ISSN: 0379-5462
IPPTA: Quarterly Journal of Indian Pulp and Paper Technical Association
Vol. 38, E1, 2026, p. 148-152

Strategic Enhancement of Biomass-Derived Thermal Energy Utilization: Maximizing Substitution Rates and Energy Efficiency improvement in Pulp and Paper Sector

P.V. Kiran Ananth*
Deputy Executive Director

Dinesh Ghai*
Principal Counsellor

Vaibhav Girdhar*
Senior Counsellor

Binoy Vijayan*
Counsellor

Confederation of Indian Industry-Sohrabji Godrej Green Business Centre (CII-GBC)

Abstract: *India's bioenergy landscape, currently ranking third globally with 11.6 GW of installed capacity, presents a substantial 42.3 GW theoretical potential for augmenting national energy security and achieving carbon neutrality. This paper evaluates the thermodynamic and operational paradigms of bio-residue utilization within the Indian paper sector, where the geographic distribution of 510 operational mills aligns closely with high-biomass potential regions in the North and West. We investigate the thermal efficiency of Chemical Recovery Boilers (CRB) and bagasse/non-bagasse cogeneration systems, focusing on the systemic constraints of capacity utilization and heterogeneous steam circuit configurations.*

A critical analysis of integrated mills reveals that CRB performance is highly sensitive to operating pressures, with peak efficiencies observed at 106 kg/cm², suggesting a 5–10% optimization margin through technological retrofitting. Furthermore, the study quantifies the impact of the Thermal Substitution Rate (TSR%) in mixed-fuel boilers, delineating the deleterious effects of biomass combustion—such as furnace slagging, convective surface fouling, and chlorine corrosion—on overall boiler availability. Our findings indicate that while current industrial TSR averages in mixed fuel boilers is close to 10.9%, there is significant scope to elevate this to 24.4% . Such advancements are vital for industrial compliance with emerging regulatory frameworks, including the Carbon Credit Trading Scheme (CCTS) and the Carbon Border Adjustment Mechanism (CBAM), by significantly reducing the GHG emission intensity of the production process.

Keywords: *Bio-residue, Bioenergy, Thermal Efficiency, Paper Sector, Chemical Recovery Boiler (CRB), Cogeneration, Thermal Substitution Rate (TSR), Carbon Neutrality*

Introduction

Bio-Residues in India

In a country, like India, that is characterized by an expansive geographical footprint and a highly diversified agro-economic landscape—bioresidue emerges as a strategically critical feedstock for decentralized and utility-scale energy generation. The valorization of agricultural and agro-industrial residues into bioenergy has historically contributed, and continues to offer substantial potential, toward fortifying India's energy security matrix by mitigating structural dependence on imported fossil fuels such as crude oil and coal. From a life-cycle assessment (LCA) perspective, biomass-based energy systems are widely recognized as carbon-neutral, since the greenhouse gas (GHG) emissions released during thermochemical or biochemical conversion are broadly offset by the biogenic carbon sequestration that occurs during biomass growth, and are comparable to emissions that would otherwise arise from natural aerobic or anaerobic decomposition of the same bioresidues. This intrinsic carbon neutrality is pivotal not only for attenuating the environmental externalities associated with industrial energy consumption but also for enabling manufacturing enterprises to align with emerging climate-centric regulatory frameworks aimed at reducing GHG emission intensity. Mechanisms such as the Carbon Credit Trading Scheme (CCTS) and the Carbon Border Adjustment Mechanism (CBAM) impose tangible financial and compliance implications on emissions-intensive sectors, thereby enhancing the strategic relevance of bioenergy adoption as a decarbonization lever.

Within the Indian context, bioenergy derived from biomass resources may be systematically classified as follows:

A. Biomass Power and Bagasse Cogeneration

This is the most dominant sub-category, accounting for 84.79% of the total installed capacity in the bio-power sector.

These installations utilize bagasse (the fibrous residue remaining after sugarcane is crushed) and other agricultural residues. Cogeneration refers to the simultaneous production of electricity and useful heat, which provides a circular energy solution, particularly in agrarian and industrial states like Maharashtra and Uttar Pradesh.

B. Biomass Cogeneration (Non-Bagasse)

This category accounts for 7.96% of the bio-power installed capacity.

Similar to bagasse cogeneration, these systems produce both heat and power but utilize non-sugarcane organic materials and various other agricultural residues. It allows for energy recovery from a broader range of farming byproducts outside of the sugar industry.

C. Waste to Energy (Grid-connected)

This category represents 2.67% of the sector's installed capacity.

These are utility-scale plants that convert urban, industrial, or organic waste into electricity that is fed directly into the power grid. While its absolute share is small, this sector has seen an impressive 720% growth over the last decade.

D. Waste to Energy (Off-grid)

This sub-category accounts for 4.58% of the bio-power capacity.

These are decentralized or decentralized renewable energy systems that convert waste into power for localized use rather than for the national grid. These projects often support rural energy needs and waste management at the source, such as in community or industrial settings.

Demographic distribution of Bio-residues in India

India ranks 3rd globally in bioenergy installed capacity. India has a total Biomass based installed capacity of 11.6 GW. The total installed capacity of Bioenergy in India can be classified as follows in Table 1:

Table 1 Breakup of cumulative installed Bio-power in India[4]

Breakup of cumulative installed Bio-Power, in MW				
	BM Power/ Bagasse Cogen.	BM Cogen. (Non Bagasse)	Waste to Energy	Waste to Energy (Off grid)
Total	9821.32	921.79	309.34	530.87

An assessment of the regional deployment profile of biomass-based power generation in India, as given by Figure 1, indicates that, out of the aggregate 11.6 GW of installed biopower capacity, the southern region commands the largest share, accounting for 33% of the national installed capacity. This is closely followed by the northern region, which contributes 31%, reflecting a substantial concentration of biomass-to-energy infrastructure in these zones. In contrast, the central Indian states exhibit a markedly lower penetration, collectively representing only 4% of the total installed capacity derived from biomass-based energy systems. This uneven spatial distribution underscores region-specific disparities in feedstock availability, technology adoption, policy implementation, and infrastructure readiness across the Indian biopower landscape.

According to reports, the theoretical and realizable potential for renewable electricity generation from biomass resources in India is estimated to be as high as 42.3 GW, as can be observed in figure 2. Within this national biomass energy potential envelope, the northern states are projected to dominate, contributing approximately 36% of the total biomass-based renewable energy output. The southern and western regions are each anticipated to account for 23%, reflecting substantial feedstock availability and conversion capacity in these geographies. In contrast, the central Indian states are estimated to contribute a comparatively modest 9% of the aggregate biomass-derived energy generation, highlighting regional asymmetries in biomass resource mobilization, supply-chain logistics, and bioenergy infrastructure development across the country.

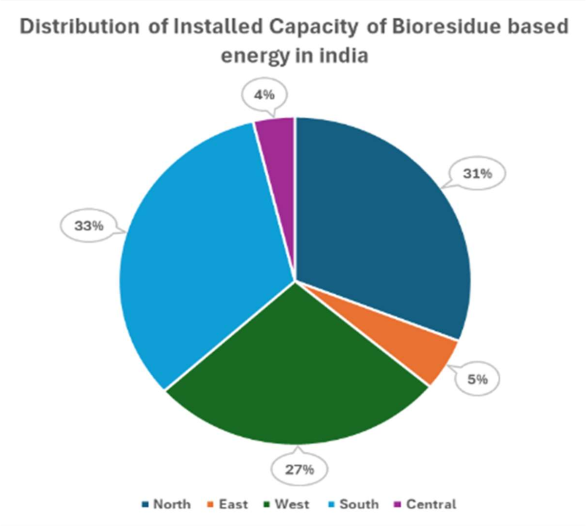

Figure 1 Distribution of Biomass based Installed energy in India

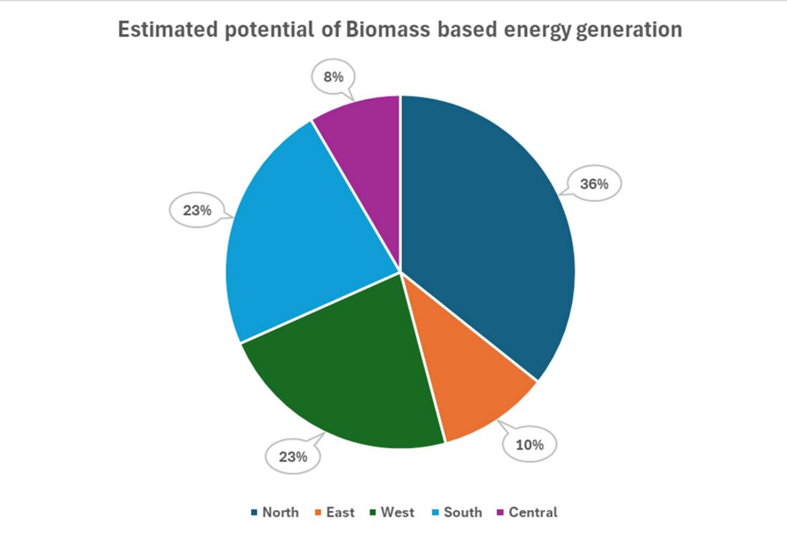

Figure 2 Estimated potential for Biomass based energy generation in different regions of India

The National bioenergy potential in India is quantified at 42.3 GW, which is substantially greater than the currently deployed biomass-based installed capacity of 11.6 GW, as seen in figure 3. This pronounced gap indicates an untapped expansion potential of approximately 3.65 times relative to existing operational capacity for biomass-derived power generation. Such a disparity underscores a significant strategic opportunity to scale up bioenergy deployment, thereby enhancing national energy security, curbing greenhouse gas (GHG) emissions through low-carbon energy substitution, and enabling industrial and commercial entities to achieve compliance with evolving regulatory frameworks governing GHG emission intensity and climate accountability.

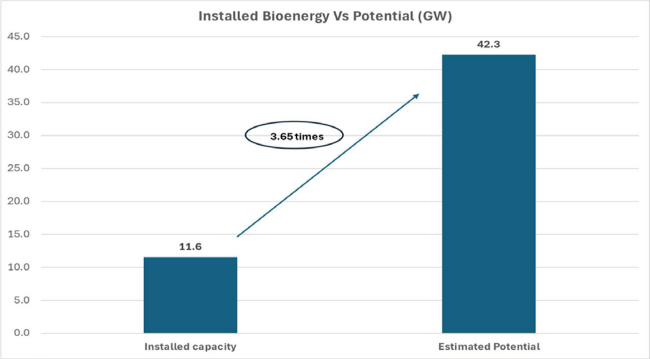

Figure 3 Installed Bioenergy Vs Potential Bioenergy generation (GW)

Usage of Bioresidue based energy in Paper mills

If paper manufacturing facilities are categorized into integrated and non-integrated units, a distinct differentiation emerges in the pathways of bioresidue utilization. In integrated paper mills, bioresidues are predominantly valorized within the chemical recovery boiler (CRB) in the form of lignin-rich organics and residual fibrous matter entrained in black liquor, which undergo controlled combustion for energy recovery, in addition to being deployed in cogeneration boiler systems for meeting the steam and power demand of the unit. Within the Indian paper industry, cogeneration boilers operate on coal, biomass, or hybrid fuel configurations combining coal and biomass, depending on site-specific fuel economics and availability. Conversely, in non-integrated paper mills, biomass is primarily utilized as a fuel input for process steam generation and cogeneration applications, serving as a key thermal energy source in the absence of chemical recovery operations.

Scope for optimized usage of Chemical recovery boilers in Integrated Mills

The efficient usage of chemical recovery boiler depends on multiple factors like capacity utilization, common steam circuits with cogeneration boiler, design pressure of the boiler, etc.

The operational capacity utilization of the chemical recovery boiler (CRB) in different paper mills typically ranges between 37% and 69% , contingent upon the throughput and load factor of the associated pulp mill. Pulp mill utilization is intrinsically linked to paper production rates, which are, in turn, governed by prevailing market demand dynamics for paper products. Consequently, market demand emerges as an indirect yet critical determinant influencing the effective operating efficiency and load optimization of the chemical recovery boiler, thereby impacting overall energy recovery performance and process efficiency within integrated paper manufacturing systems.

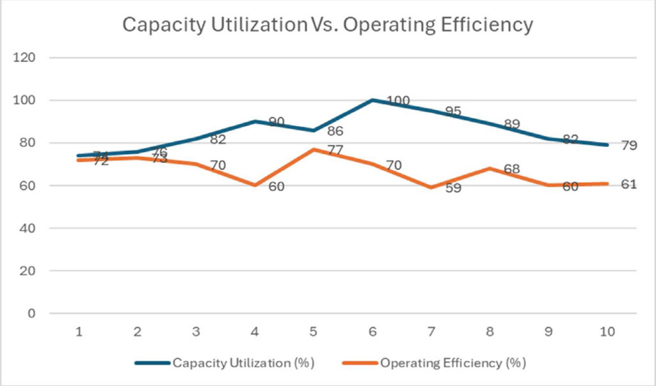

Figure 4 Capacity utilization Vs Operating Efficiency

Ideally the efficiency of a boiler varies directly with capacity utilization of the boiler. But in case of Chemical recovery boilers, in paper mills it was found that this may even be contradictory because of factors external to the boiler, as observed in figure 4.

Empirical observations across multiple paper manufacturing facilities indicate that the main steam header of the chemical recovery boiler is frequently interconnected or integrated with the steam header of a cogeneration boiler, often operating at a different pressure regime. Analysis of operational data from several integrated paper mills reveals that approximately 88% of such mills operate chemical recovery and cogeneration boilers at dissimilar pressure ratings, with the headers combined to enhance overall plant operability and reliability. In these configurations, the fraction of energy routed through lower-pressure steam circuits ranges from 33% to 62% , representing a substantial thermodynamic penalty and exerting a significant impact on the effective efficiency and exergy utilization of the overall steam system.

An evaluation of operating conditions across chemical recovery boilers (CRBs), as depicted in figure 5, indicates that approximately 70% of units are operated at or near a pressure level of 65 kg/cm², while around 20% function within the lower pressure band of 38–40 kg/cm², as most of these units were commissioned CRB with pressure as high as 106 kg/cm² were not available. The maximum commercially deployed operating pressure for a chemical recovery boiler extends up to 106 kg/cm². A comparative analysis of performance metrics, as illustrated in the referenced chart, clearly demonstrates that boilers operating at higher pressure regimes exhibit superior operating efficiency, underscoring the strong correlation between elevated steam pressure levels and enhanced thermodynamic efficiency in CRB systems

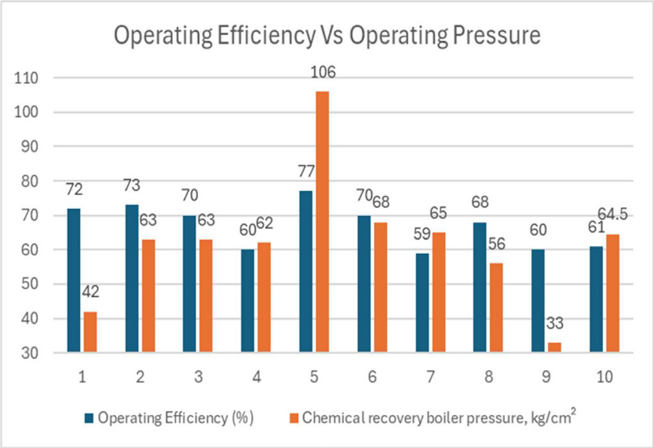

Figure 5 Operating efficiency Vs Operating Pressure of Chemical Recovery boilers

Hence, it may be concluded that for Chemical recovery boilers, there is a need for modification of the existing system while also considering the possibility of upgrading to a more advanced technological option which is commercially available. It should be noted that based on end utilization of steam the design pressure of the boiler should be chosen i.e in case of power generation the design pressure of the respective boiler should be higher to increase the work output of the power cycle while in case of process heating requirements the design pressure of the respective boiler should be sufficient to meet the pressure demand of the process while overcoming the line losses in the distribution system.

In Cogeneration boilers, as observed from figure 6, it is clearly evident that capacity utilization is one of the major factors that plays a major role in deciding the operating efficiency of the boiler7. The other factor that can have a major impact on the performance of a Coal based. boiler, that is also firing biomass, is the Thermal Substitution Rate (TSR%). In figure 7, is a chart depicting the impact of TSR for coal based boilers at different capacity utilizations.

Scope for optimized usage of Bioresidues in Cogeneration boilers

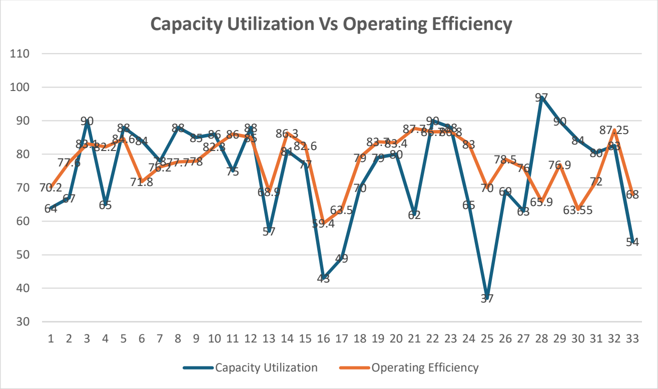

Figure 6 Capacity Utilization% Vs Operating Efficiency%

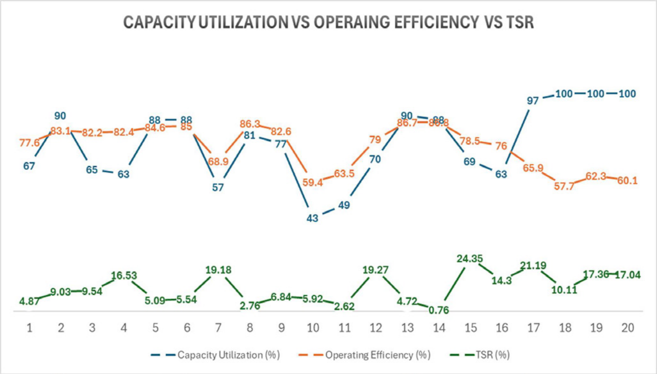

Figure 7 Capacity Utilization% Vs Operating efficiency% Vs TSR%

From the chart, it can be clearly observed that the impact of increase in TSR% in a coal fired boiler is to reduce the efficiency of the boiler.

The detrimental impact of biomass that affects the performance of the boiler are as follows, in table 2:

Table 2 Detrimental impact of Biomass on Boiler, mitigation measures, etc

Challenge / Detrimental Impact	Effect on Boiler Performance	Mitigation Measures / Solutions	How It Helps Increase Biomass Usage
High moisture content in biomass	a. Lower flame temperature b. Higher latent heat loss c. Reduction in boiler efficiency	a. Solar / waste-heat drying of biomass b. Covered storage and rain protection c. Online moisture measurement d. Blending with low-moisture coal	Allows higher biomass blending without efficiency loss
Deposits on boiler heating surfaces	a. Reduced heat transfer b. Higher flue gas temperature c. Increased fuel consumption	a. Optimized soot blowing frequency b. Acoustic soot blowers c. Use of ash-modifying additives (kaolin) d. Control of excess air	Maintains heat transfer efficiency at higher biomass ratios
Slagging in furnace	a. Blockage of furnace walls b. Reduced combustion efficiency c. Forced outages	a. Limit furnace temperature via staged combustion b. Coal-biomass blending c. Use of limestone/dolomite additives d. Selection of biomass with higher ash fusion temp	Enables stable furnace operation at increased biomass share
Fouling in convective heat surfaces	a. Fouling of Superheaters, Economizers, Evaporators b. Reduced steam generation	a. Enhanced soot blower coverage b. Maintain flue gas velocity c. Periodic chemical cleaning d. Optimized tube spacing	Prevents loss of heat absorption with higher biomass firing
Fouling in Air Preheater (APH)	a. APH choking b. Higher fan power c. Reduced combustion air	a. Maintain APH metal temperature above dew point b. APH steam/shot blowing c. Corrosion-resistant coatings d. Partial APH bypass during high biomass	Ensures stable air flow even with high-alkali biomass
Chlorine-induced corrosion	a. Superheater tube thinning b. Frequent tube failures	a. Limit chlorine content in fuel mix b. Excess air optimization	Extends boiler life and permits higher biomass co-firing
Improper fuel sizing	a. Feeding issues b. Uneven combustion c. Reduced boiler availability	a. Crushing, and screening b. Maintain Standard fuel size c. Dedicated biomass feeding systems	Improves combustion stability and reliability
Poor flow properties of biomass	a. Bridging and choking in hoppers b. Fluctuating boiler load	a. Steeper hopper angles b. Vibrators and air cannons c. Pre-blending with coal	Enables continuous and controlled biomass firing
Decay and degradation during storage	a. Loss of GCV b. Higher specific fuel consumption	a. First In First Out (FIFO) storage practice b. Covered and ventilated storage c. Limited storage duration d. Pelletization/briquetting	Maintains biomass quality for long-term use

Conclusion

Accordingly, it may be inferred that process retrofitting, system reconfiguration, and technological upgradation of chemical recovery boilers (CRBs) in integrated paper mills can yield efficiency improvements in the range of 5–15%, which is depicted in figure 8. In parallel, the latent optimization potential associated with bioresidue utilization in cogeneration boilers is considerably higher, with the Thermal Substituon Rate (TSR) exhibiting scope for enhancement from a current average of 11% to as high as 24% in boiler systems co-firing coal and bioresidues within the paper manufacturing sector. This underscores a substantial opportunity for thermodynamic performance improvement and fuel-use efficiency gains through targeted boiler and steam-cycle optimization initiatives.

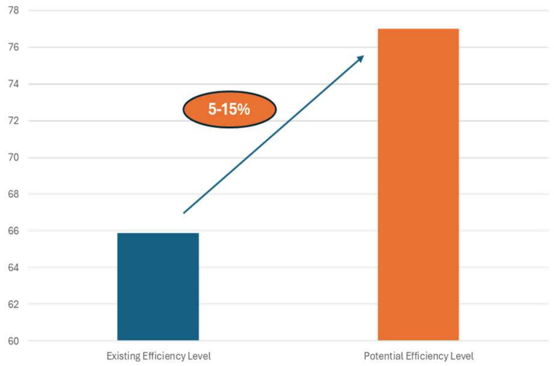

Figure 8 Scope for improving Efficiency of CRB

Analysis of the operational dataset, shown in figure 9, indicates that a TSR of up to 24% is technically achievable in coal-fired boiler configurations; however, the majority of cogeneration boilers deployed in paper mills operating on mixed-fuel regimes comprising coal and biomass exhibit significantly lower TSR values. This performance disparity highlights potential limitations arising from fuel heterogeneity, combustion dynamics, and boiler–turbine integration constraints. Accordingly, there exists a compelling requirement for case-specific reassessment and optimization of boiler design and configuration to enhance boiler availability, steam quality, and overall cogeneration performance under hybrid fuel operating conditions.

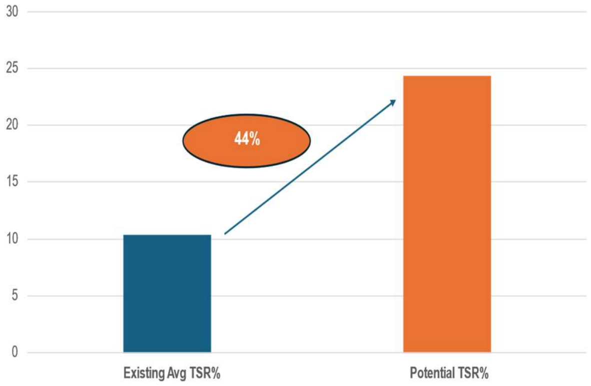

Figure 9 Scope for improving TSR in mixed fuel boilers in Paper sector