,811	549	889	18,633	21,431
Lvliang	29,828	785,441	78,476	16,637	2,454	1,672	58,548	83,461

Table S4. Water availability in each city from 1994 to 2012 unit: million m^{3}.

	Taiyuan	Datong	Yangquan	Changzhi	Jincheng	Shuozhou	Jinzhong	Yuncheng	Xinzhou	Lingfen	Lvliang
2012	505	674	379	1,176	1,127	570	1,341	728	1,822	979	1,325
2011	552	546	356	1,220	1,373	476	1,242	2,600	1,626	1,241	1,202
2010	354	668	314	884	913	510	917	1,296	1,507	756	1,037
2009	433	551	320	731	808	460	930	1,116	1,413	814	999
2008	373	651	279	872	840	553	823	953	1,651	835	909
2007	400	586	299	1,396	1,056	561	1,085	1,141	1,626	1,112	1,074
2006	360	577	312	1,011	971	477	851	1,246	1,202	1,070	775
2005	269	670	238	1,048	986	508	847	932	1,181	939	794
2004	253	777	278	1,092	943	534	896	1,060	1,368	1,056	989
2003	405	741	284	2,005	1,464	604	1,090	2,694	1,370	1,874	955
2002	362	522	351	743	867	518	643	620	1,027	785	513
2001	362	522	351	743	867	518	643	620	1,027	785	513
2000	389	602	411	736	1,029	546	709	968	1,225	829	705
1999	351	575	446	620	855	535	805	995	1,096	824	560
1998	361	700	376	739	1,309	574	732	1,552	1,482	1,161	722
1997	564	870	909	1,373	1,611	767	749	653	1,088	855	1,336
1996	502	1,083	680	865	1,302	792	1,326	953	1,164	976	1,195
1995	405	1,144	586	760	1,092	786	795	1,185	1,557	1,145	1,136
1994	343	678	474	621	1,100	620	680	1,295	1,253	1,215	939

Table S5. Proportion of water withdrawals by industry and agriculture sectors over the total water availability in 2012 Unit: %.

Taiyuan	Datong	Yangquan	Changzhi	Jincheng	Shuozhou	Jinzhong	Yuncheng	Xinzhou	Lingfen	Lvliang
77.60	68.75	32.06	34.46	26.41	75.64	42.32	142.71	28.71	61.06	30.47

Table S6. Coal productive capacity in Shanxi (2012) (C_j^c) Unit: ton.

Taiyuan	Datong	Yangquan	Changzhi	Jincheng	Shuozhou	Jinzhong	Yuncheng	Xinzhou	Lingfen	Lvliang
34,965,800	105,630,900	60,937,500	116,621,400	84,411,300	210,800,000	80,214,100	4,922	53,574,500	47,573,400	118,178,500

Table S7. Area of coal field in Shanxi (l_{ij}^S) Unit: km2.

Taiyuan	Datong	Yangquan	Changzhi	Jincheng	Shuozhou	Jinzhong	Yuncheng	Xinzhou	Lingfen	Lvliang
1,368	632	1,484	8,500	5,350	1,603	13,000	1,450	4,386	15,400	10,640

Table S8. Water withdrawals (water needed for production of a unit of coal) by technology (w_{ij}^P).

Mining	**m3/ton**	**Conversion**	
Long wall	0.25~0.30	Generic	1.89-4.54(m3 /MWh)
Opencast	0.02	Tower-Subcritical	1.49-2.51(m3 /MWh)
Backfilling	0.25~0.30	Tower-supercritical	1.73-2.25(m3 /MWh)
Underground gasification	0.25~0.30	Tower-igcc	1.20-1.66(m3 /MWh)
Processing	m3/ton	Tower-subcritical-ccs	3.57(m3 /MWh)
Wetting clearing_dense medium separation	0.1	Tower-supercritical-ccs	3.2(m3 /MWh)
Wetting clearing_water circuit	0.1	Tower-igcc-ccs	1.98-2.11(m3 /MWh)
Wetting clearing_coal floatation	0.1	One-generic	0.37-1.20(m3 /MWh)
Dry clearing	0	One-subcritical	0.27-0.52(m3 /MWh)
		One-supercritical	0.24-0.47(m3 /MWh)
		Pond-generic	1.14-2.65(m3 /MWh)
		Pond-subcritical	2.79-3.04(m3 /MWh)
		Pond-supercritical	0.02-0.24(m3 /MWh)
		Coke	0.8(m3/t)
		Gasification	0.01(m3/m3)
		Liquefaction	7(m3/t)
		Chemical	8(m3/t)

IGCC: Integrated gasification combined cycle; CCS: Carbon capture and sequestration; One: Once through

Table S9. Water withdrawals (water needed for production of a unit of crops) by crops in Shanxi (w_{km}^c) unit: m3/t.

	Taiyuan	Datong	Yangquan	Jingzhong	Xinzhou	Shuozhou	Jincheng	Lvliang	Changzhi	Lingfen	Yuncheng
Wheat	498	523	541	1,007	838	691	631	638	988	688	1,268
Corn	395	621	357	226	237	481	276	379	568	373	633
Millet	1,340	946	932	440	397	765	738	645	717	537	987
Sorghum	726	1,292	1,790	786	835	1,297	832	1,027	955	1,343	1,535
Oats	5,032	4,682	5,320	6,320	6,455	4,665	3,138	5,455	2,760	2,860	5,179
Buckwheat	3,507	3,806	5,996	5,489	4,544	4,541	4,541	3,463	3,274	3,870	3,547
bean	1,585	1,522	1,088	374	364	1,826	1,047	876	1,143	1,057	1,794
Potato	152	146	82	64	52	141	65	41	114	67	170

Table S10. Distance between major cities in Shanxi unit: km.

	Taiyuan	Datong	Yangquan	Changzhi	Jincheng	Shuozhou	Jinzhong	Yuncheng	Xinzhou	Lingfen	Lvliang
Taiyuan	0	273	111	223	304	207	42	383	71	247	183
Datong	273	0	664	498	580	134	304	667	208	528	460
Yangquan	111	664	0	287	368	305	102	473	173	343	276
Changzhi	223	498	287	0	100	438	200	350	306	315	308
Jincheng	304	580	368	100	0	520	282	257	388	221	391
Shuozhou	207	134	305	438	520	0	240	603	144	474	395
Jinzhong	42	304	102	200	282	240	0	387	109	257	213
Yuncheng	383	667	473	350	257	603	387	0	472	144	368
Xinzhou	71	208	173	306	388	144	109	472	0	342	266
Lingfen	247	528	343	315	221	474	257	144	342	0	263
Lvliang	183	460	276	308	391	395	213	368	266	263	0

Table S11. Efficiency of conversion technologies (α_{ijt}^{d}).

Technology	One_through	Closed	Air_cooled	Hybrid	Gasification	coke	liquefaction	chemical	trans
Value	0.33	0.35	0.36	0.36	0.00	1.30	4.00	2.00	1.00
Unit	ton/Mwh	ton/Mwh	ton/Mwh	ton/Mwh	ton/m3	ton/ton	ton/ton	ton/ton	ton/ton

Table S12. Demand for coal end-use products energy (D_{j}^{d}).

Products	Coke	Electricity	Gas	Oil	Chemical
Value	56,000,000	230,173,000	8,000,000,000	3,600,000	4,400,000
Unit	ton	Mwh	m3	ton	ton

Table S13. Demand for crops (D_{km}^{A}) unit: ton.

Wheat	Corn	Millet	Sorghum	Oats	Buckwheat	bean	Potato
2,146,000	9,300,000	380,000	70,000	60,000	25,000	280,000	480,000

Table S14. Water constraints and consumption data.

City	Water constraints	Water consumption in reality	Water consumption in model
Taiyuan	391,883,519	137,666,992	248,031,975
Datong	463,383,212	474,896,387	463,383,212
Yangquan	121,507,803	68,456,393	72,205,810
Changzhi	405,285,811	408,228,806	405,285,811
Jincheng	297,587,001	300,892,997	297,587,001
Shuozhou	431,146,052	410,043,084	420,988,760
Jinzhong	567,476,918	576,640,819	567,476,918
Yuncheng	1,038,932,506	763,151,356	810,936,918
Xinzhou	523,111,241	519,232,299	460,194,767
Lingfen	597,782,433	579,034,404	526,094,745
Lvliang	403,695,082	354,003,013	318,419,073

Table S15 The land requirement for each crop in sub regions unit : km^2/ton.

	Wheat	Corn	Millet	Sorghum	Oats	Buckwheat	bean	Potato
Taiyuan	0.00174	0.00203	0.00670	0.00180	0.01062	0.00779	0.00799	0.00728
Datong	0.00133	0.00215	0.00513	0.00320	0.00988	0.00846	0.00896	0.00462
Yangquan	0.00189	0.00183	0.00466	0.00444	0.01369	0.01333	0.00550	0.00393
Changzhi	0.00273	0.00144	0.00309	0.00195	0.01333	0.01220	0.00499	0.00236
Jincheng	0.00227	0.00150	0.00278	0.00207	0.01416	0.01015	0.00485	0.00194
Shuozhou	0.00173	0.00166	0.00415	0.00322	0.00984	0.01009	0.01074	0.00448
Jinzhong	0.00220	0.00142	0.00369	0.00206	0.00662	0.01009	0.00529	0.00311
Yuncheng	0.00223	0.00196	0.00452	0.00255	0.00817	0.00000	0.01103	0.00196
Xinzhou	0.00247	0.00196	0.00389	0.00237	0.00582	0.00728	0.00672	0.00363
Lingfen	0.00240	0.00193	0.00377	0.00333	0.00603	0.00860	0.00622	0.00321
Lvliang	0.00239	0.00205	0.00493	0.00381	0.01093	0.00788	0.00906	0.00539

Table S16 The list of the constraints and data in the case study.

Constraints	Water availiblity in each sube region	Land availiblity in each sub resion	Demand of the end use energy in the province	Demand of coal in the province	Demand of the crop in the province	The coal production capacity in each sub region	the wash rate of the coal
Data	Table S4, S5	Table S2	Tale S12	913 million tons	Tale S14	Tale S6	0.6

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