Exploring the carbon emission reduction potentials of low-carbon technologies in China's copper industry

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Section S1. Technology List and Source of Parameter Data

Table S1 presents a detailed inventory of low-carbon technologies and their key parameters. The technologies were compiled from multiple national-level authoritative technical guidance catalogues, including the National Industrial Energy-Saving and Carbon-Reduction Technology Application Guidelines and Case Studies, the National Green and Low-Carbon Advanced Technology Achievement Catalogue, the List of Green and Low-Carbon Advanced Technology Demonstration Projects, the Catalogue of Remanufacturing Process Technologies and Equipment (2023 Edition), the National Catalogue of Key Low-Carbon Technologies for Promotion, the National Catalogue of Advanced and Applicable Technologies and Equipment for Industrial Resource Comprehensive Utilization, and the National Catalogue of Industrial Water-Saving Processes, Technologies, and Equipment Encouraged by the State.

All of the above catalogues are issued by central government ministries or their affiliated authoritative institutions, and the majority of the technologies included have completed engineering validation or pilot demonstration, enabling large-scale deployment within existing industrial systems. By cross-checking technologies that appear repeatedly or are explicitly prioritized across different catalogues, this study ensures technological advancement while effectively avoiding the risk of overestimating emission-reduction potential due to the inclusion of immature technologies.

TableS1. Technology List and Parameters

	Low-carbon technology	CO_2 mitigation intensity ($kgCO_2/tCu$)	Permeability (%)	Equipment Cost (CNY/ tCu)	Change in energy cost (CNY/ tCu)	Cost savings (CNY/ tCu)
Mining & Mineral Processing						
1	Electric Mining Truck	16.9	5.0	100.0	0.0	21.9
2	High Pressure roller mill	56.6	5.0	175.0	0.0	59.0
3	IsaMill Horizontal Stirred Media Mill	47.2	5.0	200.0	0.0	49.1
4	Super flotation cell (600 m^3)	38.9	5.0	75.0	0.0	40.4
5	Intelligent Photoelectric Ore Sorting Technology	14.6	10.0	309.9	0.0	15.2
6	Low-carbon Explosives	10.6	5.0	0.0	9.8	0.0
7	Metal component-filled retaining walls and	17.3	5.0	15.0	0.0	0.0

	sealing technology					
Copper Smelting						
1	Mag-Polymerization Combustion Accelerator	6.4	5.0	15.0	0.0	10.7
2	Multi-O2 Combustion Tech	50.2	30.0	4.9	0.0	85.1
3	Porous Media Flameless Super-enthalpy Combustion System	7.6	50.0	34.0	0.0	12.7
4	High-efficiency Ultra-low NOx Gas Combustion Technology	3.0	30.0	6.5	0.2	5.1
5	NH_3/H_2 Mixed Low-Carbon Combustion Tech	0.1	30.0	26.0	0.0	0.2
6	Furnace Combustion Process Optimization and Energy-saving Technology	1.8	30.0	15.0	0.0	3.1

7	Industrial Boiler Intelligent Control System (BCS)	34.0	30.0	7.5	0.0	57.6
8	Gas–electric dual-drive technology for copper smelting	48.1	40.0	170.0	0.0	50.1
9	380 A/m² current-density electrolytic copper technology	140.0	72.0	37.4	0.0	145.8
10	Hydrogen anode furnace	7.4	5.0	158.5	37.9	3.7
Electric Motors						
1	Metallurgical motor system energy-saving control	43.9	40.0	10.0	0.0	45.7
2	Permanent Magnet Direct Drive Motorized Pulley Technology	2.8	5.0	7.1	0.0	2.9
3	Domestic High-Performance LV VFD	2.4	20.0	30.0	0.0	1.7

	Tech					
4	Switched Reluctance Speed-regulating Motor System Energy-saving Technology	11.5	35.0	55.0	0.0	11.9
5	Sleeve-type Permanent Magnet Speed Regulation Energy-saving Technology	17.7	5.0	49.6	0.2	18.4
6	Permanent Magnet Eddy Current Flexible Drive Energy-saving Technology	16.3	8.0	5.0	0.0	17.0
7	Brushless Self-controlled Motor Liquid Resistance Starter	14.1	10.0	10.0	0.0	14.7
8	Automatic Voltage-regulated Cooling Tower Fan	0.1	85.0	5.2	0.0	0.1

9	Permanent Magnet Retrofitting Technology for Old Motors	10.4	50.0	5.1	0.0	10.9
10	Efficient Remanufacturing for Retired Motors	7.0	30.0	60.0	0.0	7.2
11	Permanent-magnet system for grinding mills	21.1	20.0	4.2	0.0	22.0
12	High-Efficiency Energy-Saving Technology for Circulating Water	87.5	10.0	111.0	0.0	91.0
13	Intelligent Control System for Circulating Water	3.6	30.0	10.5	0.0	3.7
14	Digital P&T Cooling Water Efficiency Control	56.8	5.0	35.0	0.0	58.8
15	Digital technology for pump energy efficiency	87.4	85.0	42.5	0.0	91.0

16	Lean power management technology for large industrial enterprises	48.9	30.0	300	0	51.0
Waste Heat Recovery						
1	Low-Temp Flue Gas Waste Heat Recovery	4.5	20.0	35.0	0.9	9.6
2	Molten Salt Heat Storage & Exchange Tech	630.0	30.0	132.5	10.1	300.0
3	Absorption Heat Exchange Unit for Deep Flue Gas Waste Heat Recovery	2.1	5.0	65.4	5.2	4.2
4	Boiler Flue Gas Deep Cooling Technology	1.1	30.0	31.5	0.0	1.8
5	Integrated Technology for Flue Gas Deep Purification, Dehumidification, and	1.7	30.0	100.0	1.3	2.8

	Waste Heat Recovery					
6	Waste Heat Recovery Cooling/Heating Technology Based on Flue Gas Heat Exchangers	2.7	85.0	8.6	0.0	4.5
7	Gas-Quenching Copper Slag Heat Recovery	125.0	30.0	125.0	6.0	192.4
8	CaO Adsorption-based Multi-stage Waste Heat Recovery System for Copper Slag and Coal Gas	56.5	5.0	40.0	4.0	94.0
9	Rotary Surface Waste Heat Recovery for Cooling and Heating	2.7	30.0	11.5	0.3	15.5
10	Waste Heat Boiler Dynamic Supplementary Firing Technology	317.5	50.0	67.5	0.0	61.4

Carbon Capture						
1	CO_2 Mineralization Technology for the Production of Carbon-Negative Panels	56.4	30.0	87.5	8.8	22.2

Table S2 summarizes and standardizes the complete evaluation process of all energy-saving and carbon-reduction technologies considered in this study. Specifically, the technology assessment is conducted along two main dimensions. First, based on the type of energy-saving mechanism and the corresponding energy-saving rate of each technology, its emission-reduction intensity is quantified, which is further translated into energy-saving benefits per ton of copper. Second, the capital investment costs are estimated according to the list of key equipment required for each technology. In addition, recognizing that some critical equipment may introduce additional electricity or energy consumption, the resulting incremental operational energy costs are also explicitly accounted for.

Table S2. Technical Analysis and Sources of Parameter Data

	Low-carbon technology	Energy-saving type	Energy Savings Rate (%)	Generate auxiliary materials	Required equipment configuration or modification details	Current stage
Mining & Mineral Processing						
1	Electric Mining Truck[1]	Diesel	80	/	Electric Mining Truck [2]	Transportation
2	High Pressure roller mill [3]	Electricity	40	/	High Pressure roller mill [4]	grinding
3	Isa Mill (horizontal stirred media mill)[3]	Electricity	30	/	IsaMill Horizontal Stirred Media Mill[5]	grinding
4	Super flotation cell (600 m³)[3]	Electricity	40	/	Super flotation cell (600 m³)[3]	flotation
5	Intelligent Photoelectric	Electricity	6	/	Intelligent Photoelectric Mineral Processing Equipment、	Preliminary Selection

	Ore Sorting Technology[6]				machine、Vertical Impact Crusher、Vibrating Dewatering Screen and Auxiliary Equipment	
6	Low-carbon Explosives[7]	/	/	/	Low-carbon Explosives [7]	Blasting
7	Metal component-filled retaining walls and sealing technology[6]	Cement	100	/	Curved steel beam [6]	mining
Copper Smelting						
1	Mag-Polymerization Combustion Accelerator[6]	Natural gas	6	/	Magnetically Induced Polymerization Combustion Accelerator [6]	Smelting, refining, holding temperature
2	Multi-O2 Combustion Tech[6]	Natural gas	62	/	PLC[8]、Oxygen valve assembly, fuel valve assembly [9]、Oxygen-enriched burner [10]、Flowmeter [11]、Shut-off valve [12]、Pressure control valve, flow control valve [13]	blowing and refining

					Pressure Transmitter [14]、Filter, shut-off valve, etc.	
3	Porous Media Flameless Super-enthalpy Combustion System[15]	Natural gas	30	/	Porous Media Combustion System [14,16–19]，Air circuit, electronic control system [8]	Insulation
4	High-efficiency Ultra-low NOx Gas Combustion Technology[20]	Natural gas	10	/	Ultra-low NOx Burner [21]、Exhaust Gas Recirculation System [22]	Smelter, Refining
5	NH_3/H_2 Mixed Low-Carbon Combustion Tech[23]	Natural gas	1	/	Optimization of Burner Internal Structure [23]	Generator set
6	Furnace Combustion Process Optimization and Energy-saving Technology[24]	Natural gas	5	/	Surface-mounted specific nano-polarized materials on gas pipelines [24]	Smelter, Refining, Temperature maintenance
7	Industrial Boiler	Natural gas	5	/	Optimize the operator	Smelting and

	Intelligent Control System (BCS) [25]				workstations based on the user's existing DCS system. [26]	refining
8	Gas–electric dual-drive technology for copper smelting[27]	Electricity	20	/	Integrate the independent motors into a single dual-drive coaxial unit[27]	airframe assembly
9	380 A/m² current-density electrolytic copper technology[15]	Electricity	42	/	Integrated design of pipes and cells enables the realization of electrolytic cells. [28]、Circulatory System [29–31]、Integrated conductive systems, etc.	Electrolytic refining
10	Hydrogen anode furnace[32]	Natural gas	30	/	Hydrogen gas, hydrogen gas anode furnace [32]	Fire Refining
Electric Motors						
1	Metallurgical motor system energy-saving control[15]	Electricity	20	/	MVC1200-10K/350 High-Voltage Variable Frequency Drive [33]、Control System [8,34]	Water pump

2	Permanent Magnet Direct Drive Motorized Pulley Technology[35]	Electricity	45	/	Motor Retrofit [35]	Belt Conveyor
3	Domestic High-Performance LV VFD Tech [35]	Electricity	10	/	The power unit employs DSP for control and utilizes high-speed Ethernet communication.[35]	Low-voltage variable-frequency motor
4	Switched Reluctance Motor Energy Saving System[35]	Electricity	10	/	Increased the overlap coefficient of inductance, employing real-time control technology that combines commutation point detection, rotor position detection, and current amplitude variation[35]	Pumps、Blower
5	Sleeve-type Permanent Magnet Speed Regulation Energy-saving Technology[25]	Electricity	22	/	The regulator achieves smooth starting, overload or stall protection, and speed regulation by altering the engagement area between the permanent magnet rotor and the conductor rotor.[25]	Blower, compressor, pump, water pump

6	Permanent Magnet Eddy Current Flexible Drive Energy-saving Technology[25]	Electricity	45	/	Permanent Magnet Energy-Saving Device Main Unit[36]	blowers
7	Brushless Self-controlled Motor Liquid Resistance Starter[37]	Electricity	5	/	Optimization of Asynchronous Motor Start-up[37]	Crusher, blower, water pump
8	Automatic Voltage-regulated Cooling Tower Fan[37]	Electricity	100	/	Utilize the wasted energy within the circulating water system to replace the fan motors in cooling towers and drive the fans.[37]	blowers
9	Permanent Magnet Retrofitting Technology for Old Motors[38]	Electricity	20	/	Fully utilize the casing, stator, rotor, and other components from old (inefficient) three-phase asynchronous motors. Recondition the motor rotor base, affix permanent magnets to the rotor surface, and form a new permanent magnet rotor for the motor [38]	Old motor

10	Efficient Remanufacturing for Retired Motors[39]	Electricity	15	/	Re-evaluating the value of old motors through key technologies such as principle reconstruction, topology re-planning, structural redesign, and permanent magnetization for extended service life remanufacturing [39]	Old motor
11	Permanent-magnet system for grinding mills[35]	Electricity	20	/	Frequency Converter [40]、Permanent Magnet Direct Drive Motor [41]	Ball Mill
12	High-Efficiency Energy-Saving Technology for Circulating Water[35]	Electricity	54	/	By monitoring fluid transport conditions and collecting parameters, establish a hydraulic mathematical model to calculate the optimal circulating water delivery plan. [65]	Circulating Water Pump
13	Intelligent Control System for Circulating Water[66]	Electricity	30	/	Chemical dosing equipment [67]、Monitoring equipment [68]、Side-stream filtration equipment [69]、Surveillance equipment [8]	Circulating Water Pump

14	Digital P&T Cooling Water Efficiency Control [23]	Electricity	30	/	Establish a comprehensive artificial intelligence, system optimization, and automated control management platform, and integrate the process-side parameters of the water cooler into the intelligent optimization control platform. [70]	Recirculating Water System
15	Digital technology for pump energy efficiency[50]	Electricity	50	/	Through operational mechanism derivation, core algorithms, efficiency optimization techniques, and multi-variable control with real-time adjustment, the pump system consistently operates within its high-efficiency zone. [70]	Water pump
16	Lean power management technology for large industrial enterprises[6]	/	/	/	Smart electricity monitoring system[6]	Smelting
Waste Heat Recovery						

1	Low-Temp Flue Gas Waste Heat Recovery [25]	Flue gas residual heat	48	/	Flue Gas Condensing Waste Heat Recovery Unit, including a condenser[42]， Thermal Energy Recovery [43]， Condensate collection [44]， Induced draft fan [17]， Dust removal [45]， Control System [8]	Insulated Furnace
2	Molten Salt Heat Storage & Exchange Tech[46]	Flue gas residual heat	60	/	Molten Salt-Flue Gas Heat Exchanger [47]、High-Temperature Molten Salt Storage Tank [48]、Gravity dust removal [45]， Steam turbine [49]	Smelter, refining, acid production flue gas waste heat
3	Absorption Heat Exchange Unit for Deep Flue Gas Waste Heat Recovery[50]	Flue gas residual heat	10	/	Absorption Heat Pump [51]、Flue Gas Condensing Heat Exchanger [52]、Flue Gas Purification System [53]、Recirculating Water System [29–31]、PLC[8]	Insulated Furnace
4	Boiler Flue Gas Deep Cooling Technology[27]	Flue gas residual heat	3	/	Constant-Wall-Temperature Heat Exchanger Assembly [27]	Insulated Furnace

5	Integrated Technology for Flue Gas Deep Purification, Dehumidification, and Waste Heat Recovery[6]	Flue gas residual heat	7	/	Heat Exchanger Unit [54]、Flue Gas Waste Heat Recovery System, Digital Video Surveillance System [8]	Insulated Furnace
6	Waste Heat Recovery Cooling/Heating Technology Based on Flue Gas Heat Exchangers [6]	Flue gas residual heat	20	/	Install water tank, hot water pump, hot water pipes, cold water pipes, and cooling water pipes [6]	Insulated Furnace
7	Gas-Quenching Copper Slag Heat Recovery[55]	Residual heat from copper slag	88	/	Granulation silo, gas gun, fixed-bed boiler [56]、Waste Heat Boiler [57]、Generator set [49]	Residual heat from copper slag
8	CaO Adsorption-based Multi-stage Waste Heat Recovery System for	Residual heat from copper slag	43	/	Calcination Furnace for $CaCO_3$ [59]、CO2 absorption chamber[60]、Gasifier[61]、$CaCo_3$ Transport Room [62]、Cao Transportation Office [62]	Residual heat from copper slag

	Copper Slag and Coal Gas[58]					
9	Rotary Surface Waste Heat Recovery for Cooling and Heating [23]	Boiler surface residual heat	5	/	Radiant Heat Exchanger [63]、Hot Water Absorption Chiller Unit [64]	Boiler surface
10	Waste Heat Boiler Dynamic Supplementary Firing Technology[20]	Flue gas residual heat	50	/	Construct a new waste heat boiler and dynamic supplementary combustion system. [20]	Smelting, blowing, refining, acid production waste heat boiler
Carbon Capture						
1	CO_2 Mineralization for Carbon-Negative Panel Production[66]	/	/	Negative Carbon Panels	32 key pieces of equipment including mixing tanks, carbonization reactors, presses, and green body conveying equipment [66]	Fire Refining

Section S2. Baseline scenario construction for copper plant

In the national low-carbon technology catalog, individual technology cases are typically reported based on specific enterprise contexts, including their application conditions and corresponding emission reduction performance. However, in practical industrial settings, significant differences exist among enterprises in terms of process configurations, production scales, and operating conditions. Even for the same low-carbon technology, its emission reduction potential and economic performance may vary substantially across different contexts. Therefore, the emission reduction data derived from a single case cannot be directly generalized to a wider range of enterprises. Directly applying parameters reported in technology catalogs or demonstration projects may introduce systematic bias when extended to different operational conditions, thereby affecting the reliability of the assessment.

To address this issue, this study constructs a baseline copper plant scenario to represent the average technological level of copper enterprises in China (Table S3). The construction process is described as follows: (1) Determination of baseline production scale: To ensure representativeness, the production capacity distribution of copper enterprises in China was first systematically analyzed (Table S4). Based on industry statistics and enterprise-level data, more than 70% of the smelting capacity is concentrated within the range of 50–400 kt/year, which reflects the main structure of the industry. Within this range, a plant with an annual production capacity of 200 kt of refined copper is considered to represent a medium scale. This choice avoids the high variability in energy efficiency, process configuration, and cost structure typically observed in small-scale plants, while also mitigating the structural bias introduced by economies of scale, resource endowments, and specialized technological pathways in large-scale plants. Therefore, this capacity level is considered representative of the typical operational conditions of the Chinese copper smelting industry. (2) Construction of the key parameter system: Based on the selected baseline capacity of 200 kt/year, a comprehensive set of parameters covering the full copper production process was developed using enterprise reports and literature data. This parameter system includes: (i) fuel-related parameters (e.g., fuel oil and natural gas consumption), (ii) process operation parameters (e.g., copper slag generation and flue gas emissions), and (iii) equipment configuration parameters (e.g., motor types, quantities, and power ratings). Through the systematic integration of these parameters, a unified application context and system boundary are established, enabling the harmonization of process differences across enterprises.

Given that the performance of low-carbon technologies inherently depends on specific process operating conditions, this study identifies key activity indicators for each technology within the baseline copper plant scenario (e.g., material throughput, energy consumption intensity, and flue gas emissions) to characterize the core drivers of technology performance.

On this basis, a standardized normalization and mapping approach for technology performance is developed. First, the emission reduction and other performance metrics reported in individual technology cases are converted into intensity-based indicators per ton of cathode copper, thereby eliminating the influence of scale differences. Second, by comparing the key activity indicators of the same technology under different process conditions, their relative ratios are calculated and used to derive scaling factors for technology performance. Finally, these scaling factors are applied to map the emission reduction effects from case-specific contexts to the baseline copper plant scenario, enabling equivalent transformation across different process conditions.

Through this approach, technology performance that is originally dependent on specific enterprise contexts can be expressed under a unified baseline, allowing it to be further extended to the industry level for assessing the overall emission reduction potential of China’s copper sector.

TableS3. Main Parameter Table for the Baseline Copper Plant Scenario

Parameter Category	Parameter Name	Parameter value	Unit	Data Source/Remarks
1. Production Scale				
	Annual refined copper output	20	10k t/a	Scenario Setting
	Annual copper concentrate processing capacity	150	10k t/a	[71]
	Copper slag production per tonne of copper	2.2	t/t Cu	[72]
	Copper content in copper slag	1.30	%	[72]
	Circulating water system capacity	13,895	m^3/d	[73]
	Wastewater treatment capacity	6,085	m^3/d	[71]
	Recycled water volume	300	m^3/d	[73]

	Oil content in wastewater	92.5	mg/L	[74]
2. Energy & Power Equipment	Industrial electricity price	0.635	CNY/kWh	[75]
	Large-scale water pumps (31 units)	7,115	kW	[73]
	Ball mills (2 units)	6,600	kW	[73]
	Low-voltage variable frequency motors (112 units)	9,563.7	kW	[73]
	Various fans, conveyor belt motors (250 units)	25,315.5	kW	[73]
	Dust removal fans	2,191	kW	[76]
	Large-scale fans (single unit)	1,500	kW	[73]
	Waste gas fans	45	kW	[73]

	Backup diesel generator sets (2 units)	1,600	kW	[73]
	Number of electrolytic cells	800	one	[73]
	Number of cooling towers	4	one	[77]
3. Fuels & Carbon Emissions				
	Natural gas price	3.56	CNY/m^3	[78]
	Natural gas carbon emission factor	2.13	kg/m^3	[79]
	Diesel price	6.74	CNY/L	[80]
	Fuel oil carbon emission factor	2.6	Kg CO_2/L	[81]
	Coke carbon emission factor	2.819	t CO_2/t	[82]
	Waste heat recovery efficiency	30	%	[46]

	Carbon reduction per tonne of copper from waste heat recovery	210	Kg/t Cu	[83]
4. Raw Materials & Chemical Prices				
	Heavy oil price	3,30	CNY/t	[84]
	N-Methyldiethanolamine (MDEA)	13,000	CNY/t	[85]
	Activated carbon price	13,000	CNY/t	[86]
	Activated coke price	9,866	CNY/t	[87]
	Explosive price	1,500	CNY/t	[88]
	Low-carbon explosive price	2,000	CNY/t	[89]
	Cement price	300	CNY/t	[90]
5. Utility & Consumables				
	Steam price	210	CNY/t	[91]

	Water price	2.3	CNY/t	[92]
	Activated carbon consumption per tonne of wastewater	5.20	kg/m^3	[93]
6. Process-Specific Parameters				
	Flue gas volume from smelting/converting waste heat boilers	138,724.4	Nm^3/h	[73]
	Primary Copper Emission Intensity	4.28	kg CO$_2$ / t Cu	[83]
	Recycled Copper Emissions Intensity	1.25	kg CO$_2$ / t Cu	[94]
	Steam volume from smelting/converting/sulfuric acid waste heat boilers	100	t/h	[73]
	Flue gas volume from anode refining (CO$_2$ > 10%)	8,000	m^3/h	[73]

Natural gas consumption of the boiler house	700,000	m^3/a	[73]
Natural gas consumption of holding furnaces	300	m^3/h	[94]
Tail gas purification capacity of acid plant	120,000	Nm^3/h	[95]
Number of burners	10	one	*[73]*
Number of mining trucks	5	vehicle	[96]
Fuel consumption per 100 km for mining trucks	1,000	L	[97]

Table S4 presents the primary copper production capacity of Chinese copper enterprises. The data are sourced from the International Copper Study Group (ICSG, https://icsg.org/). Owing to licensing restrictions on the purchased dataset, the underlying raw data cannot be publicly disclosed. Accordingly, each enterprise in the table is represented by a unique identification code for analytical purposes.

TableS4. Status of Primary Copper Production Capacity

firm Code	Production capacity (kt)	firm Code	Production capacity (kt)
A1	120	C4	100
A2	300	C5	250
A3	50	C6	180
A4	100	C7	700
A5	400	C8	450
A6	250	C9	400
A7	100	C10	400
A8	200	D1	470
A9	150	D2	550
A10	100	D3	100
B1	100	D4	200
B2	150	D5	130
B3	130	D6	100
B4	600	D7	125
B5	400	D8	120
B6	150	D9	800
B7	200	D10	400
B8	100	E1	100

B9	450	E2	120
B10	400	E3	420
C1	280	E4	400
C2	120	E5	470
C3	930	E6	700

Section S3. Technical relationship and technical package analysis

Figure S1 illustrates the relationships among the low-carbon technologies considered in this study. Technology relationships are identified based on process-level mechanism analysis. Each technology is first mapped to its corresponding process unit and equipment interface. If two technologies are implemented within the same process unit and exhibit incompatible equipment-level integration or functional interference, they are classified as mutually exclusive in the technology compatibility matrix. The vertical axis lists different categories of low-carbon technologies, covering multiple technology modules such as combustion optimization, motor system energy efficiency, waste heat recovery, water system efficiency improvement, and so or, while the horizontal axis corresponds to technology indices. Color intensity represents differences in the degree of synergy or constraint among technologies. This figure provides an intuitive visualization of inter-technology interactions at the system level and serves as a structural basis for subsequent technology package construction and optimal pathway screening.

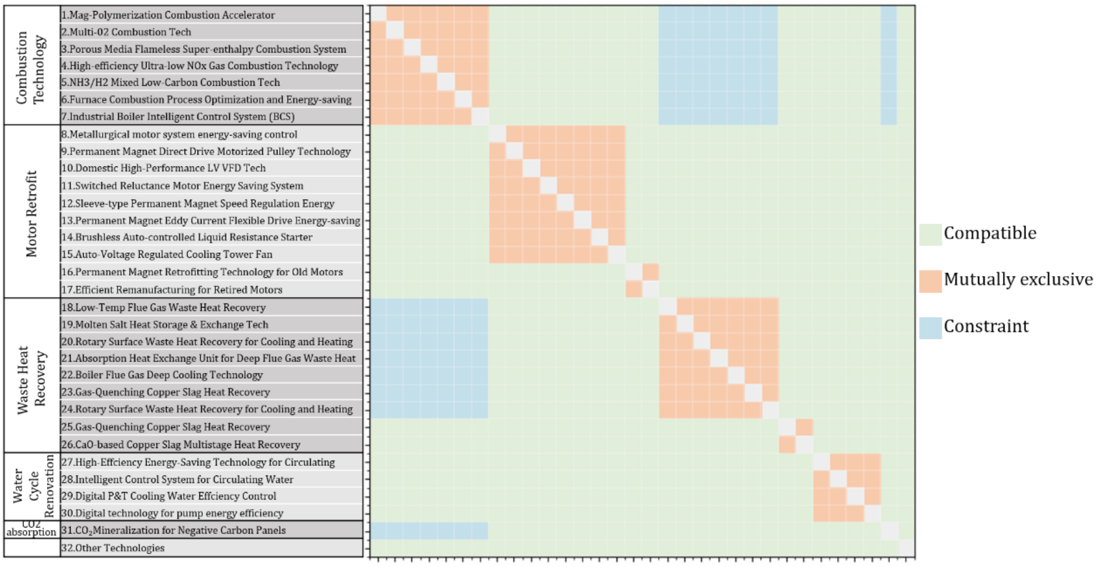

Figure S1. Technology relationship diagram

Figure S2 illustrates the overall distribution of technology package combinations constructed based on inter-technology synergies and compatibility constraints. Starting from a predefined list of candidate technologies, compatible technologies within different production stages are systematically combined according to rule-based criteria. This approach yields a technology package library encompassing hundreds of millions of potential retrofit options, designed to characterize the diverse technology choice space that enterprises may face in real-world decision-making, rather than a simple enumeration of individual technology options.

Preliminary statistical analysis of the technology package library indicates a pronounced positive correlation among investment cost, expected economic returns, and emission-reduction intensity across different technology packages. In general, technology packages with higher investment requirements tend to deliver more substantial energy-saving effects and greater emission-reduction potential. This structural pattern reflects the widely observed “high-investment–high-return” trade-off associated with energy-saving and carbon-reduction technologies in practical applications. These findings provide a necessary foundation for the subsequent screening of feasible technology packages under capital constraints and for the construction of technology adoption pathway scenarios.

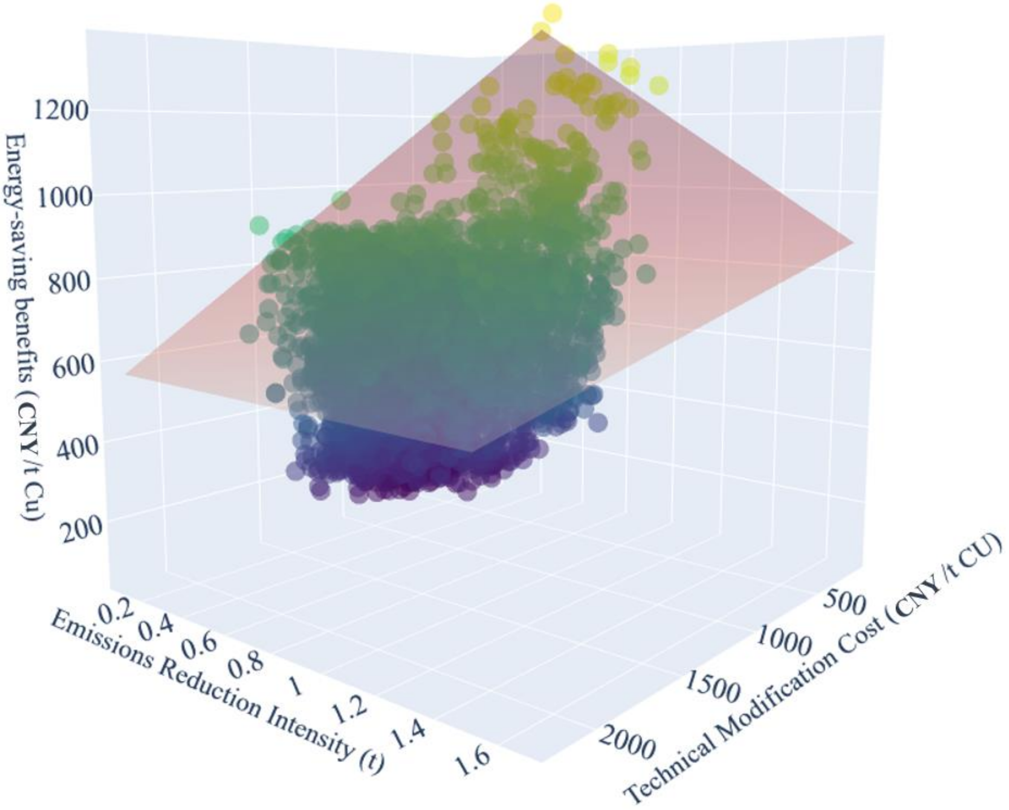

Figure S2. Technology Package Repository

Section S4. Criteria for Enterprise Technology Package Screening

Table S5 summarizes the production capacities of major domestic copper enterprises and their historical investments in technological retrofits. Based on investment data from previously implemented retrofit projects [98–107], this study selects, for each enterprise, the single retrofit project with the largest historical investment to characterize the maximum level of technological upgrade investment that the enterprise can realistically sustain under actual operating conditions. This approach is grounded in the premise that an enterprise's largest realized retrofit investment reflects the upper bound of acceptable capital exposure, shaped jointly by financial constraints, operational risk considerations, and decision-making preferences.

To eliminate the influence of scale heterogeneity across enterprises, this study further adopts retrofit investment per ton of copper as the core indicator of an enterprise's economic affordability. This metric captures the effective level of capital that can be allocated to technological upgrades on a per-unit output basis and more closely reflects the real cost constraints faced in low-carbon technology adoption decisions. Based on the historical distribution of retrofit investment per ton of copper, the sampled enterprises are classified into three categories: Type I enterprises (≤ CNY 2,600 per ton), Type II enterprises (≤ CNY 700 per ton), and Type III enterprises (≤ CNY 350 per ton).

Table S5. Profile of Domestic Copper Enterprises

Enterprise Type	Copper Enterprise Code	Production Capacity (10k t)	Annual profit(100 million CNY)	Total Cost of Technical Renovation Project (100 million CNY)	Annual Investment in Technical Renovation Projects(100 million CNY)	technology investment capacity (CNY/t Cu)
I	a	107.0	118.0	38.00	9.7	<=2600
	b	70.0	16.0	20.91	0.5	
	c	68.0	320.5	19.95	3.39	
	d	168.0	69.6	31.08	1.4	
	e	42.0	6.1	7.10	0.058	
II	f	25.0	5.4	2.00	1.03	<=700
	g	40.0	8.0	2.85	2	
	h	138.0	28.1	9.12	3.1	
	i	110.0	28.0	6.10	5	
III	j	147.0	12.7	5.15	2.65	<=350

Section S5. Screening of Optimal Penetration Rate Scenarios

Figure S3 presents the screening results of technology package adoption pathways for different types of enterprises under capital constraint conditions, where subfigures (a), (b), and (c) correspond to Type I, Type II, and Type III enterprises, respectively. In each subfigure, the grey shaded area represents the set of all technology package adoption-rate scenarios that satisfy the enterprise’s investment capacity constraints, indicating the range of technology diffusion levels that are feasible under real-world economic conditions. The differences in feasible regions across enterprise types reflect heterogeneity in their annual retrofit investment capacities.

Within each feasible region, an optimal adoption-rate scenario (green solid line) is further identified, which achieves maximum emission reductions without exceeding the enterprise’s annual investment capacity. It should be emphasized that this optimal scenario does not constitute a prediction of future technology diffusion trajectories; rather, it is designed to represent the upper bound of energy-saving and carbon-reduction potential that enterprises can unlock under given economic constraints, thereby providing a reference benchmark for assessing emission-reduction gaps across different scenarios.

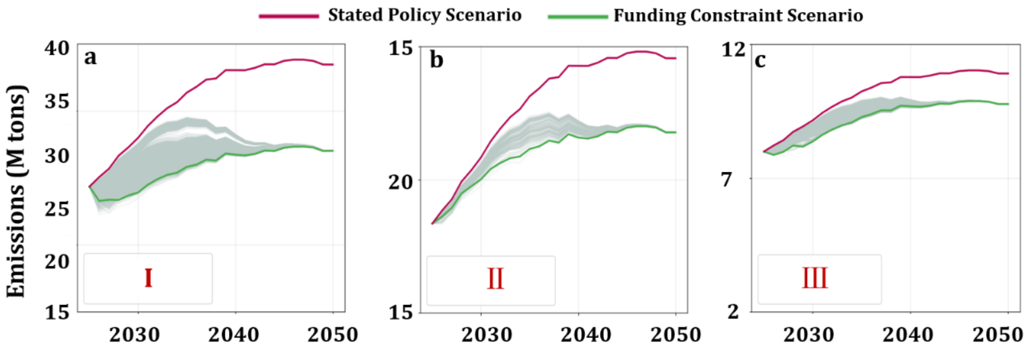

Figure S3 Screening of Optimal Penetration Rate Scenarios by Enterprise Type.

Section S6. Sensitivity and Uncertainty Analyses

Sensitivity and Uncertainty Analysis Methods

This study employs the Hedbrant and Sörme method to evaluate the data quality of key parameters and to assign corresponding uncertainty ranges or probability distributions[131,132]. The method is based on a pedigree matrix framework, in which data are evaluated across five independent dimensions—reliability, completeness, temporal correlation, geographical correlation, and technological correlation—and the coefficient of variation is subsequently derived to quantify the associated uncertainty.

$$cv_{To}=\sqrt{{cv_R}^2+{cv_I}^2+{cv_G}^2+{cv_{Ti}}^2+{cv_O}^2} \quad (1)$$

where cv_{To} denotes the overall coefficient of variation, while cv_R, cv_I, cv_G, cv_{Ti}, and cv_O represent data reliability, completeness, geographical correlation, temporal correlation, and technological correlation, respectively.

All parameters are assumed to follow a normal distribution. Based on a 95% confidence interval, the potential ranges of technology retrofit investment parameters and low-carbon technology parameters are estimated. Accordingly, sensitivity analysis of retrofit investment and uncertainty analysis of technical parameters are performed.

Sensitivity Analysis of Investment in Enterprise Technological Upgrading

Figure S4 presents the coefficients of variation (CV) for total technological transformation investment and annual investment of copper enterprises. Overall, the CVs for both total and annual investments are below 6%, indicating that the data are generally robust and reliable.

For total investment, the CVs of different enterprises range from 1.10% to 5.05%. Among them, Enterprise A (1.10%) and Enterprise D (1.56%) exhibit the lowest values, indicating the highest data stability. Most enterprises (e.g., B, C, E, H, I, and J) have CVs concentrated in the range of 2.30%–3.25%, reflecting relatively stable data. Only Enterprise F (3.98%) and Enterprise G (5.05%) show comparatively higher values, suggesting a certain degree of uncertainty in data completeness or temporal consistency.

For annual investment, the overall distribution pattern is broadly consistent with that of total investment, with CVs also ranging from 1.10% to 5.05%. Enterprise A (1.10%) remains the most stable. Enterprises C (1.56%) and E (2.30%) are at relatively low levels. Most enterprises fall within the range of 2.78%–3.25%, while Enterprise B (3.98%) and Enterprises F and G (both 5.05%) exhibit relatively higher variability, mainly due to differences in data completeness and reliability.

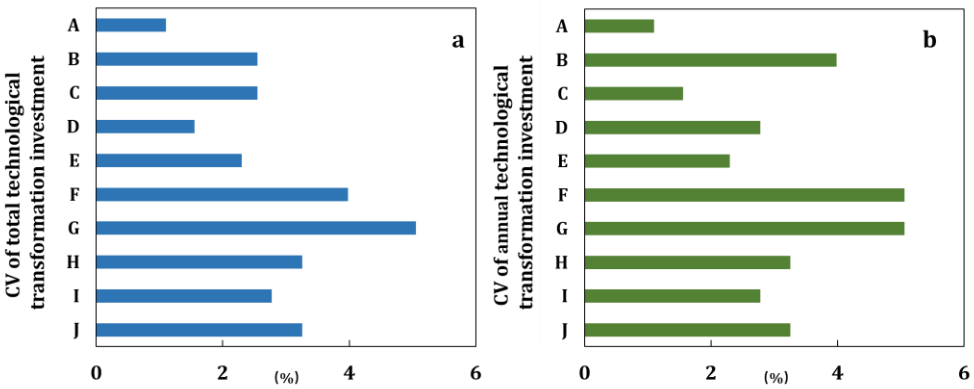

Figure S4 Coefficients of variation of total and annual technological transformation investment for copper enterprises

Figure S5 illustrates the variation ranges of total and annual technological transformation investment across different types of copper enterprises during the upgrading process. The results show that the mean total investment of Type I enterprises increases from approximately 2.02 billion RMB to 2.06 billion RMB, Type II enterprises from 0.51 billion RMB to 0.58 billion RMB, and Type III enterprises from 0.48 billion RMB to 0.53 billion RMB. The difference between the maximum and minimum total investment for each type of enterprise is about 40–70 million RMB. In terms of annual investment, the mean value for Type I enterprises rises from approximately 0.25 billion RMB to 0.30 billion RMB, for Type II enterprises from 0.19 billion RMB to 0.25 billion RMB, and for Type III enterprises from 0.25 billion RMB to 0.27 billion RMB. The variation in annual investment ranges from about 20 million RMB to 60 million RMB. Based on the identified parameter variation ranges, this study further applies the Monte Carlo simulation method with 1,000 random sampling iterations. The results indicate that, even when accounting for investment fluctuations, the optimal technological pathways for all types of enterprises remain unchanged. This is mainly because, on the one hand, the fluctuation range of total investment is relatively small compared with the scale of cumulative costs (Figures 3 c, f, and i). On the other hand, although there are certain variations in technological transformation investment, the lower bounds of both total and annual investments are still sufficient to support the optimal technological pathways that achieve a balance among emission reduction, cost, and economic benefits.

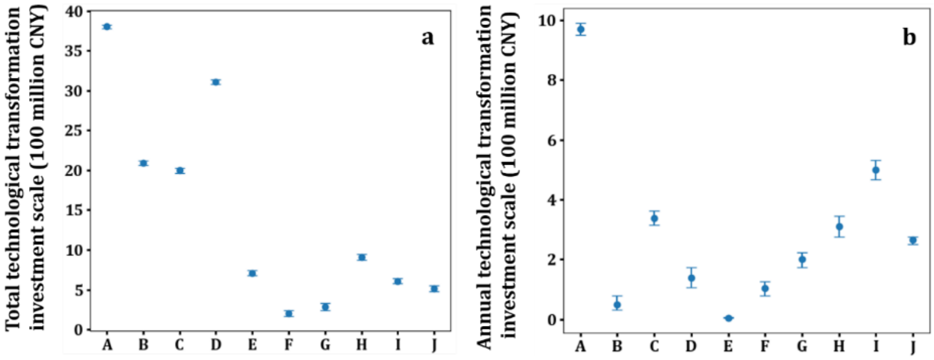

Figure S5 Coefficients of Variation of Total and Annual Technological Transformation Investment for Copper Enterprises

Uncertainty Analysis of Technical Parameters

Figure S6 presents the coefficients of variation (CVs) of parameter data for the optimal technology portfolios across different types of enterprises. Overall, the CVs of all parameters are below 8%, indicating a generally acceptable level of uncertainty.

Among them, Super Flotation Cell, IsaMill, High-Pressure Roller Mill, and Electric Mining Truck exhibit relatively higher variability, with CVs approaching 8%. This uncertainty is primarily attributed to variations in data sources, including differences in data reliability, spatial coverage (e.g., applications across different mining regions and ore conditions), and temporal factors (e.g., data collected from projects commissioned in different years). Specifically, the performance data for these technologies are derived from a combination of pilot projects, enterprise reports, and literature sources spanning multiple regions and time periods. Although such heterogeneity introduces variability, these data collectively capture the typical operational ranges of the technologies and are therefore considered representative of their real-world performance.

In addition, Hydrogen Anode Furnace and Low-Carbon Explosives show CVs of 7.26% and 6.88%, respectively, mainly due to limitations in data availability and regional differences in implementation conditions. For these emerging or less widely deployed technologies, the data are primarily obtained from a limited number of demonstration projects and recent studies. Despite the relatively higher uncertainty, the selected data still reflect the current achievable performance levels under practical conditions. Most of the remaining technologies have CVs concentrated in the range of approximately 3%–4%, indicating a relatively high level of reliability in parameter estimation. Examples include High-Efficiency Circulating Water, 380 A/m^2 Electrolytic Copper, and Permanent Magnet Grinding System. These technologies are relatively mature, with well-established engineering applications and standardized operating conditions. Their parameter values are mainly derived from multiple industrial-scale implementations with consistent performance records, resulting in lower variability and higher robustness.

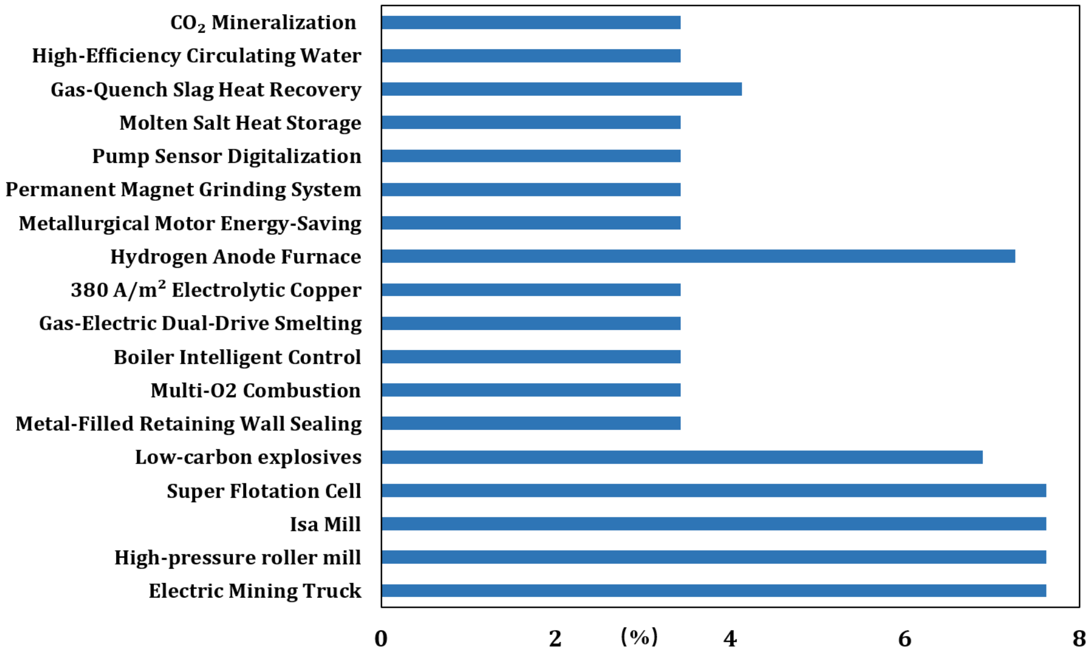

Figure S6 Coefficient of variation of low-carbon technology parameters

Figure S7 presents the uncertainty analysis results of emission reduction potential, cumulative cost, and cumulative revenue for the three types of enterprises under the optimal technology diffusion pathways. By 2050, the uncertainty ranges of emission reduction potential for the optimal pathways of the three types of enterprises are 7.583–9.167 million tons, 2.507–3.031 million tons, and 1.578–1.907 million tons, respectively. In terms of cost and revenue, the three types of enterprises exhibit similar uncertainty characteristics, all showing a gradual expansion over time. Specifically, the relative deviation of cumulative cost increases from ±0.8% in 2026 to ±10% in 2050, while cumulative revenue grows from an initial ±1.7% to ±10% over the same period. From the perspective of absolute scale, for Type I enterprises, cumulative costs increase from approximately 2.2–2.4 billion RMB in the initial stage to about 14.6–17.8 billion RMB by 2050, while cumulative revenues rise rapidly from about 2.2–2.4 billion RMB to approximately 94.2–115.1 billion RMB. For Type II enterprises, both costs and revenues are below 0.1 billion RMB initially; by 2050, costs increase to approximately 3.0–3.7 billion RMB, and revenues reach about 24.2–29.6 billion RMB. For Type III enterprises, costs rise from approximately 0.1–0.2 billion RMB to about 1.0–1.2 billion RMB by 2050, while revenues fluctuate within the range of 16.6–20.3 billion RMB. Overall, the uncertainty ranges of emission reduction potential, cost, and revenue for all three types of enterprises expand over time, but remain within a controllable range.

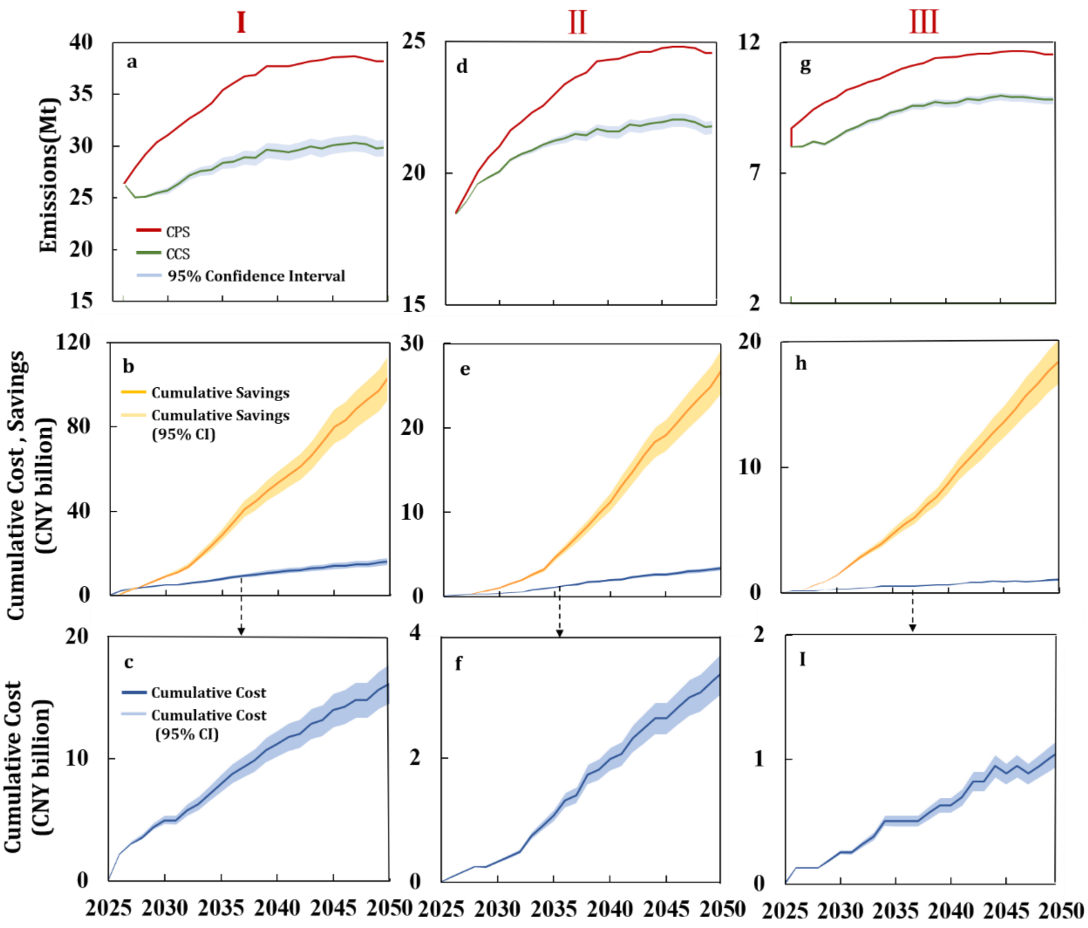

Figure S7 Uncertainty analysis of emission reduction potential (a, d, g), cumulative revenue (b, e, h), and cumulative cost (c, f, i) under optimal technology pathways across enterprise types

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