

Energycane for a Sustainable Future: Industrial Pathways to Clean Fuel and Soil Restoration

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ABSTRACT

As a rapidly growing major economy, India faces a severe economic and environmental paradox driven by an over-reliance on imported crude oil and low-quality domestic coal. Traditional food-based crop biofuels trigger "food versus fuel" conflicts and seasonal distillery downtime, while green hydrogen production remains capital-intensive. To resolve these structural bottlenecks, energycane, a specialized high-biomass hybrid developed by the ICAR-Sugarcane Breeding Institute (ICAR-SBI), Coimbatore, through the hybridization and selection of commercial sugarcane with resilient wild relatives like *Erianthus arundinaceus*, offers a scalable, decentralized solution. Bred for ultra-high fiber accumulation rather than sucrose, energycane thrives on marginal, degraded lands. Elite Type II varieties, such as SBIEC 14006, achieve massive biomass yields exceeding 265 t/ha due to an efficient C4 photosynthetic engine and deep root systems. This article outlines the industrial conversion of energycane into second-generation (2G) bioethanol, bio-compressed natural gas (bio-CNG), pure green hydrogen, and premium torrefied bio-coal. Cultivating energycane on half of India's marginal land could displace nearly 69% of baseline crude oil imports, saving \$92.8 billion annually. Simultaneously, its aggressive root networks and microbial recruitment drive biological soil remediation, offering a circular, carbon-negative blueprint for India's energy self-reliance and rural prosperity.

INTRODUCTION

As one of the world's fastest-growing major economies, India faces a critical energy paradox. Rapid industrialization and urban expansion demand unprecedented amounts of power, yet a deep reliance on traditional fossil fuels pushes national economic and environmental systems to a breaking point. India currently imports roughly 88–90% of its domestic crude oil demand, leading to an annual import bill exceeding \$134 billion. Furthermore, despite possessing massive geological coal reserves, the country imports over 200 million tonnes of coal annually. This occurs because domestic reserves are predominantly of inferior quality, characterized by high ash content and low calorific value, making them unsuitable for critical steel production (coking coal) and high-efficiency supercritical power plants. This massive outflow of foreign exchange leaves the economy highly exposed to volatile global market fluctuations and geopolitical shocks that abruptly spike petrol, diesel, and compressed natural gas (CNG) prices.

Furthermore, current renewable transitions face structural bottlenecks. The national ethanol blending program relies heavily on seasonal food-based feedstocks like molasses and grains, which leaves multi-million-dollar distilleries idle for nearly half the year. Similarly, while the National Green Hydrogen Mission is highly ambitious, producing hydrogen through traditional water electrolysis remains capital-intensive and tethered to intermittent solar and wind power. To achieve true energy self-reliance (*Atmanirbharta*), India must transition from mining its energy underground to growing it on a year-round basis.

Energycane, a specialized high-biomass clone developed by the ICAR-Sugarcane Breeding Institute (ICAR-SBI), Coimbatore, has emerged as a vital tool to address these

systemic shortcomings. Unlike traditional sugarcane, energycane is bred for ultra-high fiber and biomass accumulation, allowing it to serve as a decentralized factory for clean fuels. By utilizing India's vast marginal and degraded lands, energycane can fulfill national clean fuel targets without competing for food-growing acreage.

Botanical Architecture and Elite Genotypes

The botanical architecture of energycane represents a strategic shift in sugarcane breeding, moving from sucrose-centric selection to the optimization of lignocellulosic biomass accumulation. Developed by the ICAR-SBI, energycane is a complex hybrid resulting from the introgression of commercial sugarcane (*Saccharum officinarum*) with resilient wild relatives, primarily *Saccharum spontaneum* and *Erianthus arundinaceus*. These wild donors contribute essential traits such as ultra-high fiber content, increased tiller density, wide adaptability to abiotic stresses (drought and salinity), and superior multi-year ratoonability.

The ICAR-SBI breeding program categorizes these hybrids into two distinct archetypes based on their target industrial output:

- **Type I Energycane:** Engineered as a dual-purpose crop, these varieties (such as SBIEC 11008 and SBIEC 13008) utilize *S. spontaneum* to achieve a high juice Brix (>15%) for ethanol production while maintaining enhanced fiber levels (>20%) for electricity cogeneration.
- **Type II Energycane:** Bred strictly for dedicated biomass production, these variants focus on maximum dry matter accumulation. They typically feature ultra-high fiber content (>25%) and negligibly low juice Brix (<10%), making them ideal for whole-cane harvesting and subsequent

thermochemical conversion into green hydrogen, syngas, or bio-coal.

At the pinnacle of the Type II category is the flagship variety, SBIEC 14006, a selection derived from the open-pollinated fluff of the *Erianthus arundinaceus* clone 'IK 76-75'. This variety has set industry benchmarks with a record-breaking mean harvestable biomass yield of 265.28 t/ha across diverse environments, peaking at 289.08 t/ha under optimal irrigation (Kona *et al.*, 2025). Technically, SBIEC 14006 is distinguished by an extraordinary fiber content of 27.54% and a physical architecture reaching heights of 4 to 5 meters. Its stalks are erect and non-lodging, with tightly attached leaf sheaths that conserve biomass until harvest, features that make the variety uniquely amenable to mechanical harvesting (Kona *et al.*, 2025).

Physiological Engines of Climate Resilience

Beyond its physical stature, the physiological engine of SBIEC 14006 is built for extreme resource efficiency. As a C4 photosynthetic plant, it utilizes a specialized internal leaf structure known as Kranz anatomy that virtually eliminates photorespiration. This process ensures that the plant does not waste metabolic energy when temperatures rise, channeling its cellular resources entirely into rapid vegetative growth and fiber accumulation. This C4 engine also grants it superior water-use efficiency (WUE); the plant can efficiently pull in CO₂ even while its leaf pores (stomata) are partially closed, significantly reducing moisture loss through transpiration. In moisture-stressed environments, energycane can produce 1.5 to 2 times more biomass per cubic meter of water than traditional sugarcane varieties.

This physiological resilience is why energycane thrives on marginal, degraded, and problematic lands where standard agriculture is not commercially viable. Its underground

engine consists of an aggressive, deeply penetrating root architecture which can reach depths of 3 to 5 meters, allowing it to tap into subsurface water reserves and mine sparse nutrients from lower soil horizons. Furthermore, energycanes exhibit exceptional nutrient-use efficiency (NUE); they can produce 30–50% more dry matter per kilogram of nitrogen applied compared to commercial sugarcane. By utilizing these indigenous survival strategies, SBIEC 14006 can transform India's degraded land into productive energy hubs without competing for fertile food-growing acreage, remarkably delivering a high biomass yield of 80 to 100 tonnes of dry matter per hectare even under harsh, resource-constrained conditions (Govindaraj, 2020).

From an agronomic perspective, SBIEC 14006 offers significant economic advantages due to its ability to be ratooned for at least 7 to 8 years without replanting, which drastically reduces long-term cultivation and input costs. Furthermore, it demonstrates robust resistance to major pests; notably, it contains protease inhibitors that effectively inhibit the digestive enzymes of borer pests like the early shoot borer and internode borer. The commercial adoption of SBIEC 14006 has accelerated rapidly to support India's renewable energy mandates. In November 2024, ICAR-SBI officially licensed the variety to private entities for commercial use in green hydrogen initiatives and for the displacement of fossil coal in industrial boilers (Govindaraj *et al.*, 2025).

Industrial Conversion Pathways and Products

Energycane serves as a foundation for a cascading biorefinery platform, where 1 dry ton of biomass can be transformed into various clean energy carriers.

Liquid and Gaseous Biofuels

- **Second-Generation (2G) Bioethanol:** Unlike traditional first-generation (1G) distilleries that ferment easily accessible sucrose juice, a 2G ethanol facility targets the plant's structural cell walls. Through thermochemical pretreatment and advanced enzyme cocktails, complex polymers are broken down into basic sugars. Modern biorefineries deploy genetically engineered yeast strains to ferment both C6 and C5 sugar streams simultaneously. This chemical breakthrough allows energycane to yield an impressive 280 to 320 liters of pure ethanol per dry tonne, translating to a massive 25,000 to 35,000 liters of fuel per hectare on marginal land, representing a staggering 400% efficiency increase over traditional 1G cultivation (Sica *et al.*, 2026).
- **Bio-CNG (Biomethane):** Freshly harvested energycane is chopped and processed into an anaerobic digestion ecosystem. The biomass goes through a structured four-stage microbiological journey: hydrolysis, acidogenesis, acetogenesis, and methanation. This biochemical pathway produces 3,000 to 3,600 kg of bio-CNG per hectare annually. Because 1 kg of biomethane contains the energy equivalent of 1.3 liters of petrol, this process offers a powerful alternative to fossil transport fuels (Janke *et al.*, 2020).
- **Green Hydrogen (H₂):** Dried energycane biomass is routed to a high-temperature gasifier operating between 850°C and 1,000°C under a steam-oxygen atmosphere. This thermal environment cracks the hydrocarbons into synthesis gas (syngas). The syngas is then passed through a water-gas shift (WGS) reactor, where carbon monoxide reacts with steam ($\text{CO} + \text{H}_2\text{O} \rightarrow \text{CO}_2 + \text{H}_2$) to maximize hydrogen yield. A single hectare of marginal land can

reliably generate 1,200 to 1,800 kg of pure bio-hydrogen annually, powering zero-emission mass transit for up to 180,000 kilometers per year (Salkuyeh *et al.*, 2018).

Solid Fuels and Coproducts

- **Torrefied "Green Coal" Pellets:** Raw energycane fibers are fed into a torrefaction reactor, where a mild pyrolysis process gently roasts the biomass at 200°C to 300°C in an oxygen-deprived environment. Driving off volatile moisture and hemicellulose yields 850–900 kg of premium fuel pellets per dry ton. When torrefied, these dense pellets achieve an energy density of 22 MJ/kg, perfectly matching the thermal profile of high-grade bituminous coal (Gattuwala, 2025). This bio-coal is significantly superior to domestic Indian utility coal, which suffers from low calorific values (12–16 MJ/kg) and an extraordinarily high ash content of 35% to 45% (Gattuwala, 2025). Torrefied pellets offer nearly double the heat output per unit weight with a fraction of the residual ash, and are highly hydrophobic and grindable for seamless co-firing in existing pulverized coal power plants without requiring expensive boiler modifications.
- **Syngas and Biochar Extraction:** High-temperature gasification transforms a dry ton of energycane into 600 to 750 m³ of high-purity syngas for industrial turbines or upgrading via the Fischer-Tropsch pathway into sustainable aviation fuels (Salkuyeh *et al.*, 2018). Alternatively, fast pyrolysis yields 500–600 kg of liquid bio-oil alongside 150–250 kg of biochar per dry ton. Returning this carbon-rich biochar to degraded fields sequesters carbon for centuries while improving soil structural fertility.

- **Paper and Pulp Optimization:** Flagship energycane varieties boast a fiber content of 27.54% in their structural stalks. This high-cellulose bagasse serves as a direct, year-round alternative to wood pulp, protecting natural forests from being cleared for commercial paper production.

Macro-Economic Potential for India

The macro-economic shift toward a national energycane economy offers a powerful mechanism for India's self-reliance. Dedicating 50% of India's 38.34 million hectares of marginal land (roughly 19 million hectares) to resilient, high-fiber energycane would yield a conservative 15 dry tonnes per hectare annually, generating 285 million dry tonnes of lignocellulosic feedstock each year.

Utilizing advanced enzymatic hydrolysis to process the plant's entire structural skeleton, each dry tonne yields 300 liters of anhydrous ethanol, culminating in a national annual production of 85.5 billion liters. This output fulfills India's E20 blending mandate nearly 8.5 times over, accelerating the transition to 100% flex-fuel vehicle ecosystems. Accounting for ethanol's lower energy density (where 1.5 liters replaces 1 liter of petrol), this production substitutes 57 billion liters of petrol. Based on standard refinery yields, this displaces 1.24 billion barrels or 169 million metric tonnes (MMT) of crude annually. This effectively substitutes 68.9% of India's baseline 245.3 MMT crude imports, securing \$92.8 billion (₹7.7 Lakh Crore) in annual foreign exchange savings, insulating the economy from geopolitical supply shocks, and redirecting vital capital directly into the rural economy.

Ecological Synergy of Soil Reclamation

Deploying perennial energycane across underutilized terrains creates an immediate biological synergy, directly addressing India's vast footprint of 97 million hectares of

degraded land. When cultivated on highly degraded or marginal soils, the plant's massive, deep-penetrating root network acts as a living anchor, structurally stabilizing vulnerable topsoil against severe wind and water erosion. Rather than depleting the soil like traditional annual crops, energycane continuously deposits organic carbon into the rhizosphere throughout its extended 5-to-8-year ratoon lifecycle.

The accumulation of root exudates and decaying organic matter stimulates local microbial life, gradually rebuilding the soil's structural fertility and nutrient-holding capacity. Simultaneously, the dense vegetative canopy reduces surface evaporation, conserving precious soil moisture in arid zones.

To accelerate this underground shift, the massive root architecture of energycane dynamically recruits specialized microorganisms to revive degraded soils. Symbiotic arbuscular mycorrhizal fungi (AMF) extend root surface areas to mine locked-up nutrients, while plant growth-promoting rhizobacteria (PGPR) like *Azospirillum* and *Gluconacetobacter* facilitate biological nitrogen fixation and solubilize chemically bound phosphorus and zinc. Simultaneously, cellulolytic microbes like *Trichoderma* decompose tough, lignocellulosic leaf trash. As these biological engineers interact, AMF secrete glomalin, a sticky glycoprotein acting as a biological glue that binds mineral particles into stable soil aggregates, vastly improving aeration. Furthermore, the rapid turnover of this microbial biomass drives humification, building a stable humus layer that exponentially elevates cation exchange capacity (CEC) and acts as a sponge to retain critical moisture during extended droughts.

Transforming Rural Economies

Beyond its environmental benefits, shifting to a decentralized bioenergy infrastructure directly addresses the core socioeconomic challenges faced by India's small and marginal farmers. By establishing localized cultivation networks across underutilized lands, rural regions gain access to a reliable, long-term economic ecosystem. Unlike volatile traditional food crop markets that are vulnerable to sudden price crashes and climate shocks, energycane provides a highly predictable, climate-resilient alternative revenue stream. Because the crop thrives on low-fertility soils with minimal inputs, smallholders can successfully monetize fields that previously yielded zero commercial value, transforming underutilized land into a profitable asset.

This structural shift transforms rural communities from pure raw-material exporters into active participants in a high-value industrial value chain. Localized processing hubs create thousands of secure, non-seasonal jobs in biomass harvesting, industrial logistics, and high-tech biorefinery operations. Because energycane can be efficiently stored via ensiling for up to six months, processing facilities can operate continuously year-round, stabilizing local employment. The capital currently exported to global oil markets is instead channeled back into India's rural economy. This substantial cash infusion funds local infrastructure, drives rural wealth creation, and creates a self-sustaining economic model that discourages distressed urban migration by providing high-value technical careers right at the farm gate.

CONCLUSION

The transition from mining energy underground to growing it above ground represents the ultimate path to energy self-reliance. Energycane stands as the botanical

vanguard of this revolution, offering a scalable, indigenous solution to India's most pressing vulnerabilities. By shifting the agricultural focus from sucrose recovery to high-biomass accumulation, elite varieties like SBIEC 14006 demonstrate that the nation can generate massive power without compromising national food security. Utilizing just half of India's marginal land for energycane ethanol could slash crude oil import requirements by nearly 69%, retaining approximately \$92.8 billion in foreign exchange reserves annually. Moreover, energycane effectively resolves the "food versus fuel" trilemma by thriving on the nation's degraded land. Through its highly efficient C4 engine, the plant heals the earth by pumping organic carbon back into dead soils, stabilizing topsoil, and reclaiming alkaline or waterlogged terrains, providing a concrete blueprint for a decentralized, prosperous, and sustainable future.

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