Technological advancements in biomass conversion systems and bioenergy for circular economy roadmap

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Introduction to Gasification

What is Gasification?

Gasification is a thermochemical process that converts carbon-containing materials into synthesis gas (syngas) through partial oxidation under controlled conditions.

Versatile Feedstock

Processes coal, biomass, municipal solid waste, and industrial residues, offering flexibility in resource utilization.

Multiple Products

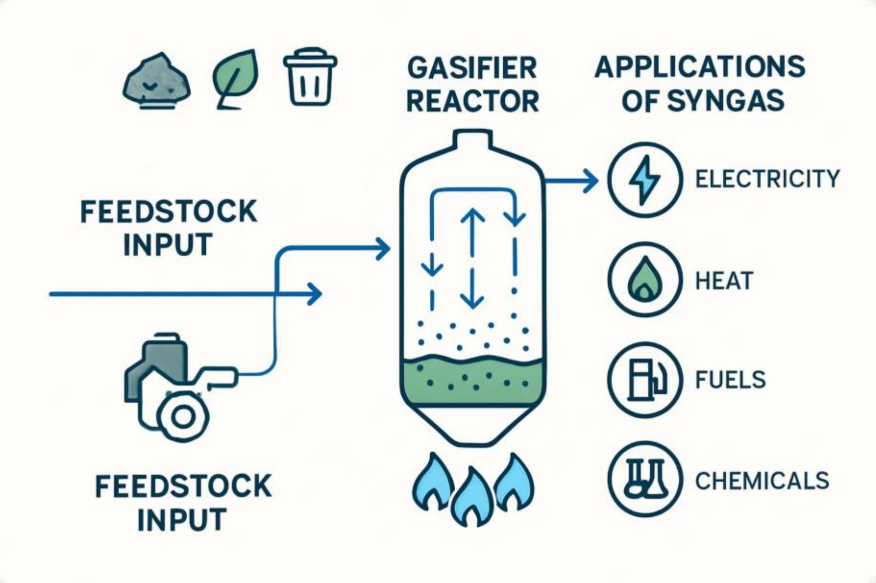
Produces syngas (H_2, CO, CH_4), which can be used for electricity, heat, fuels, and chemicals production.

Environmental Benefits

Enables cleaner energy production compared to direct combustion, with potential for carbon capture integration.

Technological Maturity

Ranges from established industrial applications to emerging advanced systems with enhanced efficiency and reduced emissions.



Research Focus:
Current research by Tarelho, Chavando, Silva, and Cardoso focuses on optimizing gasification processes through feedstock blending, catalyst development, and system integration to enhance efficiency and reduce environmental impact.

Gasification vs. Combustion vs. Pyrolysis

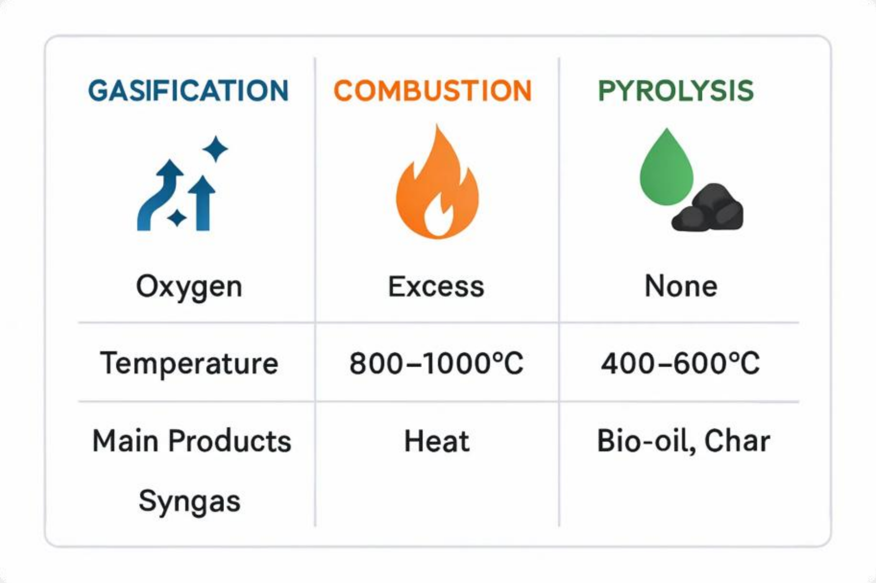
Key Differences:

Gasification aims to convert carbon-based materials into syngas

Combustion maximizes heat release through complete oxidation

Pyrolysis focuses on thermal decomposition without oxygen

Energy content: Pyrolysis < Gasification < Combustion



Gasification

Partial oxidation (limited oxygen)

700-900°C

Main product: Syngas

Combustion

Complete oxidation (excess oxygen)

800-1000°C

Main product: Heat

Pyrolysis

No oxygen

400-600°C

Main products: Bio-oil, Char

General Strategies for Process Optimization

Optimization strategies for thermochemical conversion processes (gasification, pyrolysis, and combustion) focus on enhancing efficiency, reducing emissions, and improving economic viability.

Feedstock Engineering

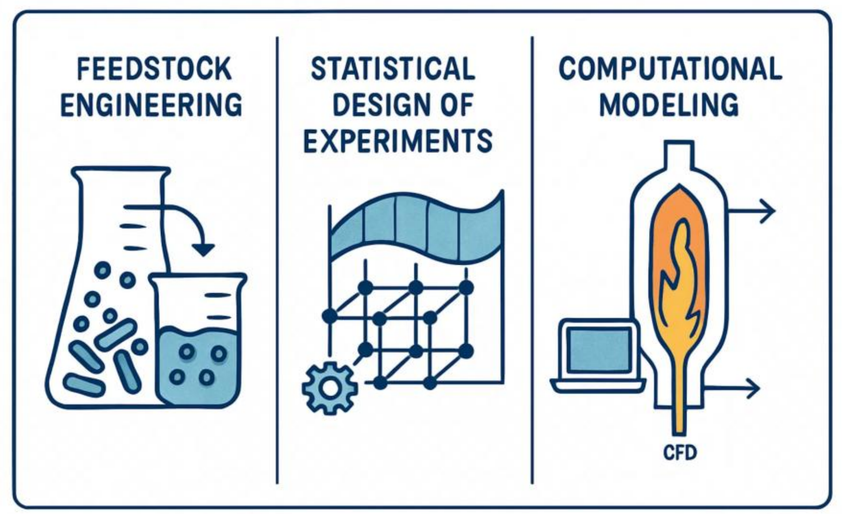
Blending different materials (coal, biomass, RDF, ammonia) to achieve synergistic effects, improve reactivity, and reduce emissions while maintaining energy content.

Statistical Design of Experiments

Systematic approach to identify optimal operating conditions and understand interactions between process variables, particularly valuable for complex fuel mixtures.

Computational Modeling

CFD and kinetic modeling to predict process behavior, optimize reactor design, and scale up from laboratory to industrial applications.



Images from Our Laboratory

Pyrolysis

Gasification and Combustion

Ammonia-Coal Co-Firing Optimization in Fluidized Bed Reactors

Objective & Methodology

Optimize ammonia (NH_3) and coal co-firing in fluidized bed reactors.

3k factorial design (9 simulations)

Input: air staging, NH_3 co-firing ratio

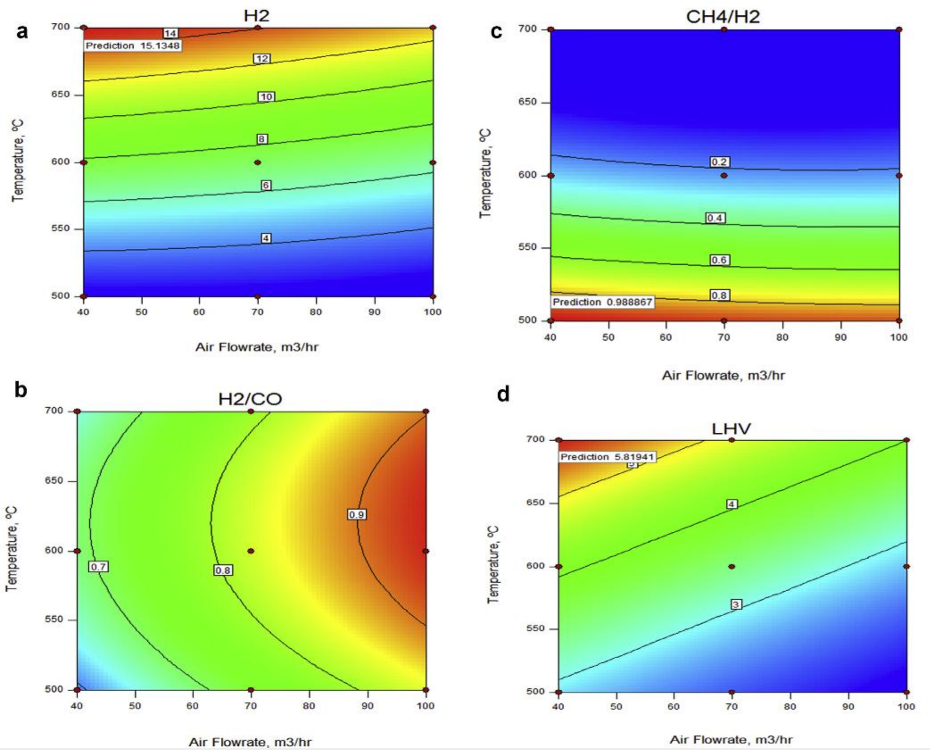
Response: NO, NH_3, CO_2 emissions

Key Findings

Optimal conditions: High air staging (~40%) and balanced NH_3 co-firing ratio (~20%)

Practical impact: Valuable insights for decarbonization in energy production

DoE effectiveness: Successfully determined optimal operating conditions while minimizing emissions



Pyrolysis and Gasification of RDF and Biomass Blends

Antonio Chavando & Valter Silva, University of Aveiro

Co-pyrolysis of RDF with biomass (75:25) increases product LHVs

Optimal temperature 500 °C maximizes liquid LHV quality while minimizing Solid formation because of ashes

Novel catalysts reduce chlorine-related corrosion issues in RDF gasification

Mayoral Chavando, J.A., et al. (2021). International Journal of Hydrogen Energy, 46(38)

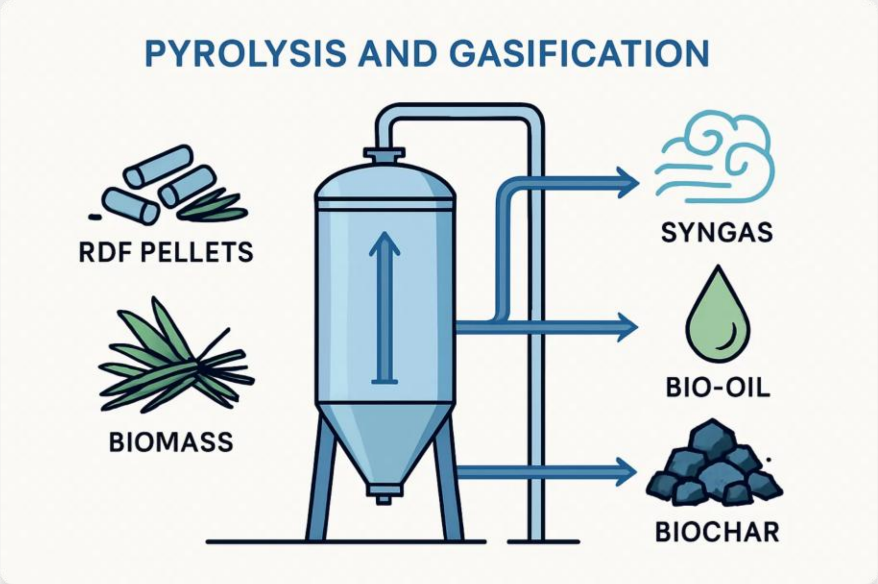
Daniel Pio & Luis Tarelho CESAM Research

Co-gasification of RDF with biomass (80:20) increases methane an ethylene concentrations.

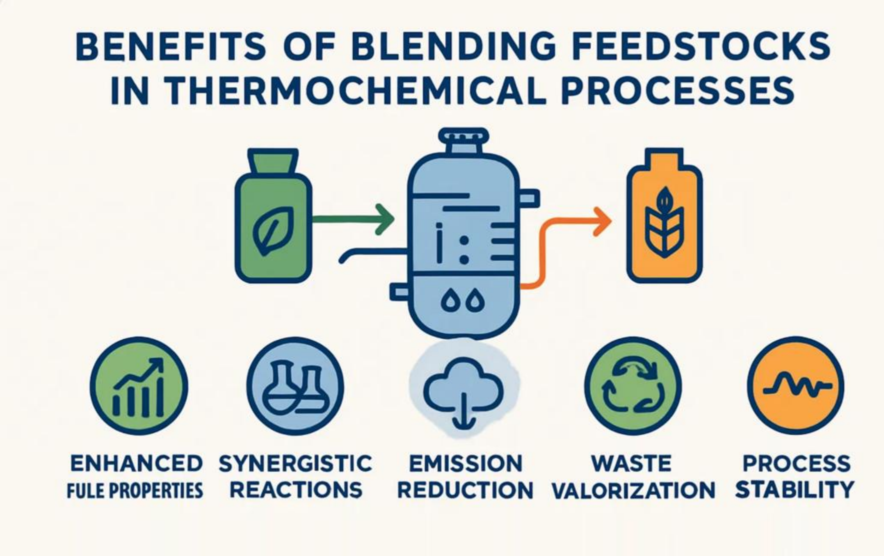
Lower ER (0.21 -0.22) enhance LHV of the syngas

Process integration enables continuous operation with heterogeneous feedstocks

Daniel Pio et al. (2020). Energy conversion and management , 206



Blending Benefits in Combustion, Pyrolysis and Gasification



Enhanced Fuel Properties

Creates more homogeneous fuel mixtures with improved calorific value, reduced moisture content, and optimized ash characteristics.

Synergistic Reactions

Co-processing induces reactions that promote more complete conversion, reduce tar formation, and improve product quality.

Emission Reduction

Strategic blending with NH3 significantly reduces pollutants such as CO2, and particulate matter by leveraging chemical properties of different feedstocks.

Process Stability & Flexibility

Improves stability by mitigating issues with single-feedstock variations and offers greater flexibility in feedstock supply.

Source: Silva, V. B., Cardoso, J., & Chavando, A. (2023). Gasification: Sustainable Decarbonization. De Gruyter.

Design of Experiments: Methodology

DoE methodologies are essential for optimizing the co-combustion and co-gasification of complex fuel mixtures, particularly those involving multiple components such as coal, biomass, RDF, and ammonia.

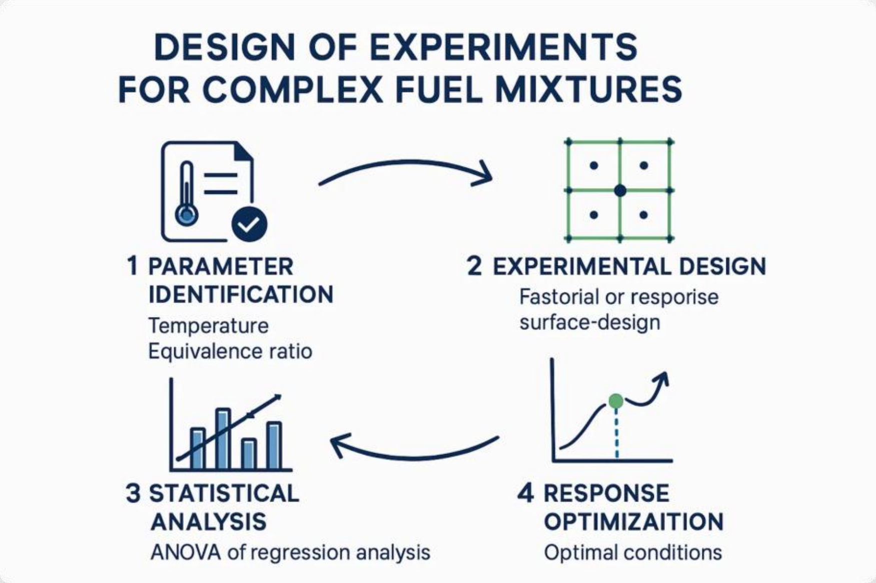
DoE for Complex Fuel Mixtures

1 Parameter Identification: Identify key process variables (temperature, equivalence ratio, blend ratios, residence time) and response variables (efficiency, emissions, syngas composition).

2 Experimental Design: Apply factorial or response surface designs to minimize experimental runs while maximizing information about parameter interactions.

3 Statistical Analysis: Use ANOVA and regression analysis to identify significant factors and develop predictive models for process optimization.

4 Response Optimization: Apply numerical optimization techniques to identify optimal operating conditions for desired performance metrics.



Research Application:
Studies by Silva, Cardoso and Chavando apply DoE methodologies to optimize the co-combustion and co-gasification of complex fuel mixtures, enabling the identification of synergistic effects between different feedstocks and process conditions that would be difficult to discover through conventional one-factor-at-a-time experimentation.

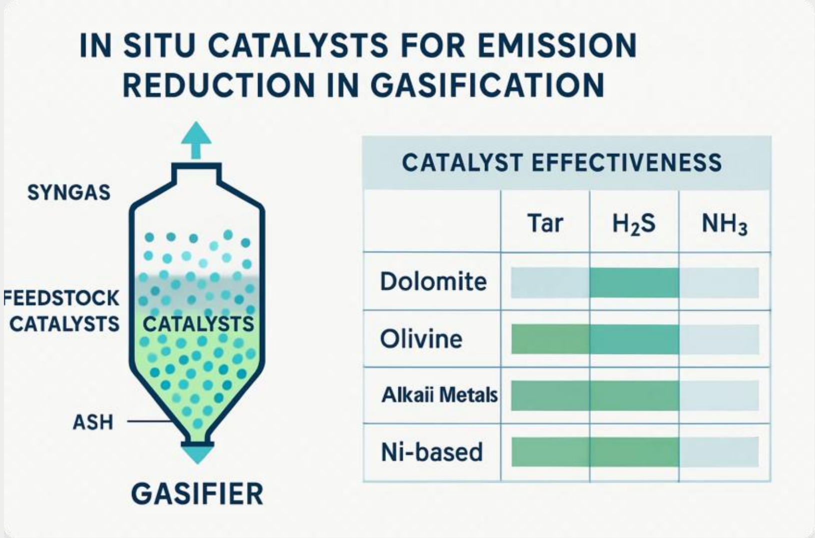
In Situ Catalysts for Emission Reduction

In Situ Catalyst Approach

In situ catalysts are mixed directly with the feedstock or introduced into the gasifier, allowing catalytic reactions to occur simultaneously with the main gasification process.

Catalyst Type & Effectiveness

Catalyst Type	Target Emissions	Effectiveness
Dolomite ($CaMg(CO_3)_2$)	Tars, Particulates	Medium
Olivine ($(Mg,Fe)_2SiO_4$)	Tars, H_2S	Medium-High
Alkali Metals (K, Na)	Char Gasification, Tars	High
Ni-based Catalysts	Tars, CH_4, NH_3	Very High



Key Advantages

Direct influence on primary reactions and product distribution

Reduction of tar formation at the source

Enhanced carbon conversion efficiency

Promotion of water-gas shift reaction for H_2-rich syngas

Lower energy requirements for downstream cleaning

Combined Systems for Emission Reduction

Integrated Gasification Combined Cycle (IGCC)

Combines gasification with gas and steam turbines for electricity generation. Syngas is cleaned before combustion, allowing for pre-combustion capture of pollutants and higher efficiency than conventional coal plants.

Dual Fluidized Bed Systems

Separates gasification and combustion into two interconnected reactors. Combustion provides heat for gasification while keeping gas streams separate, resulting in nitrogen-free syngas and reduced emissions.

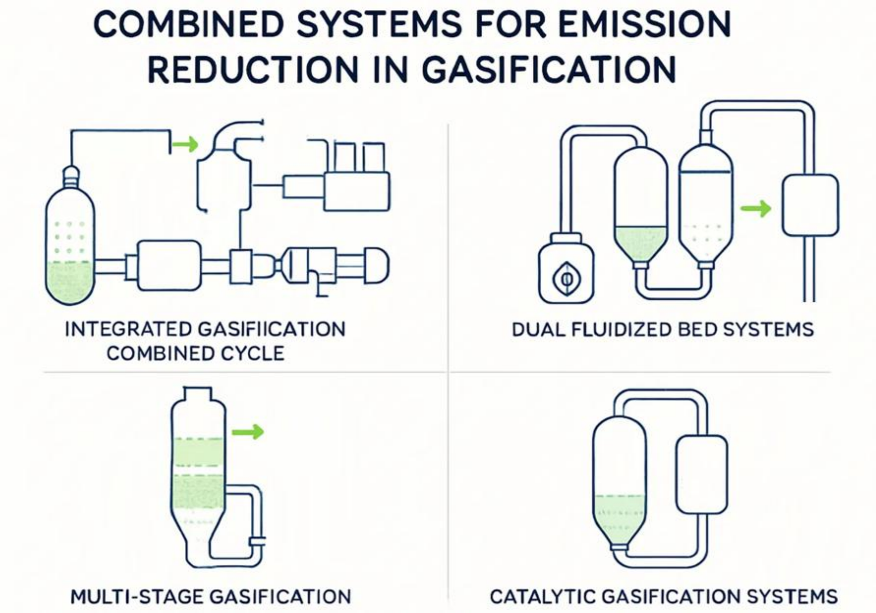
Multi-stage Gasification

Uses sequential reactors with different conditions to optimize each stage of the gasification process. Allows for targeted emission control strategies at each stage, improving overall efficiency and reducing pollutants.

Key Benefit:
Combined systems leverage synergies between different technologies to achieve emission reductions while maintaining or improving energy efficiency and economic performance.

Catalytic Gasification Systems

Integrates catalysts directly into the gasification process or in secondary reactors. Combines benefits of in situ and ex situ approaches for enhanced syngas quality and reduced emissions.



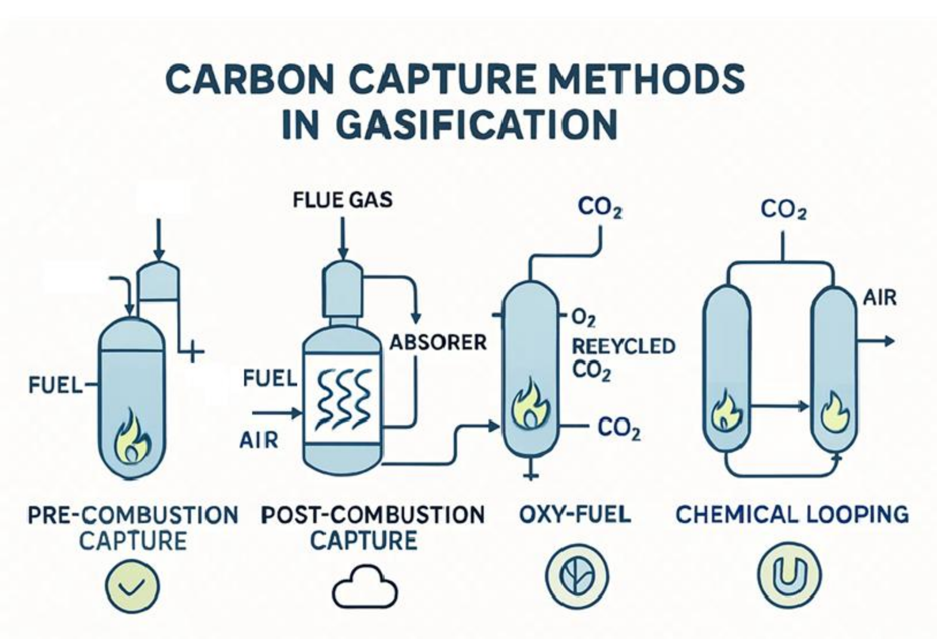
Integration with Carbon Capture

Carbon Capture Methods in Gasification

Capture Method	Integration Point	Advantages
Pre-combustion	After gasification, before syngas combustion	Higher CO_2 concentration, lower energy penalty
Post-combustion	After syngas combustion	Retrofit capability, mature technology
Oxy-fuel	During gasification process	High purity CO_2 stream, reduced NO_x
Chemical Looping	Integrated with gasification	Inherent CO_2 separation, lower energy penalty

Synergistic Benefits:

Gasification offers unique advantages for carbon capture compared to conventional combustion, particularly through pre-combustion capture where CO_2 can be removed from syngas at higher concentrations and pressures, reducing the energy penalty associated with capture.



Numerical Optimization: CFD

CFD in Gasification

Computational Fluid Dynamics (CFD) enables detailed modeling of complex fluid flow, heat transfer, and chemical reactions within gasifiers, providing insights that would be difficult or impossible to obtain experimentally.

Key Applications

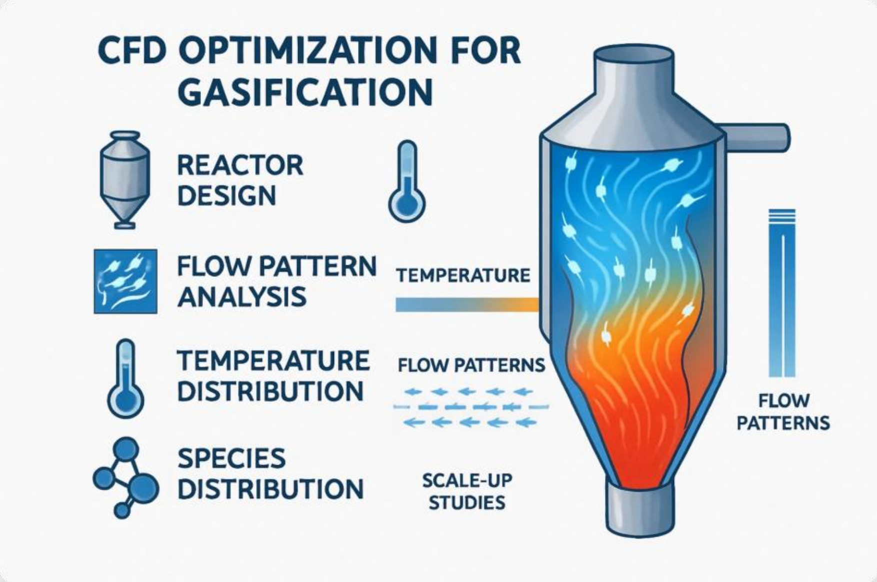
Reactor Design: Optimize geometry, injection points, and internal features

Flow Pattern Analysis: Identify dead zones, recirculation regions, and optimize residence time distribution

Temperature Distribution: Predict hot spots and thermal gradients

Species Distribution: Track formation and consumption of reactants, products, and pollutants

Scale-up Studies: Reduce risks when transitioning from laboratory to commercial scale



Challenges in CFD Modeling:
Accurate CFD modeling of gasification requires addressing multiphase flows, turbulence-chemistry interactions, particle-fluid coupling, and computational resource limitations. Validation with experimental data remains essential for reliable predictions.

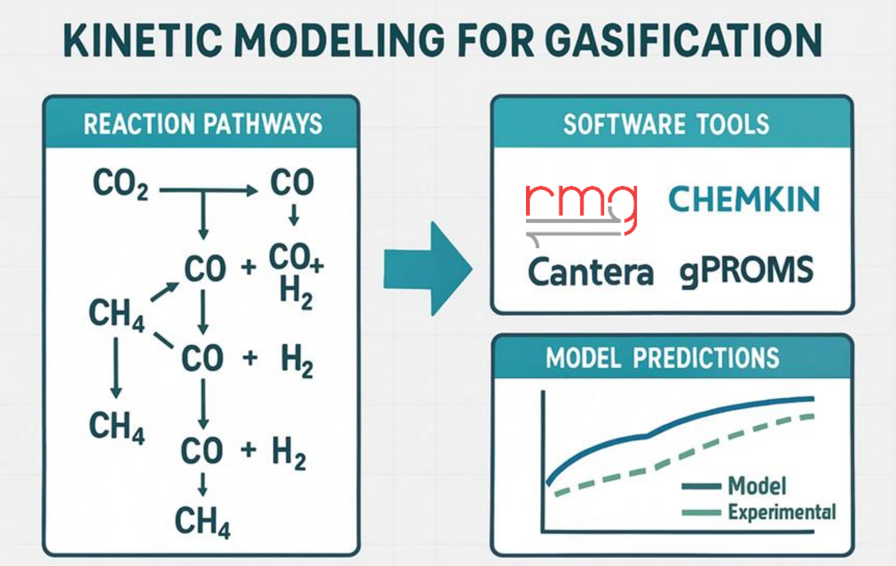
Numerical Optimization: Kinetic Modeling

Kinetic Modeling Approach

Kinetic modeling focuses on the rates of chemical reactions occurring during gasification, providing insights into reaction pathways, intermediate species formation, and product distribution under various conditions.

Software Specialization

Software	Key Features
RMG	It is an automatic chemical reaction mechanism generator that constructs kinetic models composed of elementary chemical reaction.
CHEMKIN	Detailed chemistry, Extensive reaction mechanisms, sensitivity analysis
Cantera	Open-source chemistry, Python/MATLAB integration, thermodynamic analysis
gPROMS	Custom modeling, Dynamic simulation, parameter estimation



Integration with CFD:

Modern approaches combine kinetic models with CFD to create comprehensive simulations that account for both reaction kinetics and transport phenomena, providing more accurate predictions of gasifier performance.

Gas Cleaning: Technologies

Syngas Contaminants

Raw syngas contains contaminants that must be removed for downstream applications, preventing equipment damage, catalyst poisoning, and environmental emissions.

Contaminant & Removal Technologies

Contaminant	Primary Removal Technologies	Target Level
Particulates	Cyclones, filters, electrostatic precipitators	< 1 mg/Nm³
Tars	Thermal cracking, catalytic reforming, scrubbing	< 100 mg/Nm³
Sulfur compounds (H_2S, COS)	Absorption (amine, ZnO), adsorption	< 1 ppmv
Nitrogen compounds (NH_3, HCN)	Wet scrubbing, catalytic decomposition	< 10 ppmv
Halogens (HCl, HF)	Alkaline scrubbing, solid sorbents	< 1 ppmv
Alkali metals (Na, K)	Cooling, barrier filters, getters	< 0.1 ppmv

Cleaning Strategy:
Multi-stage approach with hot gas cleaning for primary contaminants followed by cold gas cleaning for final polishing, balancing efficiency with energy conservation.

Gas Cleaning: Challenges and Solutions

Temperature Trade-offs

Challenge:
Hot gas cleaning preserves thermal efficiency but has limited contaminant removal; cold cleaning is effective but causes energy losses.

Solution:
Staged temperature approach with warm gas cleaning (300-500°C) technologies like ceramic filters and regenerable sorbents.

Tar Management

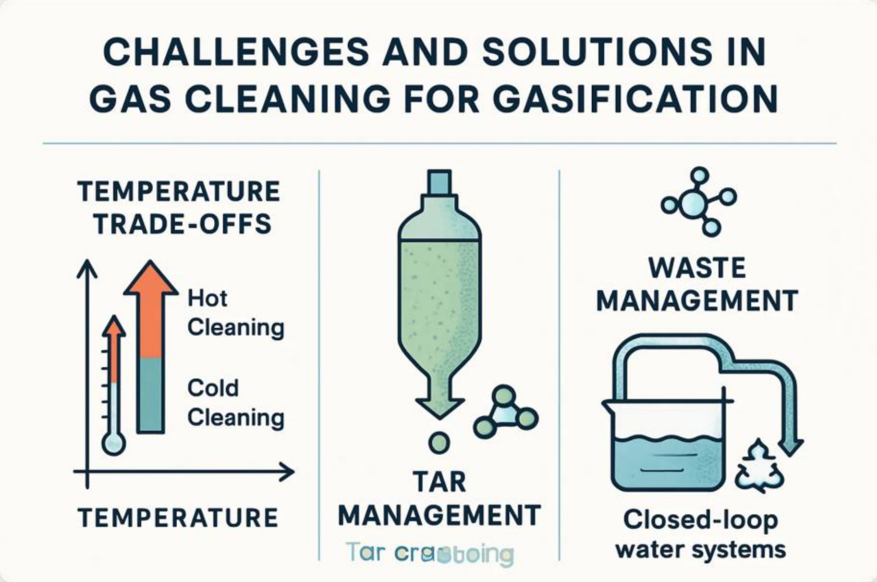
Challenge:
Tars condense at moderate temperatures, causing fouling and clogging of equipment.

Solution:
Development of catalytic tar cracking systems that operate at gasifier exit temperatures, eliminating the need for cooling and reheating.

Waste Management

Challenge:
Wet scrubbing generates contaminated wastewater requiring treatment.

Solution:
Dry cleaning technologies and closed-loop water systems with integrated treatment for zero liquid discharge.



Emerging Innovations:
Novel approaches include plasma-assisted cleaning, membrane separation technologies, and self-cleaning filter systems with integrated catalysts that simultaneously remove multiple contaminants in a single step.

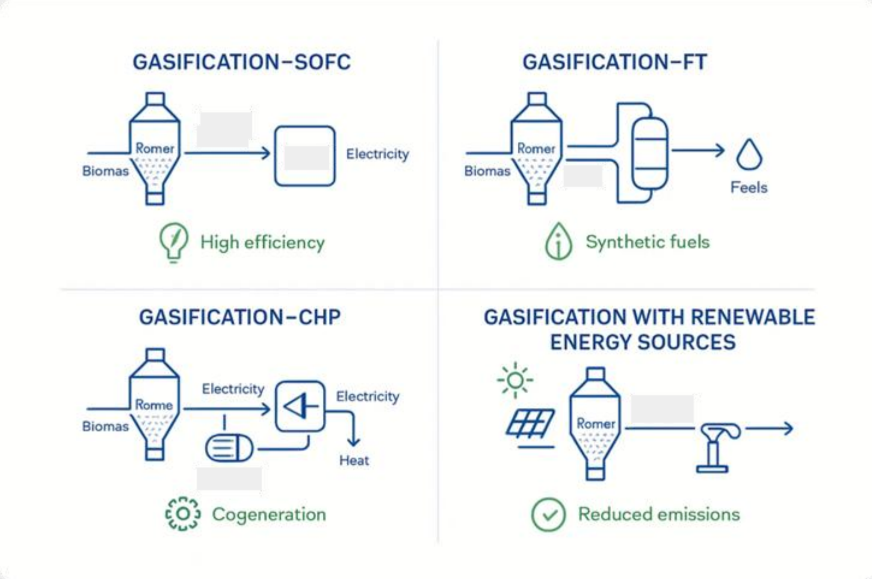
Integration of Gasification with Other Systems

Integrated Systems

Gasification can be integrated with various other energy and industrial systems to create synergistic effects, improving overall efficiency, reducing emissions, and enhancing economic viability.

Integration Type & Benefits

Integration Type	Description	Key Benefits
Gasification-SOFC	Syngas feeding solid oxide fuel cells	High electrical efficiency (>50%), reduced emissions
Gasification-FT	Syngas conversion to liquid fuels	Production of clean transportation fuels
Gasification-CHP	Combined heat and power generation	Total system efficiency >80%, district heating
Gasification-Biorefinery	Integration with biochemical processes	Diverse product portfolio, waste valorization
Gasification-Solar	Solar-assisted gasification	Reduced carbon intensity, improved syngas quality



Polygeneration Concept:
Modern integrated gasification systems often employ polygeneration strategies, producing multiple valuable outputs (electricity, heat, fuels, chemicals) from a single feedstock, maximizing resource utilization and economic returns.

Future Directions in Integrated Systems

Prof. L. Tarelho and V. Silva Research Focus

Prof. Tarelho and Silva's work highlights the importance of circular economy approaches in gasification, pyrolysis and combustion particularly focusing on waste valorization and integrated energy systems with minimal environmental impact.

Circular Economy Integration:
Developing closed-loop systems where gasification byproducts (biochar, ash) become valuable inputs for agriculture and construction, creating sustainable material cycles.

Negative Carbon Systems:

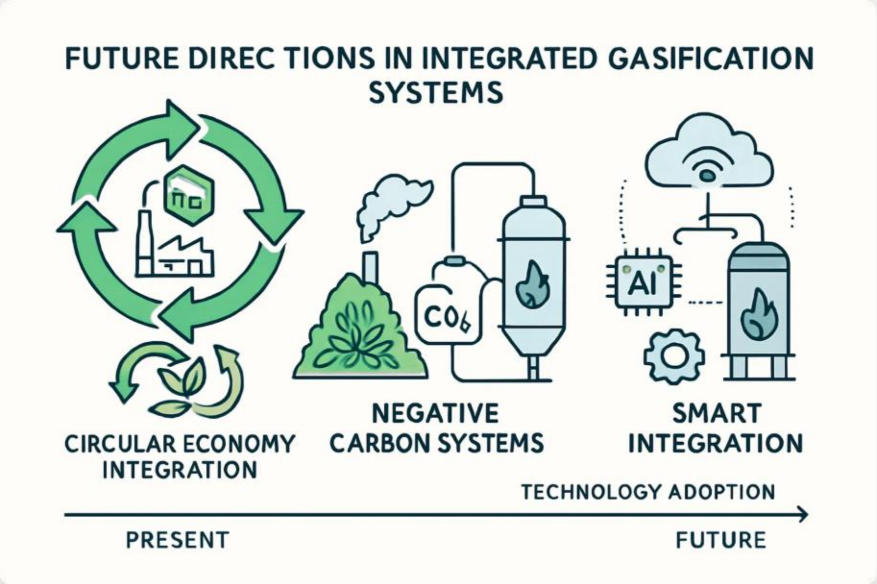
Combining biomass gasification with carbon capture to achieve negative emissions while producing energy, supporting climate mitigation goals.

Smart Integration:

Implementing AI and IoT technologies to optimize the integration of gasification with variable renewable energy sources, creating resilient and flexible energy systems.

Key Research Direction:

The future of gasification lies in its role as a flexible conversion technology within integrated energy systems, particularly for hard-to-decarbonize sectors and energy storage applications through power-to-X pathways.



Conclusion

Process Understanding

Gasification offers a versatile thermochemical conversion pathway with distinct advantages over combustion and pyrolysis, particularly for clean energy production and waste valorization.

Optimization Approaches

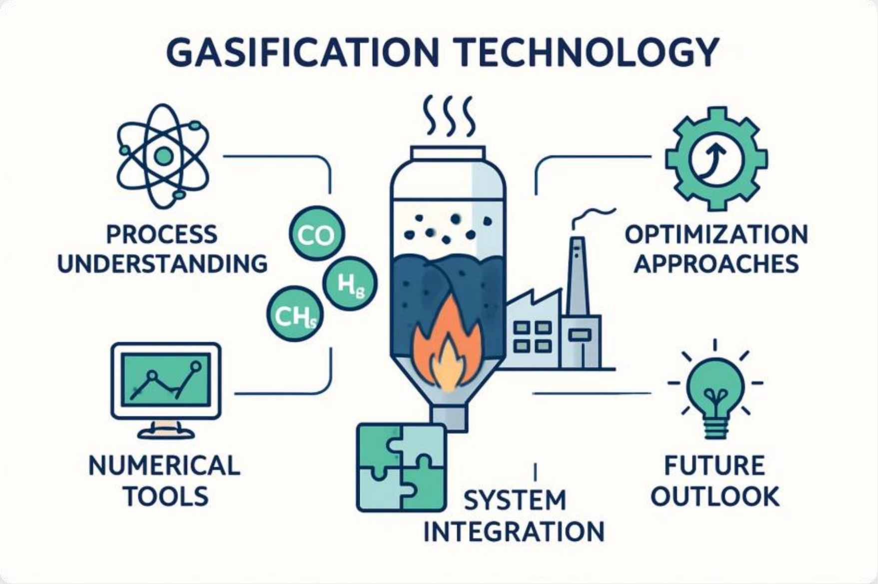
Advanced optimization strategies, including blending feedstocks, design of experiments, and catalytic treatments, have significantly improved gasification efficiency and reduced environmental impacts.

Numerical Tools

Computational modeling through CFD and kinetic simulations has become essential for understanding complex gasification phenomena and accelerating technology development without extensive experimental campaigns.

System Integration

The future of gasification lies in integrated systems that combine multiple technologies to achieve higher efficiencies, lower emissions, and greater economic viability through polygeneration approaches.



Future Outlook:

Gasification technology continues to evolve toward more flexible, efficient, and environmentally sustainable systems. Key developments will focus on integration with renewable energy sources, carbon capture technologies, and circular economy principles. The role of gasification in producing green hydrogen, advanced biofuels, and high-value chemicals positions it as a critical technology for the energy transition and decarbonization of hard-to-abate sectors.

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Acknowledgments