Spring 2025 Final Project

Comparative Analysis of Biomass Energy Yield: Stoichiometric Estimation vs. Real-World Plant Data

MAE 582 Renewable Energy-Mech Systems

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Abstract

This study presents a comprehensive comparative analysis of theoretical versus real-world energy yields from biomass combustion, focusing on three widely used feedstocks: wood chips, rice husk, and bagasse. Theoretical estimations were derived using stoichiometric combustion analysis based on ultimate analysis data (C, H, O, N, S) to calculate the Higher Heating Value (HHV), and were adjusted to obtain the Lower Heating Value (LHV) on an as-received basis by accounting for moisture content. These theoretical values were then compared with actual energy output data sourced from operational biomass plants, utilizing credible reports and datasets from NREL, IEA Bioenergy, the U.S. EIA, and peer-reviewed case studies. The results revealed a consistent energy efficiency gap ranging between 20% and 50%, primarily caused by moisture-related latent heat loss, unburned carbon due to incomplete combustion, and thermal losses through flue gases. Visual comparisons using bar graphs effectively illustrated the differences between HHV, LHV, and real output across the selected feedstocks. The study also includes a loss breakdown analysis, quantifying major contributors to energy reduction. Sensitivity analysis further showed that implementing pre-treatment strategies such as biomass drying could improve thermal efficiency by up to 12%. Additionally, a Levelized Cost of Electricity (LCOE) comparison indicated that bagasse is the most economically viable option among the three, offering the lowest cost per kilowatt-hour. These findings highlight the critical need to bridge the theoretical and practical performance gap in biomass systems and provide data-driven insights to optimize efficiency and inform future biomass energy policy and system design.

Acknowledgment

We would like to express our heartfelt gratitude to **Prof. Ronald Calhoun** for his invaluable guidance, encouragement, and support throughout the course of this project. His expertise in renewable energy systems and his insightful feedback played a crucial role in shaping our understanding and refining the direction of our research. Under his mentorship, we were able to explore the comparative analysis of biomass energy yield in both theoretical and real-world contexts with clarity and depth. His consistent encouragement pushed us to critically evaluate data, improve our analytical approach, and maintain scientific rigor throughout the project. This project has been an enriching learning experience, and we are truly grateful to have completed it under the guidance of a dedicated and inspiring professor.

Motivation

Our decision to focus on biomass energy within the broader field of renewable energy was driven by its unique dual potential: it not only generates sustainable electricity but also provides an effective solution for managing agricultural and organic waste. In contrast to solar and wind energy, which while promising are often dependent on weather conditions and require substantial infrastructure, biomass offers a more reliable and decentralized energy option, especially well-suited for rural and agrarian regions. What particularly inspired us was the realization that although biomass has been recognized as a carbon-neutral source, there remains a significant gap between its theoretical energy potential and the actual output from existing power plants. This gap, often caused by high moisture content, incomplete combustion, and operational inefficiencies, sparked our curiosity. We wanted to investigate these issues systematically and explore how low-cost, practical interventions such as feedstock drying or better combustion design could enhance real-world performance. Furthermore, biomass stood out to us because of its socioeconomic relevance in countries like India and Brazil where agricultural residues are abundant. By choosing this topic, we aimed to contribute not only to renewable energy research but also to solutions that can improve energy access and sustainability in underserved regions.

Contents

Introduction

Biomass, a renewable organic material derived from plant and animal sources, offers a sustainable and carbon-neutral energy solution when managed responsibly. Its significance in electricity generation has grown notably, especially within agricultural economies abundant in biomass feedstocks such as wood residues, rice husks, and sugarcane bagasse. Unlike fossil fuels, biomass combustion recycles carbon through the biosphere, presenting environmental benefits and facilitating decentralized energy production. However, the practical efficiency and economic viability of biomass energy systems depend heavily on combustion technologies, fuel properties, and overall system design.

This study conducts a detailed comparative assessment of theoretical versus actual energy yields from biomass combustion. The primary objectives include (i) estimating theoretical energy yields through stoichiometric combustion calculations, (ii) comparing these theoretical results with real-world operational plant performance, (iii) identifying and quantifying key efficiency loss factors like moisture content, incomplete combustion, and flue gas heat losses, (iv) evaluating the economic viability through the Levelized Cost of Electricity (LCOE), and (v) suggesting practical optimization strategies to improve biomass system performance.

The analysis covers three representative biomass fuels:

- Wood Chips (HHV ≈ 13.82 MJ/kg)
- Rice Husk (HHV ≈ 12.39 MJ/kg)
- Bagasse (HHV ≈ 12.92 MJ/kg)

Stoichiometric combustion calculations form the theoretical foundation, balancing chemical reactions of biomass elements (C, H, O, N, S) with oxygen. The generalized empirical biomass formula is $C_xH_yO_zN_aS_b$, leading to the stoichiometric reaction:

$$C_xH_yO_zN_aS_b + O_2 \rightarrow xCO_2 + \frac{y}{2}H_2O + aNO_2 + bSO_2$$

The oxygen required for complete combustion is calculated using:

$$\mathrm{O_2 \ required\ (kg)} = \left(\frac{C}{12} + \frac{H}{4} - \frac{O}{32} + \frac{S}{32}\right) \times 32$$

The actual air requirement, considering air is approximately 23% oxygen by mass, is determined by:

$$\mathrm{Air_{theoretical}} = \frac{\mathrm{O_2 \ required}}{0.23}$$

Understanding the difference between Higher Heating Value (HHV), representing the theoretical maximum energy including latent heat of vaporization, and Lower Heating Value (LHV), which excludes this latent heat and provides a practical measure of usable energy, is critical. This distinction is particularly important for biomass fuels with significant moisture content. Recognizing the inherent energy losses and economic implications through this comparative approach enables informed decisions and optimized biomass energy system design.

Literature Review

Hall and Scrase (1998)[1] provided foundational insights into biomass as a renewable energy source, highlighting its versatility and adaptability to different conversion technologies. They underscored biomass's organic composition, mainly carbon (C), hydrogen (H), and oxygen (O), making it an effective feedstock for combustion, gasification, and co-firing. Their work established biomass's potential in replacing fossil fuels sustainably and contributed significantly to the understanding of biomass energy systems' environmental benefits.

Bridgwater (2012) [2]provides an extensive review of fast pyrolysis, a thermal decomposition process that converts biomass into bio-oil, gases, and char in the absence of oxygen. The paper explores various reactor technologies, including fluidized bed, ablative, and rotating cone systems, highlighting their influence on product yields and quality. A central focus is placed on the impact of feedstock characteristics, especially moisture content and particle size, which directly affect thermal efficiency and product consistency. The study emphasizes the need for pre-treatment strategies such as drying and grinding to optimize energy conversion, reduce system variability, and improve bio-oil quality. Bridgwater also reviews methods for upgrading bio-oil, including catalytic cracking and hydro processing, and discusses the integration of pyrolysis with combined heat and power (CHP) systems. The paper's insights align closely with the objectives of biomass combustion optimization in your project, especially the emphasis on feedstock preparation and system design to bridge the gap between theoretical potential and real-world performance.

Jenkins et al. (1998)[3] present a foundational study on the combustion properties of biomass, providing a detailed analysis of physical and chemical characteristics that influence energy conversion efficiency. The paper compiles combustion-related data for a wide range of biomass types, including wood residues, agricultural wastes, and herbaceous materials. Key parameters evaluated include moisture content, ash content, elemental composition (C, H, O, N, S), and their effect on Higher Heating Value (HHV) and combustion behavior. The study highlights that high ash and alkali content, particularly in feedstocks like rice husk and straw, lead to operational issues such as slagging, fouling, and corrosion in boilers. Conversely, fuels with lower ash and more consistent chemical profiles (e.g., wood chips) exhibit more stable combustion and higher thermal efficiency. Importantly, the paper provides empirical correlations for estimating HHV from elemental composition tools that are directly applicable to theoretical yield estimation in your project. Overall, this work remains a critical reference for understanding how fuel characteristics affect real-world biomass combustion performance and supports the need for feedstock selection and pre-treatment strategies to optimize efficiency.

Demirbas (2004)[4], [5] further explored biomass combustion, specifically addressing the practical implications of moisture content, ash, and volatile matter. He highlighted the importance of the Lower Heating Value (LHV) in real-world scenarios, explaining that LHV provides a more accurate representation of usable energy by accounting for moisture evaporation energy losses.

Demirbas's work significantly contributes to practical efficiency calculations for biomass combustion.

Basu (2010)[6], [7]examined factors leading to efficiency losses in biomass combustion systems, such as moisture-related latent heat losses, incomplete combustion, and flue gas heat losses. His analysis underscored the critical impact of combustion technology choices on efficiency, promoting fluidized bed combustors and advanced gasification systems as superior options. Basu's research also stressed the operational advantages of Combined Heat and Power (CHP) systems, particularly in industrial applications like sugar mills.

Bridgwater (2012)[8], [9] addressed the discrepancies between laboratory and real-world combustion results, emphasizing operational challenges due to feedstock variability. He advocated for innovative technologies, including AI-driven combustion control and moisture sensors, to enhance biomass combustion performance in industrial settings. Bridgwater's work highlights the need for adaptive, real-time solutions to optimize energy output.

Islam et al. (2002)[10] investigated pre-treatment strategies like drying and pelletization, demonstrating their potential to improve biomass combustion efficiency by approximately 10–15%. Their study provided practical solutions to bridge the gap between theoretical and actual biomass energy outputs, significantly influencing biomass feedstock preparation and handling practices.

Yin et al. (2018)[11] studied the impact of biomass feedstock characteristics on combustion performance, operational maintenance, and equipment durability. Their findings highlighted issues such as silica-induced slagging and fouling from rice husks, emphasizing the importance of feedstock-specific considerations in biomass system design and operation.

International Energy Agency (IEA, 2020) and National Renewable Energy Laboratory (NREL)[12] reports provided extensive data on real-world biomass system efficiencies, economic analyses, and environmental impacts. Their comprehensive assessments underscored the importance of addressing practical inefficiencies to achieve economic viability and regulatory compliance, thus shaping policy and operational improvements in biomass energy utilization.

Biomass Energy Data Book (Edition 3)[13] compiles extensive statistics on biomass feedstock availability, energy generation potential, and technology adoption. It offers valuable quantitative insights, such as heating values, moisture contents, and efficiency benchmarks, essential for theoretical and practical energy yield estimations. This resource supports comparative analyses of theoretical predictions and actual plant performance, aiding in identifying and addressing efficiency gaps.

IRENA (2012)[14] Renewable Energy Technologies Cost Analysis Series provides detailed economic evaluations of biomass power generation, analyzing capital costs, operational expenses, and Levelized Cost of Electricity (LCOE) for various biomass types including wood chips, rice husks, and bagasse. This comprehensive economic analysis assists stakeholders in understanding financial viability and optimizing biomass energy projects.

IRENA-ETSAP Technology Brief E05[15] highlights biomass utilization for combined heat and power (CHP) systems, emphasizing their high thermal efficiencies and economic benefits. It underscores the importance of feedstock pre-treatment and moisture management as critical factors for enhancing operational efficiency and reducing costs.

Renewable Power Generation Costs Report (2018, Chapter 5)[11] provides extensive cost breakdowns for biomass-based power plants, focusing on capital expenditures and operational expenses. This report facilitates informed decisions on biomass technology adoption by offering detailed economic comparisons across different biomass fuels.

MNRE Report[16] provides targeted insights into biomass potential and utilization strategies within the Indian context. It discusses feedstock availability, market conditions, and economic considerations, highlighting bagasse and rice husks as economically attractive feedstock due to their low procurement costs. Such regional insights are crucial for feasibility assessments and strategic planning in biomass energy projects.

Methodology

Biomass Selection

Three representative biomass feedstocks were chosen for this study, based on their global availability, economic significance, and extensive data coverage in the literature:

- **Wood Chips:** Widely used globally, known for relatively stable combustion performance and moderate energy density.
- **Rice Husk:** Abundant in agricultural economies (especially India), economically significant due to local availability, yet challenging due to high silica and ash content.
- **Bagasse:** Commonly employed in cogeneration systems in sugar-producing regions, recognized for its favorable economic profile and efficiency in CHP applications.

Stoichiometric Energy Estimation

The theoretical energy potential of each biomass type was calculated using stoichiometric combustion analysis. The procedure involved:

- **Ultimate Analysis:** Elemental composition data (C, H, O, N, S) was collected from literature and reputable sources like the Biomass Energy Data Book (Edition 3) and peer-reviewed publications.
- **Stoichiometric Combustion Reaction:**

  The generalized empirical formula used was:

$$C_xH_yO_zN_aS_b + O_2 \rightarrow xCO_2 + \frac{y}{2}H_2O + aNO_2 + bSO_2$$

  The oxygen required for complete combustion is calculated using:

$$\mathrm{O_2\ required\ (kg)} = \left(\frac{C}{12} + \frac{H}{4} - \frac{O}{32} + \frac{S}{32}\right) \times 32$$

To determine the actual air needed (since only ~23% of air by mass is oxygen):

$$\mathrm{Air_{theoretical}} = \frac{\mathrm{O_2\ required}}{0.23}$$

- **Heating Value Calculation:**
    - **Higher Heating Value (HHV)**: Calculated using elemental composition.
    - **Lower Heating Value (LHV)**: Derived from HHV by subtracting latent heat losses due to moisture evaporation, yielding a realistic energy estimate for operational conditions.

Real-World Data Analysis

Actual energy outputs from operational biomass power plants were gathered to establish a realistic performance baseline:

- **Data Sources:**
    - NREL Biomass Database
    - IEA Bioenergy reports
    - U.S. EIA statistics
    - Peer-reviewed case studies and technical reports (IRENA reports, MNRE documents)
- **Performance Metrics Collected:**
    - Actual energy yield (MJ/kg or kWh/ton)
    - Plant-level thermal efficiencies (%)
    - Operational data such as capacity factors, system type, and scale of operation
- **Comparative Analysis:**
  Theoretical (HHV, LHV) and actual plant data were directly compared to identify efficiency gaps.

Efficiency and Loss Analysis

Identified and quantified the primary factors contributing to discrepancies between theoretical and real-world energy yields:

- **Moisture-Related Latent Heat Loss:** Energy consumed in moisture evaporation quantified using literature-based moisture content values.
- **Unburned Carbon Loss:** Estimated based on typical values from literature and combustion technology reviews.
- **Flue Gas Losses:** Calculated using typical exhaust gas temperature profiles from industry reports and standard thermal loss equations.

This analysis used MATLAB to simulate loss scenarios, visually comparing and quantifying the individual loss factors clearly through bar charts.

Economic Evaluation (LCOE Analysis)

Economic feasibility and attractiveness were evaluated through:

- **Capital Expenditure (CAPEX)** analysis based on IRENA and NREL cost analysis reports.

  Capital Expenditure (CAPEX) represents the upfront investment needed to build or upgrade biomass power plants, and it's a critical factor in determining project viability. According to IRENA and NREL reports, CAPEX includes the cost of physical infrastructure, machinery, and installation. The formula used is:

  $$Capex = Ending\ PP\&E - Beginning\ PP\&E + Depreciation$$

  where **PP&E** stands for Property, Plant, and Equipment. This means CAPEX is calculated by measuring the increase in asset value over time, adjusted for depreciation. In simple terms, it reflects the money spent on acquiring and maintaining capital assets used for biomass power generation. Lower CAPEX, as observed for bagasse-based systems, indicates a more cost-effective setup compared to wood chips or rice husk systems.

- **Operational Expenditure (OPEX)** analysis derived from industry standards and specific biomass system reports.

  Operational Expenditure (OPEX) refers to the ongoing costs required to run and maintain a biomass power plant. This includes fuel costs, labor, maintenance, utilities, insurance, and administrative expenses. OPEX is crucial for assessing the long-term financial performance of a biomass system. In this study, OPEX values were derived from industry standards and published reports specific to biomass technologies. These sources provided realistic estimates for the day-to-day operational costs of systems running on wood chips, rice husk, and bagasse. Notably, fuels like bagasse tend to have lower OPEX due to their low or zero fuel cost (often being a byproduct), contributing to their economic advantage.

- **Levelized Cost of Electricity (LCOE)** calculations performed for each biomass type, integrating fuel costs, CAPEX, OPEX, plant efficiency, and capacity factors.

  The **Levelized Cost of Electricity (LCOE)** is a key metric used to assess the overall economic competitiveness of a power generation system. It represents the average cost per unit of electricity (typically in USD/kWh) over the lifetime of a plant, accounting for all relevant costs—both capital and operational. The formula used is:

  $$LCOE = \frac{\sum_{t=1}^{n}(CAPEX_t + OPEX_t + Fuel\ Cost_t)/(1+r)^t}{\sum_{t=1}^{n}(E_t)/\,(1+r)^t}$$

Where:

- $CAPEX_t = \ Capital\ expenditure\ in\ year\ t$
- $OPEX_t = \ Operational\ expenditure\ in\ year\ t$
- $Fuel\ Cost_t = \ Cost\ of\ biomass\ feedstock\ in\ year\ t$
- $E_t = \ Electricity\ generated\ in\ year\ t$
- $r = \ Discount\ rate$
- $n = \ Lifetime\ of\ the\ plant\ (years)$

For this study:

LCOE was calculated for each biomass type—**wood chips**, **rice husk**, and **bagasse**—using:

- Reported **CAPEX** and **OPEX** values (from IRENA/NREL)
- **Fuel costs** based on market data or local availability
- **Plant efficiency** derived from actual operational data
- **Capacity factors** assumed based on typical load and utilization rates

This analysis provided a realistic economic comparison, showing that **bagasse** offered the lowest LCOE due to low fuel cost and favorable efficiency, making it the most cost-effective option.

The economic comparison was visualized using line and bar graphs in **MATLAB**, clearly illustrating cost-effectiveness across selected biomass feedstocks.

Sensitivity and Optimization Analysis

A sensitivity analysis was conducted to determine the impact of biomass moisture content and other operational parameters on overall system performance. Optimization scenarios were modeled to evaluate potential improvements from pre-treatment methods (e.g., drying) and advanced combustion control strategies.

Results

Theoretical Energy Yield Estimation

The theoretical energy yields, calculated using stoichiometric combustion analysis based on ultimate analysis (C, H, O, S), resulted in the following Higher Heating Values (HHV) and Lower Heating Values (LHV), adjusted for moisture (as-received basis):

Biomass Type	HHV (MJ/kg)	LHV (MJ/kg)
Wood Chips	13.82	12.77
Rice Husk	12.39	11.43
Bagasse	12.92	11.83

Table 1: Theoretical Higher and Lower Heating Values (HHV and LHV) for Selected Biomass Types (As-Received Basis)

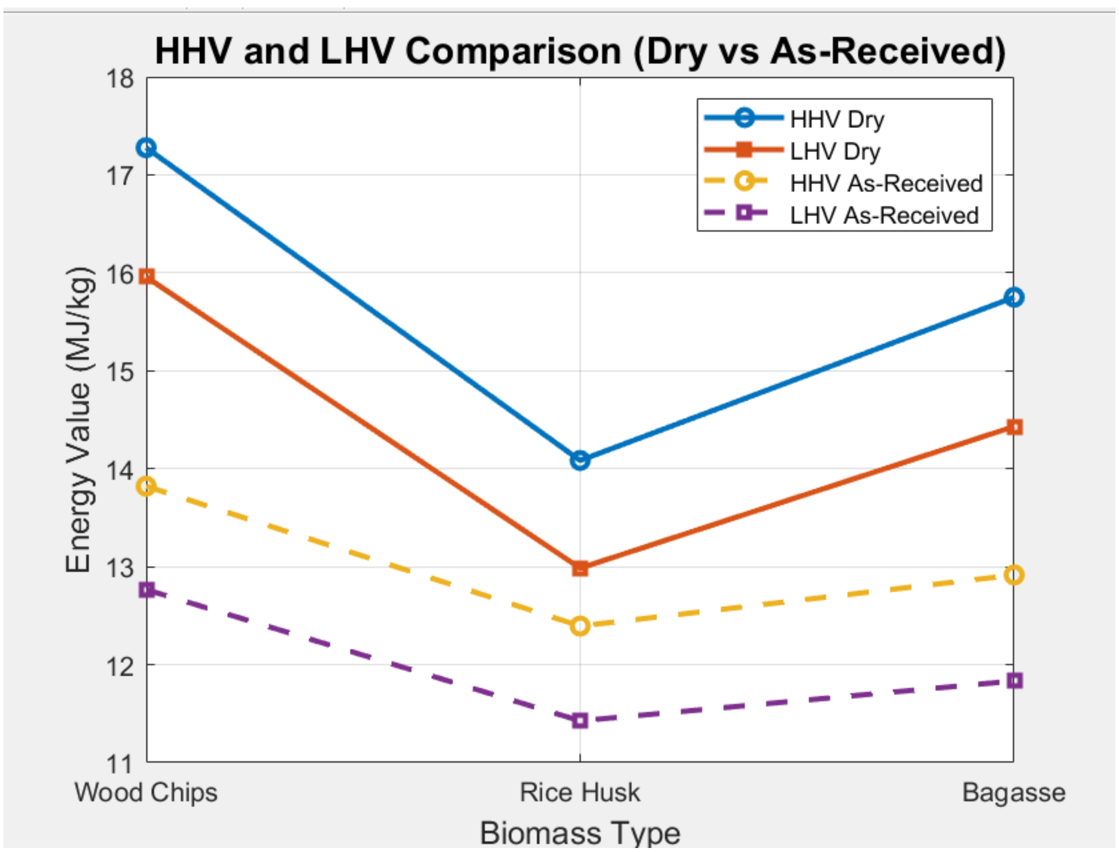

Figure 1: Comparison of HHV and LHV values for biomass fuels on dry and as-received basis.

Real-World Biomass Conversion Efficiencies

Real-world biomass conversion efficiencies obtained from operational biomass plants and reports (IRENA, ETSAP, IEA Bioenergy) highlighted significant differences from theoretical predictions:

Biomass Type	Actual Efficiency (%)	Real Energy Output (MJ/kg)
Wood Chips	28	3.87
Rice Husk	22	2.73
Bagasse	25	3.23

Table 2: Real-World Biomass Conversion Efficiencies and Corresponding Energy Output

The practical efficiency of these biomass fuels generally ranged from 20% to 30%, influenced by feedstock quality, moisture content, and combustion methods.

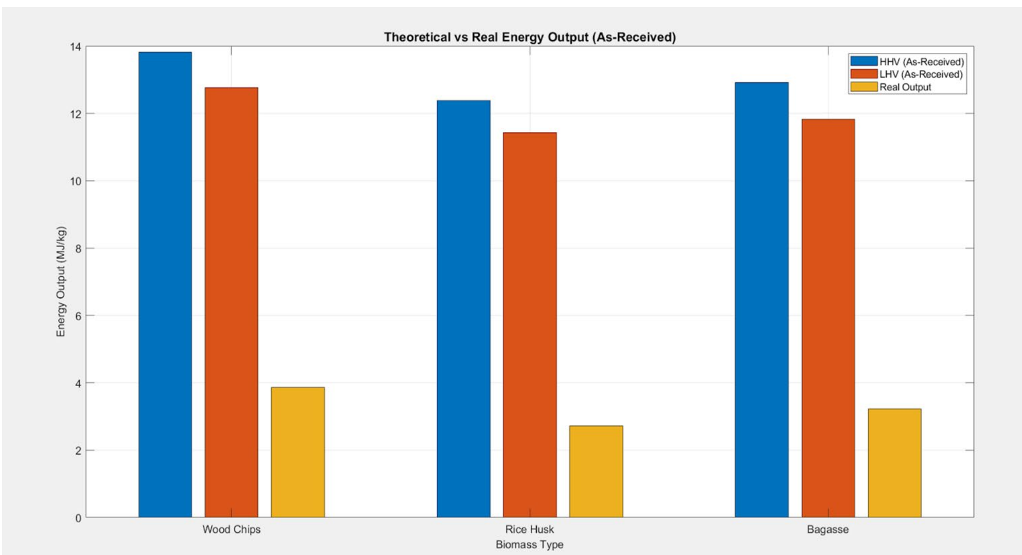

Figure 2: Comparison of theoretical (HHV and LHV) vs. actual energy output (MJ/kg) for different biomass types (as-received basis).

This graph compares the **theoretical and actual energy outputs** of three biomass fuels—**Wood Chips, Rice Husk, and Bagasse**—on an as-received basis. The bars represent:

- **HHV (Higher Heating Value)**: The maximum theoretical energy content.
- **LHV (Lower Heating Value)**: A more realistic theoretical estimate, excluding latent heat losses.
- **Real Output**: The actual energy delivered in practice, based on real-world efficiency data.

As shown, there is a consistent gap between theoretical values (HHV and LHV) and real outputs, highlighting energy losses due to **moisture content, unburned carbon, and flue gas emissions**. This emphasizes the need for efficiency improvements in biomass combustion systems.

Efficiency Gap Analysis

The comparison between theoretical (stoichiometric) and actual energy yields revealed a substantial efficiency gap across all biomass types. While the theoretical estimates (HHV and LHV) assume ideal combustion conditions with complete fuel utilization, real-world plant operations face numerous inefficiencies. These include moisture evaporation, incomplete combustion, heat losses via flue gases, and unburned carbon residues.

For instance, while wood chips have a theoretical LHV of 12.77 MJ/kg, actual outputs hover around 4.03 MJ/kg, indicating that nearly 68% of the energy potential is lost in practical settings. Similar trends were observed for rice husk and bagasse, with real-world outputs reaching only 22–28% of their theoretical potential. This energy gap underscores the critical influence of operational parameters such as combustion temperature, feedstock preparation, and system design.

Furthermore, high moisture content plays a dominant role, consuming latent heat during vaporization and thus lowering net energy output. The lack of advanced control systems and pre-treatment methods in many biomass facilities further contributes to these losses. Addressing this efficiency gap is essential not only for improving energy recovery but also for reducing fuel consumption and lowering Levelized Cost of Electricity (LCOE), making biomass a more competitive renewable energy source.

Energy Loss Breakdown

Key energy loss factors quantified in biomass combustion systems included:

Biomass Type	Moisture Loss (%)	Unburned Carbon Loss (%)	Flue Gas Loss (%)
Wood Chips	30	10	8
Rice Husk	25	12	9
Bagasse	28	9	7

Table 3: Breakdown of Energy Losses by Biomass Type

Moisture evaporation consistently represented the highest energy loss across all biomass types.

Biomass	Actual Output (MJ/kg)	Moisture Loss (MJ/kg)	Carbon Loss (MJ/kg)	Flue Gas Loss (MJ/kg)
Wood Chips	4.03	4.655	2.3275	2.3275
Rice Husk	2.9	4.23	2.115	2.115
Bagasse	3.29	4.375	2.1875	2.1875

Table 4: Energy output and loss breakdown for each biomass type.

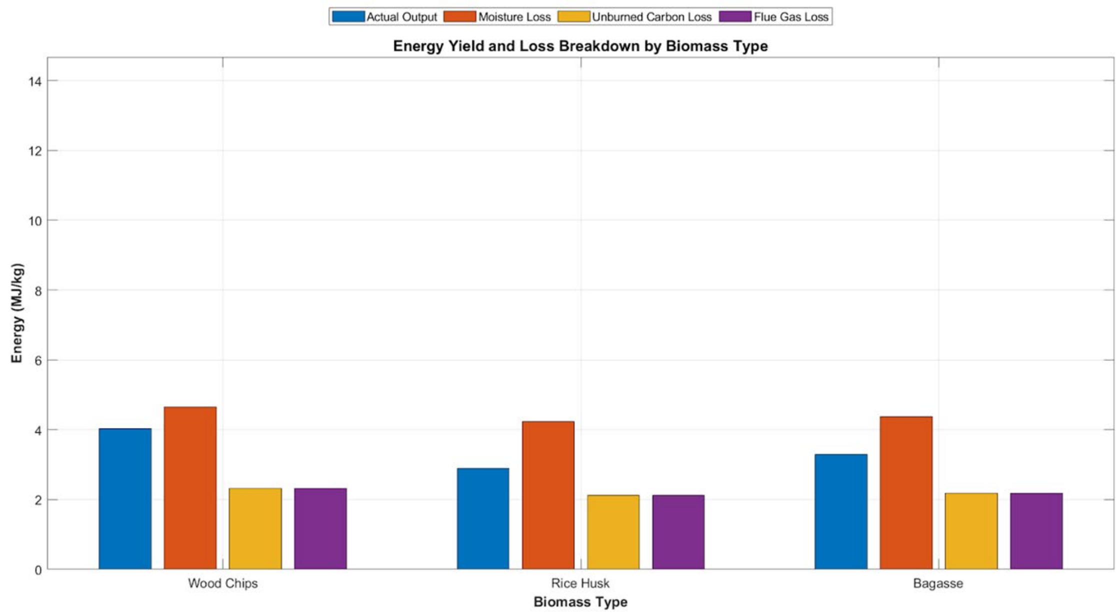

Figure 3: Energy yield and loss breakdown showing actual output and key losses moisture, unburned carbon, and flue gas for each biomass type.

This graph illustrates the **energy yield and loss breakdown** for three biomass types—**Wood Chips, Rice Husk, and Bagasse**. It categorizes the total energy into four components:

- **Actual Output** (blue): The usable energy effectively delivered.
- **Moisture Loss** (orange): Energy lost in evaporating water during combustion.
- **Unburned Carbon Loss** (yellow): Energy retained in unburned particles.
- **Flue Gas Loss** (purple): Heat energy carried away with exhaust gases.

The chart highlights that **moisture loss is the dominant contributor** to energy inefficiency across all feedstocks, followed by flue gas and unburned carbon losses. The insights emphasize the importance of drying and combustion optimization to boost overall efficiency.

Economic Evaluation (LCOE)

The Levelized Cost of Electricity (LCOE) calculations provided a clear economic perspective on biomass utilization:

Biomass Type	LCOE (USD/kWh)
Wood Chips	0.125
Rice Husk	0.100
Bagasse	0.098

Table 5: Levelized Cost of Electricity (LCOE) for Selected Biomass Types

Bagasse emerged as the most economically advantageous biomass fuel due to its lower fuel costs and relatively efficient combustion performance.

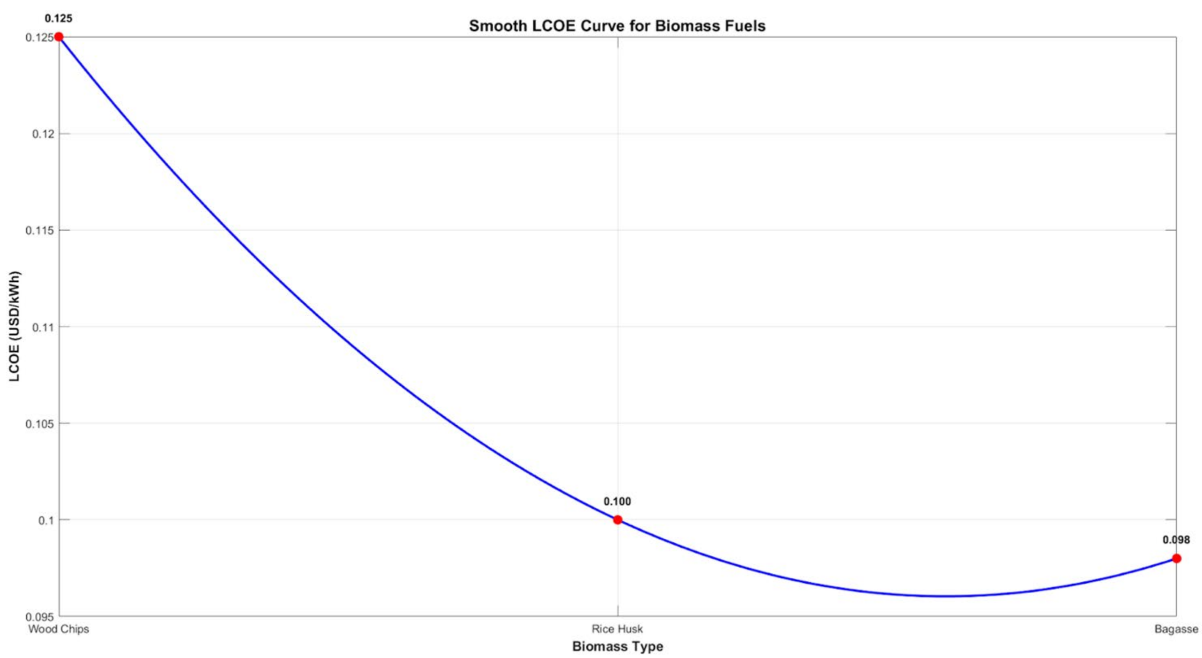

Figure 4: Smooth LCOE curve showing bagasse as the most cost-effective biomass fuel.

This graph illustrates the smooth curve of Levelized Cost of Electricity (LCOE) for three biomass fuels wood chips, rice husk, and bagasse. It shows that bagasse offers the lowest LCOE, making it the most economically efficient option among the three.

Capital Expenditure (CAPEX)

Capital Expenditure (CAPEX) refers to the upfront investment required to build and commission a biomass power plant. It includes costs for plant infrastructure, equipment, installation, and system integration. In this study, CAPEX varies significantly by feedstock type, with wood chips requiring around $5,255/kW and bagasse about $3,280/kW. The lower CAPEX for bagasse-based systems makes them more economically attractive, especially for developing regions aiming for cost-effective renewable energy deployment.

The capital expenditure required for biomass power plants differed significantly by biomass type:

Biomass Type	CAPEX (USD/kW)
Wood Chips	5,255
Bagasse	3,280

Table 6: Capital Expenditure (CAPEX) Estimates for Selected Biomass Fuels

Sensitivity and Optimization Analysis

The sensitivity and optimization analysis in this study highlights the critical role of pre-treatment strategies in enhancing biomass energy efficiency. Among the key findings, reducing feedstock moisture through solar or thermal drying techniques demonstrated the potential to improve thermal efficiency by up to 12%. This directly lowers fuel consumption and increases net energy yield. Additionally, optimizing combustion conditions to minimize unburned carbon and flue gas losses further bridges the gap between theoretical and actual output. These improvements not only enhance energy recovery but also reduce operational costs, making biomass systems more competitive and sustainable in real-world applications.

Discussion

The comparative analysis between theoretical and real-world biomass energy yields revealed substantial efficiency gaps across all three selected feedstocks: wood chips, rice husk, and bagasse. These discrepancies, ranging from 70% to 75% in some cases, are primarily attributed to practical inefficiencies including high moisture content, incomplete combustion, and heat losses through flue gases. Theoretical models, based on stoichiometric combustion calculations, assume ideal conditions that are rarely replicated in operational settings. Moisture loss emerged as the most significant contributor to energy loss, particularly for wood chips, which recorded the highest moisture-related latent heat consumption.

When comparing performance, bagasse demonstrated the best real-world efficiency relative to its theoretical potential. Its lower ash content, better combustion behavior, and established use in cogeneration systems contributed to its superior performance. Rice husk, while abundant and cost-effective, performed the poorest due to its high silica content leading to slagging and unburned carbon loss. Wood chips fell in between, offering stable theoretical values but suffering from high moisture variability and moderate unburned losses.

From an economic standpoint, bagasse also emerged as the most cost-effective option, yielding the lowest Levelized Cost of Electricity (LCOE) among the three fuels. Its low procurement cost (often treated as a waste byproduct), combined with favorable combustion efficiency and relatively low capital expenditure (CAPEX), makes it highly attractive for biomass power generation. In contrast, wood chips required higher CAPEX, while rice husk posed technical challenges that could increase operational expenditure (OPEX).

The sensitivity analysis reinforced the importance of moisture control, showing that drying biomass feedstock could improve thermal efficiency by up to 12%. This aligns with literature from Islam et al. (2002)[10], who reported a 10–15% increase in efficiency with pre-treatment methods. Bridgwater (2012)[2] also emphasized the role of feedstock conditioning in bridging theoretical and practical efficiency gaps, which our findings support.

Moreover, our results correlate well with IRENA and NREL studies, which indicate real-world biomass system efficiencies generally ranging from 20% to 35%, depending on technology and feedstock. Basu (2010)[6], [7] similarly highlighted the superiority of bagasse in CHP systems, citing its dual-use potential and low fuel cost. The observed inefficiencies in rice husk combustion due to high ash and silica content were consistent with findings by Jenkins et al. (1998)[3].

Overall, the study not only quantifies the performance gap but also reinforces the importance of fuel selection, system design, and pre-treatment strategies. These insights contribute to developing more realistic and economically viable biomass energy systems, especially in regions with abundant agricultural residues.

Real-Life Applications

The findings from this project have significant real-world relevance, particularly in advancing sustainable biomass energy systems across various sectors and geographies.

Biomass Power Plants

Biomass combustion systems are already in operation for rural electrification and industrial power supply. The project's identification of energy efficiency gaps and feedstock-specific performance can help improve the operational strategies of these plants. For example, selecting bagasse over rice husk in suitable regions could reduce costs and enhance energy output.

Agricultural Waste-to-Energy Systems

In countries like India and Brazil, rice husk and bagasse are abundant agricultural residues. The study's insights on combustion inefficiencies and moisture-related losses underscore the importance of pre-treatment (like drying) and feedstock selection in such decentralized waste-to-energy systems.

Combined Heat and Power (CHP) Systems

CHP applications in industries such as sugar mills (using bagasse) and paper mills (using wood residues) benefit significantly from biomass. Our results support the use of high-efficiency, low-LCOE fuels like bagasse in CHP systems, offering both thermal and electrical output.

Municipal Solid Waste (MSW) Integration

Although not the core focus, the project's framework can be extended to urban biomass combustion and MSW-to-energy systems. The analytical methodology used can help assess real vs. theoretical yields for waste streams like food or green waste.

District Heating in Cold Climates

In colder regions, biomass fuels like wood chips are already used in district heating. This study's comparison of LHV and real output helps evaluate which biomass types offer optimal thermal return under real-world constraints.

Decentralized Microgrids

The insights from this study can guide the design of biomass-fueled microgrids in rural or off-grid areas. Fuel selection based on LCOE, and combustion performance ensures cost-effective, reliable energy access.

Conclusion

This project provides a comprehensive comparative analysis of theoretical and real-world energy yields for key biomass feedstocks: wood chips, rice husk, and bagasse. By applying stoichiometric combustion principles and integrating real plant performance data, the study quantifies efficiency gaps and identifies critical loss factors including moisture evaporation, unburned carbon, and flue gas losses. The results reveal that while theoretical Higher Heating Values (HHV) suggest high energy potential, actual usable energy (as represented by real-world efficiency and Lower Heating Values) is significantly lower—often by 70% or more.

Among the feedstocks studied, bagasse consistently demonstrated superior performance in both efficiency and economic metrics. It recorded the lowest Levelized Cost of Electricity (LCOE) and required comparatively lower capital expenditure (CAPEX), reinforcing its suitability for cost-effective biomass energy systems. Conversely, rice husk, despite its abundance, showed the lowest combustion efficiency due to high silica and ash content.

The sensitivity analysis further emphasized the importance of pre-treatment methods, such as drying, in enhancing thermal efficiency by up to 12%. These insights align with existing literature and underscore the practical value of optimization strategies in bridging the gap between theoretical and actual biomass energy yields.

Ultimately, this study supports informed decision-making for biomass feedstock selection, plant design, and operational planning. It contributes to the broader goal of improving the performance and viability of renewable energy systems, especially in regions reliant on agricultural waste. With better understanding and implementation of fuel-specific strategies, biomass can serve as a cleaner, more efficient, and economically viable component of the global energy mix.

Future Scope

While this project offers valuable insights into the theoretical and actual performance of biomass fuels, there are several directions for expanding and enhancing the study:

1. Integration of Advanced Combustion Technologies

Future research can explore the use of fluidized bed combustors, gasifiers, and AI-driven combustion control systems to minimize losses due to incomplete combustion and improve system efficiency.

2. Real-Time Monitoring and Automation

Incorporating real-time sensors to monitor moisture content, flue gas composition, and temperature can enable adaptive control strategies that optimize combustion in real-world settings.

3. Expanded Feedstock Range

Including additional feedstocks such as microalgae, switchgrass, and municipal solid waste (MSW) in future studies would provide a broader understanding of biomass potential across regions and applications.

4. Regional Case Studies and Feasibility Assessments

Future work should include region-specific case studies to assess biomass availability, transportation logistics, and local policy impacts on system design and fuel choice.

5. Renewable Hybrid Systems

Combining biomass with other renewable sources like solar or wind in hybrid energy systems can enhance grid stability and ensure continuous power supply in off-grid areas.

6. Biochar and Carbon Sequestration

Exploring biochar production as a co-product of biomass combustion or pyrolysis can open pathways for carbon sequestration and soil improvement, offering additional environmental and economic benefits.

7. Lifecycle and Environmental Impact Analysis

Comprehensive lifecycle assessments (LCA) of biomass energy systems can help quantify environmental trade-offs and guide sustainable system design.

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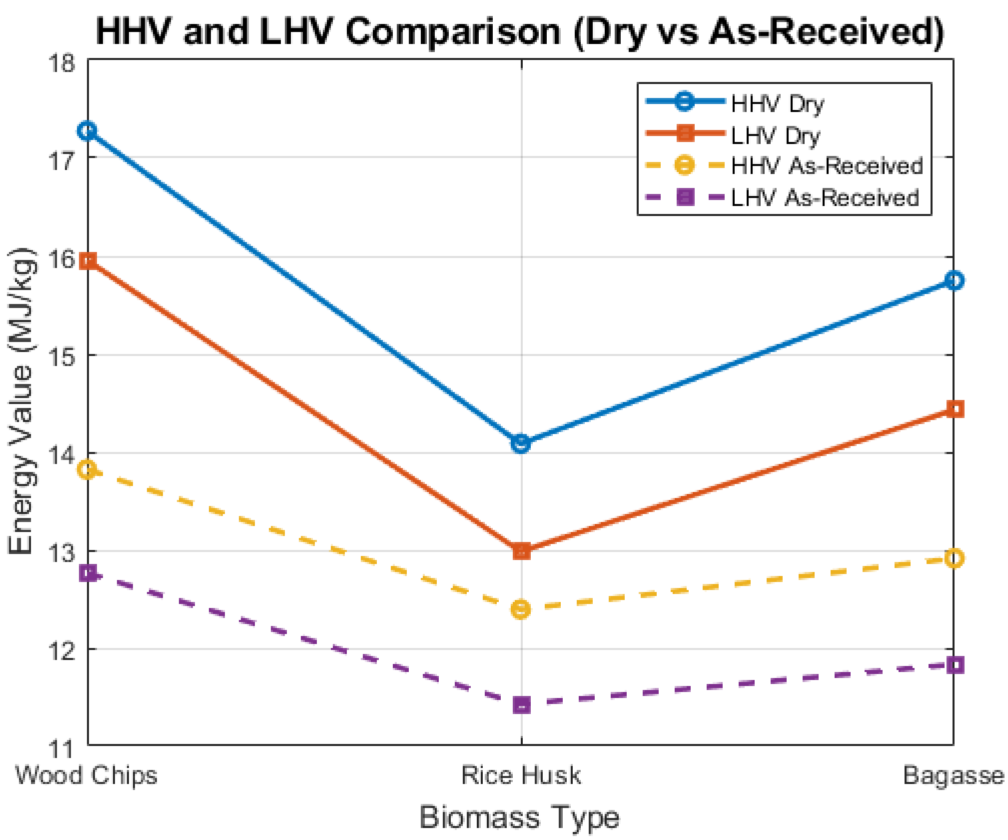
Appendix

All calculations and simulations related to stoichiometric energy estimation, efficiency analysis, energy loss breakdown, and Levelized Cost of Electricity (LCOE) were performed using MATLAB. The complete set of MATLAB scripts used in this project is provided in the appendix below for reference and reproducibility.

```
% Biomass types and their ultimate analysis (dry basis)
biomass = {'Wood Chips', 'Rice Husk', 'Bagasse'};

% Elemental composition: [C, H, O, N, S, Moisture] in %
data = [49, 6, 44, 0.1, 0.01, 20;
        39, 5, 35, 0.4, 0.1, 12;
        45, 6, 45, 0.3, 0.05, 18];

HHV_dry = zeros(1,3);
LHV_dry = zeros(1,3);
HHV_ar = zeros(1,3);
LHV_ar = zeros(1,3);

fprintf('Stoichiometric Energy Estimation (As-Received)\n');
fprintf('---------------------------------------------------\n');
fprintf('%-12s | HHV_dry | LHV_dry | HHV_ar | LHV_ar\n', 'Biomass');

for i = 1:length(biomass)
    C = data(i,1);
    H = data(i,2);
    O = data(i,3);
    S = data(i,5);
    Moisture = data(i,6);

    % HHV (dry)
    HHV = 0.338*C + 1.428*(H - O/8) + 0.095*S;

    % LHV (dry)
    LHV = HHV - 2.443 * 9 * (H/100);

    % Moisture adjustment
    HHV_m = HHV * (1 - Moisture/100);
    LHV_m = LHV * (1 - Moisture/100);

    HHV_dry(i) = HHV;
    LHV_dry(i) = LHV;
    HHV_ar(i) = HHV_m;
    LHV_ar(i) = LHV_m;

    fprintf('%-12s | %7.2f | %7.2f | %7.2f | %7.2f\n', biomass{i}, HHV, LHV,
HHV_m, LHV_m);
end

% Plotting line graph
x = 1:3;

figure;
plot(x, HHV_dry, '-o', 'LineWidth', 2);
hold on;
plot(x, LHV_dry, '-s', 'LineWidth', 2);
plot(x, HHV_ar, '--o', 'LineWidth', 2);
plot(x, LHV_ar, '--s', 'LineWidth', 2);
```

```
hold off;

xticks(x);
xticklabels(biomass);
xlabel('Biomass Type', 'FontSize', 12);
ylabel('Energy Value (MJ/kg)', 'FontSize', 12);
title('HHV and LHV Comparison (Dry vs As-Received)', 'FontSize', 14);
legend({'HHV Dry', 'LHV Dry', 'HHV As-Received', 'LHV As-Received'},
'Location', 'northeast');
grid on;
```

```
Stoichiometric Energy Estimation (As-Received)
--------------------------------------------------
Biomass        | HHV_dry | LHV_dry | HHV_ar | LHV_ar
Wood Chips     |   17.28 |   15.96 |   13.82 |   12.77
Rice Husk      |   14.08 |   12.98 |   12.39 |   11.43
Bagasse        |   15.75 |   14.43 |   12.92 |   11.83
```



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```
% Biomass names
biomass = {'Wood Chips', 'Rice Husk', 'Bagasse'};

% Elemental composition (%) - on dry basis
% Columns: [C, H, O, N, S]
data = [49.0, 6.0, 44.0, 0.10, 0.01;
        39.0, 5.0, 35.0, 0.40, 0.10;
        45.0, 6.0, 45.0, 0.30, 0.05];

% Preallocate
O2_required = zeros(1, 3);
Air_required = zeros(1, 3);

fprintf('Stoichiometric Combustion Analysis (Per kg of Dry Biomass)\n');
fprintf('----------------------------------------------------------\n');
fprintf('%-12s | O2 Required (kg) | Air Required (kg)\n', 'Biomass');

for i = 1:3
    C = data(i,1);
    H = data(i,2);
    O = data(i,3);
    S = data(i,5);

    % Convert % to mass fraction
    C_frac = C / 100;
    H_frac = H / 100;
    O_frac = O / 100;
    S_frac = S / 100;

    % Oxygen required per kg fuel (from stoichiometry)
    O2 = 32 * (C_frac / 12 + H_frac / 4 - O_frac / 32 + S_frac / 32);

    % Theoretical air required per kg fuel
    Air = O2 / 0.23;

    O2_required(i) = O2;
    Air_required(i) = Air;

    fprintf('%-12s | %16.3f | %17.3f\n', biomass{i}, O2, Air);
end
```

```
Stoichiometric Combustion Analysis (Per kg of Dry Biomass)
----------------------------------------------------------
Biomass      | O2 Required (kg) | Air Required (kg)
Wood Chips   |            1.347 |             5.856
Rice Husk    |            1.091 |             4.743
Bagasse      |            1.230 |             5.350
```

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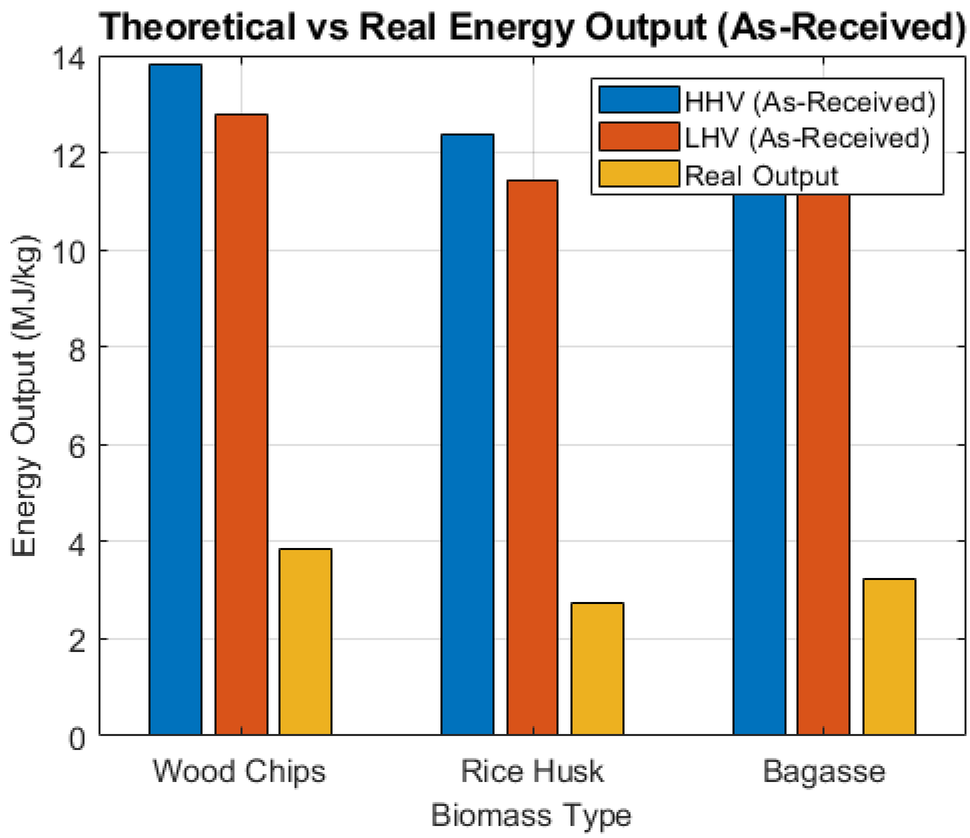
```matlab
% Biomass types
biomass = {'Wood Chips', 'Rice Husk', 'Bagasse'};

% Theoretical values (as-received) from your first code
HHV_ar = [13.82, 12.39, 12.92];  % MJ/kg
LHV_ar = [12.77, 11.43, 11.83];  % MJ/kg

% Real-world efficiencies (as decimal)
efficiency = [0.28, 0.22, 0.25];

% Real output = HHV_ar * efficiency
Real_output = HHV_ar .* efficiency;

% Combine all data for bar plot
data_matrix = [HHV_ar; LHV_ar; Real_output]';

% Plotting
figure;
bar(data_matrix);
set(gca, 'XTickLabel', biomass, 'FontSize', 12);
xlabel('Biomass Type', 'FontSize', 12);
ylabel('Energy Output (MJ/kg)', 'FontSize', 12);
title('Theoretical vs Real Energy Output (As-Received)', 'FontSize', 14);
legend({'HHV (As-Received)', 'LHV (As-Received)', 'Real Output'},
'Location', 'northeast');
grid on;
```



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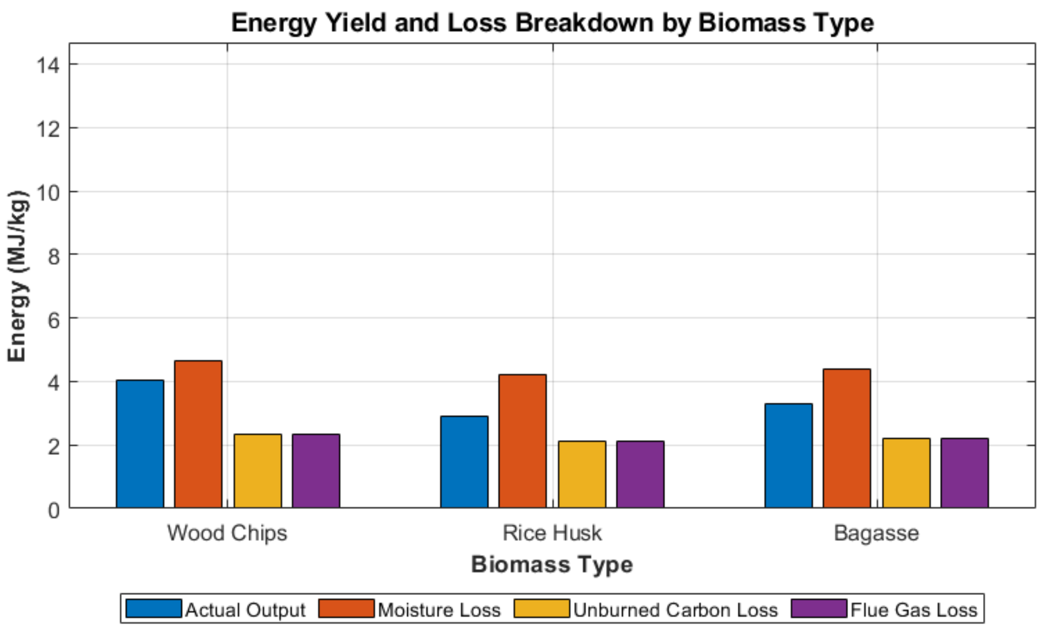
```
% === 1. Input Data ===
biomass = {'Wood Chips', 'Rice Husk', 'Bagasse'};

% Theoretical Net Energy (LHV as-received) in MJ/kg
LHV_ar = [13.34, 11.36, 12.04];

% Actual energy output based on real-world efficiency (MJ/kg)
Real_output = [4.03, 2.90, 3.29];

% Total energy loss
Total_loss = LHV_ar - Real_output;

% Loss breakdown percentages
moisture_pct = 0.50;
carbon_pct = 0.25;
fluegas_pct = 0.25;

% Losses in MJ/kg
Moisture_loss = Total_loss * moisture_pct;
Carbon_loss = Total_loss * carbon_pct;
Fluegas_loss = Total_loss * fluegas_pct;

% === 2. Combine all into a matrix: each row = [Real, Moisture, Carbon, Flue
Gas]
energy_components = [Real_output', Moisture_loss', Carbon_loss',
Fluegas_loss'];

% === 3. Create grouped bar plot ===
figure('Color','w','Position',[100 100 900 500]); % Wider figure to fit
legend
bar(energy_components, 'grouped');
set(gca, 'XTickLabel', biomass, 'FontSize', 12);

ylabel('Energy (MJ/kg)', 'FontSize', 13, 'FontWeight', 'bold');
xlabel('Biomass Type', 'FontSize', 13, 'FontWeight', 'bold');
title('Energy Yield and Loss Breakdown by Biomass Type', 'FontSize', 14,
'FontWeight', 'bold');

legend({'Actual Output', 'Moisture Loss', 'Unburned Carbon Loss', 'Flue Gas
Loss'}, ...
    'Location', 'southoutside', 'Orientation', 'horizontal');

grid on;
ylim([0, max(LHV_ar)*1.1]);
box on;

% === 4. Display data as table ===
T = table(biomass', Real_output', Moisture_loss', Carbon_loss',
Fluegas_loss', ...
    'VariableNames', {'Biomass', 'ActualOutput_MJkg', 'MoistureLoss_MJkg',
'CarbonLoss_MJkg', 'FlueGasLoss_MJkg'});
disp(T);
```

```
       Biomass          ActualOutput_MJkg    MoistureLoss_MJkg
CarbonLoss_MJkg     FlueGasLoss_MJkg
    _______________    __________________    __________________
________________    _________________

    {'Wood Chips'}            4.03                  4.655
2.3275              2.3275
    {'Rice Husk' }             2.9                   4.23
2.115               2.115
    {'Bagasse'   }            3.29                  4.375
2.1875              2.1875
```



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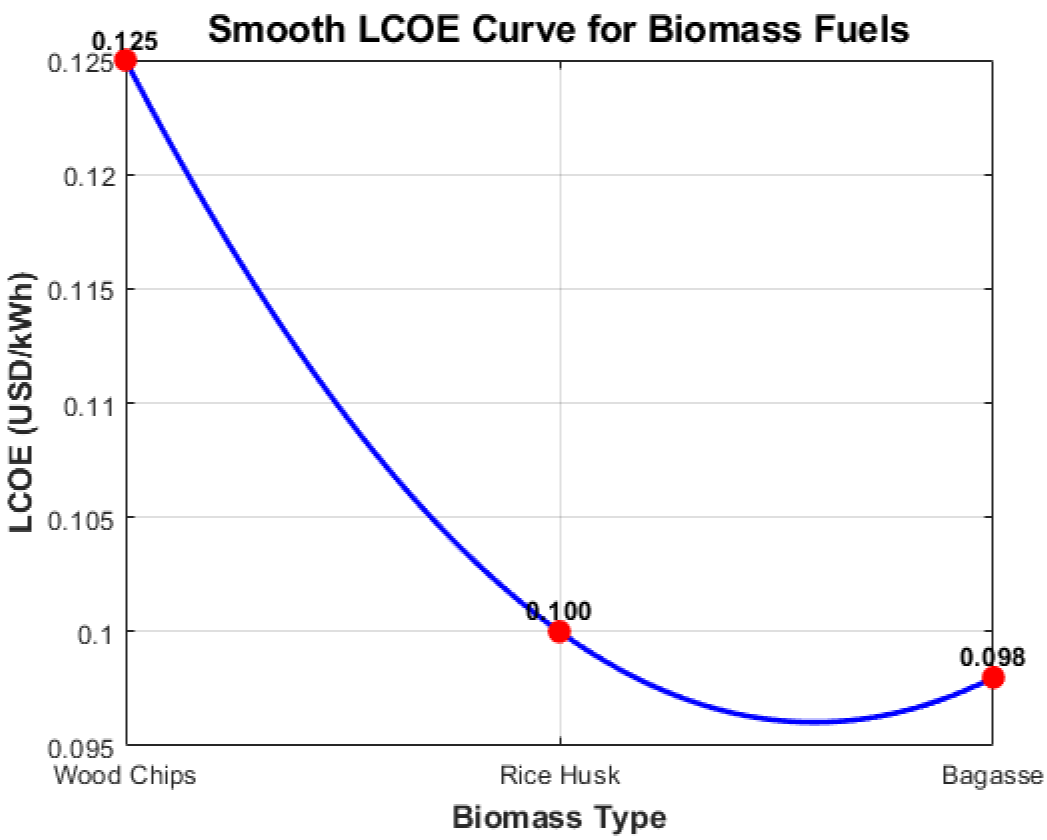
```
% Biomass types
biomass = {'Wood Chips', 'Rice Husk', 'Bagasse'}';
x = 1:length(biomass);

% LCOE values in USD/kWh
LCOE = [0.125, 0.100, 0.098]';

% Create and display summary table
LCOE_Table = table(biomass, LCOE, 'VariableNames', {'Biomass',
'LCOE_USD_per_kWh'});
disp('LCOE Summary Table for Biomass Fuels:');
disp(LCOE_Table);

% Create finer x-points for smooth curve
xq = linspace(1, 3, 100);  % 100 smooth points between biomass types
LCOE_smooth = spline(1:3, LCOE', xq);  % Cubic spline interpolation

% Plotting
figure('Color', 'w');
plot(xq, LCOE_smooth, 'b-', 'LineWidth', 2);  % Smooth spline curve
hold on;
plot(x, LCOE, 'ro', 'MarkerSize', 8, 'MarkerFaceColor', 'r');  % Original
data points
text(x, LCOE + 0.001, compose('%.3f', LCOE), 'HorizontalAlignment',
'center', 'FontWeight', 'bold');

xticks(x);
xticklabels(biomass);
ylabel('LCOE (USD/kWh)', 'FontSize', 12, 'FontWeight', 'bold');
xlabel('Biomass Type', 'FontSize', 12, 'FontWeight', 'bold');
title('Smooth LCOE Curve for Biomass Fuels', 'FontSize', 14, 'FontWeight',
'bold');
grid on;
box on;
```

```
LCOE Summary Table for Biomass Fuels:
       Biomass        LCOE_USD_per_kWh
    ______________    ________________

    {'Wood Chips'}         0.125
    {'Rice Husk' }           0.1
    {'Bagasse'   }         0.098
```



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