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Assessing the Techno-Economic Feasibility of Bamboo Residue-Derived Hard Carbon

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Abstract

Bamboo residues represent an abundant, renewable biomass feedstock that can be converted into hard carbon—an emerging anode material for sodium-ion batteries. This study presents a detailed techno-economic analysis of hard carbon production from bamboo residues across China's ten most bamboo-rich provinces. Regional feedstock availability was estimated from provincial production statistics, while average transportation distances were derived using a square-root-area-based approximation method. The process includes hydrothermal pretreatment, acid washing, carbonization, graphitization, and ball milling. Material and energy inputs were estimated for each stage, and both capital and operating expenses were evaluated using a discounted cash flow model assuming a 15% internal rate of return. The resulting minimum selling price of bamboo-derived hard carbon ranges from 14.47 to 18.15 CNY/kg. Assuming 10% of bamboo residues can be feasibly collected and processed, these ten provinces could collectively support an annual hard carbon production capacity of approximately 1.04 million tons. The results demonstrate that bamboo residues are a strategically distributed and underutilized resource for producing cost-competitive hard carbon at scale, particularly in provinces with existing bamboo industries and supply chains.

Keywords: hard carbon; biomass; pyrolysis; economic analysis; sodium ion battery; bamboo residue

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1. Introduction

Energy storage is one of the critical challenges in achieving a sustainable energy transition. Renewable energy sources such as solar, wind, and tidal power are inherently intermittent and cannot serve as stable primary energy sources without reliable and efficient energy storage solutions [1]. Among various forms of energy carriers, electricity is the most versatile, making electrochemical batteries a leading option for large-scale energy storage. However, existing commercial battery systems—especially lithium-ion batteries—remain costly, and alternatives often suffer from insufficient energy density or limited scalability. Sodium-ion batteries have emerged as a promising substitute due to the earth abundance of sodium and their potential for cost reduction. Notably, one of the most promising anode materials for sodium-ion batteries is hard carbon, which can be derived from lignocellulosic biomass—the most abundant and renewable carbon source on the planet [2].

Hard carbon is a non-graphitizable carbon material formed by thermally converting organic precursors at elevated temperatures. Unlike highly ordered graphite, hard carbon consists of disordered, anisotropic graphite-like microdomains that aggregate into a turbostratic structure [3]. This unique morphology contributes to its favorable electrochemical properties, including low voltage plateaus and good sodium storage capacity. A key advantage of hard carbon lies in its feedstock flexibility—most lignocellulosic biomass, including agricultural and forestry residues, can serve as viable precursors. Despite the growing interest in biomass-derived hard carbon for sodium-ion batteries, the economic feasibility of producing hard carbon from low-cost and regionally abundant feedstocks such as forestry residues remains underexplored [4].

The production of hard carbon from biomass typically involves high-temperature thermal conversion under an inert atmosphere [4]. In the initial pyrolysis stage (usually below 900 °C), oxygen and other heteroatoms are removed, resulting in a solid carbonaceous intermediate commonly referred to as biochar. This is followed by further carbonization and graphitization at elevated temperatures, where disordered carbon structures reorganize into short-range graphite-like layers with turbostratic morphology [5]. The entire process involves complex physicochemical transformations, along with the generation of by-products such as bio-oil, syngas, and tar [6]. The properties of the final hard carbon product are highly sensitive to thermodynamic conditions, heating rates, precursor type, and temperature profiles. Accordingly, significant research efforts have been dedicated to elucidating the mechanisms of sodium-ion storage in hard carbon, linking structural features—such as pore size distribution, interlayer spacing, and defect density—to specific charge–discharge behavior [7,8]. Over the past decade, progress in both mechanism understanding and pilot-scale production has enabled early-stage commercialization efforts [9]. However, there remains a lack of systematic evaluation of the economic viability of biomass-derived hard carbon production, which is essential for accelerating its industrial adoption as a competitive alternative to lithium-ion battery materials.

Among various lignocellulosic biomass feedstocks, bamboo is particularly attractive for hard carbon production due to its high areal yield, short growth cycle, and minimal input requirements. In bamboo-rich regions such as southern and southwestern China, extensive cultivation and mature downstream industries—ranging from construction materials to paper and textiles—generate substantial quantities of bamboo residues (BRs) as by-products. These residues are typically concentrated near processing hubs, which can significantly reduce feedstock transportation and logistics costs [10]. Moreover, previous studies have shown that bamboo-derived hard carbon exhibits favorable electrochemical properties for sodium storage, including high capacity and stable cycling performance [11]. Given the spatial concentration of bamboo industries and the consistent generation of residues, BR represents a stable, scalable, and underutilized resource for cost-effective hard carbon production in key provinces such as Fujian, Jiangxi, and Zhejiang [12].

Techno-economic analysis (TEA) is a widely adopted tool for assessing the commercial viability of emerging technologies, particularly in the fields of bioeconomy and energy storage. TEA provides a structured framework to evaluate capital investments, operating costs, and economic returns under defined technical assumptions and financial conditions [13]. In recent years, TEA has been extensively applied to biomass thermochemical conversion pathways and carbon material manufacturing. For instance, one study reported that bio-based activated carbon production could achieve an energy efficiency of 8.0%, with a minimum selling price of 9.72 CNY/kg, an internal rate of return (IRR) of 13.93%, and a payback period of 7 years [14]. Peng et al. optimized the co-carbonization of waste mushroom substrate and bagasse, resulting in a carbon yield of 66.7%, a net present value of USD 80.5 million, and a climate benefit of −2.37 kg CO_2-eq per kg of product [15]. Another study by Struhs

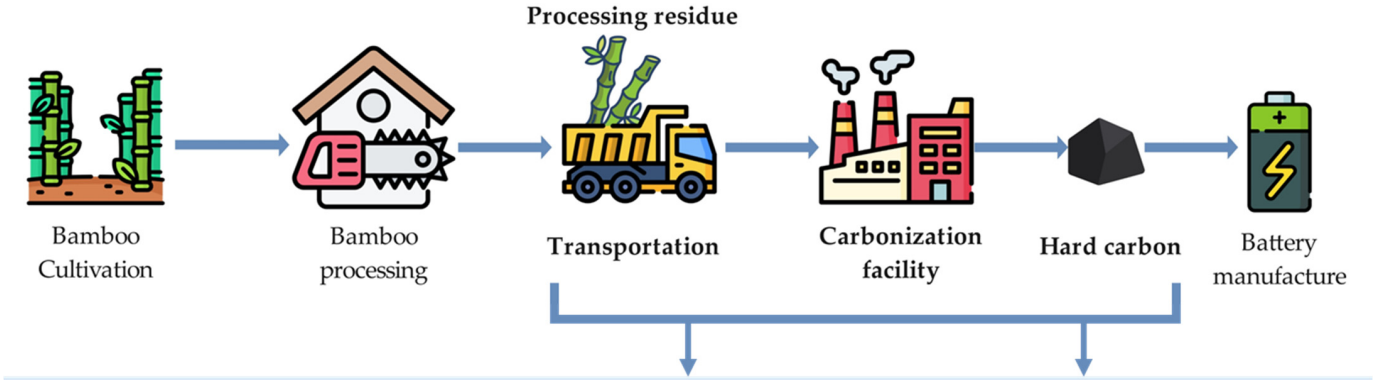
et al. used a portable refining system to produce biochar from cattle manure, estimating a production cost of USD 237 per tonne and emissions of 951 kg CO_2-eq per tonne [16].

Although techno-economic analyses (TEAs) have been widely applied to assess various biomass-derived solid materials, the economic feasibility of producing biomass-based hard carbon—a critical anode material for sodium-ion batteries—remains unexplored. To the best of our knowledge, this study represents the first TEA focused specifically on biomass-derived hard carbon production, addressing a crucial gap within the emerging sodium-ion battery supply chain literature. In this study, we conduct a process-level techno-economic analysis of hard carbon production from bamboo residues, focusing on ten representative provinces in China with the highest bamboo resource availability. Based on an established life cycle inventory (LCI) framework and a discounted cash flow (DCF) model, we estimate capital and operational costs and determine the minimum selling price (MSP) required to achieve a 15% internal rate of return. The results provide critical insights for investors, policymakers, and technology developers aiming to scale up sustainable anode material production from regional biomass resources.

2. Materials and Methods

2.1. Hard Carbon Manufacturing Process

This study focuses on the techno-economic performance of producing hard carbon from bamboo processing residues, a by-product of the established bamboo industry. As illustrated in Figure 1, the full value chain includes bamboo cultivation, primary processing, transportation, carbonization, and integration into battery manufacturing. However, this work only evaluates the bolded segments in the figure: transportation of bamboo residues and the manufacturing of hard carbon via thermal and chemical processing. A detailed breakdown of capital and operating expenditures (CAPEX and OPEX) within this system boundary is also provided in Figure 1 to clarify the scope of the analysis.



CAPEX	OPEX
- Equipment (furnace, reactor, etc.)	- Feedstock purchase and transportation
- Installation (buildings, electrical systems)	- Sulfuric acid
- Engineering & Contingency	- Electricity / Utilities
- Land, Working capital	- Labor
	- Maintenance
	- Waste treatment (incl. acid effluent)

Figure 1. The hard carbon production process and system boundary.

The manufacturing process is constructed based on the optimized industrial pathway identified in previous life cycle assessments of hard carbon for sodium-ion batteries [17]. In this study, bamboo residues are first subjected to acid washing using sulfuric acid to remove mineral impurities and enhance carbon yield. After drying, the material undergoes pre-carbonization to eliminate most volatiles at a moderate temperature (~500 °C), followed by high-temperature pyrolysis at 1300 °C in an inert atmosphere to induce graphitization and form disordered graphite microcrystals. These are then further processed via ball milling to achieve the particle size required for sodium-ion battery anodes.

2.2. Feedstock Availability, Transportation Model, and Cost Assumptions

BR generated as by-products from harvesting and processing activities, represent a valuable yet underutilized lignocellulosic biomass resource in China. This study focuses on ten provinces—Fujian, Guangxi, Guangdong, Jiangxi, Zhejiang, Hunan, Chongqing, Sichuan, Yunnan, and Anhui—where bamboo residue availability exceeds 1 million tons per year. Provincial selection was guided by the national-scale spatial inventory methodology proposed by Wang et al., which integrates statistical regression, crop-to-residue ratio modeling, and GIS-based downscaling to construct a high-resolution geospatial distribution of biomass residues across China [18].

To estimate the average transportation distance from decentralized BR sources to centralized carbonization facilities, each province was geometrically simplified as a circular area. The mean straight-line distance from any point within the province to the center was approximated as

$$D_E = 0.66 \times \sqrt{A} \quad (1)$$

where D_E is the mean straight-line distance; A is the area of the province [19]. To correct for real-world road network detours, an empirical mobility correction was applied using the following formula:

$$D_R = \alpha \cdot D_E + \beta \quad (2)$$

where α is 1.287, β is 0.4 km for expresses with R^2 = 0.900, based on large-sample transportation studies in China [20].

Feedstock cost assumptions were based on national procurement data, with the price of BR ranging from 200 to 500 CNY per tonne [21–23]. The transportation cost was set at 0.3 CNY per tonne-kilometer, reflecting the average within the reported range of 0.2–0.4 CNY/tkm from national logistics pricing reports [24]. These cost parameters, combined with the transport distance estimates, were used to compute the delivered feedstock cost to the facility gate for each province.

2.3. Manufacturing Data

The manufacturing inventory data used in this study is based on the industrial-scale scenario reported by Liu et al. (2024), who developed a multi-scale life cycle inventory (LCI) for hard carbon production from lignocellulosic biomass [17]. Among the three cases presented—lab scale, pilot scale, and industrial scale—we selected the baseline industrial case without energy or material recovery optimization. This choice was made to reflect the typical operating conditions and efficiencies of first-generation commercial hard carbon facilities, rather than idealized or future-improved performance scenarios.

The modeled process includes four main stages: (1) acid washing with sulfuric acid, (2) thermal drying, (3) pyrolysis and carbonization at up to 1300 °C, and (4) ball milling. These steps are consistent with the thermochemical sequence described in Liu et al. and are broadly representative of the industrial pathways used for manufacturing sodium-ion battery anodes [17]. The production system does not incorporate energy recovery from

pyrolysis gas or by-product valorization, which aligns with a conservative cost assessment strategy. Table 1 summarizes the specific material and electricity inputs required to produce 1 kg of hard carbon. The total electricity demand across all unit operations is 6.0 kWh/kg. For conservative estimation, we additionally assume an overall thermal system efficiency of 70%, which reflects the typical performance of first-generation industrial plants without integrated heat recovery systems.

Table 1. Specific material and energy inputs for producing 1 kg of hard carbon [17].

	Materials/kg					**Power/kWh**			
Specific input	BR	H_2SO_4	Water	Stirring	Washing	Drying	Pyrolysis	Carbonization	Milling
Value	4.45	3.56	10.43	0.00040	0.037	0.64	3.35	1.98	0.03

2.4. Discounted Cash Flow Analysis

A TEA was conducted to evaluate the economic viability of producing hard carbon from bamboo residues at an industrial scale. The analysis was based on a DCF framework, following established methodologies widely applied in biomass-to-materials and biofuel systems from the U.S. National Renewable Energy Laboratory [25]. The model integrates both CAPEX and OPEX across the full production chain from bamboo residue procurement to hard carbon output at the factory gate. The objective was to determine the MSP of hard carbon required to achieve a target IRR of 15%.

The DCF model considers time-adjusted cash flows over a project lifetime, and accounts for installation, inflation-adjusted equipment costs, working capital, tax effects, and depreciation schedules. Cost estimation was performed using standard process engineering approaches, including the six-tenth scaling law (we used a scaling factor of 0.7) for capacity adjustment and CEPCI-based cost normalization. Region-specific inputs such as feedstock cost, transportation distance, and electricity price were incorporated for each of the ten bamboo-rich provinces. In addition, a one-way sensitivity analysis was conducted to examine the impact of key technical and financial parameters on MSP outcomes. The details of capital cost estimation, operational cost structure, financing assumptions, and sensitivity scenarios are described in the following subsections.

2.4.1. Capital Expenditure Estimation

The capital investment of the hard carbon production facility was evaluated using a bottom-up approach, integrating literature-derived unit costs with standard cost multipliers widely adopted in chemical process engineering [26]. The equipment list includes biomass handling, drying, pyrolysis, acid washing, carbonization, graphitization, and ball milling. While baseline costs for the thermal units (pyrolysis, feedstock handling, waste treatment) were adapted from a U.S. DOE techno-economic analysis of lignocellulosic biorefineries [27]. The cost of the graphitization step was estimated independently based on commercial quotations for silicon carbide vacuum sintering furnaces, with a unit price of approximately 80,000 USD per unit and a throughput of 3 tons per day per furnace [28]. This price was scaled to match a production capacity of 2000 tons per day, consistent with the design basis of the reference system. A total graphitization investment of 384 million CNY was assumed based on this match, in alignment with the capital intensity of comparable high-temperature carbon treatment systems. All equipment costs reported in Table 2 are benchmarked to a reference year of 2021.

The total purchased equipment cost was then scaled up based on the production capacity and number of batches and augmented using standard installation factors as shown in Table A1 in Appendix A. Specifically, installation (40%), instrumentation (20%), piping (15%), electrical systems (15%), buildings (30%), yard improvements (10%), and

service facilities (20%) were all computed as percentages of the delivered equipment cost. These constitute the direct capital cost.

Table 2. Equipment cost assumptions and throughput capacity (2021 baseline).

Parameter	Cost/CNY	Capacity
Feedstock and Product Treatment	2,160,000	2000 tons per day
Pyrolysis	223,920,000	2000 tons per day
Graphitization	384,000,000	2000 tons per day
Cooling Water and Other Utilities	33,840,000	2000 tons per day
Water Management	51,840,000	2000 tons per day

Indirect costs include engineering and supervision (25%), contingency (30%), contractor fees (10%), and startup expenses (10%). The Fixed Capital Investment (FCI) is the sum of the direct and indirect costs. A working capital equivalent to 15% of the FCI was also considered, leading to the Total Capital Investment (TCI).

The land cost was assumed to be 6% of the delivered equipment's value. All cost estimates were adjusted to 2024 values using the Chemical Engineering Plant Cost Index (CEPCI). This capital cost structure aligns with established methods used in biorefinery evaluations and reflects current commercial estimates for high-temperature processing of battery materials.

2.4.2. Operating Expenditure Assumptions

The OPEX for the hard carbon production facility was estimated based on a combination of literature values, industrial engineering assumptions, and region-specific market prices. The main cost categories include feedstock procurement and transport, chemical inputs, utilities, labor, maintenance, and regulatory overheads, as shown in Table A1.

Feedstock and chemical costs were calculated using the BR and sulfuric acid consumption intensities presented in Table 1. The baseline BR price was set at 350 CNY per tonne, while sulfuric acid was assumed at 750 CNY per ton [29]. The BR transportation cost was based on estimated province-level distances and a unit freight cost of 0.3 CNY per tonne-kilometer, as discussed in Section 2.2.

Utility costs were derived from the process-specific energy demand (6.0 kWh/kg of hard carbon) and water consumption. Electricity prices for each province were sourced from https://www.nengy.net/ [30], and the industrial electricity rate was selected based on the "single-rate" tariff category for medium- to high-voltage users (35 kV or 110 kV), which is commonly applied to large-scale manufacturing facilities in China. A state-wide water price (4.83 CNY/ton) is applied. A conservative thermal efficiency of 70% was assumed to account for losses in all stages.

Labor costs were estimated using the DOE Labor Estimator Mini Tool based on the book Chemical Process Engineering: Design And Economics [31,32], with the inclusion of a 0.95 overhead multiplier to account for supervision and fringe benefits. To reflect a conservative estimation strategy and ensure robustness under potential labor-intensive operations, the workforce size was doubled relative to the baseline staffing requirement suggested by the tool.

Maintenance and repair costs were assumed to be 6% of the total fixed capital investment (FCI) annually. An additional 15% of this maintenance cost was allocated for spare parts, consumables, and routine maintenance supplies.

Depreciation was calculated using the Modified Accelerated Cost Recovery System (MACRS) 7-year schedule. Local taxes and insurance were included as 3% of FCI annually, covering property tax, operational insurance, and regulatory compliance.

2.4.3. Financial Structure and MSP Calculation

The financial analysis was structured using a DCF framework to calculate the MSP of hard carbon required to achieve a target IRR of 15%. The capital investment was assumed to be financed through a combination of 40% equity and 60% debt. The debt was amortized over a 10-year term at a country-specific interest rate, with annual payments. Corporate income tax was applied at a representative national rate of 25%, unless otherwise noted (see in Section 2.4.4).

Asset depreciation was modeled using the MACRS over a 7-year schedule. The construction period was assumed to span 3 years, with capital expenditure distributed as 8% in Year −2, 60% in Year −1, and 32% in Year 0. A 0.5-year startup period was also included, during which operating costs were incurred at 100% while revenues were realized at 50% of full capacity.

The MSP of hard carbon (in CNY/kg) was calculated as the price at which the project's net present value (NPV) equals zero at the specified IRR (15%). All financial assumptions, depreciation schemes, and cash flow structures were embedded in the model to simulate realistic industrial investment conditions.

2.4.4. Sensitivity Analysis

To evaluate the robustness of the techno-economic performance under uncertain or regionally variable conditions, a one-way sensitivity analysis was conducted using the Fujian Province scenario as the baseline. Fujian was selected due to its highest availability of bamboo residues among the ten provinces analyzed, making it a representative high-resource case for hard carbon production.

Several technical and economic parameters were varied individually while keeping other variables constant, in order to assess their marginal impact on the MSP of hard carbon. The tested parameters and their respective low, baseline, and high values are summarized in Table 3.

Table 3. Sensitivity parameters values.

Parameter	Low	Base	High
Labour salary (CNY/year)	4294	5638	6724
Equity percentage	0.2	0.4	0.6
Average transportation distance (km)	−20%	Baseline	+20%
Income Tax Rate	0.15	0.25	0.35
Transportation price (CNY/tkm)	0.2	0.3	0.4
Scaling factor	0.6	0.7	0.8
Bamboo residue price (CNY/ton)	200	350	500
H_2SO_4 price (CNY/ton)	500	750	1000
El price (CNY/kWh)	0.45	0.62	0.78
Hard carbon yield	−20%	Baseline	+20%
El efficiency	0.5	0.7	0.9

Labor salaries were varied across the minimum and maximum average levels observed among the ten selected provinces. The income tax rate ranged from 15% to 35%, with the lower bound reflecting preferential tax policies for certified high-tech enterprises in China. The bamboo residue procurement cost was varied between 200 and 500 CNY/ton, as previously established from regional market sources. Electricity prices were also varied based on the observed industrial tariff range (35–110 kV users) across the ten provinces.

Technical parameters such as the scaling factor (used in the CAPEX estimation), sulfuric acid price, hard carbon yield, and overall electric heating efficiency were also perturbed to reflect plausible process variability or supplier differences. Transportation-

related factors—including unit transport cost and average distance—were varied by ±20% around the baseline.

3. Results

3.1. Feedstock and Transportation Analysis

Bamboo processing waste is spatially concentrated in several southeastern provinces of China, reflecting the maturity and industrial intensity of regional bamboo processing sectors. As shown in Figure 2, the most resource-rich province is Fujian, followed by Guangxi, Guangdong, and Jiangxi. These provinces jointly account for a significant share of China's total bamboo residue, making them ideal candidates for large-scale hard carbon production.

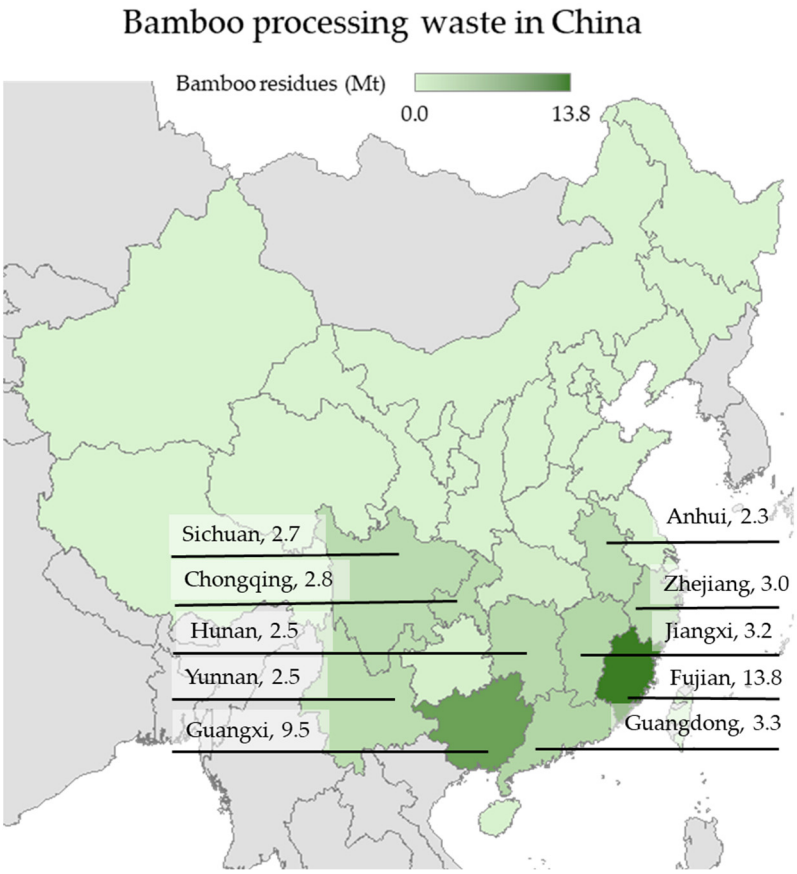


Figure 2. Spatial distribution of bamboo processing residues across China [18].

The ten provinces with the highest estimated bamboo residue availability were selected for scenario-based techno-economic analysis. As detailed in Section 2.2, average transportation distances from feedstock sources to centralized carbonization facilities were estimated using a simplified geometric model combined with empirically derived detour correction factors to reflect road-based transport conditions.

Table 4 summarizes key geographic and logistical indicators, including provincial area, estimated average straight-line and road-based transport distances, and total bamboo residue availability. Fujian stands out with 13.8 Mt of residues and a relatively short transport distance of 167.4 km. Other provinces such as Guangxi and Guangdong also exhibit favorable combinations of feedstock supply and logistical feasibility. In contrast, more remote regions such as Sichuan and Yunnan face longer average transport distances, potentially raising delivery costs.

Table 4. Geographic and transport parameters of ten bamboo-rich provinces.

Province	Area (10^3 km^2) [33]	Avg. Straight Distance (km)	Avg. Transport Distance (km)	Annual Bamboo Residue (Mt) [18]
Fujian	121.4	129.7	167.4	13.8
Guangxi	236.7	181.2	233.6	9.5
Guangdong	179.8	157.9	203.6	3.3
Jiangxi	167.0	152.2	196.2	3.2
Zhejiang	105.5	120.9	156.1	3.0
Hunan	211.8	171.4	221.0	3.0
Chongqing	82.4	106.9	138.0	2.8
Sichuan	485.0	259.3	334.1	2.7
Yunnan	394.0	233.7	301.2	2.5
Anhui	140.1	139.4	179.8	2.3

3.2. Capital Cost

Figure 3 presents the total capital investments required for hard carbon production facilities across the ten bamboo-rich provinces, assuming a 10% utilization rate of available bamboo residues. The investment scale is directly proportional to the annual residue availability, which determines the plant processing capacity. Fujian, with the highest bamboo residue (13.8 Mt/year), requires the largest capital investment of approximately CNY 2.05 billion, followed by Guangxi (CNY 1.58 billion) and Guangdong (CNY 0.75 billion). In contrast, provinces such as Anhui, Yunnan, and Sichuan—each with residue availability below 3 Mt/year—require significantly smaller investments, generally under CNY 700 million.

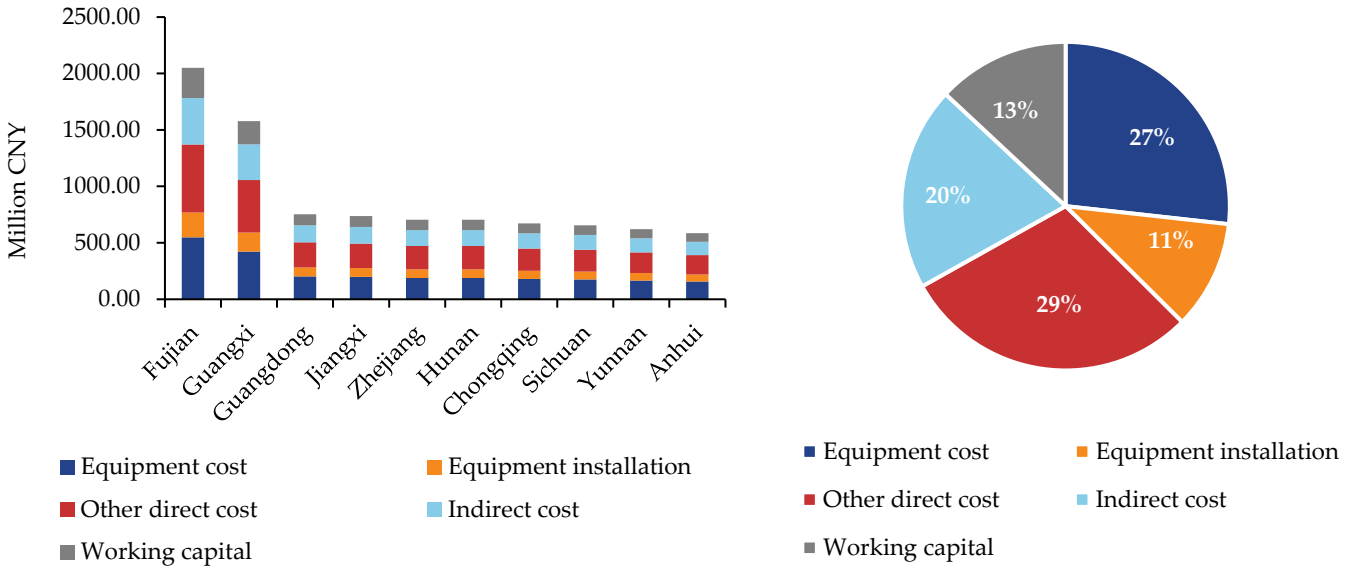


Figure 3. Capital cost for ten provinces (**left**); breakdown capital cost for Fujian case (**right**); corresponding numerical results are presented in Table A2.

Despite large variations in absolute capital requirements, the structure of the capital cost remains relatively consistent across provinces. As shown in Figure 3 (right), based on the Fujian case, "Other direct costs"—including piping, electrical systems, buildings, and service facilities—constitute the largest share (29%) of total capital. The equipment cost and indirect costs account for 27% and 20%, respectively, followed by equipment installation (11%) and working capital (13%). This reflects the typical cost composition for biomass pyrolysis and graphitization systems with centralized processing infrastructure.

To better understand the capital efficiency, we further analyzed the unit capital cost per ton of annual hard carbon capacity. Provinces with smaller scales (e.g., Anhui, Chongqing) tend to have higher per-ton capital costs due to limited economies of scale, whereas larger plants in Fujian and Guangxi benefit from size advantages. These results emphasize the importance of aligning plant scale with regional feedstock availability to optimize capital deployment.

3.3. Operating Cost

Figure 4 shows the operating costs of hard carbon production across the ten provinces, along with the detailed breakdown for the Fujian case. Fujian, with the largest production scale, exhibits the highest annual OPEX at approximately CNY 3.97 billion, followed by Guangxi at CNY 3.08 billion. Provinces with smaller bamboo residue availability, such as Anhui and Yunnan, require substantially lower operating costs, generally below CNY 800 million.

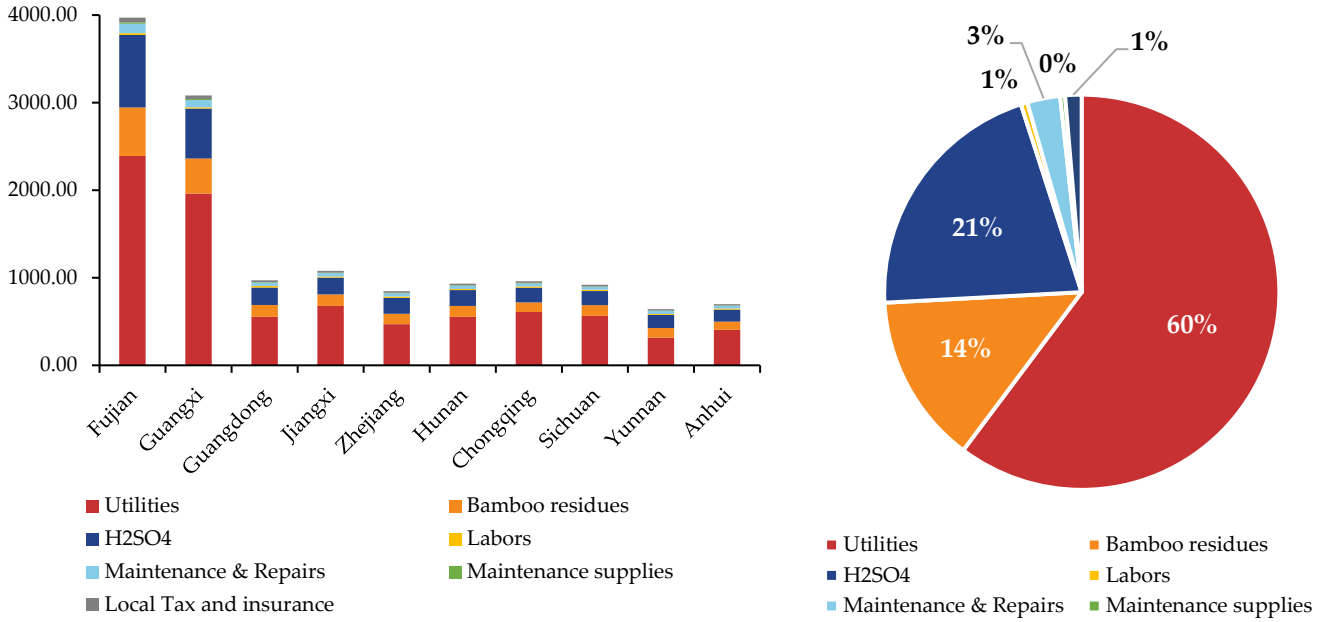


Figure 4. Operating cost for ten provinces (**left**); breakdown operating cost for Fujian case (**right**); corresponding numerical results are presented in Table A3.

Utilities represent the dominant share of the operating costs, particularly due to the high electricity consumption required for the pyrolysis and graphitization processes. In the case of Fujian, utilities account for nearly 60% of the total OPEX, followed by sulfuric acid input (21%), bamboo residue procurement (14%), and labor (1%) (Figure 4, right). Other components such as maintenance, local tax, and insurance together constitute approximately 4% of the total.

This cost structure indicates that the hard carbon industry is energy-intensive and feedstock-sensitive. The H_2SO_4 consumption cost, while relatively high, remains consistent across provinces due to fixed stoichiometric requirements. Labor costs are minor but reflect regional salary differences, while maintenance and tax costs scale proportionally with FCI, thus remaining relatively stable across locations.

Notably, despite similar bamboo availability, provinces like (Guangdong vs. Jiangxi) and (Zhejiang vs. Hunan) show different OPEX patterns—largely due to differences in electricity pricing and slightly from the feedstock acquisition cost (due to differences in transportation distance, see Table 4). This demonstrates the importance of regional electricity price policies and supply chain optimization for reducing costs in future hard carbon deployment.

3.4. Minimum Selling Price

The MSP of hard carbon for each province was calculated based on the DCF model under a targeted 15% internal rate of return. Figure 5 presents the MSP components for the ten provinces, along with the cost breakdown for Fujian province.

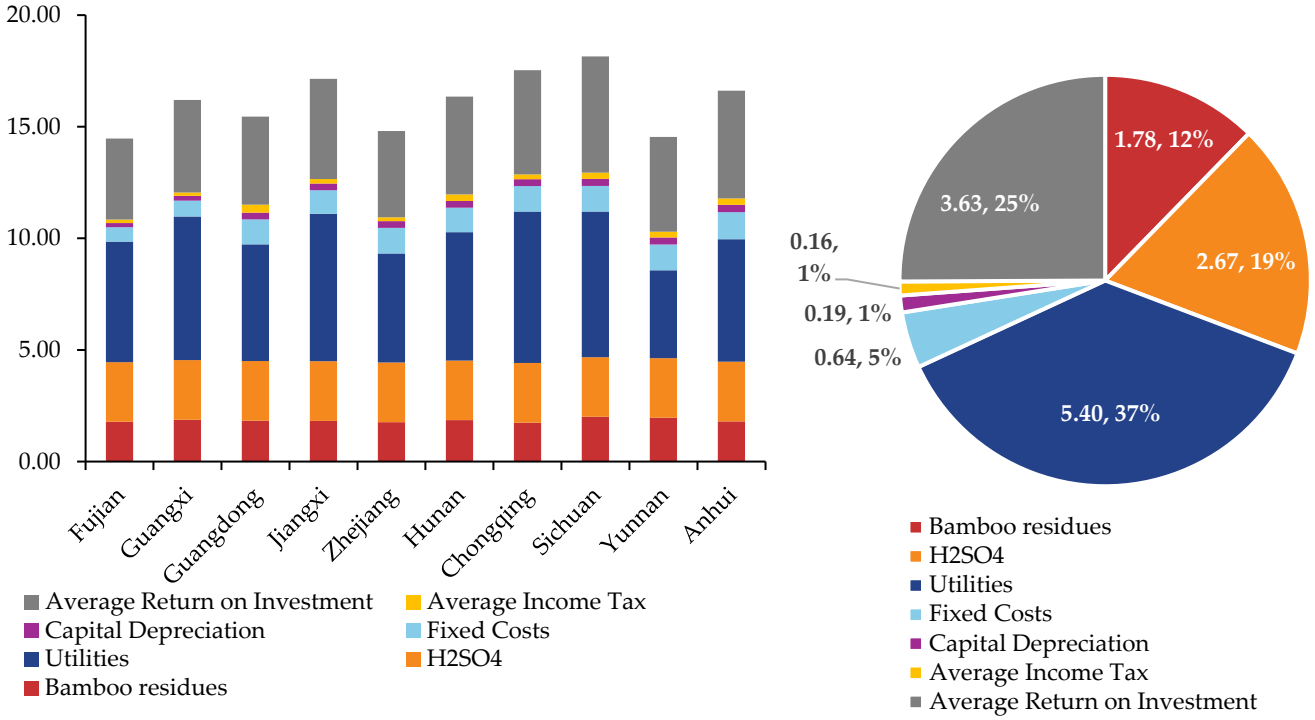


Figure 5. MSP of BR derived hard carbon for ten provinces (**left**); MSP breakdown for Fujian case (**right**); corresponding numerical results are presented in Table A4.

MSP values range from 14.47 CNY/kg in Fujian to 18.15 CNY/kg in Sichuan. The lower MSPs in provinces such as Fujian are driven by relatively larger scales and, in Yunnan, are driven by relatively lower utility costs. In contrast, provinces like Sichuan and Chongqing exhibit higher MSPs due to elevated capital investment and utility expenditures despite their abundant bamboo resources.

Across all cases, utilities remain the largest cost contributor, accounting for 27–37% of the total MSP, followed by the return on investment (21–29%) and sulfuric acid input (≈2.67 CNY/kg fixed across all provinces). For Fujian, which represents the base case, utilities (5.40 CNY/kg), H_2SO_4 consumption (2.67 CNY/kg), and average return on investment (3.63 CNY/kg) collectively account for over 80% of the total MSP (Figure 5, right). Notably, bamboo residues themselves account for only ~12% of the MSP, reflecting the relatively low cost of this feedstock.

It is also observed that fixed costs and capital depreciation become more pronounced in provinces with smaller plant sizes, such as Anhui and Jiangxi, where scale economies are weaker. The average income tax burden remains minor across all regions, ranging from 0.15 to 0.36 CNY/kg.

3.5. Sensitivity Analysis Insights

To assess the robustness of the techno-economic outcomes, a one-way sensitivity analysis was conducted on eleven key parameters (Figure 6). Fujian Province was chosen as the baseline case due to its highest bamboo residue availability (13.8 Mt/y). The parameter ranges were selected based on provincial-level data across the top ten bamboo-producing provinces, literature values, and policy scenarios (Table 3). For instance, the labor salary

ranged from 4294 to 6724 CNY/year across provinces, and the income tax rate was varied from 15% (representing high-tech enterprise exemption) to 35% (representing the upper limit of corporate income tax in China). The ranges for bamboo residue and electricity prices reflected actual market volatility from 2023–2024 sources.

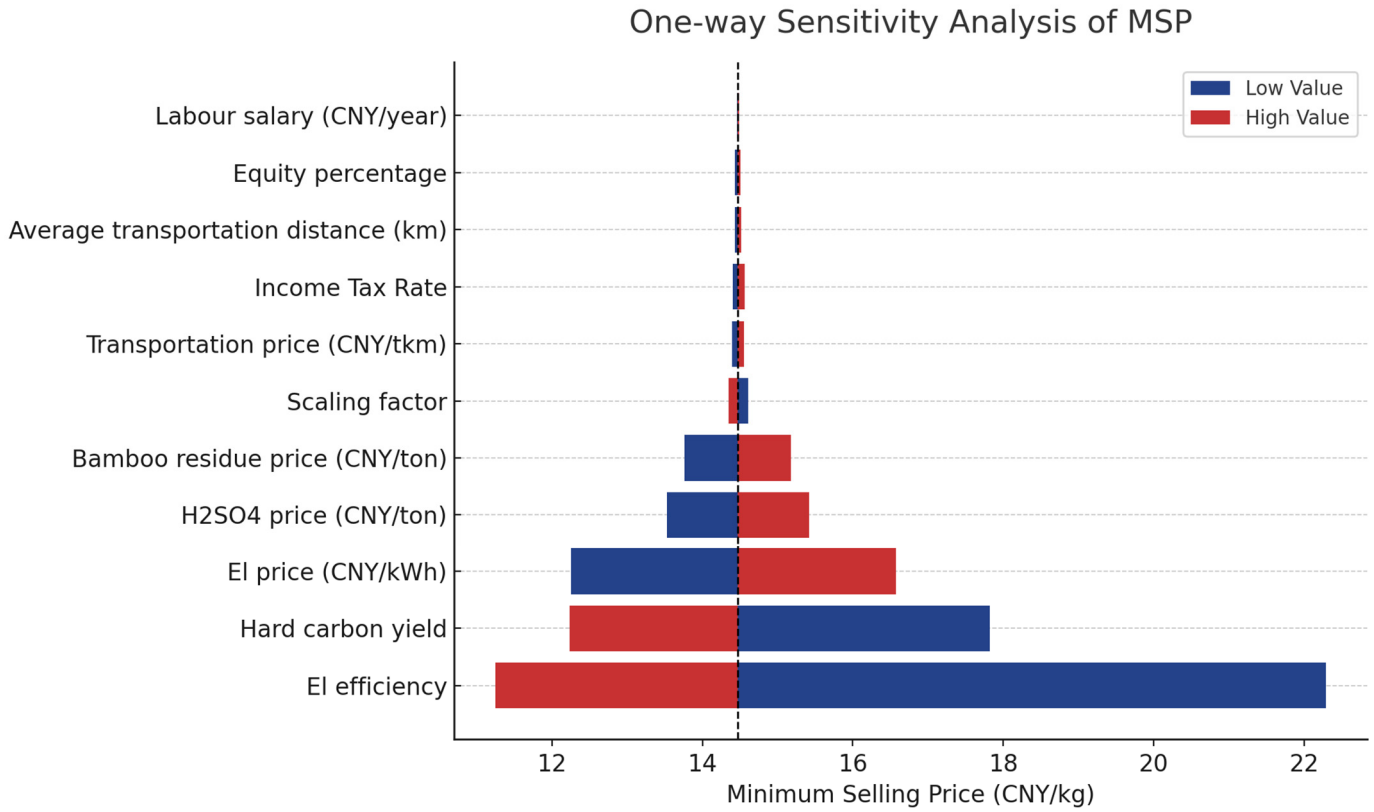


Figure 6. One-way sensitivity analysis of minimum selling price (MSP) for the Fujian case. Parameters are detailed in Table 3; corresponding numerical results are presented in Table A5.

Figure 6 shows that electricity efficiency, hard carbon yield, and electricity price were the most influential variables affecting the MSP. A 20% decrease in electricity efficiency increased the MSP from 14.47 to 22.29 CNY/kg, while a 20% increase in yield lowered the MSP to 12.23 CNY/kg. This is consistent with the nature of high-temperature carbonization and the associated energy intensity of the process. Additionally, a low yield leads to significant material losses, amplifying feedstock and utility costs per kg of product.

Feedstock price also had a moderate impact. Increasing the bamboo residue price from 200 to 500 CNY/t raised the MSP by 1.42 CNY/kg. In contrast, financial parameters such as equity percentage and tax rate, as well as logistical factors like average transportation distance, had minor effects within the tested range (<0.1 CNY/kg).

Overall, the sensitivity analysis suggests that improving thermal efficiency and material yield, as well as securing stable electricity and feedstock pricing, are key to reducing MSP and improving investment feasibility for bamboo-based hard carbon production.

4. Discussion

This study provides the first techno-economic assessment of bamboo residue-derived hard carbon production at a national scale in China. By integrating LCI data, spatially resolved feedstock distribution, and process-specific cost modeling, our results demonstrate that, even with only 10% utilization of bamboo processing residues in ten major bamboo-producing provinces, over 1 million tons of hard carbon could be produced annually within a price range from 14.47 to 18.15 CNY/kg. This is highly significant when compared to

the global natural graphite production is approximately 1.3 million tons, while synthetic graphite production reaches approximately 3 million tons [34]. Our findings suggest that bamboo-based hard carbon alone could provide a scalable and renewable domestic substitute for a substantial share of China's current and future anode material supply.

The MSP translates to 14,470–18,150 CNY/ton, which is highly competitive in the current global market. For reference, commercial hard carbon from leading Japanese suppliers such as Kuraray is priced from 150,000 to 200,000 CNY/ton [35]. This price advantage suggests that bamboo-derived hard carbon has strong potential not only to displace fossil-derived graphite but also to expand sodium-ion battery production by lowering material cost thresholds.

It should be noted that wastewater treatment costs were not included in the rigorous MSP calculation due to the lack of reliable data. To provide a rough estimation of its potential impact, we referenced typical treatment costs for acidic industrial wastewater, which range from 5 to 80 CNY per ton depending on acid concentration and local environmental regulations [36,37]. According to the LCI source, the production of 1 kg of hard carbon generates approximately 14 kg of wastewater [17]. Based on this, the additional cost attributable to wastewater treatment would be between 70 and 1120 CNY per ton of hard carbon. This increase remains acceptable, as the adjusted MSP will still be around 20,000 CNY/ton. This value remains well within the range between synthetic graphite (up to 20,000 USD/ton) and activated carbon (around 2000 USD/ton), which are functionally and structurally related materials [38,39].

Another critical implication of this study is the geographical concentration and maturity of bamboo supply chains. Unlike many other lignocellulosic biomass types that are dispersed or seasonal, bamboo residues are generated year-round from well-established industries (e.g., construction, pulp and paper), often in centralized clusters. This enables efficient feedstock collection, reduces transportation cost, and enhances long-term investment feasibility. As shown in our results, the MSP differences between provinces are relatively modest, highlighting a robust economic profile even under varying local conditions. Furthermore, the capital investment needed to construct a large-scale 2000 t/day facility was within reasonable bounds (<6 billion CNY) compared to other emerging bio-carbon technologies, indicating attractive scale-up opportunities.

The sensitivity analysis revealed that electricity efficiency, product yield, and electricity price are the dominant drivers of MSP. These results point to critical leverage points for further cost reduction. For example, future efforts to develop low-temperature graphitization technologies or renewable-powered carbonization systems could directly improve energy efficiency and decouple production from fossil-based grid electricity. Similarly, process optimization to improve carbon yield—e.g., through feedstock pretreatment or process control—can significantly reduce cost per unit output. Notably, financial parameters such as tax rate, equity percentage, and salary had relatively minor effects, indicating that technological factors are the main bottlenecks for economic performance.

In addition to economic viability, environmental performance further supports bamboo-based hard carbon as a promising anode material. Based on the industrial-scale LCA results of Liu et al., the production of 1 kg of bio-based hard carbon results in approximately 3.5 kg CO_2-eq emissions (cradle-to-gate), assuming typical industrial energy efficiency and no direct energy recovery [17]. This is substantially lower than the 9.6 kg CO_2-eq per kg reported by Engels et al. for natural graphite anode production under similar system boundaries [40]. The nearly threefold reduction in carbon footprint indicates a strong environmental advantage, especially if bamboo residue is utilized in regions with renewable energy access and efficient carbonization infrastructure.

5. Conclusions

Leveraging regionally abundant bamboo residues, this study evaluates the economic potential of producing hard carbon for sodium-ion battery anodes under conservative industrial assumptions. Across ten major bamboo-producing provinces, the calculated minimum selling prices (MSPs) range from 14.47 to 18.15 CNY/kg, with over 1 million tons of annual production capacity achievable by utilizing just 10% of the available residues.

Regional differences in MSP are primarily driven by plant scale and electricity prices, while other factors such as labor cost and transport distance play secondary roles. Despite these variations, all the modeled provinces remain within a commercially viable range, reinforcing the robustness of bamboo-derived hard carbon as a scalable anode material option.

While the core analysis excludes wastewater treatment infrastructure and energy recovery systems, a bounding estimate of 70–1120 CNY/ton for potential treatment costs confirms that environmental compliance would not significantly undermine overall economic feasibility.

Overall, the findings support bamboo residues as a promising domestic feedstock for sustainable battery materials, with immediate relevance for supply chain localization and cost reduction. Future work should incorporate dynamic system improvements and full life cycle modeling to further validate deployment pathways.

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Data Availability Statement: All the data used to generate the results in this study are explicitly documented within the main text, tables, Appendix A, and references. The Excel-based macro model used for techno-economic calculations is available from the corresponding author upon reasonable request.

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Abbreviations

The following abbreviations are used in this manuscript:

BR	Bamboo Residue
CAPEX	Capital Expenditure
CEPCI	Chemical Engineering Plant Cost Index
CNY	Chinese Yuan
DCF	Discounted Cash Flow
DE	Euclidean Distance
DR	Road-Based Transport Distance
DOE	Department of Energy
El	Electricity
FCI	Fixed Capital Investment

IRR	Internal Rate of Return
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
MACRS	Modified Accelerated Cost Recovery System
MSP	Minimum Selling Price
OPEX	Operating Expenditure
ROI	Return on Investment
TEA	Techno-Economic Analysis
TCI	Total Capital Investment
tkm	Ton-Kilometer
USD	United States dollar

Appendix A

Table A1. General financial parameters used in the discounted cash flow rate of return analysis; parameters are from [27,41].

Economic Parameters	Description
Equity	40% of FCI
Loan Interest	0.05
Loan Term	10 years
Plant Life	30 years
Income Tax Rate	25%
Construction Period	3 years
% Spent in Year −2	8%
% Spent in Year −1	60%
% Spent in Year 0	32%
Start-up Time	0.5 years
Land Cost	6% of Costequip
CAPEX	
1. Direct cost	
1.1 Purchased equipment	Costequip
1.2 Equipment installation	40% of Costequip
1.3 Instrumentation and controls	20% of Costequip
1.4 Piping	15% of Costequip
1.5 Electrical systems	15% of Costequip
1.6 Buildings	30% of Costequip
1.7 Yard improvements	10% of Costequip
1.8 Service facilities	20% of Costequip
2. Indirect capital cost	
2.1 Engineering and supervision	25% of Costequip
2.2 Contingency	30% of Costequip
2.3 Contractors fees/overheads/profits	10% of Costequip
2.4 Start-up	10% of Costequip
3. Additional investment	
3.1 Working capital	15% of FCI
Fixed capital investment (FCI)	FCI = direct cost + indirect cost
Total capital investment (TCI)	TCI = FCI + WC
OPEX	
Raw materials collection	Depend on BR price and transportation cost
Labor hours	DOE Labor Estimator Mini Tool
Overheads	0.95
Maintenance and repairs	6% of FCI
Maintenance supplies	15% of maintenance and repairs
Depreciation	MACRS 7 years model
Local taxes and insurance	3% of FCI

Table A2. Capital cost components (in million CNY) for ten provinces under a 10% bamboo residue utilization scenario. Categories include equipment cost, installation, other direct costs, indirect costs, and working capital.

	Equipment Cost	Equipment Installation	Other Direct Cost	Indirect Cost	Working Capital
Fujian	548.20	219.28	603.02	411.15	267.25
Guangxi	422.11	168.84	464.32	316.58	205.78
Guangdong	201.36	80.55	221.50	151.02	98.16
Jiangxi	197.07	78.83	216.78	147.80	96.07
Zhejiang	188.37	75.35	207.20	141.28	91.83
Hunan	188.37	75.35	207.20	141.28	91.83
Chongqing	179.49	71.79	197.43	134.61	87.50
Sichuan	174.97	69.99	192.47	131.23	85.30
Yunnan	165.80	66.32	182.38	124.35	80.83
Anhui	156.40	62.56	172.04	117.30	76.24

Table A3. Annual operating cost breakdown (in million CNY) for hard carbon production in ten provinces, including utility consumption, raw materials, labor, maintenance, and local taxes.

	Utilities	Bamboo Residues	H_2SO_4	Labors	Maintenance and Repairs	Maintenance Supplies	Local Tax and Insurance
Fujian	2391.32	552.30	828.00	21.63	106.90	16.03	53.45
Guangxi	1961.84	399.08	570.00	15.06	82.31	12.35	41.16
Guangdong	553.56	135.66	198.00	18.30	39.27	5.89	19.63
Jiangxi	678.55	130.84	192.00	12.43	38.43	5.76	19.21
Zhejiang	470.01	119.05	180.00	16.48	36.73	5.51	18.37
Hunan	553.08	124.89	180.00	13.36	36.73	5.51	18.37
Chongqing	609.24	109.59	168.00	13.94	35.00	5.25	17.50
Sichuan	565.05	121.56	162.00	13.43	34.12	5.12	17.06
Yunnan	315.53	110.09	150.00	11.45	32.33	4.85	16.17
Anhui	404.92	92.91	138.00	12.38	30.50	4.57	15.25

Table A4. Minimum selling price (MSP, CNY/kg) and component-wise cost contributions for each province. Includes raw material, utility, capital, tax, and return-related cost elements.

	Bamboo Residues	H_2SO_4	Utilities	Fixed Costs	Capital Depreciation	Average Income Tax	Average Return on Investment	Total MSP
Fujian	1.78	2.67	5.40	0.64	0.19	0.16	3.63	14.47
Guangxi	1.87	2.67	6.44	0.71	0.21	0.15	4.15	16.20
Guangdong	1.83	2.67	5.23	1.12	0.29	0.36	3.94	15.45
Jiangxi	1.82	2.67	6.61	1.06	0.30	0.20	4.49	17.14
Zhejiang	1.77	2.67	4.88	1.14	0.30	0.17	3.86	14.81
Hunan	1.85	2.67	5.75	1.10	0.30	0.29	4.39	16.35
Chongqing	1.74	2.67	6.78	1.14	0.31	0.22	4.67	17.54
Sichuan	2.00	2.67	6.52	1.15	0.31	0.28	5.21	18.15
Yunnan	1.96	2.67	3.93	1.15	0.32	0.26	4.25	14.54
Anhui	1.80	2.67	5.49	1.21	0.33	0.29	4.83	16.62

Table A5. Results of one-way sensitivity analysis on the Fujian case, showing the effect of parameter variations on MSP (CNY/kg). Parameters include technical, economic, and policy variables with low, baseline, and high scenarios.

Sensitivity Parameters	Parameter Description	Result (CNY/kg Hard Carbon)		
		Low Value	Baseline	High Value
Labor salary (CNY/year)	Low: 4294/Base: 5638/High: 6724	14.46	14.47	14.49
Equity percentage	Low: 0.2/Base: 0.4/High: 0.6	14.43	14.47	14.51
Average transportation distance (km)	Low: −20%/Base: 0/High: +20%	14.43	14.47	14.52
Income Tax Rate	Low: 0.15/Base: 0.25/High: 0.35	14.40	14.47	14.56
Transportation price (CNY/tkm)	Low: 0.2/Base: 0.3/High: 0.4	14.39	14.47	14.55
Scaling factor	Low: 0.6/Base: 0.7/High: 0.8	14.61	14.47	14.35
Bamboo residue price (CNY/ton)	Low: 200/Base: 350/High: 500	13.76	14.47	15.18
H_2SO_4 price (CNY/ton)	Low: 500/Base: 750/High: 1000	13.53	14.47	15.42
El price (CNY/kWh)	Low: 0.45/Base: 0.62/High: 0.78	12.25	14.47	16.57
Hard carbon yield	Low: −20%/Base:0/High: +20%	17.82	14.47	12.23
Electricity efficiency	Low: 0.5/Base: 0.7/High: 0.9	22.29	14.47	11.25

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