Supplementary Materials for

Breaking the "hard-to-abate" bottleneck in China's path to carbon neutrality

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Table S1. Key mitigation technologies in iron and steel industry with carbon mitigation potential and abatement costs

Type	No.	Technology name	CO_2 abatement cost	Carbon emission abatement	TRL scale	TRL type
			$/ton	$kgCO_2/t$		
Material efficiency	1	Coke dry quenching device of high temperature and high pressure	24	2.3	Mature	TRL 11
	2	Sintering waste heat power generation technology in the iron and steel industry	126	0.7	Mature	TRL 11
	3	Dry recovery technology of converter gas	92	1.2	Mature	TRL 11
	4	Moisture Control and Air Separation Technology for Coking Coal	90	9.6	Mature	TRL 11
	5	Waste heat utilization technology of flue gas in mineral furnace	121	5.0	Mature	TRL 11
	6	Unsteady waste heat recovery and saturated steam power generation technology	29	1.4	Mature	TRL 11
	7	High-temperature flue gas dry purification and recycling technology of fully enclosed submerged arc furnace	20	6.2	Mature	TRL 11
	8	Sintering waste heat recycling technology	66	1.7	Mature	TRL 11
	9	Recovery and utilization of sensible heat of coke oven waste gas	31	8.9	Mature	TRL 11
	10	Regenerative combustion technology: Regenerative rotary hearth furnace treatment of metallurgical dust and recovery of iron and zinc technology	260	1.1	Mature	TRL 11
	11	Energy saving technology of rotary cutting type high air temperature top burning hot blast stove	105	5.7	Mature	TRL 11
	12	New energy-saving technology of high thermal conductivity and high-density silica bricks for large coke ovens	43	4.6	Mature	TRL 11
	13	Integral optimization of cold ramming and paste forming furnace energy saving technology	3	3.8	Mature	TRL 11

	14	High-emissivity coating technology	5	5.3	Mature	TRL 11
	15	Energy-saving technology of heat storage combustion without induced draft fan and directional valve	8	4.5	Mature	TRL 11
Technology performance	16	Screw expansion power drive energy-saving technology	43	3	Mature	TRL 11
	17	Application technology of coaxial unit for energy recovery of metallurgical waste heat and pressure	11	5	Mature	TRL 11
	18	Recovering waste heat by direct heat exchange with blast furnace slagging water	21	7	Mature	TRL 11
	19	Blast furnace blast dehumidification and energy-saving technology	25	3	Mature	TRL 11
	20	Liquid sealing technology of annular cooler	117	0	Mature	TRL 11
	21	Technology of waste gas recovery and pressure automatic regulation in coke oven carbonization chamber	76	0	Mature	TRL 11
	22	Intelligent energy-saving technology for large-scale blast furnace based on optimization of gas volume index	121	16	Mature	TRL 11
	23	Energy management and control technology in the iron and steel industry	4	13	Mature	TRL 11
	24	Energy Saving Technology of Blackbody Enhanced Radiation in Heating Furnace	6	11	Mature	TRL 11
	25	Intermediate and low temperature solar energy industrial thermal application system technology	81	3	Mature	TRL 11
Electrification	26	BF-BOF (H2+Zero-C elec)	120	640	Large prototype	TRL 5
	27	BF-BOF (Zero-C elec)	118	164	Large prototype	TRL 5
	28	EAF-scrap (Zero-C elec)	118	421	Large prototype	TRL 5
	29	DRI-coal (Zero-C elec)	118	793	Large prototype	TRL 5
	30	DRI-gas (Zero-C elec)	118	427	Large prototype	TRL 5
	31	DRI-gas (H2+Zero-C elec)	235	1088	Large prototype	TRL 5

Hydrogen	32	DRI-NG H2: Green H2-30% injection	147	150	Pre-commercial demonstration	TRL 7
	33	DRI-NG H2: Green H2-90% injection	147	449	Large prototype	TRL 5
	34	DRI-NG H2: Green H2-100% injection	147	498	Large prototype	TRL 5
	35	Hydrogen as auxiliary reduction (BF-BOF)-Hydrogen green	62	1380	Pre-commercial demonstration	TRL 7
	36	HYBRIT- carbon abatement 1575kg/ton-large scale 60Mt/yr-hydrogen green	128	1575	Full prototype at scale	TRL 6
	37	HYBRIT- carbon abatement 1575kg/ton-Middle scale 23Mt/yr-hydrogen green	173	1024	Full prototype at scale	TRL 6
	38	HYBRIT- carbon abatement 1575kg/ton-Small scale 7Mt/yr-hydrogen green	211	551	Pre-commercial demonstration	TRL 7
	39	GrInHy2.0- carbon abatement 1600kg/ton-large scale 60Mt/yr-hydrogen green	130	1600	Full prototype at scale	TRL 6
	40	GrInHy2.0- carbon abatement 1600kg/ton-Middle scale 23Mt/yr-hydrogen green	176	1040	Full prototype at scale	TRL 6
	41	GrInHy2.0- carbon abatement 1600kg/ton-Small scale 7Mt/yr-hydrogen green	290	560	Pre-commercial demonstration	TRL 7
	42	GrInHy2.0- carbon abatement 1200kg/ton-large scale 60Mt/yr-hydrogen green	98	1200	Full prototype at scale	TRL 6
	43	GrInHy2.0- carbon abatement 1200kg/ton-Middle scale 23Mt/yr-hydrogen green	132	780	Full prototype at scale	TRL 6
	44	GrInHy2.0- carbon abatement 1200kg/ton-Small scale 7Mt/yr-hydrogen green	217	420	Pre-commercial demonstration	TRL 7
CCUS	45	SR-BOF with CCUS	36	1470	Pre-commercial demonstration	TRL 7

	46	DRI-gas (CCUS)	25	670	Early adoption	TRL 10
	47	DRI-coal (CCUS)	25	742	Early adoption	TRL 10
CCUS+Hydrogen	48	DRI-NG H2: Blue H2(SMR+89%CCUS)-30% injection	294	131	Demonstration	TRL 8
	49	DRI-NG H2: Blue H2(SMR+89%CCUS)-90% injection	294	394	Demonstration	TRL 8
	50	DRI-NG H2: Blue H2(SMR+89%CCUS)-100% injection	294	437	Demonstration	TRL 8
	51	Hydrogen as auxiliary reduction (BF-BOF)-hydrogen blue: SMR89% CCUS	123	1200	Demonstration	TRL 8
	52	HYBRIT- carbon abatement 1575kg/ton-large scale 60Mt/yr-hydrogen blue: SMR89% CCUS	256	1382	Demonstration	TRL 8
	53	HYBRIT- carbon abatement 1575kg/ton-Middle scale 23Mt/yr-hydrogen blue: SMR89% CCUS	346	898	Demonstration	TRL 8
	54	HYBRIT- carbon abatement 1575kg/ton-Small scale 7Mt/yr-hydrogen blue: SMR89% CCUS	422	484	Demonstration	TRL 8
	55	GrInHy2.0- carbon abatement 1600kg/ton-large scale 60Mt/yr-hydrogen blue: SMR89% CCUS	260	1404	Demonstration	TRL 8
	56	GrInHy2.0- carbon abatement 1600kg/ton-middle scale 23Mt/yr-hydrogen blue: SMR89% CCUS	351	912	Demonstration	TRL 8
	57	GrInHy2.0- carbon abatement 1600kg/ton-small scale 7Mt/yr-hydrogen blue: SMR89% CCUS	579	491	Demonstration	TRL 8
	58	GrInHy2.0- carbon abatement 1200kg/ton-large scale 60Mt/yr-hydrogen blue: SMR89% CCUS	195	1053	Demonstration	TRL 8
	59	GrInHy2.0- carbon abatement 1200kg/ton-Middle scale 23Mt/yr-hydrogen blue: SMR89% CCUS	263	684	Demonstration	TRL 8
	60	GrInHy2.0- carbon abatement 1200kg/ton-small scale 7Mt/yr hydrogen blue: SMR89% CCUS	434	368	Demonstration	TRL 8

Table S2. Key mitigation technologies in cement industry with carbon mitigation potential and abatement costs

Type	No.	Technology name	Carbon emission abatement	CO_2 abatement cost	TRL scale	TRL type
			kg /t CO_2	\$/t CO_2		
Energy efficiency	1	Mining optimization	1.6	233	Mature	TRL 11
	2	Power system of ore transportation	1.0	78	Mature	TRL 11
	3	New steel tape hoist	1.3	119	Mature	TRL 11
	4	Efficient pre-calciner pre-heater system	13.0	46	Mature	TRL 11
	5	Increase in pre-heater stages	8.6	5	Mature	TRL 11
	6	New efficient burner	2.6	48	Mature	TRL 11
	7	Oxy-fuel technology for Cement clinker	7.8	15	Mature	TRL 11
	8	Fan inverter technology with high temperature	1.8	45	Mature	TRL 11
	9	The fourth-generation grate cooler technology	13.0	52	Mature	TRL 11
	10	New efficient drying technology	2.6	42	Mature	TRL 11
	11	Vertical mill for Raw material Grinding	9.6	94	Mature	TRL 11
	12	Roller Press for Raw material Grinding	11.9	84	Mature	TRL 11
	13	Co-grinding system	7.7	63	Mature	TRL 11
	14	Pure low-temperature waste heat Cogeneration technology	25	75	Early adoption	TRL 10
	15	Pentane media pure low temperature Cogeneration technology	4	36	Early adoption	TRL 10
Alternative fuels	16	Fuel switching (coal/oil/gas/biomass)	50	19	Early adoption	TRL 10
	17	Pre-treatment of alternative fuel (grinding, drying)	8	0.4	Early adoption	TRL 10
	18	Gasification or pre-combustion of alternative fuels	41	2	Early adoption	TRL 10
	19	Alternative fuel technology for cement production	87	17	Early adoption	TRL 10
	20	Electrolyzer-based process for decarbonating CaCO3	979	65	Concept	TRL 3

Reducing the clinker to cement ratio	21	Non-carbonated raw material for cement production–use of calcium carbide residue (CCR)	374	20	Mature	TRL 11
	22	Alternative de-carbonated raw materials for clinker production-10%-15% granulated blast furnace slag (GBFS)	100	5	Mature	TRL 11
	23	Further reduction of clinker content in cement by use of fly ash	98	1	Mature	TRL 11
	24	Further reduction of clinker content in cement by use of natural pozzolanas	92	4	Mature	TRL 11
CCUS	25	Carbon capture and storage (CCUS)	933	6	Demonstration	TRL 8
	26	Post-combustion capture using absorption technologies	800	60	Demonstration	TRL 7
	27	Post-combustion capture using membrane processes	955	30	Small prototype	TRL 4
Green Hydrogen	28	Green H2 heating-30% injection-average	150	28	Large prototype	TRL 5
	29	Green H2 heating-30% injection-Large NSP kiln	225	20	Large prototype	TRL 5
	30	Green H2 heating-90% injection-average	449	28	Large prototype	TRL 5
	31	Green H2 heating-90% injection-Small NSP kiln	236	56	Large prototype	TRL 5
	32	Green H2 heating-90% injection-Middle NSP kiln	438	36	Large prototype	TRL 5
	33	Green H2 heating-90% injection-Large NSP kiln	674	20	Large prototype	TRL 5
	34	Green H2 heating-100% injection-average	498	28	Large prototype	TRL 5
	35	Green H2 heating-100% injection-Small NSP kiln	262	56	Large prototype	TRL 5
	36	Green H2 heating-100% injection-Middle NSP kiln	486	36	Large prototype	TRL 5
	37	Green H2 heating-100% injection-Large NSP kiln	747	20	Large prototype	TRL 5
Blue hydrogen with CCUS	38	Blue H2(SMR+89%CCUS) heating-30% injection-average	131	32	Demonstration	TRL 8
	39	Blue H2(SMR+89%CCUS) heating-30% injection-Large NSP kiln	197	17	Demonstration	TRL 8
	40	Blue H2(SMR+89%CCUS) heating-90% injection-average	394	32	Pre-commercial demonstration	TRL 7
	41	Blue H2(SMR+89%CCUS) heating-90% injection-Small NSP kiln	207	48	Pre-commercial demonstration	TRL 7

	42	Blue H2(SMR+89%CCUS) heating-90% injection-Middle NSP kiln	384	32	Pre-commercial demonstration	TRL 7
	43	Blue H2(SMR+89%CCUS) heating-90% injection-Large NSP kiln	591	17	Pre-commercial demonstration	TRL 7
	44	Blue H2(SMR+89%CCUS) heating-100% injection-average	437	32	Pre-commercial demonstration	TRL 7
	45	Blue H2(SMR+89%CCUS) heating-100% injection-Small NSP kiln	229	48	Pre-commercial demonstration	TRL 7
	46	Blue H2(SMR+89%CCUS) heating-100% injection-Middle NSP kiln	426	32	Pre-commercial demonstration	TRL 7
	47	Blue H2(SMR+89%CCUS) heating-100% injection-Large NSP kiln	656	17	Pre-commercial demonstration	TRL 7

Table S3. Technology readiness level (TRL) classification and detailed description (consistent with IEA principle)

TRL scale	TRL level	Detail	Description
Concept	1	Initial idea	Basic principles have been defined
	2	Application formulated	Concept and application of solution have been formulated
	3	Concept needs validation	Solution needs to be prototyped and applied
Small prototype	4	Early prototype	Prototype proven in test conditions
Large prototype	5	Large prototype	Components proven in conditions to be deployed
	6	Full prototype at scale	Prototype proven at scale in conditions to be deployed
Demonstration	7	Pre-commercial demonstration	Solution working in expected conditions
	8	First-of-a-kind commercial	Commercial demonstration, full scale deployment in final form
Early adoption	9	Commercial operation in relevant environment	Solution in commercially available, needs evolutionary improvement to stay competitive.
	10	Integration needed at scale	Solution is commercial and competitive but needs further integration efforts
Mature	11	Proof of stability reached	Predictable growth

Table S4. Technology penetration in typical hard-to-abate sectors in BAU, NDC, ZERO-NH, and ZERO-H scenario (2020-2060)

Industry																					
Sub-sector	Technology	BAU					NDC					ZERO-NH					ZERO-H				
		2020	2030	2040	2050	2060	2020	2030	2040	2050	2060	2020	2030	2040	2050	2060	2020	2030	2040	2050	2060
Iron and Steel	BOF-BF	87%	84%	80%	76%	72%	87%	77%	70%	64%	55%	87%	73%	64%	51%	37%	87%	72%	56%	43%	25%
	EAF	13%	16%	20%	24%	28%	13%	23%	30%	36%	45%	13%	27%	36%	49%	63%	13%	25%	35%	39%	44%
	Hydrogen-DRI	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	3%	9%	18%	31%
Cement	Shaft kiln	12%	7%	4%	2%	0%	12%	4%	1%	0%	0%	12%	1%	0%	0%	0%	12%	1%	0%	0%	0%
	Mid-/Small NSP kiln	48%	37%	28%	22%	16%	48%	32%	22%	17%	12%	48%	24%	15%	9%	0%	48%	22%	11%	7%	0%
	Large NSP kiln with CCUS	37%	48%	56%	60%	61%	37%	53%	54%	47%	43%	37%	57%	51%	32%	15%	37%	52%	42%	23%	5%
	NSP with WHR and CCUS	3%	8%	12%	17%	23%	3%	11%	23%	36%	45%	3%	18%	34%	59%	85%	3%	20%	35%	52%	71%
	NSP with hydrogen heat	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	5%	12%	18%	24%
Ammonia	Coal-based	75%	73%	71%	72%	70%	72%	63%	52%	41%	32%	72%	48%	26%	12%	0%	72%	45%	23%	9%	0%
	Gas-based	25%	27%	29%	28%	30%	28%	37%	48%	59%	68%	28%	52%	74%	88%	100%	28%	50%	66%	74%	80%
	Gas-based with hydrogen heat	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	**0%**	**5%**	**11%**	**17%**	**20%**
Methanol	CTM	56%	57%	59%	62%	67%	56%	43%	38%	34%	31%	56%	33%	20%	11%	0%	56%	30%	17%	8%	0%
	CGTM	21%	20%	19%	18%	17%	21%	18%	15%	12%	11%	21%	14%	9%	6%	5%	21%	12%	7%	4%	0%
	NTM	23%	23%	22%	20%	16%	23%	39%	47%	54%	58%	23%	53%	71%	83%	95%	23%	52%	62%	69%	79%
	CGTM/NTM	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	**0%**	**6%**	**14%**	**19%**	**21%**

Transport																					
Sub-sector	Technology	BAU					NDC					ZERO-NH					ZERO-H				
		2020	2030	2040	2050	2060	2020	2030	2040	2050	2060	2020	2030	2040	2050	2060	2020	2030	2040	2050	2060
LDV	Gasoline LDVs	92%	93%	95%	96%	97%	92%	76%	56%	44%	38%	92%	62%	34%	18%	0%	92%	59%	31%	16%	0%
	Gasoline-Elec hybrid LDVs	7%	6%	4%	3%	2%	7%	16%	28%	36%	37%	7%	22%	24%	3%	0%	7%	25%	28%	9%	0%
	Electric LDVs	1%	1%	1%	1%	1%	1%	8%	16%	20%	25%	1%	16%	42%	79%	100%	1%	15%	39%	71%	95%
	Hydrogen fuel cell LDVs	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	2%	4%	5%
BUS	Gasoline/Diesel Buses	48%	49%	51%	53%	55%	48%	20%	9%	4%	0%	48%	13%	7%	3%	0%	48%	12%	3%	1%	0%
	CNG/CPG buses	37%	36%	33%	31%	29%	37%	47%	40%	32%	17%	37%	45%	22%	8%	0%	37%	50%	36%	20%	0%
	Electric buses	15%	15%	16%	16%	16%	15%	33%	51%	64%	83%	15%	42%	71%	89%	100%	15%	24%	32%	36%	39%
	Hydrogen fuel cell buses	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	14%	29%	43%	61%
Light Trucks	Diesel/Gasoline LDTs	71%	69%	67%	65%	64%	71%	56%	52%	49%	48%	71%	42%	24%	13%	0%	71%	39%	19%	7%	0%
	CNG/Ethanol LDTs	29%	31%	33%	35%	36%	29%	44%	47%	48%	47%	29%	55%	49%	28%	0%	29%	50%	48%	26%	0%
	Electric LDTs	0%	0%	0%	0%	0%	0%	0%	1%	3%	5%	0%	3%	27%	59%	100%	0%	2%	12%	29%	47%
	Hydrogen fuel cell LDTs	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	9%	21%	38%	53%
Heavy Trucks	Diesel HDTs	96%	95%	93%	90%	87%	96%	91%	82%	71%	59%	96%	71%	43%	21%	0%	96%	68%	39%	16%	0%
	Bio diesel/CNG HDTs	4%	5%	7%	10%	13%	4%	9%	17%	27%	39%	4%	22%	30%	21%	0%	4%	26%	31%	26%	0%

	Electric HDTs	0%	0%	0%	0%	0%	0%	0%	1%	2%	2%	0%	7%	27%	58%	100%	0%	4%	15%	22%	34%
	Hydrogen fuel cell HDTs	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	2%	15%	36%	66%
Shipping	Fuel Oil Ships	90%	91%	91%	90%	88%	90%	67%	58%	54%	49%	90%	57%	29%	12%	0%	90%	55%	26%	11%	0%
	LNG/Duofuel Ships	10%	9%	9%	10%	12%	10%	33%	42%	46%	51%	10%	42%	66%	77%	80%	10%	35%	45%	38%	23%
	Ammonia Ships	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	5%	11%	20%	0%	9%	24%	43%	65%
	Hydrogen ships	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	5%	8%	12%
Aviation	Jet fuel flights	96%	95%	94%	94%	93%	96%	78%	62%	51%	48%	96%	70%	42%	18%	0%	96%	65%	33%	11%	0%
	Biofuel flights	4%	5%	6%	6%	7%	4%	16%	29%	37%	37%	4%	18%	34%	53%	68%	4%	24%	44%	51%	51%
	Hydrogen flights	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	3%	9%	17%	24%
	Other flights	0%	0%	0%	0%	0%	0%	6%	9%	12%	15%	0%	12%	24%	29%	32%	0%	8%	14%	21%	25%

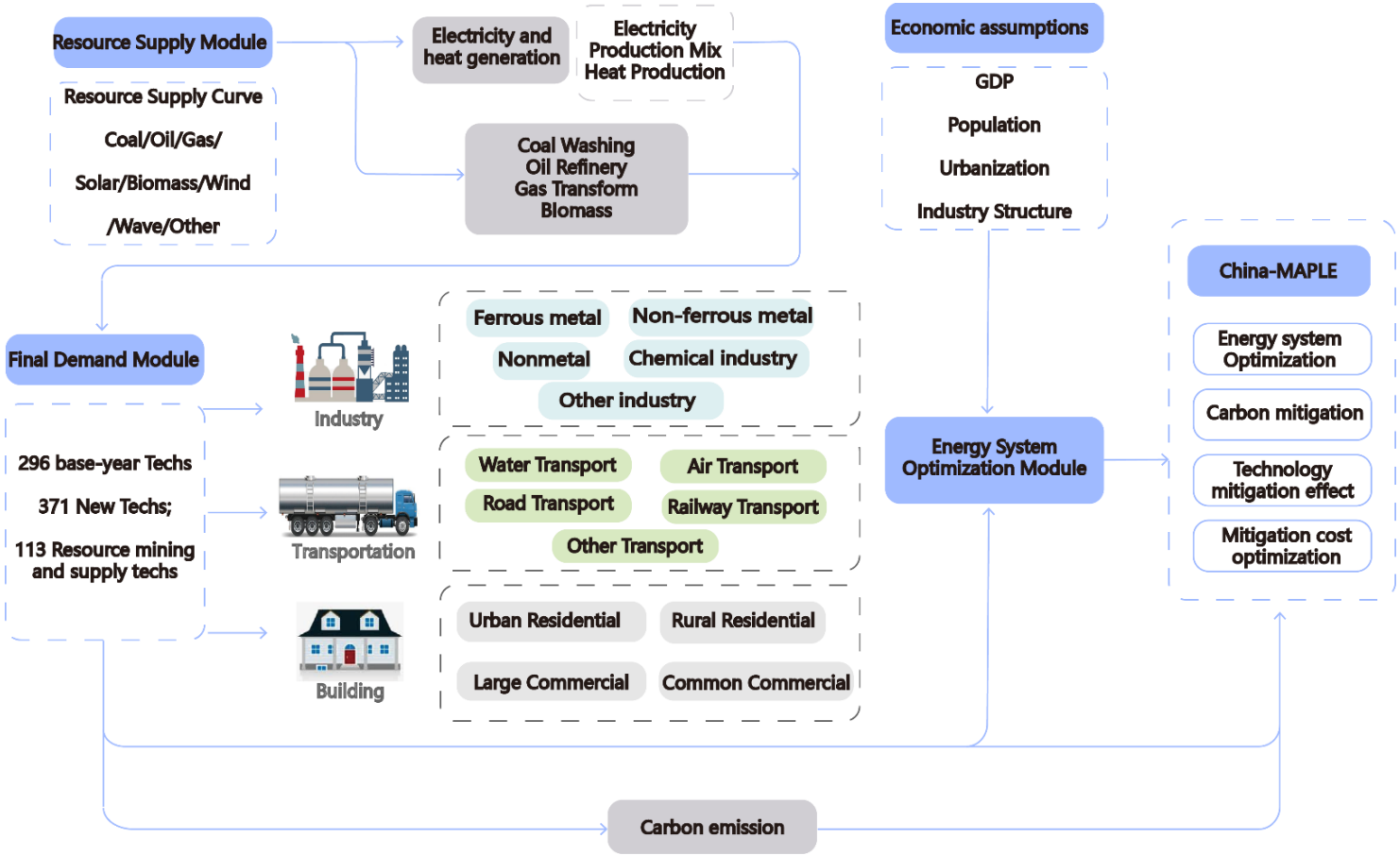

Fig. S1. Framework of MAPLE model