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Review

Bioenergy in Three Largest Energy-Consuming Nations: An Overview of Policy, Markets and Implications

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Abstract

Bioenergy plays a differentiated yet increasingly strategic role in national energy transitions, shaped by distinct policy architectures, market structures, and developmental priorities. This review compares the bioenergy policies and markets of China, the United States (US), and India, three of the world's largest energy consumers, to assess their implications for global bioenergy transitions. China's bioenergy sector is embedded within a centralized, planning-based governance framework, emphasizing waste-to-energy conversion, agricultural residues, and biogas. Installed biomass power capacity exceeds 45 GW, with annual bioenergy generation of over 200 TWh, while policy support prioritizes system integration, waste management, and controlled expansion rather than rapid market growth. In contrast, the US operates the world's largest biofuel market, driven by legally mandated demand under the Renewable Fuel Standard and reinforced by tax credits. The US produces more than 60 billion liters of biofuels annually, dominated by corn ethanol and rapidly expanding renewable diesel and sustainable aviation fuels (SAF), with cumulative private investment exceeding USD 200 billion over the past two decades. India represents a mission-oriented and developmental model, with bioenergy policies linked to rural income generation, waste utilization, and energy access. Ethanol blending capacity has expanded rapidly, supporting production of over

6 billion liters per year, while biogas and compressed biogas deployment is accelerating through capital subsidies and guaranteed offtake mechanisms. Comparative analysis reveals a trade-off between policy stability and market flexibility. China offers long-term certainty but limited space for innovation; the US enables scale and innovation amid policy volatility; and India prioritizes inclusivity and diffusion, with uneven implementation. These contrasting pathways underscore the need for context-specific bioenergy strategies and highlight bioenergy's diverse roles in supporting decarbonization, waste management, and sustainable development globally.

Keywords

Bioenergy; biogas; decarbonization; ethanol blending; renewable fuel; waste-to-energy

1. Introduction

The global energy landscape is undergoing a profound transformation as nations strive to address climate change and energy security challenges. The increasing global energy demand underscores the need for sustainable alternatives, with bioenergy emerging as a pivotal solution [1, 2]. Unlike intermittent renewable energy sources, bioenergy provides dispatchable and reliable energy while enabling the valorization of agricultural residues, forestry by-products, and organic waste streams [3]. These characteristics position bioenergy as a uniquely flexible renewable option capable of delivering electricity, heat, and transport fuels, while contributing to greenhouse gas mitigation through low-carbon or potentially net-negative emission pathways [4]. Consequently, bioenergy plays a crucial role in climate mitigation, renewable energy transition, energy security, and rural socio-economic development, offering a dual pathway to meet growing energy needs while reducing dependence on fossil fuels [5].

Bioenergy is harnessed through the conversion of biomass, derived from agricultural residues, forestry by-products, organic municipal waste, animal manure, and dedicated energy crops, into usable forms of energy via thermochemical, biochemical, and physicochemical processes [6]. Thermochemical pathways, including combustion, gasification, and pyrolysis, convert solid biomass into heat, syngas, or bio-oil for electricity and heat generation [7, 8]. Biochemical processes, such as anaerobic digestion and fermentation, utilize microbial activity to transform wet biomass into biogas or liquid biofuels, including bioethanol and biomethane [8]. In addition, physicochemical methods, such as transesterification, are employed to produce biodiesel from vegetable oils and waste fats [9]. These conversion pathways enable bioenergy to be deployed across multiple energy sectors, supplying electricity, heat, and transport fuels, while allowing flexibility in feedstock selection and scale of application [4].

Despite its potential, bioenergy development remains unevenly distributed across the world's leading economies, and the policies, market structures, and opportunities for bioenergy deployment vary significantly among the world's largest energy-consuming nations. Advanced economies such as the European Union and the United States (US) have developed relatively mature bioenergy sectors, supported by long-term policy instruments, sustainability certification schemes, and established supply chains for biofuels, biogas, and biomass-based power generation [10]. In contrast, rapidly industrializing economies, including China and India, possess substantial biomass resources but prioritize bioenergy primarily for waste management, rural electrification, and energy security, with deployment shaped by land-use constraints, competing development objectives, and evolving regulatory frameworks [11, 12]. Resource-rich economies with high fossil fuel dependence often exhibit limited bioenergy integration due to weaker policy incentives and infrastructure gaps, while emerging economies in Southeast Asia and Latin America focus predominantly on first-generation biofuels linked to agricultural export markets [13, 14]. These structural and policy differences result in divergent scales of deployment, technological pathways, and sustainability outcomes, ultimately determining the role of bioenergy within national and regional energy transitions [15].

Globally, bioenergy remains the largest source of renewable energy, supplying approximately 70% of total renewable energy consumption and contributing nearly 6% of the global total final energy consumption, with particularly important roles in the heat and transport sectors [16, 17]. Global biofuel production has continued to increase in recent years, driven by expanding demand for sustainable aviation fuels (SAF), renewable diesel, biomethane, and advanced biofuels, while investments in biomass-based power generation and waste-to-energy technologies have accelerated under net-zero commitments and energy security concerns [18]. These trends underscore the growing strategic importance of bioenergy in complementing solar and wind power by providing dispatchable renewable energy and supporting the decarbonization of hard-to-abate sectors.

Understanding bioenergy's role in the global energy transition requires examining how major economies approach this renewable energy source through distinct policy frameworks and market mechanisms. However, few reviews delve into this dimension, and the existing ones are highly localized, focusing predominantly on Europe [19-21]. Other reviews highlight the challenges and opportunities of bioenergy implementation within specific social segments, such as Chinese rural areas [22] and African smallholder farmers [23]. While previous reviews have examined bioenergy policies, biofuel markets, waste-to-energy systems, or country-specific deployment pathways, they generally focus on individual regions, technologies, or policy instruments [8, 21, 24]. For instance, Papilo et al. [25] reviewed policies specific to bioenergy derived from palm oil in Indonesia and Malaysia, while the review of Alazaiza et al. [26] is confined to technologies converting biomass waste to energy without expanding to policy and market aspects. Comprehensive comparative analyses that simultaneously evaluate policy frameworks, market dynamics, sustainability considerations, and future deployment opportunities across the world's largest energy-consuming nations remain limited. This review, therefore, addresses an important knowledge gap by integrating these dimensions within a unified comparative framework, enabling a more holistic assessment of how differing governance models and development priorities shape bioenergy transitions.

Examining bioenergy policies, market structures, and deployment opportunities in the largest energy-consuming nations is critical because these economies collectively account for a substantial share of global energy demand, greenhouse gas emissions, and biomass utilization [27, 28]. Policy choices and market signals in these countries strongly influence global bioenergy investment trends, technology development, feedstock supply chains, and sustainability standards. China, the US, and India were selected because they represent distinct yet highly influential pathways in the global bioenergy transition. Together, these countries account for a significant proportion of global energy consumption, agricultural production, biomass availability, and greenhouse gas emissions. The US represents a mature market-driven bioenergy system characterized by advanced biofuel industries and established policy incentives [29]; China exemplifies a centrally coordinated energy transition emphasizing waste utilization, energy security, and industrial-scale deployment; whereas India represents a rapidly expanding emerging economy leveraging bioenergy for rural development, agricultural residue management, and energy access [30, 31]. Comparing these three nations provides valuable insights into how different governance structures, resource endowments, market maturity levels, and policy priorities influence bioenergy development and sustainability outcomes.

Therefore, this article provides a comprehensive overview of bioenergy's policy environment, market dynamics, and growth implications across the three largest energy-consuming nations: China, the US, and India. By examining the regulatory frameworks, investment landscapes, and technological innovations driving bioenergy adoption in these key markets, this review provides valuable insights into the effectiveness of policy instruments, market readiness, and strategic priorities that will ultimately determine the global role of bioenergy in the low-carbon energy transition.

2. Review Methodology

This review adopted a structured narrative-review approach to evaluate bioenergy policies, market development, technological pathways, and sustainability considerations in China, the US, and India. Relevant literature was identified through searches of Scopus, Web of Science, and ScienceDirect, using combinations of keywords such as "bioenergy policy", "biofuel policy", "biomass energy", "biogas", "waste-to-energy", "renewable energy transition", "China", "United States", and "India". Additional sources were identified through citation tracking and reference screening. To ensure that recent developments were adequately captured, the review focused primarily on literature published between 2016 and 2026, with particular emphasis on studies published from 2020 onward.

The review included peer-reviewed journal articles, conference papers, government publications, policy documents, and reports from international organizations that addressed bioenergy-related policies, markets, technologies, sustainability issues, or implementation challenges. Studies lacking direct relevance to bioenergy deployment, policy, or market development were excluded. To complement the scientific literature, policy and market information was collected from authoritative sources, including the International Energy Agency (IEA), US Energy Information Administration (US EIA), Food and Agriculture Organization (FAO), United States Department of Agriculture (USDA), China's National Energy Administration (NEA), National Development and Reform Commission (NDRC), and India's Ministry of New and Renewable Energy (MNRE). Market statistics and policy information were cross-checked against multiple sources, particularly authoritative sources, wherever possible, to improve reliability and minimize inconsistencies.

A comparative analytical framework was employed to ensure consistent evaluation across the three countries. The analysis focused on key dimensions typically used to compare energy policies, including policy orientation, governance structures, policy instruments, policy objectives, sectoral focus, feedstock governance incentive design, policy stability, the role of state-owned enterprises, and sustainability safeguards. For comparison of market size, indicators comprising installed bioenergy capacity, bioenergy electricity generation, biofuel production/output, bioenergy share of energy consumption, investment trends, and market value indicators were used. Through qualitative synthesis and cross-country comparison, the review identifies similarities, differences, strengths, and challenges in bioenergy development, providing insights into how contrasting policy approaches and market conditions shape bioenergy's role in the global energy transition.

Despite efforts to ensure methodological rigor, several limitations should be acknowledged. First, as a structured narrative review, this study relies on qualitative synthesis rather than formal systematic review or meta-analytic procedures, which may introduce some subjectivity in the selection and interpretation of the literature. Second, although market statistics and policy information were cross-validated using multiple authoritative sources, inconsistencies may exist due to differences in reporting methodologies, definitions, data availability, and update frequencies across countries. Third, bioenergy policies and market conditions are evolving rapidly, meaning that newly introduced regulations, investment programs, and technological developments may not be fully captured. Fourth, the review does not conduct quantitative lifecycle assessments or standardized greenhouse gas comparisons across bioenergy pathways, thereby limiting direct evaluation of environmental performance among technologies and countries.

3. Bioenergy Policy

Bioenergy policy development in China, the US, and India is closely intertwined with rapid technological advancements in bioenergy conversion systems. In particular, improvements in biomass gasification and pyrolysis have enhanced the efficiency and flexibility of converting solid biomass into syngas, heat, and power, while advancements in anaerobic digestion and upgrading technologies have enabled higher yields of biomethane from organic waste [32]. At the same time, second- and third-generation biofuel technologies, including cellulosic ethanol and advanced liquid biofuels such as SAF, are expanding the scope of low-carbon transport energy options [33]. Waste-to-energy systems have also evolved toward higher-efficiency combustion, improved emission controls, and integrated material recovery, strengthening their role in urban waste management [34]. In addition, emerging pathways such as bioenergy with carbon capture and storage (BECCS) further link bioenergy systems with deep decarbonization goals [2]. These technological developments provide the foundation for the evolution of national policy across the three countries.

3.1 China

China's bioenergy policy is embedded within its broader energy security, rural revitalization, and decarbonization strategies, with a strong emphasis on the utilization of agricultural residues, forestry waste, livestock manure, and organic municipal waste [35]. Since the mid-2000s, the Chinese government has progressively promoted bioenergy through a combination of national plans, including successive Five-Year Plans, the Renewable Energy Law, and sector-specific policies targeting biomass power generation, biogas, and biofuels [36]. Policy instruments have primarily focused on feed-in tariffs for biomass power, fiscal subsidies for rural biogas systems, and pilot programs for advanced biofuels, while strictly regulating grain-based bioethanol to safeguard food security [37].

The Renewable Energy Law, first enacted in 2006 and amended in 2009, constitutes the foundational legal framework for bioenergy development in China [38]. The law formally recognizes biomass energy, alongside wind, solar, and hydropower, as a strategic component of the national energy system and establishes the principle of mandatory grid connection for renewable electricity, including biomass power generation [38]. It also provides the legal basis for government-led price mechanisms, cost-sharing arrangements, and fiscal incentives to promote renewable energy deployment. For bioenergy, the law is particularly significant in legitimizing feed-in tariffs for biomass power plants and enabling the central government to subsidize the incremental costs of renewable electricity relative to coal-fired power [39]. While the law itself does not prescribe detailed technological pathways, it creates a stable institutional environment that allows subsequent national plans and sectoral policies to promote bioenergy in alignment with energy security, environmental protection, and rural development objectives [38, 39].

During the Eleventh (2006-2010) and Twelfth (2011-2015) Five-Year Plan periods, bioenergy policy focused on rapid capacity expansion and rural energy access. Biomass power generation, large-scale biogas projects, and household biogas digesters were strongly promoted as tools for rural development, pollution reduction, and agricultural waste utilization [40]. Policy support during this phase emphasized installed capacity targets, capital subsidies, and guaranteed electricity prices for biomass power [40]. Grain-based bioethanol development was deliberately constrained during this period due to food security concerns. Instead, policy attention shifted toward non-grain feedstocks such as cassava, sweet sorghum, and agricultural residues, reflecting an early recognition of land-use and food-energy trade-offs [30].

The Thirteenth Five-Year Plan (2016-2020) marked a strategic shift from capacity expansion toward efficiency improvement and system integration. Bioenergy was increasingly framed as part of a circular economy, with explicit links to agricultural waste management, rural environmental remediation, and urban organic waste treatment [41]. Key policy priorities included (1) reducing overreliance on direct combustion biomass power, (2) promoting biogas upgrading to bio-natural gas for grid injection and vehicle fuel, and (3) integrating bioenergy projects with livestock waste treatment and municipal solid waste management [41, 42]. During this period, the government began phasing down subsidies for inefficient or poorly located biomass power projects, signaling a move toward more market-oriented deployment while maintaining strategic oversight [43].

Under the Fourteenth Five-Year Plan (2021-2025), bioenergy policy is explicitly aligned with China’s carbon peaking and carbon neutrality goals. Rather than emphasizing large-scale expansion, the plan prioritizes high-quality, regionally appropriate bioenergy development, particularly in areas with abundant biomass residues [44]. Bioenergy is positioned as a complementary energy source that supports low-carbon heating in rural and peri-urban areas, decarbonization of hard-to-electrify sectors, and methane emission reduction from agricultural and waste streams [45]. Advanced biofuels, bio-natural gas, and waste-to-energy systems are favored over conventional biomass power, reflecting concerns about land-use efficiency, emissions performance, and economic sustainability [44, 46].

China’s Medium- and Long-Term Renewable Energy Development Plans provide quantitative targets and sectoral roadmaps that operationalize the Renewable Energy Law. These plans specify capacity targets for biomass power generation, biogas production, and liquid biofuels, while also identifying priority technologies and feedstocks [47]. In bioenergy policy, these plans consistently emphasize the utilization of agricultural residues (e.g., straw, corn stover), forestry by-products and processing residues, as well as livestock manure and organic municipal waste. They also reinforce restrictions on food-based biofuel production and promote technological upgrading to improve conversion efficiency and emissions performance [47, 48].

China's biofuel policy is characterized by a cautious and state-controlled approach. Early ethanol programs were limited to designated pilot provinces and state-owned enterprises, with production quotas and feedstock restrictions tightly regulated by the central government [30]. Subsequent policies explicitly prohibit the expansion of grain-based bioethanol and instead promote non-grain and cellulosic biofuels through pilot projects and demonstration programs [49]. This reflects a strong policy commitment to safeguarding national food security while continuing to explore the decarbonization potential of liquid biofuels, particularly in the transport sector.

Feed-in tariffs have been the primary economic instrument supporting biomass power generation. These tariffs initially provided strong financial incentives, leading to rapid growth in installed capacity [37]. However, uneven project quality, feedstock supply constraints, and rising subsidy burdens prompted policy reforms [12]. Recent policy adjustments have reduced reliance on fixed subsidies and encouraged cost control, technological upgrading, and better alignment between biomass resource availability and plant location. This transition reflects a broader shift in China's renewable energy governance toward market-based mechanisms and performance-oriented regulation [50].

Biogas policy has evolved from household-scale digesters toward larger, centralized systems integrated with livestock farming and waste management. National policies promote the upgrading of biogas to bio-natural gas, enabling injection into natural gas grids or use as vehicle fuel. These policies align bioenergy development with methane emission reduction, rural environmental improvement, and energy substitution objectives, making biogas a key component of China's agricultural decarbonization strategy.

3.2 United States

Bioenergy policy in the US is characterized by a market-oriented and incentive-driven framework, underpinned by federal mandates, tax incentives, and state-level initiatives. Unlike the centralized planning approach adopted in some countries like China, the US bioenergy policy relies heavily on regulatory signals and fiscal mechanisms to stimulate private investment and technological innovation across electricity, transport fuels, and biogas markets [51].

The Renewable Fuel Standard (RFS), established under the Energy Policy Act of 2005 and significantly expanded by the Energy Independence and Security Act (EISA) of 2007, is the cornerstone of US bioenergy policy for the transport sector [52]. The RFS mandates annual minimum volumes of renewable fuels to be blended into the national transportation fuel supply, with specific sub-targets for conventional biofuels, advanced biofuels, biomass-based diesel, and cellulosic biofuels [53]. Compliance is enforced through Renewable Identification Numbers (RINs), which function as tradable credits and create a market-based incentive structure [54]. The RFS has been instrumental in scaling bioethanol and biodiesel production, while also encouraging technological development in advanced and cellulosic biofuels [52, 53]. However, its implementation has been marked by volatility in annual volume obligations, legal disputes, and concerns regarding feedstock sustainability and indirect land-use change [55].

The US Farm Bill represents a critical policy vehicle linking bioenergy development with agricultural and rural economic objectives. Successive Farm Bills have authorized a suite of bioenergy-related programs, including loan guarantees, grants for biorefinery construction, and support for bio-based product markets [56]. Key programs include the Bioenergy Program for

Advanced Biofuels, which provides payments to producers of non-corn-starch biofuels, and the Biorefinery, Renewable Chemical, and Biobased Product Manufacturing Assistance Program [57]. These initiatives reflect the US policy emphasis on leveraging domestic agricultural and forestry resources while fostering rural employment and value-added processing.

Fiscal incentives play a central role in US bioenergy policy. Production tax credits (PTCs), investment tax credits (ITCs), and fuel-specific tax credits, such as those historically applied to biodiesel and renewable diesel, have been critical in improving project economics and reducing investment risk [58]. More recently, federal tax incentives have been expanded and extended under broader climate and energy legislation, reinforcing support for renewable electricity generation, biofuels, and emerging pathways such as SAF [59]. These incentives are generally technology-neutral within defined eligibility criteria, encouraging competition and innovation among bioenergy pathways.

The Inflation Reduction Act (IRA) represents a significant evolution in US bioenergy policy by embedding bioenergy support within a comprehensive climate mitigation framework. The IRA introduces long-term, stable tax credits tied to lifecycle greenhouse gas performance rather than technology type alone [60]. For bioenergy, the IRA strengthens incentives for low-carbon biofuels, including SAF and renewable diesel, BECCS, as well as biogas and renewable natural gas (RNG) derived from waste streams [61]. This performance-based approach signals a policy shift toward emissions outcomes, aligning bioenergy deployment with national decarbonization targets while addressing longstanding sustainability critiques [60, 61].

Biogas policy in the US is shaped by interactions between energy, agricultural, and environmental regulations. RNG projects benefit from eligibility under the RFS (as cellulosic biofuel), California's Low Carbon Fuel Standard (LCFS), and federal tax incentives [62]. These overlapping policy mechanisms have stimulated rapid growth in anaerobic digestion projects linked to livestock operations, landfills, and wastewater treatment plants. The policy emphasis on methane emission reduction has positioned biogas as a cost-effective climate mitigation option, particularly in the agricultural sector [63].

Biomass electricity generation in the US has received comparatively less policy emphasis than liquid biofuels [64]. Federal support mechanisms include eligibility for renewable electricity tax credits, while state-level Renewable Portfolio Standards (RPS) determine market demand for biomass power. State RPS frameworks vary considerably in their treatment of biomass, with some states imposing strict sustainability criteria and others excluding certain biomass pathways altogether [65]. This decentralized governance has resulted in uneven market outcomes and limited new investment in dedicated biomass power plants.

3.3 India

India's bioenergy policy is embedded within its broader objectives of energy security, rural development, waste management, and climate mitigation. Given India's high dependence on imported fossil fuels and its large agricultural and organic waste base, bioenergy has been positioned as a domestically available, employment-generating, and multifunctional energy option [66]. Unlike purely electricity-oriented renewable strategies, India's bioenergy policies span power generation, transport fuels, cooking energy, and waste-to-energy, reflecting the diversity of national development priorities [24]. The importance of bioenergy has further increased as India seeks to achieve its climate commitments, including its target of reaching net-zero emissions by 2070, while simultaneously addressing energy access and agricultural sustainability challenges [67]. Consequently, bioenergy is increasingly viewed not only as a renewable energy source but also as a strategic component of the country's circular economy and resource-efficiency agenda.

Bioenergy policy in India is primarily coordinated by the Ministry of New and Renewable Energy (MNRE) under the umbrella of the National Bio-Energy Mission. The mission provides a unified framework covering biomass power, bagasse cogeneration, biogas, waste-to-energy, and biofuels, with differentiated support mechanisms for each pathway [68]. The policy architecture emphasizes decentralized deployment, particularly in rural and semi-urban areas, aligning bioenergy development with goals related to agricultural residue management, sanitation, and livelihood creation [69]. Capital subsidies, viability gap funding, and generation-based incentives have historically been central instruments under this mission [68]. This decentralized approach is particularly important in India, where significant quantities of agricultural residues are generated across dispersed rural regions, creating opportunities for localized energy production while reducing open-field residue burning and associated air pollution [70].

India has long promoted biomass power and bagasse-based cogeneration, particularly within the sugar industry. Policy support includes preferential tariffs, renewable purchase obligation (RPO) eligibility, and capital subsidies for high-efficiency cogeneration systems [71]. Bagasse cogeneration is notable for its industrial integration, allowing sugar mills to meet internal energy demand while exporting surplus electricity to the grid [72]. Biomass power plants using agricultural residues are promoted as dispatchable renewable sources that complement variable wind and solar generation, though feedstock availability and logistics remain key policy concerns [73]. Recent policy discussions have also emphasized the role of biomass-based power generation in enhancing grid reliability and supporting renewable-energy integration, particularly in regions with high solar and wind penetration [74].

The National Biogas and Organic Manure Program focuses on household- and community-scale biogas systems using cattle dung and organic waste. This program targets clean cooking energy access, reduction of indoor air pollution, and production of organic fertilizer, directly linking energy policy with public health and agricultural productivity [75]. The Sustainable Alternative Towards Affordable Transportation (SATAT) initiative, launched in 2018, represents a major policy effort to commercialize compressed biogas as a transport and industrial fuel [76]. Under SATAT, oil marketing companies provide long-term offtake agreements for compressed biogas, creating demand certainty and attracting private investment [77]. SATAT reflects a strategic policy shift toward bio-natural gas as a substitute for compressed natural gas, while simultaneously addressing agricultural residue burning and organic waste disposal challenges [76, 77].

India's National Policy on Biofuels establishes a comprehensive framework for liquid biofuels, with a strong emphasis on ethanol blending in petrol [24]. The policy permits a wide range of feedstocks, including sugarcane, food grains, damaged grains, and agricultural residues, while promoting second-generation (2G) bioethanol technologies. The policy adopts a flexible feedstock approach to balance fuel supply with food security considerations, supported by administered pricing mechanisms and assured procurement by oil marketing companies [78].

The Ethanol Blended Petrol Program is the central implementation mechanism, with progressively increasing blending targets. The program links agricultural policy with energy security by creating a stable market for surplus agricultural produce and crop residues, while reducing oil import dependence and transport emissions [79]. India's waste-to-energy policy operates at the intersection of renewable energy regulation and environmental governance. Bioenergy recovery from municipal solid waste, sewage sludge, and industrial organic waste is supported through preferential tariffs and eligibility under renewable energy obligations [80]. This policy stream is closely aligned with national urban initiatives, such as the Swachh Bharat Mission, reflecting a governance approach in which bioenergy serves both energy generation and environmental remediation [81]. A summary of the bioenergy policies of the three countries is presented in Table 1.

Table 1 Summary of Bioenergy Policy Frameworks in China, the United States, and India.

Dimension	China	United States	India
Overall policy orientation	Centralized, planning-oriented	Market-driven, mandate-based	Mission-oriented, developmental
Governance structure	Strong central government leadership; provincial implementation	Federal framework with strong state-level roles	Central policy direction with state-level execution
Core policy instruments	Five-Year Plans, feed-in tariffs (declining), capacity targets, administrative approvals	RFS, tax credits, state LCFS programs	National Bio-Energy Mission, Ethanol Blended Petrol Programme, subsidies
Primary policy objectives	Waste management, rural revitalization, energy security	Transport decarbonization, energy security, private investment mobilization	Rural development, waste utilization, energy access
Sectoral focus	Biomass power, waste-to-energy, biogas	Liquid biofuels (ethanol, renewable diesel, SAF), biogas/RNG	Ethanol, compressed biogas, biomass power
Feedstock governance	Strict controls on food-based biofuels; emphasis on residues and waste	Lifecycle greenhouse gas-based eligibility; food-based biofuels permitted	Flexible feedstock policy using surplus crops and residues
Incentive design	Historically subsidy-heavy; transitioning toward market mechanisms	Demand mandates plus fiscal incentives; high private-sector participation	Capital subsidies, viability gap funding, guaranteed offtake
Policy stability	High (long-term planning cycles)	Moderate; subject to political and regulatory change	Moderate; implementation varies across states
Role of state-owned enterprises	Dominant	Limited	Significant (oil marketing companies, utilities)

Sustainability safeguards	Administrative controls, food security considerations	Lifecycle greenhouse gas accounting, environmental regulation	Emerging sustainability criteria, administratively managed
Strategic role of bioenergy	Complementary support to renewables and waste systems	Strategic decarbonization tool for hard-to-electrify sectors	Transitional and developmental energy solution
Implications of policy model	High scalability and policy stability due to centralized planning; lower investment uncertainty but innovation largely guided by state priorities	Strong innovation and private-sector participation driven by market incentives; higher exposure to policy and regulatory uncertainty	Greater inclusiveness through alignment with rural development and waste management goals; scalability constrained by regional implementation and infrastructure disparities

4. Bioenergy Market

4.1 China

China’s bioenergy market has evolved into a heterogeneous and regionally differentiated segment of the national energy system, shaped by the country’s large biomass resource base, industrial organization, and demand for waste management and low-carbon energy solutions [37]. Unlike wind and solar powers, which are dominated by utility-scale deployment, China’s bioenergy market is characterized by a mix of centralized industrial facilities and distributed, feedstock-constrained projects closely linked to agricultural, forestry, and municipal waste streams [35].

By early 2025, China’s biomass power installed capacity had reached approximately 46.9 GW across all biomass power technologies, including agricultural and forestry residues and municipal waste-to-energy plants (Figure 1) [82]. Growth in capacity has been sustained, with several gigawatts of new biomass power added annually; for example, industry surveys indicate that 1.99 GW of new biomass capacity was connected in 2024 [83]. China accounts for a leading share of global bioenergy power capacity; 2023 datasets estimated about 19.1 GW operating capacity (around 27% of global bioenergy capacity) and 7.6 GW of prospective projects (in planning or construction), reflecting continued market expansion [84].

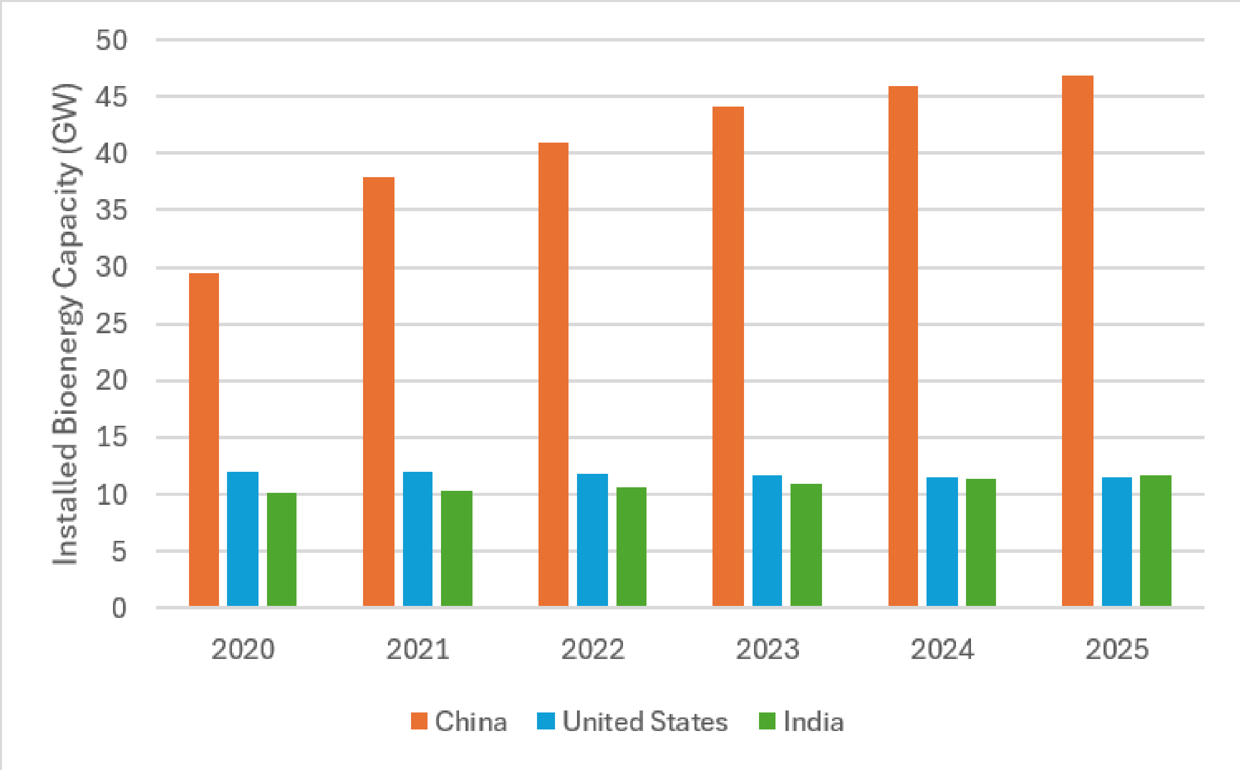


Figure 1 Installed Bioenergy Capacity of China, the United States, and India (2020-2025).

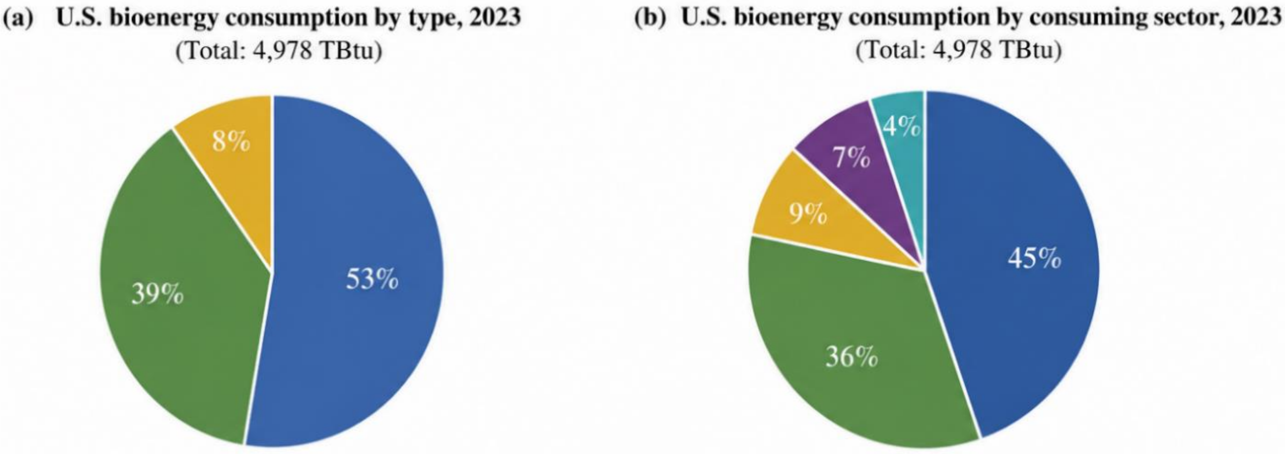
Annual biogas output in China's commercial sector was estimated at ~500 million m^3 at the end of 2024, from a growing number of centralized anaerobic digesters processing livestock and organic waste [85]. Biogas power capacity was estimated at around 1.22 GW in 2022, with biomethane utilization still emerging compared with conventional natural gas markets [86]. China's bioethanol production capacity has expanded substantially, with industry reports placing total installed capacity at ~5 million tonnes per year. Bioethanol output was reported at ~3.4 million tonnes in 2023, up from ~3 million tonnes in 2022, while biodiesel and other advanced liquid biofuels remain smaller but emerging segments. In the SAF segment, Chinese refiners received export quotas totaling approximately 1.2 million tonnes annually in 2025, signaling capacity growth oriented to both domestic and export markets [87].

The annual electricity generation from biomass (i.e., biopower output) was reported at roughly 208 billion kWh (208 TWh) for 2024 across biomass power plants in China. This figure signals continued growth from earlier years and positions China as a global leader in biopower output, accounting for ~30% of global bioenergy electricity generation in recent statistics [88]. While comprehensive national biogas power generation figures are less systematically published, the reported 500 million m^3 of biogas production reflects a sizeable emerging market, with much of this volume directed to local heat or on-site power applications [85]. Bioethanol production (primarily from agricultural feedstocks) reached ~3.4 million tonnes annually, reflecting the commercialization of fuel ethanol for blending and transport use [89].

Precise, publicly consolidated figures for total national investments in bioenergy are scarce compared with solar and wind. However, global bioenergy investment (led by ethanol and biodiesel) was projected to reach about USD 16 billion in 2025, with China among the key Asian contributors to that growth [88]. Industry reports further indicate that investment in biomass infrastructure (facilities for power generation, biogas upgrading, and fuel production) continues to benefit from both private capital and financing linked to integrated waste-to-energy and rural development projects, although the pace of growth in bioenergy investments remains more moderate relative to solar and wind capacity investment [84, 88].

4.2 United States

In 2023, biomass energy consumption in the US was approximately 4,978 trillion British thermal units (TBtu), accounting for about 5% of total US energy consumption (Figure 2). Within that bioenergy mix, biofuels accounted for 53%, wood and wood waste for 39%, and waste/manure and other organic feedstocks for about 8% of biomass energy use (Figure 2) [90]. Market valuations for the broader US bioenergy sector (including biofuels, biopower, and related products) indicate a base-year market value of around USD 199 billion in 2024, with projections to exceed USD 214 billion in 2025 and continue growing through the 2030s at an annualized rate near 7-8% [91].



Type	Consumption (TBtu)	Share (%)
Biofuels	2,662	53
Wood and wood waste	1,918	39
Municipal solid waste, animal manure, and sewage	398	8

Sector	Consumption (TBtu)	Share (%)
Industrial	2,225	45
Transportation	1,788	36
Residential	450	9
Electric power	329	7
Commercial	185	4

Figure 2 Bioenergy Consumption in the United States in 2023 [90].

Recent industry analyses estimate that the US bioenergy capacity (electricity generation from biomass and related technologies) is ~13.6 GW in 2025, reflecting utility-scale biomass facilities and distributed industrial combined heat and power systems [92]. However, the installed bioenergy capacity is 11.5 GW in 2025, down from 11.7 in 2023 (Figure 1). Biomass power is a relatively small component of total US electric generation capacity compared with wind or solar, but it remains significant in specific regions and for dispatchable renewable generation. Revenue from the US biomass power segment was estimated at ~USD 15.64 billion in 2023, with expectations of growth to about USD 22.23 billion by 2030 (compound annual growth rate ~5.3%) [93].

The US is one of the world's largest producers of liquid biofuels. Based on the US Department of Agriculture data, ethanol production capacity in 2022 was around 15.4 billion gallons per year, while combined biodiesel and renewable diesel capacity totaled roughly 3.1 billion gallons per year (Figure 3) [94]. According to the US Energy Information Administration, total US biofuel production capacity (renewable diesel plus other fuels) increased modestly in 2024, with key expansions such as the Phillips 66 Rodeo plant (~767 million gallons/year) and Diamond Green Diesel (~982 million gallons/year) illustrating growth in renewable diesel and related fuels [95]. Contemporary US biogas operations recycle about 12.8 million tonnes of organic waste, producing over 35 billion cubic feet of biogas annually, enough energy to power roughly 283000 households per year [96].

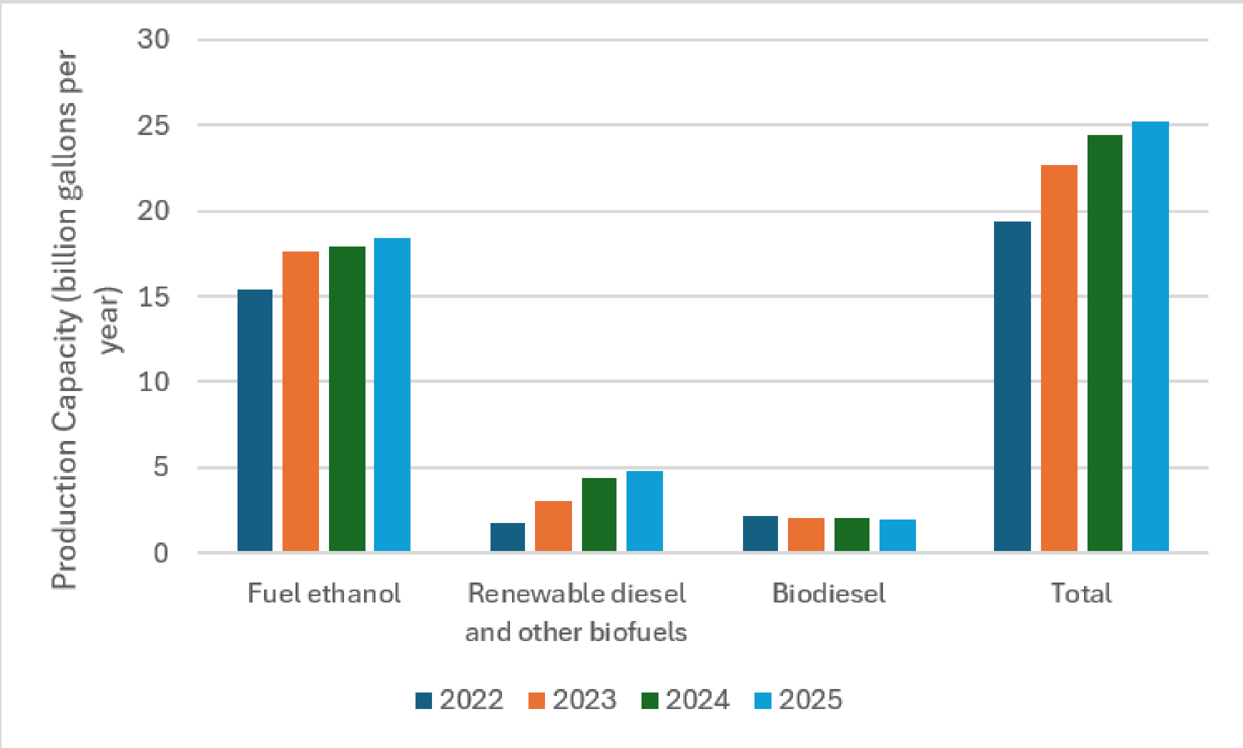


Figure 3 Biofuel Production Capacity of the United States (2022-2025) [89, 95]. Note: Other biofuels include SAF, renewable hydrocarbons, and other emerging biofuels.

The US remains a leading global producer of biofuels, particularly ethanol. Historical data show production of ~15.4 billion gallons of ethanol in 2022, with biodiesel and renewable diesel production comprising an additional ~3.1 billion gallons [94]. Federal biofuel blending mandates under the Renewable Fuel Standard continue to drive high volumetric requirements (e.g., proposals for ~24 billion gallons in 2026-2027), underscoring the scale of demand in transport fuels [97].

4.3 India

India's bioenergy sector, while smaller than solar and wind, represents an important component of the country's renewable energy mix, particularly for rural energy access and waste valorization. As of mid-2025, India's total bioenergy installed capacity stood at approximately 11,600 MW (≈11.6 GW) across biomass power (Figure 1), bagasse cogeneration, and waste-to-energy plants, with biomass power and bagasse cogeneration contributing about 9,821 MW, biomass cogeneration (non-bagasse) 922 MW, waste-to-energy (on grid) 309 MW and waste-to-energy (off-grid) 544 MW [98].

From 2015 to 2025, about 2,361 MW of new biomass power capacity and 228 MW of waste-to-energy capacity were added [99]. Over the same period, roughly 288,000 small biogas plants have been installed across rural and peri-urban regions, reflecting market expansion beyond grid-connected power. These capacity figures indicate modest growth relative to India's total renewable mix, where bioenergy represented approximately 11.7 GW of ~254 GW of overall renewable capacity by late 2025 (including solar, wind, and hydro) [100].

According to international market projections, India's bioenergy electricity generation is expected to reach ~41.25 billion kWh in 2025 [101]. This figure reflects the contribution of biomass and waste-to-energy plants to India's electricity mix, particularly where biomass is used consistently for base-load and cogeneration in industrial settings. As of early 2026, India had 132 compressed biogas plants operating nationwide, with a combined production capacity of ~920 tonnes per day [102]. This output represents an emerging bioenergy sub-market aimed at replacing transport fuels and deploying clean energy in urban areas. Compressed biogas production is concurrent with national biofuel blending mandates and feedstock valorization strategies. Utilization of biomass fuel for power production is increasing. Utilization in the power sector is projected to reach ~2.5 million tonnes in the 2025 fiscal year, nearly triple prior usage estimates. Higher utilization indicates stronger market demand for biomass feedstocks in grid and industrial power production [103].

The National Bioenergy Program Phase-I (2022-26) represents a key catalyst for investment in the sector. The program was notified with a total budget of ₹998 crore (~USD 120 million) to support biomass power, biogas, bio-compressed natural gas, and waste-to-energy projects [99]. As of mid-2025, several private investments in biofuel and biogas infrastructure are underway. For example, initiatives in Gujarat involve planned investments nearing ₹1,000 crore (~USD 120 million) for new compressed biogas plants and ancillary biogas units [104]. International forecasts suggest India will be one of the fastest-growing bioenergy markets globally between 2023 and 2030, with robust expansion in solid biomass use, liquid biofuels, and biogas demand [105]. Table 2 summarizes the bioenergy market indicators of the three countries.

Table 2 Quantified Bioenergy Market Indicators.

Indicator	China	United States	India
Installed bioenergy capacity - Power (approx.)	~46.9 GW (early 2025)	~11.7 GW (2023)	~11.6 GW (2025)
Bioenergy electricity generation (annual)	~208 TWh (2024)	~133 TWh biopower (2022)	~41.25 billion kWh (2025 projected)
Biofuel production - Ethanol	Significant but < US levels (China ~4.8 billion L in 2023)	~58 billion L ethanol (2022)	~6.4-16 billion L capacity (2023-2025)
Biofuel output - Biodiesel/renewable Diesel	Multiple billion-liter scale (China ~2.1 billion L in 2023)	~3.1 billion gallons biodiesel/renewable diesel capacity (2022)	~2 billion L biodiesel capacity (2024)
Biogas production	~500 million m^3 biogas (2024 estimate)	Extensive but decentralized; ~991 million m^3 biogas estimated globally (2021)	132 operational compressed biogas plants (~920 t/day capacity)
Bioenergy share of energy consumption	Bioenergy significant in renewables mix; solid biomass and modern use share growing (FAOSTAT: China ~4.7 EJ final consumption, 2023) [106]	Bioenergy ~5% of US energy production; ethanol ~7% of gasoline energy (2022)	Bioenergy ~2.5% of total electricity and growing share through national initiatives
Investment trends (global context)	Asia (China and India) major driver of capacity	US expects biofuel and RNG investment growth	India receiving rising capital for compressed biogas and ethanol blended petrol segments
Market value indicators	No consolidated national value figure; Asia bioenergy contributing large share globally	US biofuel market value significant: ethanol and diesel sectors in tens of billions USD annually (implied by production scale)	India's bioenergy industry expanding with significant private mobilization, national targets

5. Policy Architecture Comparison

The policy architecture governing bioenergy development in China, the US, and India reflects fundamentally different institutional logics, governance traditions, and strategic priorities, which in turn shape the scale, structure, and technological orientation of national bioenergy markets. Rather than converging toward a single global model, these three countries exhibit distinct policy regimes that condition how bioenergy contributes to energy transition, rural development, and decarbonization objectives.

5.1 Centralized Planning Versus Market-Oriented Governance

China's bioenergy policy architecture is characterized by centralized, planning-based governance, embedded within the country's broader system of Five-Year Plans and sectoral development strategies [44, 107] (Figure 4). Bioenergy targets, feedstock priorities, and technology pathways are largely determined through top-down coordination by central ministries, with implementation delegated to provincial governments and state-owned or state-affiliated enterprises [48]. This architecture enables strong alignment between bioenergy deployment and national priorities such as waste management, rural revitalization, and energy security [30, 108]. However, it also constrains market flexibility, as subsidy eligibility, feedstock use (particularly grain-based biofuels), and project approval are tightly regulated [49, 50] (Figure 4). As a result, China's bioenergy policies emphasize controlled expansion and system integration, rather than rapid market-driven growth.

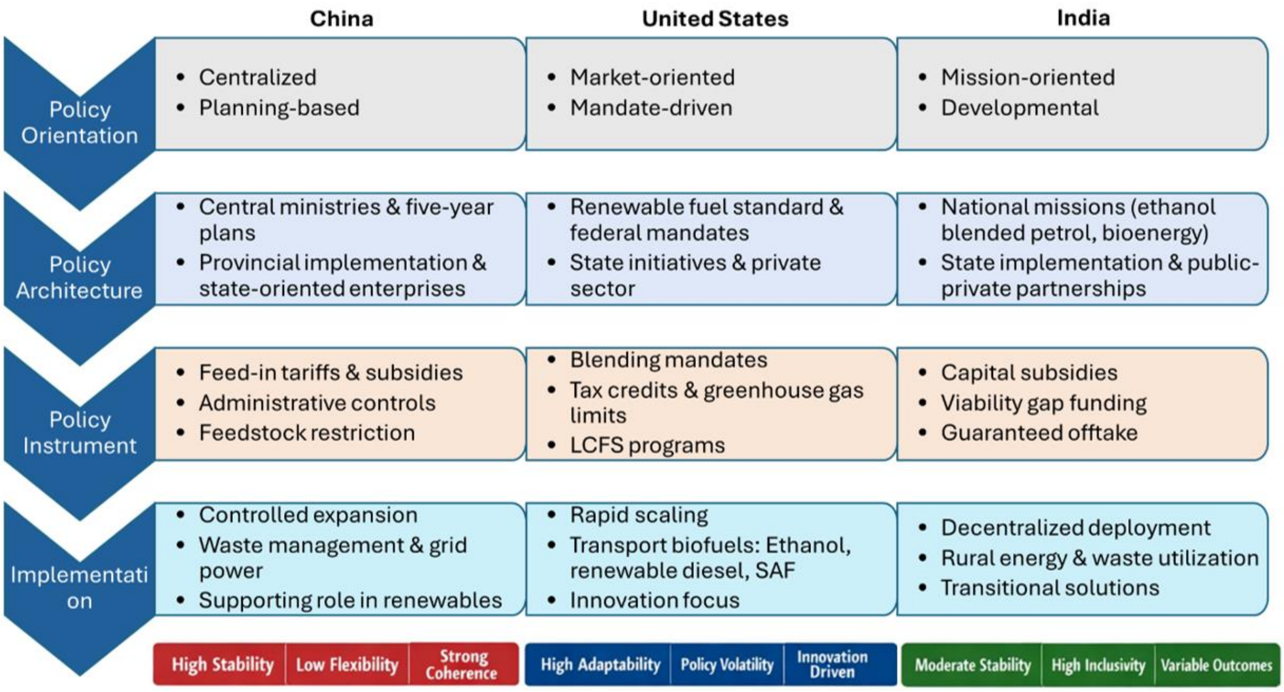


Figure 4 Comparison of Bioenergy Policies of China, the United States, and India.

In contrast, the US exhibits a market-oriented and legally mandated policy architecture, anchored by federal instruments such as the RFS, complemented by tax credits and state-level initiatives [53, 59] (Figure 4). Rather than prescribing specific technologies or project types, US bioenergy policy relies on obligatory demand creation, allowing market actors to determine how compliance is achieved [109]. This approach has facilitated rapid scaling of certain bioenergy pathways, most notably corn-based ethanol and, more recently, renewable diesel and SAF, while simultaneously exposing the sector to policy volatility linked to annual rulemaking, litigation, and political shifts [59, 65]. The fragmented federal-state governance structure further introduces regional heterogeneity, reinforcing innovation in some jurisdictions while limiting uniform national outcomes [53, 65].

India occupies an intermediate position, characterized by a mission-oriented and programmatic policy architecture that blends central coordination with decentralized implementation [69]. National missions such as the National Bio-Energy Mission and the Ethanol Blended Petrol Program set broad objectives and indicative targets, while implementation relies heavily on state governments, public-sector undertakings, and public-private partnerships [24, 68] (Figure 4). This architecture reflects India's developmental priorities, with bioenergy policies explicitly linked to rural income generation, waste management, and energy access. Compared with China, India's policies are less prescriptive regarding technology choice, but compared with the US, they rely more heavily on administrative support mechanisms such as capital subsidies, viability gap funding, and long-term offtake agreements.

5.2 Policy Instruments and Incentive Design

Differences in policy architecture are further reflected in the choice and combination of policy instruments. China has historically relied on feed-in tariffs and direct subsidies for biomass power and biogas, gradually transitioning toward competitive pricing and reduced fiscal support as technologies mature [37, 39] (Figure 4). Importantly, these instruments are embedded within a broader regulatory framework that restricts unsustainable feedstock use and prioritizes waste-based bioenergy, reinforcing policy coherence but limiting entrepreneurial experimentation [49, 110].

The US, by contrast, employs a complex mix of quantity-based mandates, fiscal incentives, and carbon accounting frameworks, including lifecycle greenhouse gas thresholds [59] (Figure 4). This instrument mix encourages private investment and innovation but also generates debates about distribution and sustainability, particularly around land-use change and food-fuel competition [64]. The absence of long-term statutory certainty beyond specific tax credit windows introduces investment risk, even as overall market scale remains large.

India's incentive structure emphasizes risk mitigation and bankability, reflecting constraints in capital access and infrastructure [68]. Policies such as guaranteed ethanol procurement by oil marketing companies and fixed pricing formulas reduce market uncertainty for producers, while subsidies for compressed biogas and biomass projects aim to accelerate early-stage deployment [11, 76, 79] (Figure 4). This approach prioritizes inclusivity and rapid diffusion but may slow cost discovery and technological upgrading in the absence of strong competitive pressures.

5.3 Policy Stability, Flexibility, and Transition Alignment

A critical distinction among the three policy architectures lies in their balance between stability and adaptability. China's planning-based approach offers high policy stability and long-term visibility, which is conducive to infrastructure-heavy investments such as waste-to-energy plants [48]. However, adaptability to emerging technologies or shifting sustainability concerns may be slower due to administrative rigidity [40, 111]. The US system, while highly adaptive and innovation-friendly, is vulnerable to policy reversals and regulatory uncertainty, particularly in politically contested domains such as biofuels [59]. India's mission-driven architecture provides moderate stability, but implementation effectiveness varies across states, creating uneven outcomes [69].

From an energy transition perspective, these architectural differences imply divergent roles for bioenergy. China's policies position bioenergy as a supporting component within a broader electrification and renewables strategy; the US treats bioenergy as a strategic decarbonization tool, especially for hard-to-abate transport sectors; and India frames bioenergy as a developmental and transitional solution, addressing energy access, waste, and agricultural surplus simultaneously. Table 3 summarizes the strengths, weaknesses, opportunities, and challenges of the bioenergy policies of China, the US, and India.

Table 3 Comparative SWOT Assessment of Bioenergy Policies of China, the United States, and India.

Aspect	**China**	**United States**	**India**
Strengths (S)	Strong central planning ensures policy stability and alignment with national goals; effective large-scale deployment and coordination	Market-driven system promotes innovation and rapid scaling of advanced biofuels; strong private-sector participation	Hybrid governance links bioenergy to rural development and waste management; strong offtake support improves investability
Weaknesses (W)	Limited market flexibility and restricted private-sector innovation due to top-down controls	Policy volatility and fragmented federal-state governance	Dependence on subsidies and uneven state-level implementation
Opportunities (O)	Expansion of waste-based bioenergy, biomethane, and advanced technologies (e.g., BECCS)	Growth of SAF, renewable diesel, RNG, and carbon-based performance systems	Large biomass and waste resource base; expansion of ethanol and biogas systems
Challenges/Threats (T)	Balancing control with innovation; improving efficiency after subsidy reduction	Ensuring policy stability and addressing sustainability concerns (e.g., land-use change)	Financial sustainability, feedstock logistics, and balancing competing land-use priorities

6. Comparison of Market Size, Structure, and Technology Pathways

The bioenergy markets of China, the US, and India differ markedly in scale, internal structure, and dominant technological pathways, reflecting the interaction between policy architecture, resource endowments, and broader energy transition strategies. While all three countries rank among the world's largest energy consumers, bioenergy plays distinct functional roles within their national energy systems, resulting in divergent market configurations rather than convergent development trajectories.

6.1 Market Size and Relative System Importance

In absolute terms, China possesses the largest bioenergy market by installed capacity and electricity generation, driven primarily by biomass power generation and waste-to-energy facilities [112]. Bioenergy contributes a modest but stable share to China's power mix, with deployment closely aligned with municipal solid waste treatment and agricultural residue management [46]. Despite its large absolute size, bioenergy occupies a secondary position in China's rapidly expanding renewable energy system, which is dominated by wind and solar [113].

The US exhibits a bioenergy market of comparable economic significance but with a different center of gravity. While bioenergy electricity capacity is smaller than China's, the overall market is substantially larger when liquid biofuels are included [92]. Bioenergy in the US is therefore more consequential at the system level, particularly in the transport sector, where biofuels account for a sizable share of liquid fuel consumption [114]. This distinction highlights the importance of sectoral boundaries in market size assessments: China's bioenergy market is electricity-centric, whereas the US market is fuel-centric.

India's bioenergy market is smaller in absolute size than those of China and the US, but its relative importance is arguably greater. Bioenergy contributes meaningfully to decentralized electricity generation, clean cooking fuel substitution, and waste management, particularly in rural and peri-urban areas [11, 73, 81]. As a result, India's bioenergy market is characterized by high socio-economic relevance, even where aggregate capacity and output remain limited.

6.2 Market Structure

Market structure varies significantly across the three countries. China's bioenergy market is highly centralized and infrastructure-intensive, with large-scale biomass power plants and waste-to-energy facilities concentrated near urban centers and industrial zones (Figure 5) [30, 37]. Project ownership is dominated by state-owned enterprises or large private firms operating under close regulatory oversight [46]. This structure favors capital-intensive technologies and standardized project designs, reinforcing economies of scale but limiting the penetration of small and community-based systems.

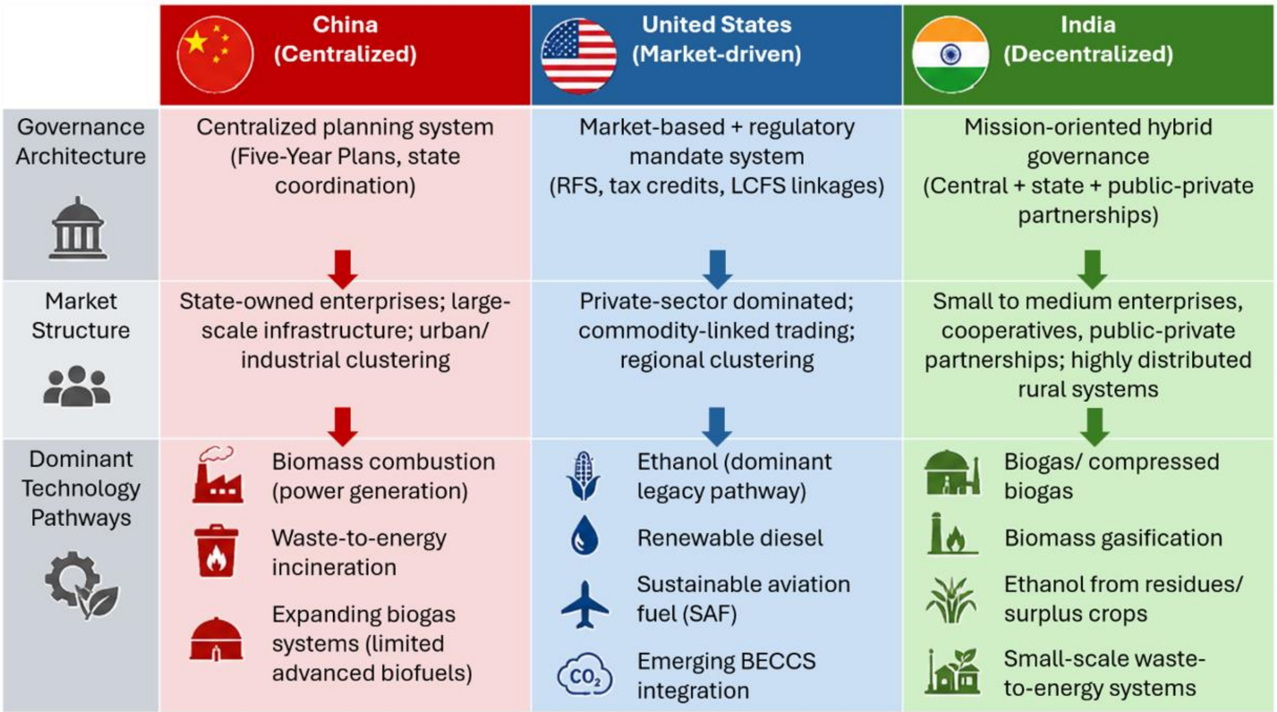


Figure 5 Comparative Bioenergy Pathways: China, the United States, and India.

By contrast, the US bioenergy market exhibits a hybrid structure, combining large industrial biofuel refineries with a growing number of distributed biogas and RNG facilities [115]. Market participation is predominantly private, supported by sophisticated financial instruments and commodity trading mechanisms (Figure 5) [56, 92]. Spatially, bioenergy deployment mirrors agricultural production patterns, resulting in strong regional clustering [116]. This decentralized yet commercially integrated structure enables rapid technology diffusion but also amplifies regional disparities.

India's bioenergy market is the most decentralized and heterogeneous of the three. It consists largely of small- to medium-scale biomass power plants, biogas units, and compressed biogas facilities, often integrated into local agricultural and waste systems [24, 69]. Market actors include cooperatives, small enterprises, and public-private partnerships, reflecting policy efforts to align bioenergy development with rural livelihoods and local resource availability (Figure 5) [76, 117]. While this structure enhances inclusivity and resilience, it also introduces challenges related to aggregation, quality control, and financial scalability.

6.3 Technology Pathways and Policy-Induced Specialization

Differences in market structure are closely linked to technology pathway specialization. China's bioenergy development is dominated by direct combustion of biomass and waste-to-energy incineration, with limited emphasis on advanced biofuels (Figure 5) [82, 110]. This pathway reflects policy constraints on food-based biofuels and a strategic preference for technologies that simultaneously address waste disposal and energy recovery [12, 49]. Biogas is expanding, but largely within controlled and planned deployment frameworks.

The US follows a markedly different trajectory, characterized by strong specialization in liquid biofuels, particularly ethanol, renewable diesel, and increasingly, SAF (Figure 5) [59, 115]. This pathway has been reinforced by long-standing demand mandates and lifecycle greenhouse gas accounting frameworks. In recent years, technological innovation has shifted toward upgrading existing biofuel infrastructure and integrating carbon capture, positioning bioenergy as a potential source of low- or negative-carbon fuels [53].

India's technology pathways are shaped by feedstock flexibility and developmental priorities. Anaerobic digestion, biomass gasification, and ethanol production from surplus crops and residues dominate the market, reflecting the need to accommodate diverse and regionally variable biomass resources (Figure 5) [75, 99]. Unlike China and the US, India's bioenergy technologies are often evaluated not solely on energy efficiency but also on co-benefits such as waste reduction, air quality improvement, and rural income generation.

7. Implications for Global Bioenergy Transitions

The comparative analysis of bioenergy policies and markets in China, the US, and India offers important insights into the evolving role of bioenergy in global energy transitions. As the world's three largest energy consumers, these countries collectively shape international technology development, biomass trade flows, sustainability norms, and investment priorities. Their divergent bioenergy trajectories suggest that future global bioenergy transitions will be pluralistic rather than uniform, shaped by national institutional contexts and sector-specific decarbonization needs.

One of the clearest implications is the absence of a single, universally optimal model for bioenergy development. China's centralized and planning-driven approach, the US market-based and mandate-oriented system, and India's mission-driven developmental framework each demonstrate distinct strengths and limitations. Globally, this implies that bioenergy transitions are unlikely to converge toward a standardized policy or market structure [118]. Instead, successful bioenergy deployment appears contingent on alignment between policy architecture, governance capacity, and national development priorities [119].

This finding challenges assumptions embedded in some international energy scenarios that implicitly treat bioenergy as a homogeneous and scalable technology option [120, 121]. In practice, bioenergy systems are deeply embedded in local agricultural, waste, and energy infrastructures, making context-specific governance more important than technology availability alone [121].

The three-country comparison highlights a growing functional specialization of bioenergy across sectors. China's bioenergy system emphasizes waste management and grid-stable power generation; the US prioritizes liquid biofuels for transport decarbonization; and India focuses on decentralized energy access, agricultural residue utilization, and clean cooking fuel substitution. At the global level, this suggests that bioenergy's contribution to decarbonization will be sectorally differentiated, rather than economy-wide.

For global climate mitigation strategies, this implies that bioenergy is most defensible and impactful in hard-to-electrify sectors, such as aviation, heavy transport, industrial heat, and waste-derived energy recovery [122]. Attempts to scale bioenergy uniformly across all sectors may exacerbate sustainability trade-offs, including land use pressure and biomass competition [123].

The contrasting policy approaches also underscore that sustainability governance, rather than resource availability, is likely to be the binding constraint on global bioenergy expansion. China's strict controls on food-based biofuels, the US reliance on lifecycle greenhouse gas accounting, and India's flexible but administratively managed feedstock policies reflect different strategies to manage food-fuel-land tensions. The lack of convergence among these approaches points to persistent challenges in establishing globally harmonized sustainability standards [120].

For international bioenergy markets, this divergence raises concerns about carbon leakage, indirect land-use change, and inconsistent emissions accounting [124]. It also suggests that future global governance efforts, whether through multilateral climate frameworks or voluntary certification schemes, will need to accommodate multiple sustainability paradigms, rather than impose uniform thresholds that may be politically or institutionally infeasible.

Differences in market structures and policy certainty across the three countries also affect global investment and innovation patterns. The US model demonstrates how strong demand-side mandates can mobilize private capital and accelerate technological upgrading, particularly in advanced biofuels and carbon capture integration. China's approach illustrates the role of long-term planning in supporting infrastructure-heavy projects with stable returns, while India's experience highlights the importance of de-risking mechanisms for early-stage and decentralized technologies.

Globally, this suggests that bioenergy innovation is likely to remain policy-driven and regionally clustered, rather than purely market-led [125]. International technology transfer may therefore be more effective when focused on system integration and business models, rather than standalone technologies. Moreover, the coexistence of capital-intensive and small-scale bioenergy pathways implies that transition finance mechanisms must be flexible enough to support diverse project typologies [126].

A final implication concerns the long-term positioning of bioenergy within global energy transitions. Across all three countries, bioenergy plays a complementary role rather than serving as the primary decarbonization pathway. Even in the US, where biofuels are central to transport policy, bioenergy operates alongside electrification and efficiency improvements. In China and India, bioenergy is increasingly framed as a solution for waste management, rural development, and system balancing, rather than as a large-scale energy substitute.

This convergence toward a complementary role suggests that global bioenergy transitions should be evaluated not on the basis of maximum deployment potential, but on strategic value and co-benefits [123]. Bioenergy's future relevance is likely to depend on its ability to deliver multiple objectives, including emissions reduction, waste management, rural livelihoods, and energy security, within clearly defined niches.

In sum, the experiences of China, the US, and India indicate that global bioenergy transitions will be multi-speed, multi-model, and highly context-dependent. Policymakers and international organizations should therefore shift from promoting bioenergy as a monolithic solution toward supporting context-sensitive policy design, sustainability governance, and sector-specific deployment strategies. Recognizing and accommodating diversity in bioenergy pathways may ultimately prove more effective than pursuing convergence in an inherently heterogeneous energy domain.

8. Environmental Implications and Feasibility

Although bioenergy offers important benefits for decarbonization, waste valorization, and rural development, its sustainability and large-scale feasibility remain subject to considerable debate. The environmental performance of bioenergy depends strongly on feedstock type, conversion pathway, system boundaries, and local conditions. Lifecycle greenhouse gas emissions can vary substantially among bioenergy systems [127]. Waste-based pathways, such as biogas from livestock manure and municipal organic waste, often achieve substantial greenhouse gas reductions by avoiding methane emissions from uncontrolled decomposition, whereas crop-based biofuels may deliver more modest climate benefits once cultivation, fertilizer use, transportation, and processing emissions are considered [128, 129]. Furthermore, indirect land-use change associated with feedstock expansion can offset or even negate carbon savings by releasing carbon stored in forests, grasslands, and soils [130].

Large-scale bioenergy deployment may also create trade-offs involving land, water, and biodiversity. Dedicated energy crop production can intensify competition for arable land and freshwater resources, particularly in regions already experiencing resource constraints [131]. Expansion of monoculture feedstock systems may reduce habitat diversity and ecosystem resilience, while increased fertilizer and agrochemical use can contribute to soil and water degradation [132]. Air pollutant emissions from biomass combustion, including particulate matter and nitrogen oxides, remain a concern where advanced emission-control technologies are absent [133]. These considerations underscore the importance of prioritizing residues, organic waste, and degraded lands as feedstock sources and implementing robust sustainability safeguards.

Beyond environmental considerations, the economic feasibility of bioenergy remains highly dependent on policy support and market conditions. Bioenergy systems generally face higher feedstock collection, transportation, and storage costs than other renewable technologies due to the dispersed and bulky nature of biomass resources. Feedstock logistics can therefore represent a major barrier to commercial viability, particularly in decentralized systems [134]. In China, declining feed-in tariffs and the transition toward market-based mechanisms have increased pressure to improve operational efficiency and optimize plant location [135]. In the US, tax credits, RINs, and emerging carbon-based incentives have enhanced competitiveness but have also exposed investors to policy uncertainty and fluctuating credit values [136]. In India, capital subsidies, viability-gap funding, and guaranteed offtake arrangements have reduced investment risks, although long-term financial sustainability remains challenging [117].

These environmental and economic complexities suggest that bioenergy should not be viewed as inherently sustainable. Rather, its contribution to energy transitions depends on context-specific deployment strategies, rigorous lifecycle assessment, effective sustainability governance, and stable policy frameworks that align economic incentives with environmental outcomes. Prioritizing waste-derived feedstocks, improving conversion efficiencies, incorporating lifecycle greenhouse gas accounting, and integrating carbon pricing or performance-based incentives may enhance both the sustainability and feasibility of future bioenergy systems.

9. Conclusions and Practical Implications

This overview synthesizes the bioenergy policies and market dynamics of China, the US, and India, demonstrating that bioenergy transitions among the world's largest energy consumers are shaped by distinct policy architectures and market structures rather than converging toward a single model. China's centralized, planning-oriented framework has supported large-scale deployment of biomass power and waste-to-energy systems, prioritizing system integration and environmental management but limiting market flexibility. In contrast, the mandate- and incentive-driven approach of the US has enabled the world's largest and most commercially dynamic bioenergy market, particularly in liquid biofuels, while exposing the sector to regulatory uncertainty and sustainability concerns. India's mission-oriented policies have facilitated decentralized bioenergy deployment aligned with development objectives, though challenges persist in scaling investment and ensuring long-term financial viability. Across the three countries, bioenergy fulfills different functional roles within national energy systems. China emphasizes electricity generation and waste treatment, the US prioritizes transport fuel substitution and technological innovation, and India focuses on decentralized energy services, agricultural residue utilization, and rural livelihoods. These differences suggest that bioenergy's contribution to decarbonization is most effective when targeted toward sector-specific niches, particularly waste management, rural energy systems, and hard-to-electrify transport sectors, rather than as a universal energy substitute.

The findings carry several practical implications. Policymakers should avoid replicating foreign bioenergy models without regard to institutional capacity and instead design policies aligned with national governance structures and resource constraints. Strengthening sustainability governance, especially feedstock regulation and lifecycle emissions assessment, is essential to mitigating food-fuel and land-use trade-offs. Moreover, investment frameworks should recognize bioenergy's multi-functional value, supporting projects that deliver environmental and socio-economic co-benefits alongside energy production. Specifically, in China, policymakers could strengthen market confidence by gradually transitioning from direct subsidies to performance-based incentives while expanding feedstock certification systems and lifecycle greenhouse gas accounting frameworks to improve sustainability transparency. Continued investment in advanced biomass conversion technologies and waste-to-energy integration would further enhance resource efficiency and emissions reductions. In the US, greater policy stability and harmonization between federal and state programs could reduce investment uncertainty and accelerate the commercialization of advanced biofuels, renewable natural gas, and SAF. Strengthening lifecycle accounting methodologies and providing long-term regulatory certainty for low-carbon fuel markets would further encourage private-sector investment. In India, expanding rural feedstock aggregation networks, improving biomass logistics infrastructure, and scaling biogas offtake mechanisms under initiatives such as SATAT could improve project bankability and feedstock security. Greater support for second-generation biofuel facilities, including targeted financing mechanisms and technology-transfer programs, could accelerate the commercialization of advanced biofuels while reducing dependence on food-based feedstocks. Across all three countries, the adoption of robust feedstock certification schemes, transparent emissions accounting systems, and risk-sharing financial instruments could enhance investors' confidence while ensuring that bioenergy expansion remains aligned with sustainability objectives.

Future research should focus on long-term policy effectiveness, comparisons of cross-country lifecycle emissions, and the integration of bioenergy into whole-system energy models that account for interactions with electrification, hydrogen, and negative-emissions technologies. Greater attention is also needed to identify pathways for enhancing sustainable bioenergy adoption in both developed and developing economies. In developed economies, research should explore policy mechanisms that improve investment certainty, strengthen sustainability governance, advance carbon accounting methodologies, and accelerate the commercialization of advanced biofuels and carbon-negative technologies such as BECCS. In developing economies, priority areas include improving feedstock supply chains, reducing technology and financing barriers, strengthening institutional capacity, and designing inclusive business models that maximize co-benefits for rural livelihoods, waste management, and energy access. Overall, the experiences of China, the US, and India highlight that successful bioenergy transitions depend on the co-evolution of policy design, market structure, and societal priorities, underscoring the need for context-sensitive, sector-specific bioenergy strategies.

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No new data were generated or analyzed in this study. All data discussed in this review are derived from previously published studies, which are cited in the reference list.

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The author used Grammarly® as a writing support tool for grammar, spelling, and stylistic improvements. Grammarly® did not generate content, analyze data, or influence the scientific interpretation presented in this work.

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