Exploring Research Trends and Innovations in Syngas Production with Carbon Capture and Storage for Sustainable Power Generation

Explorando tendencias de investigación e innovaciones en la producción de gas de síntesis con captura y almacenamiento de carbono para la generación de energía sostenible

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ABSTRACT

The integration of syngas production routes with Carbon Capture and Storage (CCS) represents a relevant approach for the decarbonization of thermal power generation. This work presents a systematic and techno-scientific analysis of syngas-based power systems integrated with CCS, focused on identifying research trends, thematic structures, and high-performance technological pathways. Following the PRISMA 2020 protocol, 2268 publications (2020–2026) were retrieved from Scopus and Web of Science. After duplicate removal and relevance screening, 115 core documents were analyzed using VOSviewer and Bibliometrix. The results show a consolidated growth phase between 2020 and 2023, led by China (32 publications, 512 citations), followed by the United Kingdom (≈10%), Iran (≈8%), and the United States (≈8%), evidencing the predominance of Asian and European research groups. Keyword co-occurrence analysis identifies two dominant clusters: (i) thermodynamic performance and advanced combined cycles, and (ii) syngas processing and CO_2 capture integrated with chemical conversion routes. The technical review highlights five main technological platforms—IGCC, SEG, CLCG, IGFC, and SCWG—reporting net electrical efficiencies up to 43.9% (chemical looping), overall energy efficiencies up to 52.95% (supercritical water gasification), and CO_2 capture rates of 95–99.2% in fuel-cell-integrated systems, with emission indices as low as 110 g CO_2/kWh. These results support the technical maturity and scalability of syngas–CCS systems for near-zero-emission power generation.

Keywords: *Carbon-Dioxide, Fischer-Tropsch Synthesis, Power Plants, CO_2 Capture.*

RESUMEN

La integración de rutas de producción de gas de síntesis con tecnologías de Captura y Almacenamiento de Carbono (CCS) representa un enfoque relevante para la descarbonización de la generación termoeléctrica. Este trabajo presenta un análisis sistemático y tecnocientífico de sistemas de generación basados en syngas integrados con CCS, orientado a identificar tendencias de investigación, estructuras temáticas y rutas tecnológicas de alto desempeño. Siguiendo el protocolo PRISMA 2020, se registraron 2268 publicaciones (2020–2026) de las bases de datos Scopus y Web of Science. Tras la eliminación de duplicados y el filtrado por relevancia, se analizaron 115 documentos base utilizando VOSviewer y Bibliometrix. Los resultados muestran una fase de crecimiento consolidada entre 2020 y 2023, liderada por China (32 publicaciones, 512 citaciones), seguida por el Reino Unido (≈10 %), Irán (≈8 %) y Estados Unidos (≈8 %), lo que evidencia la predominancia de grupos de investigación asiáticos y europeos. El análisis de coocurrencia de palabras clave identifica dos clústeres dominantes: (i) desempeño termodinámico y ciclos combinados avanzados, y (ii) procesamiento de syngas y captura de CO_2 integrados con rutas de conversión química. La revisión técnica destaca cinco plataformas tecnológicas principales —IGCC, SEG, CLCG, IGFC y SCWG—, que reportan eficiencias eléctricas netas de hasta 43,9 % (chemical looping), eficiencias energéticas globales de hasta 52,95 % (gasificación en agua supercrítica) y tasas de captura de CO_2 del 95–99,2 % en sistemas integrados con celdas de combustible, con índices de emisión tan bajos como 110 g CO_2/kWh. Estos resultados respaldan la madurez técnica y la escalabilidad de los sistemas syngas–CCS para la generación de potencia cercana a cero emisiones.

Palabras clave: *Dióxido de Carbono, Síntesis de Fischer-Tropsch, Plantas de Energía, Captura de CO_2.*

1. INTRODUCTION

The integration of syngas production processes and Integrated Gasification technologies into the operations of Combined Cycle Power Plants (CCPP) represents a promising strategy for enabling low-carbon power generation and advancing sustainable energy systems [1]. These thermochemical approaches have catalyzed the development of biogas production, particularly in countries such as Germany, Sweden, Switzerland, the United Kingdom, and the United States where they contribute to enhanced energy efficiency and significant reductions in the fossil fuel use for transportation and power generation [2]. In parallel, countries like Colombia, Costa Rica, China, and India have stablished natural gas infrastructures capable of incorporating biofuels derived from methanol synthesis, thereby reducing dependency on conventional resources [3].

Fossil fuels have accounted for approximately 78.4% of global energy demand since 2014. Furthermore, the demand for natural gas has grown steadily at an annual rate of 0.5% in recent years [4]. Given these trends, the current technological state of CCPP requires intensified research into the integration of biomass gasification processes to reduce greenhouse gas emissions from power generation [5]. These thermodynamic systems typically combine gas turbine (Brayton) and steam turbine (Rankine) technologies, achieving energy efficiencies between 47% and 58% in large-scale plants ranging from 60 to 1500 MW [6].

The application of thermochemical processes for biogas production from biomass has gained increasing attention, particularly due to the rising industrial demand for methanol within the energy sector [7]. Biswal [8] provided a comprehensive review of methanol applications, highlighting key statistical trends in its global development. According to recent projections, methanol production capacity is expected to increase from 157 to 311.4 million metric tons between 2020 and 2030 [9]. The characteristics of the synthesis gas produced during gasification depend on multiple factors, including reactor configuration, biomass composition, gasification temperature, and the specific gasifying agent employed.

A set of numerical models has been developed to evaluate the optimal thermodynamic behavior of industrial processes, aiming to reduce costs associated with the experimental analysis [10]. Liu [11] developed a simulation using Aspen PLUS considering a thermal integration of a steam power plant, a methanol production unit, and a water desalination unit. Numerical evaluation of the exergy and energy balances indicated a total exergy efficiency of 68.81% and an energy efficiency of 35.57%. The total rate of exergy destruction was equal to 202841 kW, with associated CO_2 emissions of 154306.82 kg/h.

Carbon Capture and Storage (CCS) methods have been implemented in both pre-combustion and post-combustion processes within Integrated Gas Combined Cycle (IGCC) power plants. Padurean [12] conducted numerical modelling to evaluate various CO_2 capture technologies applied to different power plant configurations, aiming to quantify the energy penalty associated with CCS integration. The simulation results using Aspen PLUS demonstrated that the use of dimethyl ethers of polyethylene glycol (DEPG) achieved the highest energy efficiency among the tested scenarios. However, this configuration resulted in a 22.55% increase in capital cost to attain 90% CO_2 capture efficiency [13].

Building on these findings, Esquivel and Napoles [14] managed a performance analysis of a biogas-fueled CCPP integrated with an Organic Rankine Cycle (ORC) to recover waste heat from combustion gases and a post-combustion carbon capture system. This study evaluated emission reductions achieved through the integration of a CO_2 mass generation control system within the thermal power plant. The thermodynamic model demonstrated an annual reduction of 0.055 CO_2-eqt emissions as a result of this configuration [15].

The scientific literature has demonstrated the critical role of CCS in enhancing the performance of CCPP [16]. The application of PRISMA 2020 methodology within engineering research provides valuable insights into the evolution of scientific inquiry, particularly in the integration of CCS technologies with CCPP systems [17]. By systematically analyzing bibliometric metadata, researchers are able to identify emerging trends, influential contributors, and the developmental trajectory of CO_2 capture methods [18].

This analytical configuration not only underscores the growth and diversification of literature driven by technological advancements in CCPP but also facilitates the identification of novel techniques and strategies aimed at reducing greenhouse gas emissions. Consequently, relational bibliometric methods serve as powerful tools to mapping the CCS research landscape, providing a comprehensive overview that supports improved energy management and optimization of thermodynamic cycles within power generation systems.

Such analyses contribute to guiding future engineering research and development efforts toward more efficient and sustainable carbon mitigation solutions.

In this sense, Malekli et al. [19] measured the research indicators of CO_2 capture methods from CCPP by means of bibliometric analysis and data mining to study the gaps between the studies of the energy production observed with VOSviewer software. Likewise, Zhu et al. [20] developed a bibliometric analysis of carbon capture, utilization, and storage (CCUS) technologies based on 11915 pieces of patent data from Derwent Innovations Index. The results shown the distribution of patents between China, USA, and Japan with twelve topics identified in energy and electricity industries.

Building upon the current state of the art, this paper presents a comprehensive bibliometric analysis of carbon capture CCS technologies, specifically as they relate to improving applied to enhance the energy efficiency of CCPP and significantly reducing CO_2 emissions. This is achieved by optimizing the use of exhaust gases generated by the gas turbine in the Brayton Cycle. Through this rigorous bibliometric study, the paper identifies critical trends, research gaps, and emerging innovations that have not been systematically addressed in previous literature. These insights offer a novel, data-driven foundation for advancing the integration of CCS technologies into CCPP and provide a strategic roadmap for accelerating the development of sustainable energy solutions. By disseminating these findings, this study seeks to catalyze further research and innovation aimed at addressing the global challenge of reducing greenhouse gas emissions in power generation [21].

The first section of this paper introduces the research scope and methodological framework providing an overview of CCS technologies and their influence on the performance characteristics of CCPP under real-world operating conditions [22]. The second section outlines the bibliometric methodology based on the PRISMA 2020 approach [23], applied to metadata retrieved from Scopus and Web of Science (WoS) database from 2000 to 2026. Finally, the third section presents the results and discussion of the meta-analysis, along with technical review in the application of CCS technologies within CCPP systems.

2. METHODOLOGY

The Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines were applied to collect data from Scopus and Web of Science (WoS) databases. This methodology enabled the identification of relevant trends, minimization of bias, and exclusion of low-quality studies from the dataset. The systematic analysis only includes peer-reviewed journal articles that describe the application of CCS technologies and synthetic fuels aimed at reducing CO_2 emissions in CCPP [24]. The structured steps began with the definition of search terms using the PECO framework (Population, Exposure, Comparison, and Outcome) as summarized in Table 1. Each PECO element was associated with a core keyword to define a query equation across a comprehensive dataset [25].

Table 1. Main Concepts of PECO model to define the query equation.

Element	Description	Concept
Population	Power Generation System	Combined Cycle Power Plant (CCPP)
Exposure	Technology Assessment	Carbon Capture and Storage (CCS)
Comparison	Alternative	Syngas Production
Outcome	Possible Results	CO_2 Reduction

A meta-analysis was conducted for each concept in the PECO framework, defining 4 keywords Plus based on the Bibliometric metrics assessed with Bibliometrix software. Then, the underpinning CWTS algorithm defined the first 10 Micro topics with relevance in the record count parameter and citation relationships for articles of each research topic to build the query equation with Boolean operators [26]. This query equation was designed and applied to the Scopus and Web of Science databases on November 30, 2025, to identify a dataset focused on CCS technologies employed in syngas production for CO_2 reduction in CCPP (Eq. 1). A total of 2268 peer-reviewed publications were retrieved covering the period from 2020 to 2026. This dataset was subsequently refined using a set of inclusion and exclusion criteria, which involved the removal of duplicates, irrelevant or low-quality documents and the retention of peer-review publications.

(TITLE-ABS-KEY ("Fischer-Tropsch Synthesis" OR "CO Oxidation" OR "CO_2 Reduction" OR "Dimethyl Carbonate" OR "Gasification" OR "hydroxymethylfurfural" OR "Photocatalysis" OR "Metal-organic Frameworks" OR "Selective Catalytic Reduction" OR "Zno") AND TITLE-ABS-KEY ("Adsorption" OR "Dark Energy" OR "Entropy" OR "Vapor-liquid Equilibria" OR "Protein Folding" OR "Excess Molar Volumes" OR "Cocrystals" OR "Ionic Liquids" OR "Hydrogen Storage" OR "Organic Rankine Cycle") AND TITLE-ABS-KEY ("Organic Rankine Cycle" OR "CO_2 Capture" OR "Gasification" OR "Solar Air Heater" OR "Euler Equations" OR "Unit Commitment" OR "Solid Oxide Fuel Cell" OR "Combustion Simulation" OR "Fischer-Tropsch Synthesis" OR "Environmental Kuznets Curve") AND TITLE-ABS-KEY ("CO_2 Capture" OR "Microbial Biomass" OR "Enhanced Oil Recovery" OR "Dendrochronology" OR "Metal-organic Frameworks" OR "Environmental Kuznets Curve" OR "Ecosystem Services" OR "Fischer-Tropsch Synthesis" OR "Seagrass" OR "Permafrost")) AND (LIMIT-TO (PUBYEAR , 2000) OR LIMIT-TO (PUBYEAR , 2026)) AND (LIMIT-TO (DOCTYPE , "ar")) AND (LIMIT-TO (LANGUAGE , "English")). (1)

540 duplicated peer-review articles, 2 publications flagged as negligible by automation tools, and 1799 publications deemed to have low impact to syngas applications in sustainable power generation systems were excluded. Subsequently, 115 articles were assessed for their eligibility and relevance to the application of CCS techniques, using a predefined set of inclusion and exclusion criteria [23]. The excluded studies comprised those focused-on Metal Organic Frameworks (n=17), adsorption techniques (n=23), surfaces (n=12), and porous media for materials (n=11). A total of 58 articles and 35 reports were included for a systematic analysis with a methodology based on the traceability and replicability of the metadata. This curated collection of literature reflects the current state of knowledge on CCS technologies integrated with CCPP for CO_2 reduction and serves as a foundation for defining a roadmap for future applications.

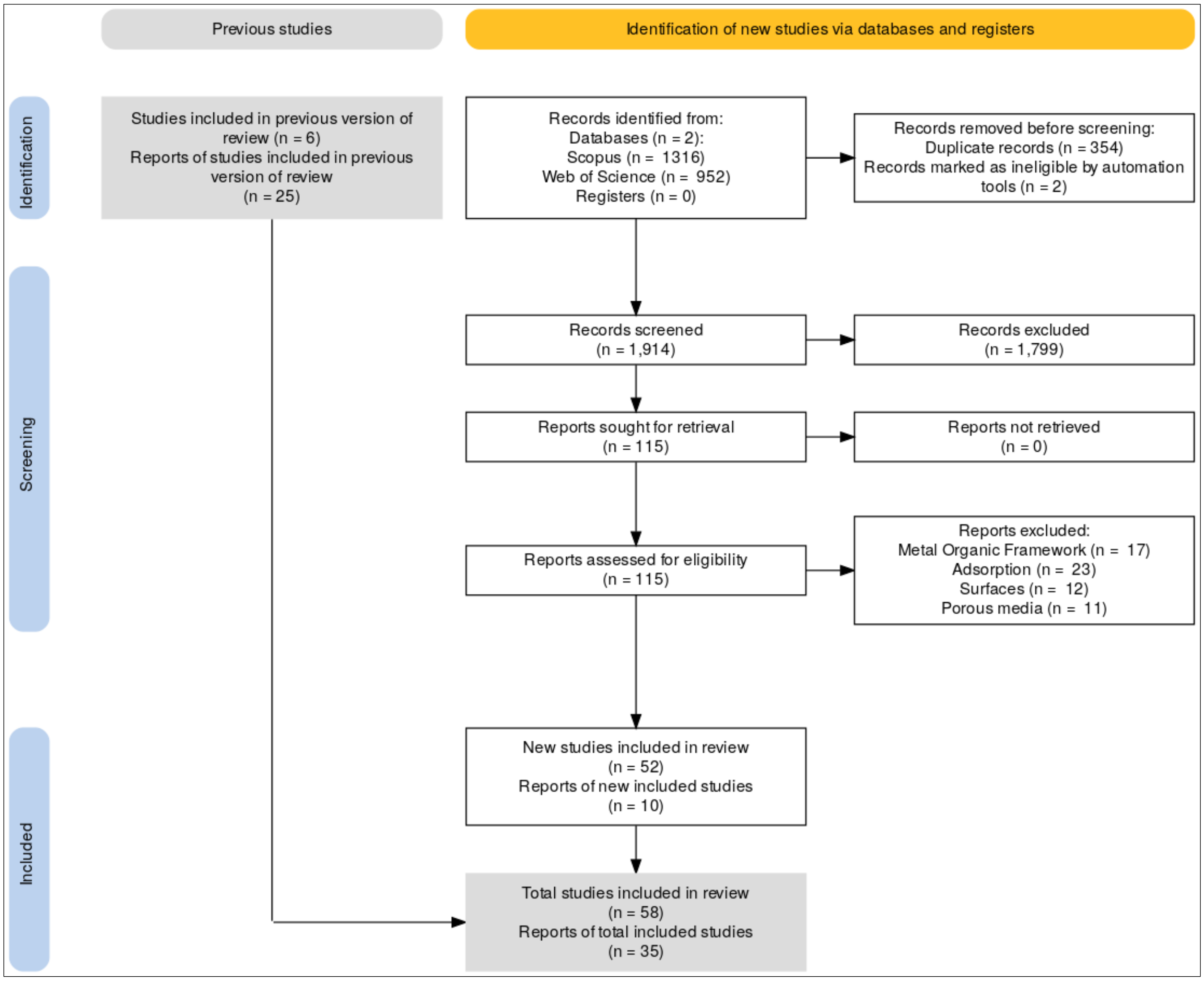

Fig. 1. Systematic analysis methodology.

Fig. 1 presents the stepwise methodology, illustrating the flow diagram from data extraction via Scopus and Web of Science to bibliometric insights. The raw data imported to VOSviewer and RStudio (version R-4.5.1 for Windows) provide a robust platform equipped with specialized bibliometric packages that support both qualitative and quantitative analyses [27]. Using the Bibliometrix package (version 5.1.0), a comprehensive bibliometric mapping workflow was conducted: (i) Metadata Analysis, involving descriptive statistics and relational analyses such as co-citation and co-occurrence networks across keywords, journals articles, countries, researchers, and specific research components of CCS integrated with CCPP [28]; (ii) Data Visualization, which involved generating graphical outputs such and description of trends to elucidate the structure and dynamics of the research field [29]; and (iii) the technical overview of bibliometric sources related to syngas generation and its applications for power generation in thermal power plants [30].

3. RESULTS

This bibliometric analysis evaluates publication trends, keyword co-occurrence, co-authorship networks, and citation index. The dataset spans from 2020 to 2026, incorporating scientific contributions related to gasification and power generation using liquid fuels, carbon capture techniques from adsorption processes, advanced combined cycles with noteworthy improvements in waste heat recovery processes and carbon storage from post-combustion schemes.

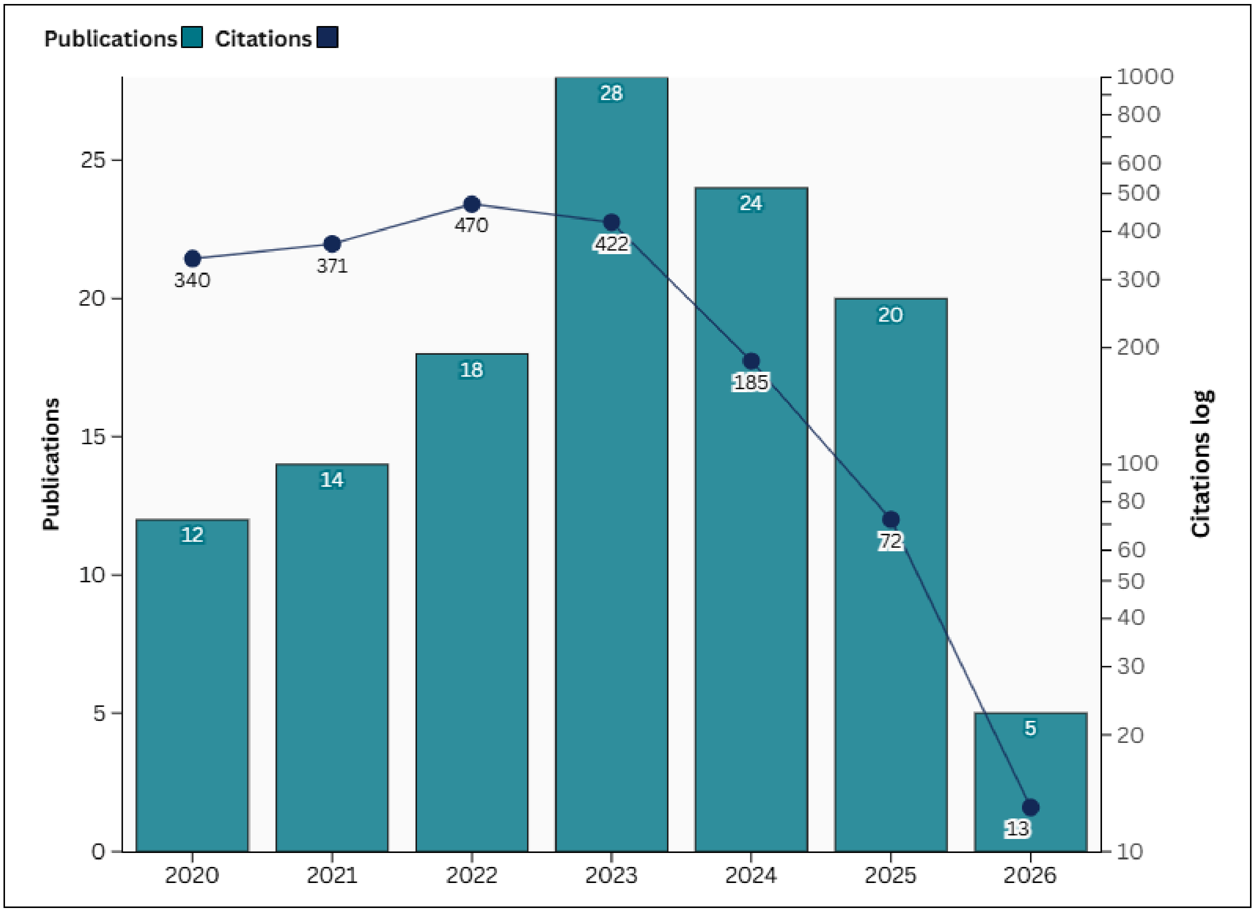

Fig. 2. Publication and Citation Trends from WoS database.

Fig. 2 illustrates the temporal evolution of scientific production and the corresponding number of citations in secondary logarithmic axis. A clear growth phase with publications increasing from 12 (2020) to a peak of 28 (2023) indicating a rapid expansion of research activity. In the same period, 470 citations in 2022 and 422 citations in 2023 reflect strong scientific impact and visibility of the publications emphasizing a consolidation and peak of research activity around 2022 and 2023. After 2023, a decline in both indicators is observed. Publications/citations decrease to 24/185 (2024), 20/72 (2025) and 5/13 (2026) respectively. This behavior is reliable with the citation time-lag effect due to more recent publications having had less time to accumulate citations.

Fig. 3 presents the percentage distribution of publications in function of thematic categories with a strong predominance of engineering-energy-and chemistry-oriented research fields. These thematic categories correspond to Chemistry physical (0.23), Engineering Chemical (0.19), Chemistry Multidisciplinary (0.14), Materials Science Multidisciplinary (0.13), Energy and Fuels (0.09), Nanoscience and Nanotechnology

(0.07), Engineering Environmental (0.05), Chemistry applied (0.04), Environmental Sciences (0.03) and Green and Sustainable Science and Technology (0.03) [6] [31].

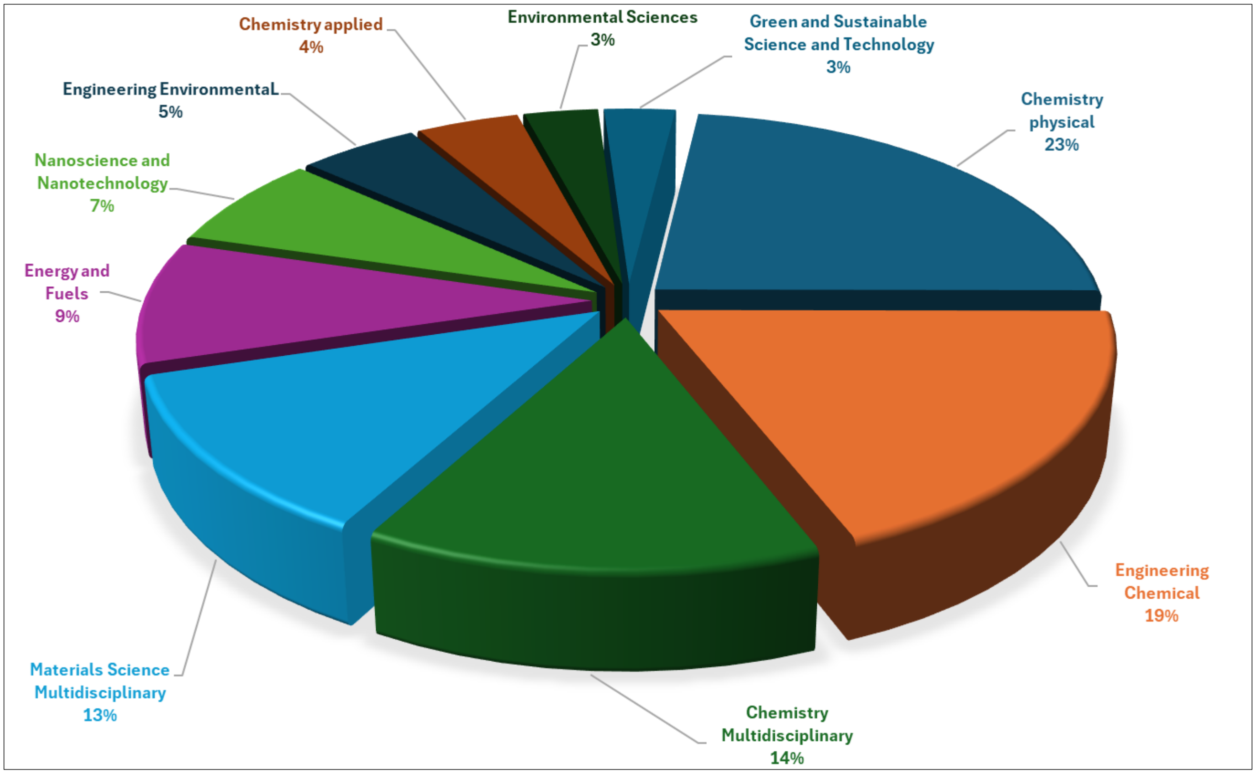

Fig. 3. Distribution of publications by thematic categories.

The h-index, g-index, and m-index of the journals with the highest number of citations (TC) in the research areas of CCS and syngas production via Fischer-Tropsch synthesis are presented in Table 2, together with the total number of publications (TP). These indicators provide an integrated measure of scientific productivity, citation impact, and time-normalized influence of the leading sources in the field of research. Table 1 shows the main Micro Topics identified for each thematic cluster and their corresponding record.

Table 2. Top 10 distribution of main micro-topics by cluster based on record count.

Source	h-index	g-index	m-index	TC	TP
Nature Communications	39	62	3.250	83	3
Energy Conversion and Management	39	60	3.250	103	8
Energy	34	54	2.833	108	8
Applied Energy	32	60	2.909	50	3
Journal of Cleaner Production	32	52	2.667	81	5
Renewable Energy	31	47	2.583	103	3
International Journal of Hydrogen Energy	30	59	2.500	104	4
ACS Catalysis	26	34	2.167	37	3
Separation and Purification Technology	26	50	2.364	78	1
Chemosphere	25	35	2.083	65	1

Considering the above, an analysis of scientific production by country was conducted using Bibliometrix and VOSviewer software. The dataset covers the period from 2020 to 2026 screening 115 documents from the exclusion and exclusion criteria. Fig. 4 shows the geographical distribution of scientific production and citation impact. A strong concentration of publications in Asia and Europe, with China leading scientific production (32 publications and 512 citations). Iran follows with 9 publications and 210 citations, while United Kingdom reports 12 publications and 120 citations, maintaining both productivity and visibility. Moderate research contributions are observed from the United States (9, 55), Brazil (3, 51), Spain (2, 43), Germany (5, 41), and India (4, 39).

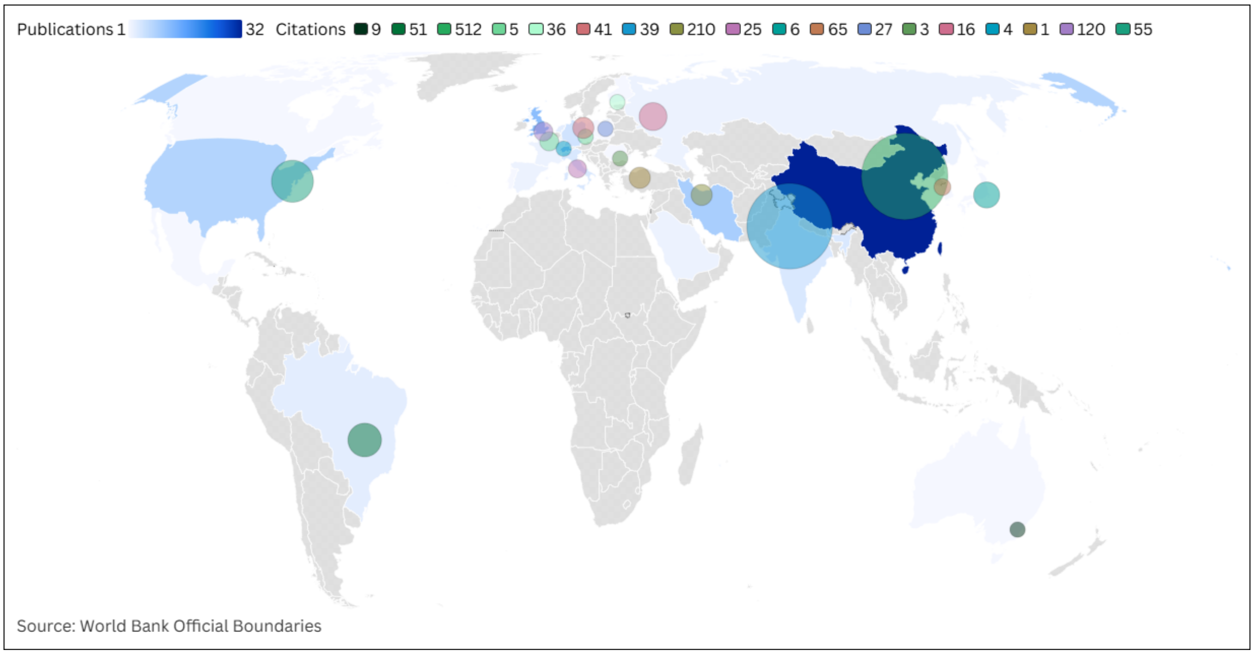

Fig. 4. Geographical distribution of scientific production and citation impact by country.

Emerging contributions are identified in Finland, Poland, Italy, Russia, Japan, and Czech Republic, each with lower scientific production but consistent citation activity. Overall, the country level contribution highlights the significant influence of Asian and European research groups in the development of CCS technologies, with a strong tendency towards the numerical and experimental studies focused on chemical processes for synthetic fuel production from renewable sources. These efforts aim to develop alternatives to reduce fossil-fuel dependence in CCPP, ORC, or CO_2 Supercritical [32], [33].

Fig. 5 shows the keyword co-occurrence network generated with VOSviewer, demonstrating the conceptual structure of research on CCS, syngas production, and advanced power generation systems. Each node size represents the frequency of keyword occurrence in the set of metadata, while link indicates the strength of co-occurrence relationships between terms. Two main thematic clusters are identified: red cluster is centered on energy system performance and thermodynamic optimization with the keywords energy, power, exergy, exergy efficiency, organic Rankine cycle, and power generation [34].

This cluster echoes strong research in efficiency assessment, waste heat recovery, exergy-based assessment of advanced combined cycles, and hybrid power systems. The green cluster is structured around process engineering and carbon management, with the keywords process (as the most central node) strongly connected to syngas, CO_2, CO capture, and effect. This cluster highlights the standing of chemical and process-oriented studies addressing syngas production routes, CO_2 mitigation strategies, and their effects on system performance [35].

The dense interconnections between the two clusters indicate an elevated level of interdisciplinarity, evidencing that recent research increasingly integrates thermodynamic performance analysis with chemical process design for carbon capture and storage technologies.

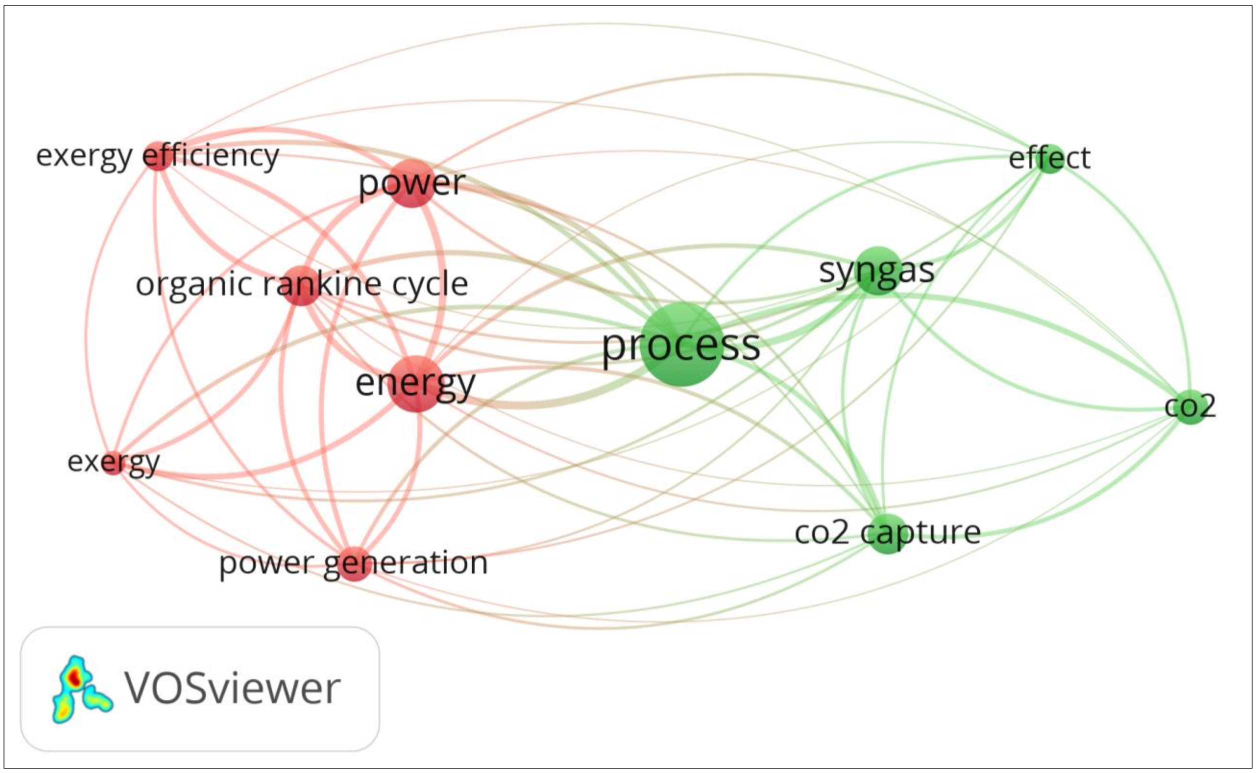

Fig. 5. Keyword co-occurrence network.

Fig. 6 confirms the incorporation of CCS and syngas-related investigations form a tightly coupled research framework aimed at improving the efficiency and environmental performance of emerging power generation systems. In this sense, the author density visualization generated by VOSviewer illustrates the distribution and influence of leading authors in CCS, syngas production, and advanced power generation research. The color density represents the relative density of publications and citation relationships with warmer colors indicating higher research concentration and influence.

Fig. 6. Author density map of leading contributors in CCS and syngas-related research.

Davagaran, S., Mousavi Rabeti, S.A., Khoshgoftar Manesh, M.H., and Blanco-Marigorta, A.M. dominate the cluster red, indicating a strong research group with high productivity and strong thematic conference, associated with thermodynamic analysis, energy systems, and process optimization. The second cluster (blue) reflects an Asian research nucleus with Zhang, P., Li, S., Chen, S., and Wang, P. dedicated to syngas processing, catalytic routes, and CCS technologies. The third cluster (green) represented by Kirtania, B. and Shilapuram, V., corresponds to an emerging research group focused on gasification and advanced fuel conversion systems.

3.1. Technological pathways for syngas production and power generation under carbon CCS schemes

Advanced methods for the production of synthetic fuels and their valorization in power generation systems integrates technological advancements in catalysts and reactor design through processes such as Fischer – Tropsch synthesis and syngas reforming [36]. The authors analyze a range of CCS technologies such as hydrophobic systems, palladium membranes, pre- and post-combustion processes to mitigate environmental impacts due to power generation [37]. In this sense, technical and economic studies are presented to use solid waste and renewable energy sources for hydrogen and valued-added hydrocarbons to enable a low – carbon economy and advance toward global climate neutrality. The following section details the most relevant publications identified for each of the five syngas-based power generation technologies based on the screening of bibliometric data.

3.1.1. Integrated Gasification Combined Cycle (IGCC)

Extensive research in power generation from gasified biomass has been conducted to extract energy from renewable resources efficiently to produce fuel for gas engine or turbine operations. IGCC are an emergent technology able to improve power production, increasing thermal and power efficiencies in thermal power plants and facilitate the carbon capture process. IGCC incorporates air-blown pressurized circulating bed reactors to cover wood chips to a producer gas with the typical composition: (9.5 – 12) H_2; (16 – 19) CO; (14.4 – 17.5) CO_2; (5.8 – 7.5) CH_4; (48 – 52) N_2 maintaining a heating value span of 5.0 – 6.3 MJ/Nm^3 [38]. Fig. 7 presents the schematic overview of the Güssing CHP gasification plant with a thermal fuel power input of 8 MW, an electrical output of 2 MW, and a thermal output of 4,5 MW conforming a district heating. The overall efficiency is equal to 81.3%, distributing 25% to electrical efficiency, and 56.3 for thermal efficiency [39]. This technology enables the conversion of solid fuels such as coal or biomass into a synthesis gas composed of CO and H_2, which feeds H-class gas turbines for electricity generation. The assessment of IGCC systems is necessary for their improvement in environmental performance and lower CO_2 capture costs compared to conventional pulverized coal plants. IGCC can integrate gas switching combustion (GSC) technologies to enhance operational flexibility and carbon capture.

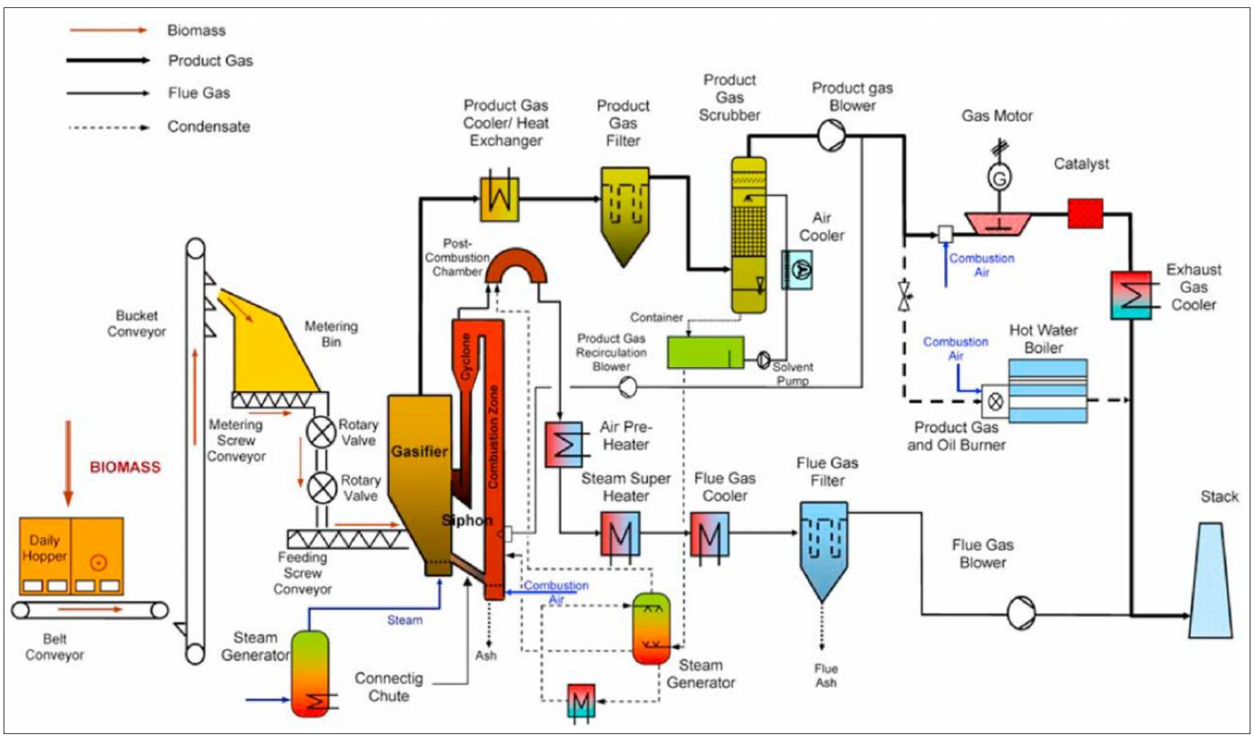

Fig. 7. Güssing CHP gasification plant with a thermal fuel power input of 8 MW. Source: [39].

Table 3 describes the most relevant studies for CO_2 reduction and the application of renewable sources in the implementation of IGCC based on record count, considering the application of techno-economic analyses, simulation of chemical processes and the application of thermodynamic models to describe the impact in the integration of CCS technologies in the operation of IGCC.

Table 3. IGCC applications to reduce CO_2 based on record count.

Author	Description	Contributions
[40]	Methodology: Techno-economic analysis of IGCC power plants incorporating MAWGS reactors and GSC. Results: GSC-IGCC plants have CO2 avoidance costs of €24.9-36.9/ton, lower than €44/ton for the benchmark plant.	The article discusses the integration of gas switching combustion (GSC) and IGCC reaching CO2 capture and outperforming benchmark with 41.9% net efficiency. GSC-IG plants can flexibly produce either electricity or hydrogen depending on demand, maximizing the utilization of the expensive gasification train.
[41]	Methodology: Development of a reduced-order model for a plug-flow reactor equipped with palladium membranes. Results: It was determined that increasing the retentate pressure from 40 to 120 atm leads to a linear increase in the H_2 flux of 0.05 $kg \cdot m^{-2} \cdot h^{-1}$ per atm.	The study develops a reduced-order model for palladium membrane reactors integrated into IGCC systems. H_2 permeation is strongly temperature-driven and that increasing retentate pressure. Reducing permeate pressure increases hydrogen flux exponentially, providing a fast predictive tool for low-carbon H_2 system design.
[42]	Methodology: Investigation of hydrate formation in a fixed-bed reactor using macroporous silica and chemical promoters. Results: A CO_2 uptake of 5.45 mmol CO_2/g H_2O was achieved using promoters such as SDS and EGME, optimizing CO_2 capture under IGCC operating conditions.	Hydrate-based CO_2 capture enhanced with macroporous silica and optimized promoters can achieve CO_2 uptakes of up to 5.45 mmol CO_2/g H_2O (EGME 0.10 mol % + SDS 0.01 mol %), and that TBAB supplementation and fixed-bed configuration further increase operating capacity, providing an experimental basis for continuous hydrate-based CCS under relevant conditions.
[43]	Methodology: Thermodynamic analysis of high-temperature adsorption processes compared with the Selexol process. Results: CO_2 removal at temperatures close to the steam cycle minimizes power losses, although high temperatures increase the heat of adsorption.	The study quantifies the performance limits of adsorption-based warm CO_2 capture in IGCC. Higher capture temperatures increase the heat of adsorption and electricity losses relative to Selexol under most conditions, establishing a clear quantitative design criterion for high-temperature CCS integration to minimize CO_2 emissions.
[44]	Methodology: Aspen Plus modeling of seven plants with capacities ranging from 54 to 543 MW using physical solvents. Results: As plant capacity increases, the levelized cost of CO_2 capture (LCOC) decreases from 12.50 to 7.58 $/ton due to economies of scale.	A techno-economic assessment of pre-combustion CO_2 capture in modular-scale gasification power plants demonstrates that economies of scale reduce capture costs as plant capacity increases. The study defines a framework to support the design of cost-effective CCS systems and syngas-based energy plants by integrating physical solvents and PC-SAFT thermodynamic modeling.

3.1.2. Sorption-Enhanced Gasification (SEG)

SEG is a flexible technology that employs a dual fluidized-bed system in which a solid sorbent (typically limestone or CaO) captures CO_2 in situ during the gasification process. This process shifts the chemical equilibrium (via the water–gas shift reaction) toward enhanced H_2 production, resulting in a hydrogen-rich synthesis gas (up to 94% purity) suitable for direct use thermodynamic cycles for power generation. Table 4 presents the main contributions for SEG applications in thermal power cycles for CCS.

Table 4. Sorption Enhanced Gasification (SEG) applications.

Author	Description	Contributions
[45]	Methodology: Design of a 300 MWth power plant integrated with supercritical CO_2 cycles and an Organic Rankine Cycle (ORC) for power generation. Results: A net electrical efficiency of 43.89% was achieved, attaining net-negative CO_2 emissions when the biomass blending ratio exceeded 50%.	The article discusses the integration of sorption-enhanced gasification (SEG) with concentrated solar power and calcium looping to enable simultaneous hydrogen production, power generation, and in-situ CO_2 capture. The proposed solar-driven SEG system achieves 0.58 kg/s of high-purity hydrogen, 13.96 MW of net electrical power, and 95% CO_2 capture efficiency.
[46]	Methodology: Development of a model that accounts for gasification kinetics and CO_2 capture in bubbling fluidized beds. Results: It was validated that the limestone make-up flow rate strongly influences syngas composition in the temperature range of 600–650 °C.	The study demonstrates that limestone make-up flow and gasification temperature (600–650 °C) critically control syngas composition and validates a hydrodynamic–kinetic SEG model against a 200 kW pilot plant, providing a performance framework for load-flexible hydrogen and gasification systems.
[47]	Methodology: Aspen Plus modeling of fixed-bed gasification of municipal and food waste. Results: Hydrogen purity reached 99.4% at 20 bar, with a carbon capture efficiency exceeding 90%.	The study describes an in-situ CO_2 capture using CaO shifts reaction equilibria toward hydrogen formation, thereby establishing a scalable and near–carbon-neutral thermochemical pathway for sustainable hydrogen generation.
[48]	Methodology: Thermodynamic simulations of gasification of mixed waste streams with plastics using CaO-based sorbents. Results: Syngas with up to 93 mol% H_2 was produced, achieving a CO_2 capture efficiency of 92% when steam was used as the gasifying agent.	The study presents an optimized feedstock blends and CaO-assisted gasification can produce syngas with up to 93 mol% hydrogen and achieve CO_2 capture efficiencies above 90%, establishing a thermochemically validated pathway for high-yield hydrogen production and effective carbon isolation from complex waste streams.
[49]	Methodology: Use of a dual-function Ni–Na_2ZrO_3 catalyst to enable simultaneous high-temperature CO_2 capture and biomass reforming. Results: At 950 °C, a hydrogen yield of 0.95 m^3/kg was achieved, with an almost negligible carbon deposition rate.	The study demonstrates that adsorption-enhanced reforming at 900–950 °C significantly promotes hydrogen-rich syngas production, achieving hydrogen yields of 0.95 m^3/kg with nearly zero carbon deposition, thereby establishing a high-temperature, sorbent-catalyst pathway for integrated hydrogen production and in-situ CCS.

Fig. 8 presents the flow diagram of the SEG system integrated with a waste heat recovery system to produce electrical power, H_2 and liquefied CO_2. SEG is considered a secondary power cycle, and the CO_2

liquefaction unit allows CO_2 storage at low temperatures. This gasification process comprises CO_2, CO, H_2, and CH_4 in a sorption enhanced gasifier which is a fluidized bed reactor [50].

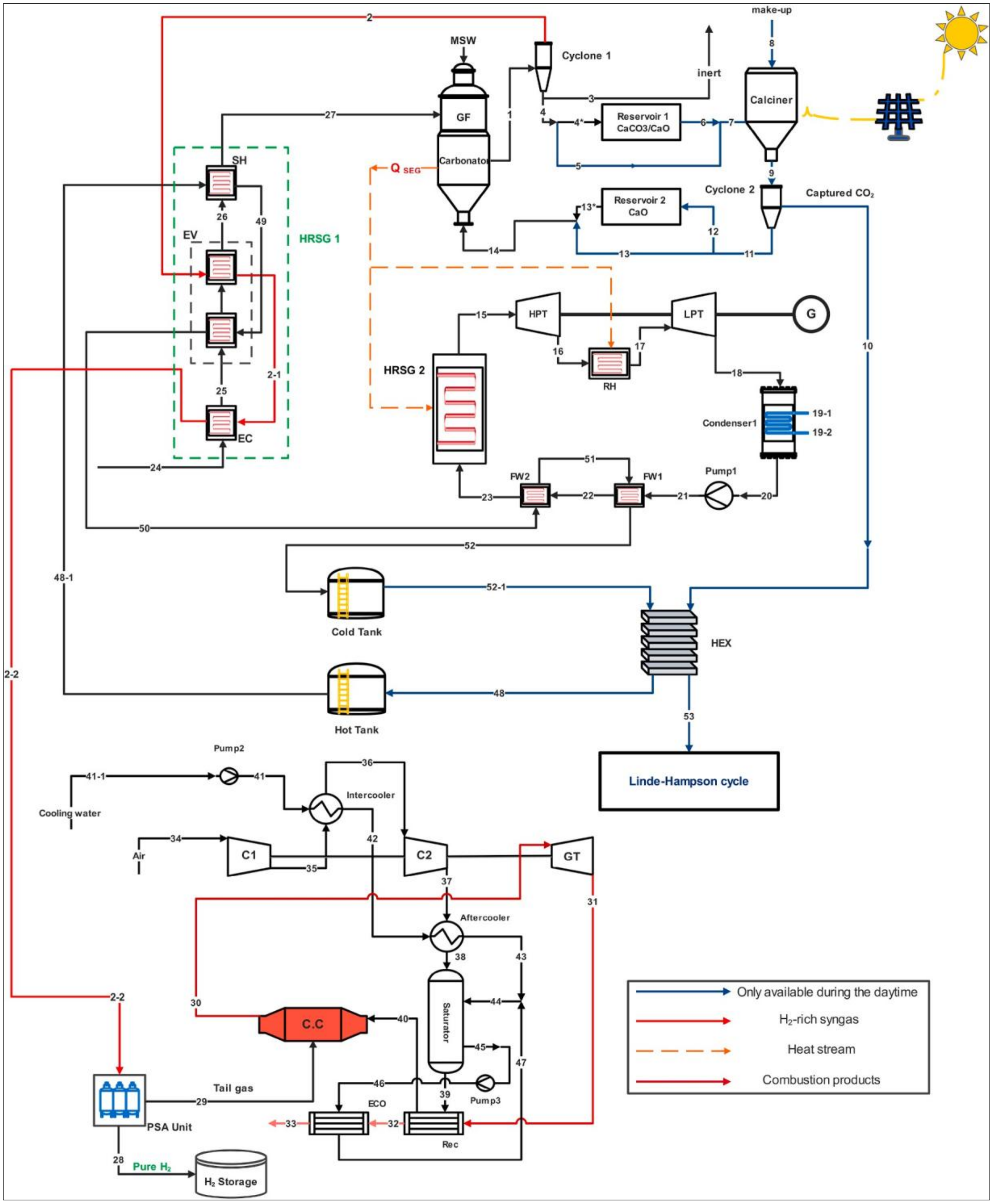

Fig. 8. Flow diagram of SEG system coupled to a secondary power cycle. Source: [50].

3.1.3. Chemical Looping Combustion and Gasification (CLCG)

CLCG is an advanced thermochemical conversion process characterized by producing Nitrogen-free syngas without an air separation unit. This process maintains a precise control of oxidation degree with an intrinsic CO_2 capture process and biomass or waste fuels integration for low-carbon or negative-emission energy systems. This technique uses solid oxygen carriers (such as iron oxides or perovskites) to transfer oxygen to the fuel, thereby avoiding direct contact between air and fuel. In thermal power plants, chemical looping combustion (CLC) enables a combustion process that inherently facilitates high-efficiency CO_2 capture integrated with supercritical CO_2 cycles and organic Rankine cycles to maximize net electrical efficiency, reaching values close to 43.89% [51].

Metal oxide carries oxygen from air to fuel, thereby avoiding direct contact between the fuel and air. In this way, highly efficient oxygen carriers (OCs) enable inherent carbon capture while supporting hydrogen producing reactions and the synthesis of high value-added chemicals. Unlike conventional combustion methods, CLCG is based on the cyclic transfer of oxygen by solid OCs between a fuel reactor and an air reactor. In the first step, the OC reacts with the fuel in the fuel reactor. Next, the OC is converted while the fuel changes to CO_2 to H_2O. A high concentration of CO_2 stream is obtained by condensation of steam from the off gas of the flame retardant [52]. Fig 9 illustrates the flow diagram of the CLCG power generation with eight principal blocks in sequence: gasifier, combustor, air separation unit (ASU), heat recovery steam generator (HRSG), gas cleaning, de-sulfuring unit (Selexol), sulfur recovery unit (Claus), Gas Turbine and Steam Turbine units [53].

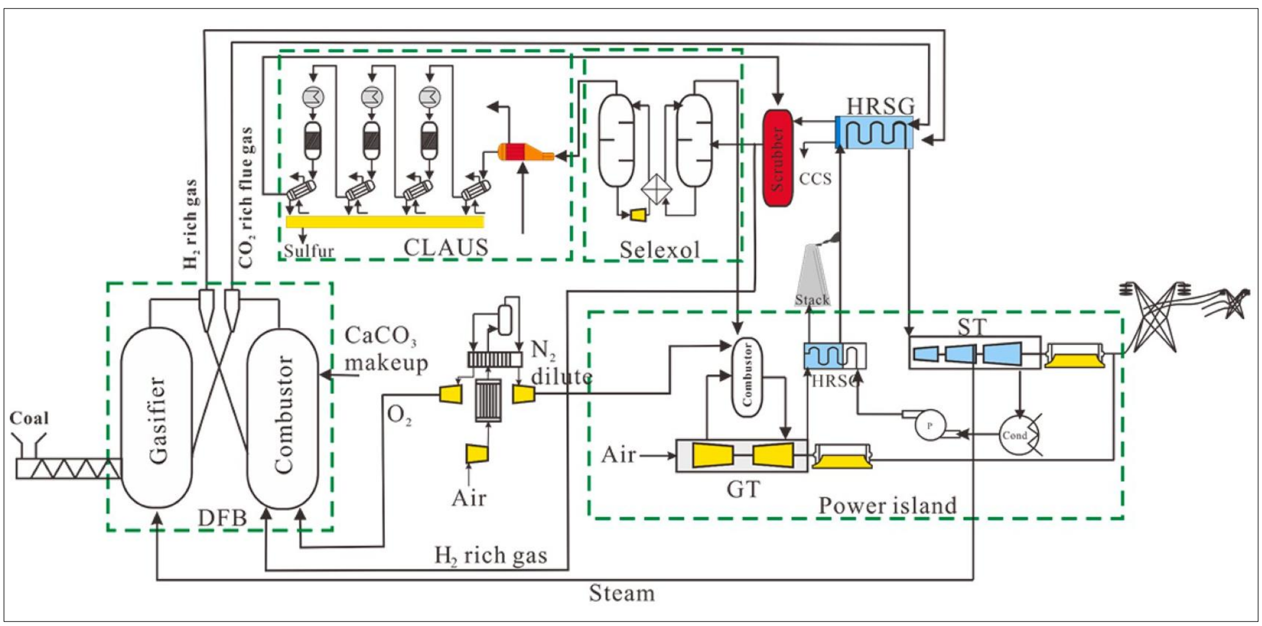

Fig. 9. Flow diagram of SEG system coupled to a secondary power cycle. Source: [53].

Table 5 presents the main CLCG applications in thermal power plants considering the integration of Super Critical CO_2 cycles, Organic Rankine cycles to improve the energy performance and reduction of greenhouse emissions due to the integration of CCS technologies with CLCG processes.

Table 5. Chemical Looping Combustion and Gasification applications in power plants.

Author	Description	Contributions
[54]	Methodology: Design of a 300 MWth power plant integrated with supercritical CO_2 cycles and an Organic Rankine Cycle (ORC) for power generation. Results: A net electrical efficiency of 43.89% was achieved, attaining net-negative CO_2 emissions when the biomass share exceeded 50%.	The study shows that increasing biomass co-firing improves fuel conversion and CO_2 capture efficiency, achieving negative emissions beyond a 50 MWth biomass share while maintaining a net electrical efficiency of 43.89%, establishing a techno-economic pathway for biomass–coal power plants under carbon pricing schemes.
[55]	Methodology: Development of a perovskite-based oxygen carrier for the partial oxidation of methane at temperatures above 900 °C. Results: A syngas selectivity higher than 99% was achieved, with the capability to convert more than 94% of CO_2 or H_2O into carbon monoxide or hydrogen.	The study demonstrates complete methane conversion with >99% selectivity to syngas and the direct utilization of CO_2 or H_2O as oxidants, converting more than 94% into CO or H_2 over more than 4,000 redox cycles, thereby establishing a robust and contamination-free chemical looping route for integrated syngas production and CO_2 utilization.
[56]	Methodology: Integrated system modeling using iron oxide as oxygen carrier, CaO as adsorbent, and biochar as reducing agent. Results: Biochar significantly enhances H_2 yield, while CaO improves gas purity and reduces the reactor thermal demand.	The study integrates biochar and CaO into an iron-oxide looping process simultaneously increases hydrogen yield, improves H_2 purity, and lowers thermal requirements through exothermic carbonation, thereby establishing a flexible and low-carbon thermochemical pathway for high-efficiency hydrogen production from biomass.
[57]	Methodology: Integration of CC and the water–gas shift (WGS) reaction within a single reactor for processing polystyrene waste. Results: Process efficiency increased to 80% (compared to 39% for the conventional route), and hydrogen production cost was reduced by 10%.	The study validates an increasing in the integrated design efficiency to 80% (from 39%), improves exergy efficiency to 82.5%, reduces life-cycle emissions to 4.84 kg CO_2-eq/kg H_2 (64% lower than the conventional route) and lowers hydrogen production cost by 10%, establishing a high-performance waste-to-hydrogen pathway for CC.
[58]	Methodology: Use of integrated tubular reactors for indirect combustion of PSA purge gases. Results: A 5% reduction in the levelized cost of hydrogen (LCOH) was achieved compared with conventional gasification with pre-combustion capture.	The study improves the overall efficiency and enables a 5% reduction in LCOH compared to conventional O_2-blown gasification with pre-combustion capture. This advanced gas treatment can further lower costs by up to 12% for efficient biomass utilization and large-scale carbon removal.

3.1.4. Integrated Gasification Fuel Cell Systems (IGFC)

This technology combines the gasification of coal or biomass with high-temperature fuel cells, such as molten carbonate fuel cells (MCFC) or solid oxide fuel cells (SOFC). MCFCs are particularly innovative because they can simultaneously operate as power generators and CO_2 separators, achieving capture efficiencies of up to 95% and significantly reducing the specific emission intensity per kWh generated. Table 6 presents the main contributions of IGFC from the systematic analysis of the bibliometric database.

Table 6. IGFC systems for high-efficiency power generation and CO_2 capture applications.

Author	Description	Contributions
[59]	Methodology: Simulation of six configurations integrating MCFC systems with cryogenic CO_2 capture and calcium looping (CaL). Results: Integration with CaL achieved a CO_2 capture efficiency of 95% and an emission index low as 110.2 g CO_2/kWh.	The study demonstrates that coupling MCFCs with calcium looping achieves the highest capture efficiency (95%) and reduces the emission index to 110.2 g CO_2/kWh compared to 457.1 g CO_2/kWh for standalone MCFCs, while other configurations (VCC and OMCC) offer superior net electrical efficiencies above 51%.
[60]	Methodology: Biomass gasification plant coupled with SOFCs, CO_2 capture using MCFCs, and waste heat recovery through an Organic Rankine Cycle (ORC). Results: A CO_2 capture rate of 99.2% was achieved, enabling a negative-emissions system capable of removing about 1100 tons of CO_2 annually.	The article integrates steam gasification, solid oxide fuel cells (SOFC), molten carbonate fuel cells (MCFC) for post-combustion CO_2 capture, and ORC-based waste heat recovery. This study establishes a technically and economically assessed pathway for negative-emission electricity generation through fuel cell–integrated CCS systems for the reduction of CO_2 emissions.
[61]	Methodology: System integrating an externally heated gas turbine with an MCFC unit for post-combustion CO_2 capture. Results: An energy efficiency of 50.8% and a levelized electricity price (LEP) of 0.097 $/kWh were achieved, with a CO_2 capture rate of 90%.	The study presents a hybrid configuration can achieve up to 50.8% energy efficiency, generate 16.21 MW of power, while removing up to 112,400 tons of CO_2 per year. By showing both superior energetic and economic performance compared with other biomass-based carbon-negative systems.
[62]	Methodology: Investigation of integrated gasification fuel cell (IGFC) technology and pressure/temperature swing adsorption processes. Results: A cycle was designed capable of simultaneously removing H_2S and CO_2 with removal efficiencies higher than 99.9%.	The article validates gasification kinetics models and analyzes ash behavior with pollutant formation. By integrating advanced gasification, purification, and fuel cell subsystems, this work determines a comprehensive technological framework for high-efficiency, ultra-clean IGFC power plants.
[63]	Methodology: Integration of a gasifier, SOFCs, thermoelectric generators, and photovoltaic–thermal collectors. Results: Net power production of 427.98 MW and hydrogen generation of 101.88 kg/h were	The study demonstrates a multi-energy platform through multi-objective artificial intelligence optimization, establishes performance trade-offs among exergy efficiency, economic indicators, and environmental metrics. This work provides a

	achieved, with an exergy efficiency of 18.51%.	comprehensive system-level framework for designing and optimizing low-carbon plants supporting sustainable energy integration.

Fuel cells convert chemical energy of fuels to electricity at high operating temperatures to achieve adequate conductivity of carbonate electrolyte (MCFC). MCFC requires CO_2 into the cathode to react with O_2 to form an oxidizing gas which reacts with H_2 to produce H_2O and CO_2 enriched in the outlet stream of the anode. MCFC may be applied to concentrate and separate CO_2 for carbon capture in a natural gas-fired combined cycle. Fig. 10 presents the flowsheet of CCPP integrated with MCFC and CO_2 compression [64].

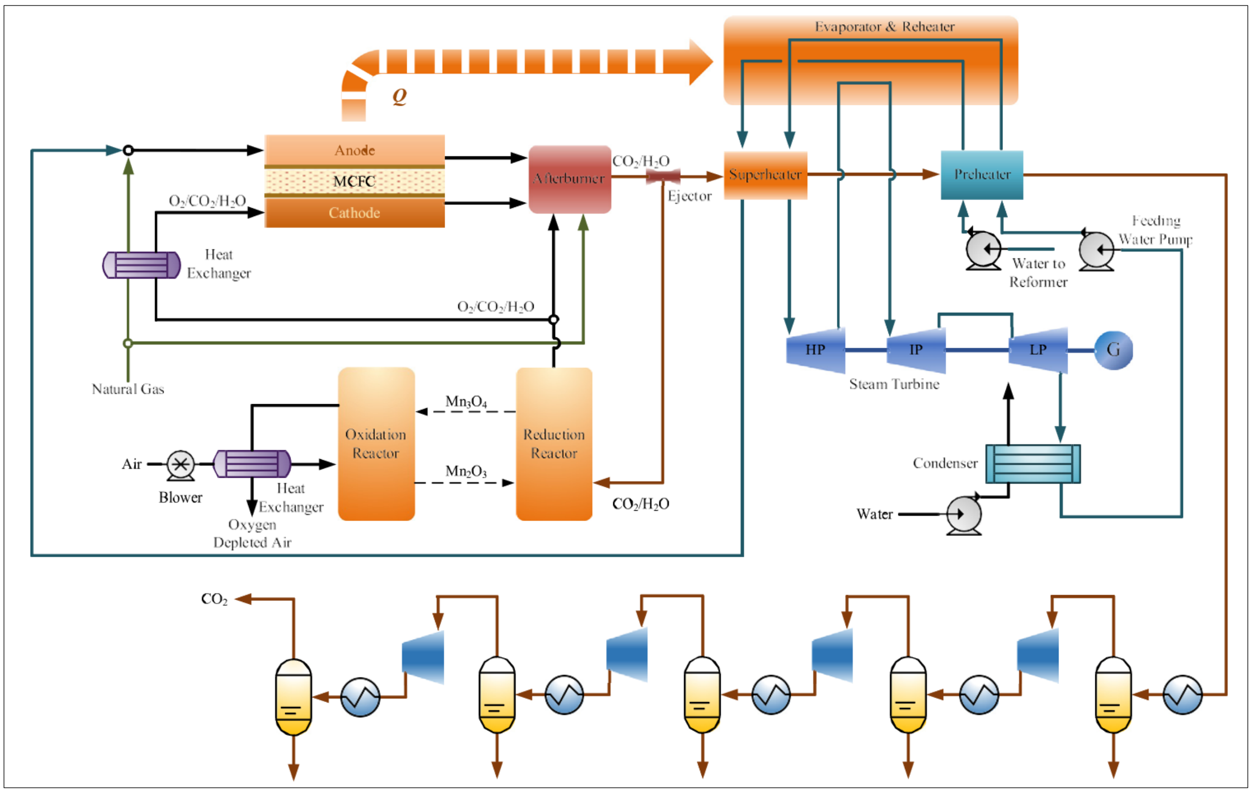

Fig. 10. Flow diagram of SEG system coupled to a secondary power cycle. Source:

3.1.5. Supercritical Water Gasification (SCWG)

SCWC is an advanced alternative for coal-fired power plants, achieving autothermal gasification through the partial oxidation of coal under supercritical conditions. This system enables total CO_2 capture and, when integrated with Organic Rankine Cycles (ORC) to recover residual heat from the turbine exhaust, can achieve energy efficiencies exceeding 52.95%. Compared to conventional coal gasification technologies, SCWG maintains a lower gasification temperature (500 °C to 700°C). The oxidation product of SCWG syngas consists of H_2O and CO_2 with an autothermal gasification generated by the partial oxidation of coal with pure oxygen. In this system, the cooling and gas-liquid separation process generates the CCS [65].

Fig. 11 describes the SCWG power generation system composed of the gasification unit, oxidation and power unit, water preheating unit, ORC and CO_2 capture unit, air separation unit, high pressure turbine, low pressure turbine, and reheater unit [66]. Gasification water is preheated by turbine exhaust, and ORC recovers the waste heat of turbine exhaust in the integration with the SCWG system. In this system, the irreversibility of heat transfer remains in water heat exchanger and ORC accounting for 4.81% and 5.59% of the total loss. The carbon conversion efficiency in SCWG is set to 100% considering a gasified syngas that only contain H_2, CO_2, CH_4, CO, H_2O without a gas cleaning part.

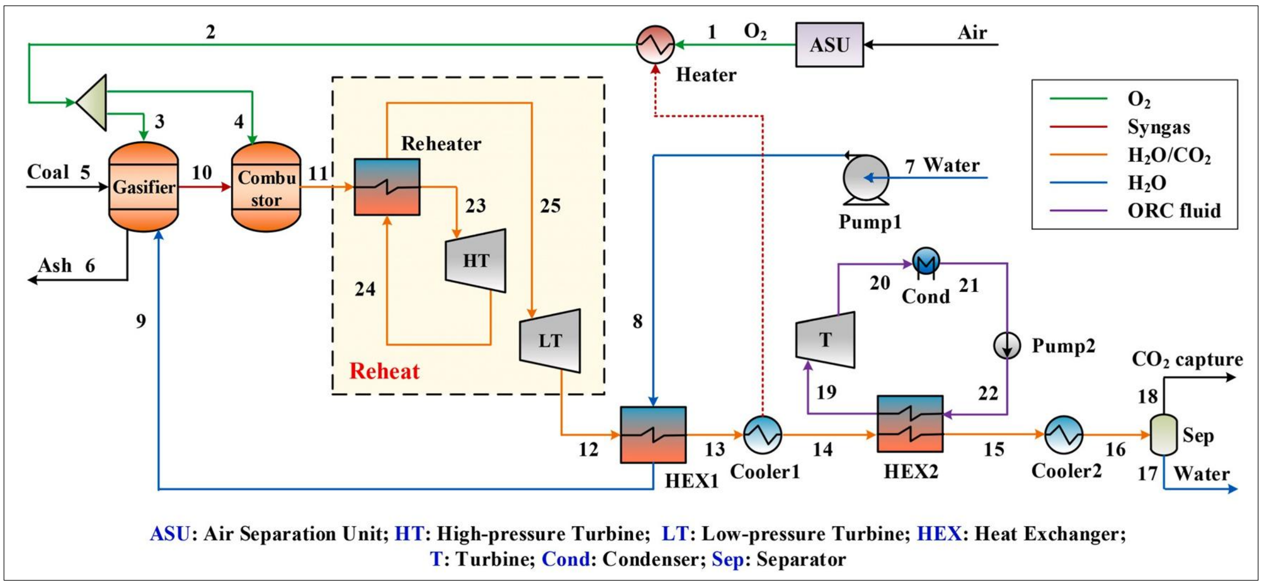

Fig. 11. Flow diagram of SCWG integrated to a power cycle. Source: [66].

Table 7 presents recent studies on the SCWG application for power generation, and CO_2 capture, comparing performance outcomes, energy and exergy efficiencies, carbon capture integration, and waste heat recovery technologies such as ORC, Kalina cycles, thermoelectric generators, and LNG-based heat sinks.

Table 7. Applications of SCWG in power generation.

Author	Description	Contributions
[67]	Methodology: Partial oxidation of coal in supercritical water with full CO_2 capture and waste heat recovery through an Organic Rankine Cycle (ORC). Results: An energy efficiency of 52.95% and an exergy efficiency of 54.11% were achieved, while identifying the gasifier as the dominant source of irreversibility with 41.36% of total exergy destruction.	The article presents the development of a coal-based power generation system founded on supercritical water gasification (SCWG) with complete CO_2 capture and integrated waste heat recovery. This work establishes SCWG as a high-efficiency pathway for near-zero-emission coal power systems and provides clear design guidance for thermodynamic and economic optimization.
[68]	Methodology: Multigeneration system integrating a Kalina cycle, cascade organic Rankine cycles, and thermoelectric generators. Results: An	The article discusses a novel LNG-integrated gas turbine multigeneration system that simultaneously produces electricity, hydrogen, and cooling while incorporating carbon capture

	exergy efficiency of 47.41% was achieved, and the levelized cost of electricity presented a reduction of 7.08 cents/kWh by using LNG regasification as a cryogenic heat sink.	and advanced waste heat recovery. Coupling a high-temperature Kalina cycle, cascade ORCs, and thermoelectric generators with LNG gasification enhances an efficient low- and high-temperature energy recovery.
[69]	Methodology: Integration of a Kalina cycle, Fischer–Tropsch synthesis, and an electrolyzer powered by LNG regasification. Results: Overall energy and exergy efficiencies of 74.21% and 76.41%, respectively, were achieved, enabling the simultaneous production of liquid fuels and methanol.	The article develops a highly integrated LNG-based energy conversion platform combining a Kalina power cycle, Fischer–Tropsch synthesis, organic Rankine cycle, electrolyzer, and methanol production unit. The LNG gasification exploiting for power generation and process integration enables the simultaneous production of electricity, liquid fuels, methanol, and cooling.
[70]	Methodology: Closed-loop regasification system for FSRU units integrating an Organic Rankine Cycle (ORC) and CO_2 capture using monoethanolamine (MEA). Results: Fuel consumption was reduced by 18% and CO_2 emissions by approximately 75% compared to conventional open-loop systems.	The article validates the development of a novel closed-loop LNG regasification system for floating storage regasification units (FSRUs) integrating ORC-based power generation and post-combustion CO_2 capture using MEA. The exploiting LNG of cold energy for both electricity generation and CO_2 capture processes enables the system to fully supply onboard power demand while achieving 90% CO_2 capture efficiencies.
[71]	Methodology: Comparison of membrane-based and cryogenic hydrogen separation integrated with an Organic Rankine Cycle (ORC) for waste heat recovery from water–gas shift reactors. Results: The membrane-based process shows lower energy consumption (0.50 kWh/kg H_2), while the cryogenic route is better due to lower compression costs ($10.2 M vs. $17.7 M).	The article demonstrates that membrane exhibits the highest exergy efficiency (28.4%), whereas cryogenic separation achieves lower capital cost and overall economic advantage. By explicitly quantifying the trade-offs between efficiency, purity, and cost, this work provides a decision-oriented framework to guide the selection of hydrogen separation technologies for advanced syngas processing and hydrogen economy applications.

3.2. Technical overview of syngas production technologies in thermal power plants

A curated set of reports was identified by retrieving relevant documents from the Google Patents and Office of Scientific and Technical Information (OSTI) databases, utilizing the primary keywords previously defined in the systematic analysis of carbon capture (CC), carbon storage (CS), and Fischer-Tropsch synthesis processes applied for syngas fuel production in chemical manufacturing facilities. The quantitative analysis of energy conversion processes incorporating advanced carbon harvesting systems offers valuable insights into the application and advancement of technologies grounded in chemical reactions, as well as their operational requirements for producing hydrocarbons from biomass or renewable feedstocks.

An example of the above is the carbon conversion process greater than 95% with additional advantages in the implementation of sustainable power production plants [72]. The state of the art is based on the application of inventions and syngas production processes. empathizes with the importance of the Fischer-Tropsch synthesis to produce synthetic fuels from biological resources. As mentioned by [73], the Fischer-Tropsch synthesis is a promising option which may replace conventional fuels using a chemical synthesis derived from the biomass extraction. In this sense, Fig. 12 expresses the relationship between the synthetic fuel production (Ton/day) and the temperature of the Fischer-Tropsch processes. The 2D bubble diagram illustrates the production of synthetic fuels as a function of the operating temperature required for syngas production through Integrated Gasification systems, where differential pressures below 3 MPa are typically applied. Particular attention is given to the reaction mechanisms governing hydrogenation and methanol synthesis over Cu/ZnO/Al2O3 catalysts, which play a central role in enhancing the performance of industrial catalytic processes [74]. Within a temperature range of 150 ºC to 600 ºC, several chemical pathways (including hydrogenation, methanation, Cr2O3/ZnO catalysts, Tall Oil Fatty Acid (TOFA) conversion, and methanol synthesis) are identified as relevant routes for synthetic fuel production, with reported capacities ranging from 0.014 Ton/day to 3312 Ton/day. These results emphasize the critical influence of reactor configuration on both fuel yield and product quality [75], [76], [77].

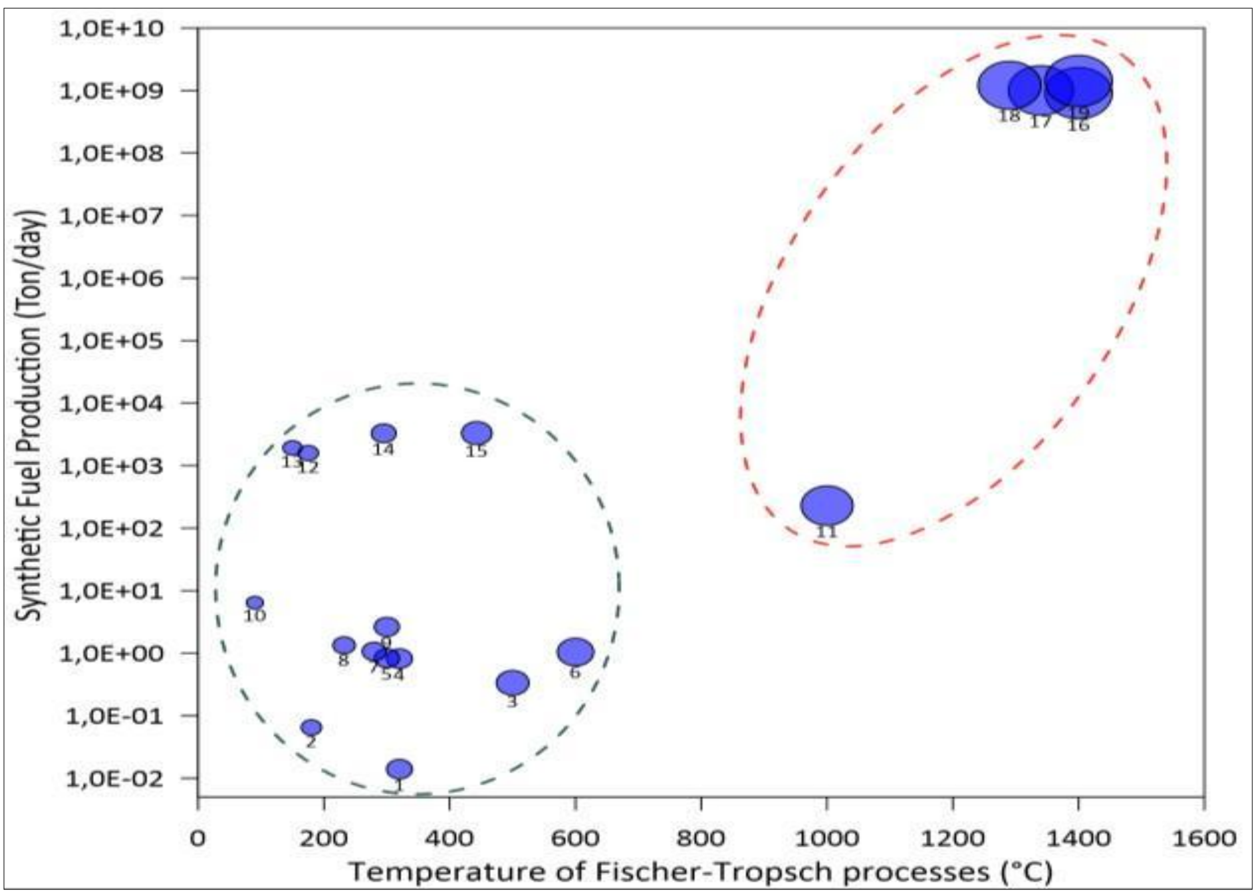

Fig. 12. 2D bubble diagram of technologies for syngas production methods.

The red region in Fig. 12 corresponds to coal gasification plants and flare gas recovery processes, where synthesis reactions are typically conducted at temperatures equal to or exceeding 1000 ºC. Coal gasification systems register the highest synthetic fuel production capacities, reflecting the complexity and scale of the processes and equipment required to convert coal into fuels, with reported capacities ranging from $9.04x10^8$ Ton/day to $1.4x10^9$ Ton/day. Integrated Gasification Combined Cycles (IGCC) are power generation systems designed to maintain high syngas production rates from coal or carbon-based feedstocks for subsequent conversion into turbine fuels in thermal power plants. This technology constitutes a pathway for CO_2 emissions mitigation and is capable of producing 3000 Ton/day of synthetic fuel at operating temperatures between 300 ºC and 400 ºC [78]. The numerical data of this analysis is brief in Table 8.

Table 8. Overview of syngas production methods, temperature ranges, and fuel production scales.

Item	Syngas Production Method	Temp. (°C)	Syngas quantity (Ton/day)
1	Cr2O3/ZnO catalysts for methanol synthesis	320	0.014
2	Cu/ZnO/Al2O3 Catalyst for CH4 Production	180	0.065
3	Methanation with molten salt-based catalyst	500	0.336
4	High-Pressure Gas-Phase Methanol Synthesis	300	0.820
5	Mittash and Schneider of BASF	300	0.833
6	Redox Based system for fuel production	600	1.044
7	CO2 conversion to Hydrocarbons Via Hydrogenation	280	1.070
8	Hydrocarbon fuel synthesized from CO_2.	232	1.340
9	Spinel-Structured ZnCr2O4 with excess Zn Is the Active ZnO/Cr2O3 Catalyst for High Temperature Methanol Synthesis	300	2.64
10	Production of methane/gaseous and liquid hydrocarbons	90	6.43
11	Flare Gas Recovery Alternatives	1000	229.41
12	Tall oil fatty acid (TOFA) from pulp mill tall oil production	175	1591
13	TOFA as HDO feed and synthesis gas from wood slash, waste wood and bark	150	1922
14	Low temperature Shifted syngas on IGCC power plants	303	3288
15	Low-temperature Raw syngas on IGCC power plants	443	3312
16	Raw Syngas of Coal gasification: HT-L	1400	904400000
17	Raw Syngas of Coal gasification: SIEMENS GSP	1350	1003200000
18	Raw Syngas of Coal gasification: ECUST OMB	1300	1208400000
19	Raw Syngas of Coal gasification plant: Shell SCGP	1400	1421200000

CONCLUSIONS

A combined bibliometric and technical assessment of syngas-based power generation systems integrated with Carbon Capture and Storage (CCS) was performed using the PRISMA 2020 framework. A total of 2268 publications from 2020 to 2026 were retrieved from Scopus and Web of Science data base. 115 core documents were selected after removed duplicates, screen and analyze the dataset using VOSviewer and Bibliometrix software. The systematic analysis demonstrated a merging phase between 2020 and 2023, with annual publications increasing from 12 to 28 and citations. China led scientific production with 32 publications and 512 citations, followed by the United Kingdom (≈10%), Iran (≈8%), and the United States (≈8%), confirming a strong concentration of research activity in Asia and Europe.

Keyword co-occurrence analysis identified two dominant research structures: one centered on thermodynamic performance, exergy analysis, and advanced power cycles, and a second focused on syngas processing, catalytic routes, and CO_2 capture technologies.

The technical review identified five recurrent technological platforms: IGCC, SEG, CLCG, IGFC, and SCWG. Reported system performances include net electrical efficiencies up to 43.9% for chemical looping cycles, overall energy efficiencies up to 52.95% for supercritical water gasification systems, and CO_2 capture rates between 95% and 99.2% in fuel-cell-integrated configurations. Emission indices as low as 110 g CO_2/kWh and the feasibility of negative-emission layouts were consistently reported.
From a production-scale perspective, mid-temperature catalytic routes (150°C - 600 °C) achieve synthetic fuel capacities from 0.014 to 3312 ton/day, whereas large-scale coal gasification plants operating above 1000 °C reach capacities close to $1x10^9$ ton/day, evidencing their industrial maturity.

Overall, the combined bibliometric and technical evidence indicates that syngas and CCS systems have reached a level of development supported by measurable efficiency gains, high capture performance, and scalable production potential. Future research should prioritize system integration, exergy-driven optimization, cost reduction, and the deployment of negative-emission configurations.

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