TESIS

Universidad de Jaén

Campus Científico Tecnológico de Linares

PRODUCCIÓN DE ENERGÍA MEDIANTE EL USO DE SISTEMAS COMBINADOS DE CALOR Y ENERGÍA (CHP) CON GASIFICACIÓN DE DESECHOS DE PALMA: CASO DE IRAK

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ENERGY PRODUCTION BY USING COMBINED HEAT AND POWER SYSTEM (CHP) WITH THE GASIFICATION OF PALM WASTES: CASE OF IRAQ

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Brief overview

in 150 words

This Doctoral Thesis explores Iraq's potential for biomass energy and the transformative potential of biomass gasification for distributed cogeneration and heating. It demonstrates the technical feasibility of gasifying palm tree residues in a downdraft gasifier, producing power, heat, and biochar. The development of an intelligent model ensures reliable prediction of producer gas. By proposing an integrated gasification plant as a cost-effective solution for renewable power and waste management, this research reduces environmental impact and fosters sustainability in the palm residue supply chain. The proof-of-concept for decentralized syngas production underscores the advantages of biomass gasification. Overall, this work provides valuable insights into the technical, economic, and environmental benefits of gasification technology, highlighting its potential to transform waste management and drive renewable energy production in the date palm sector.

Breve resumen

en 150 palabras

Esta Tesis Doctoral explora el potencial de Iraq para la energía de biomasa y el potencial transformador de la gasificación de biomasa para la cogeneración y calefacción distribuidas. Demuestra la viabilidad técnica de gasificar los residuos de las palmeras en un gasificador de corriente descendente, produciendo energía, calor y biochar. El desarrollo de un modelo inteligente asegura una predicción fiable del gas de síntesis. Al proponer una planta de gasificación integrada como una solución rentable para la energía renovable y la gestión de residuos, esta investigación reduce el impacto ambiental y fomenta la sostenibilidad en la cadena de suministro de residuos de palma. El concepto probado para la producción descentralizada de gas de síntesis destaca las ventajas de la gasificación de biomasa. En general, este trabajo proporciona valiosos conocimientos sobre los beneficios técnicos, económicos y ambientales de la tecnología de gasificación, destacando su potencial para transformar la gestión de residuos e impulsar la producción de energía renovable en el sector de la palma datilera.

RESUMEN

La intrincada relación entre el consumo de recursos y el medio ambiente es un determinante crucial del funcionamiento biológico, evolucionando como una fuerza impulsora desde la Revolución Industrial. Sin embargo, la creciente escala de explotación de recursos y generación de residuos desafía nuestra comprensión actual de la vida. Medidas urgentes son imperativas para abordar las consecuencias ambientales de las actividades humanas y garantizar la supervivencia en medio de los avances tecnológicos. Esto subraya la necesidad vital de una fuente de energía confiable, rentable y respetuosa con el medio ambiente que beneficie a la sociedad, la economía y el entorno. La adopción contemporánea de la biomasa emerge como una prometedora alternativa de energía limpia, ofreciendo soluciones para mitigar las emisiones de gases de efecto invernadero y reducir la dependencia de los combustibles fósiles.

La creciente demanda de fuentes de energía sostenibles y renovables ha llevado a la exploración de vías alternativas alineadas con la conservación del medio ambiente y la seguridad energética. Esta tesis profundiza en la utilización de residuos de palma para la producción de energía, abordando los desafíos de la gestión de residuos y la necesidad de soluciones respetuosas con el medio ambiente. Irak, un importante actor mundial en la agricultura y exportación de dátiles, se enfrenta a cantidades sustanciales de residuos de palma, incluyendo hojas, racimos de frutas vacíos y troncos. Estos subproductos a menudo pasados por alto poseen un considerable potencial energético no aprovechado. El estudio integra evaluaciones tecnológicas, económicas y ambientales, evaluando la viabilidad y eficiencia de convertir los residuos de palma en energía.

Los sistemas de biomasa a electricidad basados en gasificación destacan por su eficiencia en comparación con sistemas de combustión directa y sistemas basados en carbón de alta eficiencia. Notablemente, estas eficiencias pueden lograrse a una escala más pequeña, ofreciendo una opción atractiva para productores de melaza de dátiles que buscan autonomía. La tesis tiene como objetivo evaluar el potencial bioenergético agrícola de Irak mediante el desarrollo de modelos para plantas de gasificación de pequeña escala de energía combinada y calor. Utilizando residuos de palmas y de la industria de la melaza de dátiles, cálculos termodinámicos evalúan parámetros óptimos de rendimiento. Simulaciones de diseño, utilizando el software de termodinámica Cycle-Tempo, buscan configurar un sistema óptimo de energía combinada y calor de pequeña escala.

SUMMARY

The intricate interplay between resource consumption and the environment is a crucial determinant of biological functioning, evolving into a driving force since the Industrial Revolution. However, the escalating scale of resource exploitation and waste generation challenges our current understanding of life. Urgent measures are imperative to address the environmental consequences of human activities and ensure survival amid technological advancements. This underscores the vital need for a reliable, cost-effective, and eco-friendly energy source benefitting society, the economy, and the environment. The contemporary adoption of biomass emerges as a promising clean energy alternative, offering solutions to mitigate greenhouse gas emissions and reduce reliance on fossil fuels.

The rising demand for sustainable and renewable energy has prompted exploration into alternative avenues aligning with environmental conservation and energy security. This thesis delves into utilizing palm waste for energy production, addressing waste management challenges and the need for eco-friendly solutions. Iraq, a significant global player in agriculture and date palm fruit export, grapples with substantial palm waste, including fronds, empty fruit bunches, and trunks. These often-overlooked by-products hold untapped energy potential. The study integrates technological, economic, and environmental assessments, evaluating the feasibility and efficiency of converting palm waste into energy.

Gasification-based biomass-to-electricity systems excel in process efficiencies compared to direct combustion and high-efficiency coal-based systems. Remarkably, these efficiencies can be achieved on a smaller scale, providing an appealing option for date molasses producers seeking autonomy. The thesis aims to assess Iraq's agricultural bioenergy potential by developing models for small-scale Combined Heat and Power (CHP) gasification plants. Employing residues from palm trees and the date molasses industry, thermodynamic calculations evaluate optimal performance parameters. Design simulations, using Cycle-Tempo thermodynamics software, aim to configure an optimal small-scale CHP system.

Abbreviations

CHP	Combined Heat and Power	LHV	Low Heating Value
HHV	High Heating Value	EFB	Empty fruit bunches
DIG	diesel generators	BG	biomass gasifiers
EU	the European Union's	FAO	Food and Agriculture Organization
MT	Microturbine	LHV_b	The lower heating value of biomass
R_F	The residue factor	C_P	The annual crop production
W_F	the dry-weight factor	A_F	the availability factor
O_C	stands for organic content	B_P	stands for biogas potential
H_N	The number of animal heads	V_F	stands for daily volatile solids
C_S	stands for solid concentration	B_E	stands for biogas yield per kg
E_P	E_P stands for energy potential	M_F	stands for methane-conversion factor
ORC	Organic Rankine cycle	LHV_{pg}	The lower heating value of product gas
C	Carbon	η_{cg}	The efficiency of cold gas
CO	Carbon monoxide	η_{hot}	The efficiency of hot gas
CO_2	Carbon dioxide	PPTD	Pinch point temperature difference
CH_4	Methane	X_{of}	Air-fuel ratio
db	dry basis	Ar	As received
H_2O	Water	H_2	Hydrogen
N_2	Nitrogen	H	Enthalpy
COS	Carbonyl sulfide	B	Biomass
HCl	Hydrogen chloride	W	Water
H_2S	Hydrogen sulfide	m_b	Mass flow rate of biomass
HCN	Hydrogen cyanide	X_{of}	Air-fuel ratio
NH_3	Ammonia	ar	as received
Db	dry basis	PC_{GT}	The mechanical power of the compressor
TIT	Turbine Inlet Temperature		
EFGT	Externally Fired Gas Turbine	P_{th}	Thermal power net
ΔT	Temperature fluctuation about the ambient circumstances,	Π	Pressure ratio
C_p	Specific heat	Mton	Million tons
m_{pg}	Rate of mass flow of product gas	ha	Hectare
Pg	Producer gas	$\dot{m}$	Rate of mass flow of product gas

η_{gen}	Generator's electrical efficiency	GWP	Global Warming Potential indicator
P_{el}	Electrical power	$EFGT_{el}$	Efficiency of EFGT sub-electrical system
P_{pump}	The mechanical energy of the pump	HTHE	High-Temperature Heat Exchanger
kJ	Kilojoules	T_{hs}	Hot side temperature
MJ	Megajoule	gen	Generator’s electrical efficiency

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Chapter 1 Introduction

1.1 Objectives of Thesis

The main goal of this work is to address environmental and climate concerns by adopting modern, renewable energy, and waste management practices. It focuses on efficiently and sustainably tapping into Iraq's organic materials for energy production through biomass gasification, which converts materials like wood and agricultural residues into syngas. The following goals are the focus of the current thesis:

1. To assess Iraq's capacity for bioenergy and research sustainable electricity generation in the country: This objective focuses on understanding Iraq's potential for bioenergy and exploring methods for sustainable electricity generation.
2. To investigate the prospect of generating sustainable electricity in Iraq using biomass resources, such as agricultural remnants and organic waste, through combustion and gasification processes: This objective involves examining the feasibility of using biomass resources for electricity generation, especially in areas abundant in palm waste and crop residues.
3. To develop an effective approach to generating electricity from palm waste by determining the optimal waste material through simulations: This objective aims to identify the most suitable palm waste components for electricity generation through simulations and gasification processes, utilizing software tools like Cycle Tempo for modeling.
4. To demonstrate that biomass gasification technology is a successful valorization technology for the generation of energy (CHP) for medium- to small-scale applications: This objective focuses on showcasing the effectiveness of biomass gasification technology for energy generation, particularly in medium- to small-scale applications like Combined Heat and Power (CHP) systems, with the support of software like Cycle Tempo for analysis and simulation.

1.2 Introduction of Energy

Energy is the lifeblood of our modern world, driving everything from our daily activities to global industries. Whether it's the electricity lighting up our homes, the fuel propelling our vehicles, or the sunlight nurturing our crops, energy is omnipresent and indispensable. Understanding its sources, transformations, and efficient utilization is paramount for sustainable development and ensuring a prosperous future for generations to come.

Sustainable development encompasses various aspects and can be described as a type of development that meets current requirements while ensuring the capacity to meet future ones. In 2015, the United Nations introduced the Sustainable Development Goals (SDGs), which consist of 17 global objectives aimed at achieving inclusive and sustainable economic, social, and environmental well-being for all. These SDGs collectively aim to enhance the overall quality of life by fostering global economic growth while preserving the environment's integrity [1]. As a result, development planners worldwide are increasingly focused on identifying strategies and mechanisms that can promote both economic growth and environmental sustainability on a global scale [2]. The sustainable development goals provide a comprehensive framework for addressing urgent issues such as climate change. To achieve the target of limiting global warming to 1.5°C, it is crucial to swiftly adopt renewable energy sources across all sectors of energy consumption and production. Bioenergy plays a vital role in rapidly reducing carbon emissions in various areas like industry, transportation, heating, and cooking. Bioenergy can serve as a substitute for fossil fuels and be utilized as a raw material in industrial processes. According to IRENA's 1.5-degree scenario, meeting the 1.5°C climate goal requires a substantial fourfold increase in primary biomass supply, reaching 153 EJ by 2050 compared to current usage. Additionally, there is growing evidence that Europe aims to fully decarbonize its energy sector by the mid-2030s to stay within the 1.5-degree Celsius limit [3]. Over the past few decades, many nations have shown an increasing inclination towards harnessing and investing in renewable energy sources to generate electricity and mitigate the impacts of climate change. According to the primary scenario projection from the International Energy Agency, the annual increase in global renewable power capacity is anticipated to average about 305 GW between 2021 and 2026.

During this projected period, Asia is expected to surpass Europe's total biofuel production, primarily due to strong domestic policies, rising demand for liquid fuels, and a focus on export-oriented production. Asian countries are poised to contribute approximately one-third of the new production during this period. The implementation of blending targets for biodiesel in Indonesia and Malaysia, along with India's ethanol policies, plays a crucial role in driving this growth. By 2026, North America is set to experience the most significant growth in biofuel demand, with around 40% of this increase attributed to the recovery of demand following the declines caused by the COVID-19 pandemic. The United States and Brazil continue to be the leading centers for both biofuel demand and production [4].

If countries fully adhere to their Nationally Determined Contributions, long-term low greenhouse gas emission development strategies, and net-zero targets, it is possible to achieve a 6% reduction in carbon dioxide (CO_2) emissions by 2030 and a 56% reduction by 2050, compared to the emission levels recorded in 2022 [5]. The global transition to a low-carbon economy is primarily driven by the urgent need to combat global warming and the diminishing reserves of fossil fuels. This transition reflects a growing global commitment to protecting the environment from the adverse impacts of climate change, leading to increased support for decentralized renewable energy resources.

Conventional large-scale power plants, with their centralized approach and long-distance energy transmission, suffer from drawbacks such as energy loss during distribution and a heavy reliance on large power facilities, compromising energy security. To address these issues, small-scale renewable energy technologies are becoming increasingly important in electric power distribution systems. However, the move towards decentralized electricity generation, often involving intermittent energy production, presents challenges in matching energy supply with fluctuating demand. Biomass is one of the few renewable energy sources capable of adapting its supply to meet demand. To maximize the efficiency of biomass use, distributed cogeneration, known as CHP (Combined Heat and Power), simultaneously generates electrical and thermal energy in a decentralized manner, closer to consumers. This approach minimizes thermal losses associated with heat transport and storage, making it a promising solution for more sustainable and efficient energy production and distribution systems.

Biomass gasification technology is gaining popularity for decentralized cogeneration and small-to-medium-scale renewable hydrogen production. Gasification is a thermochemical process that converts solid carbonaceous feedstocks like biomass into a gaseous fuel. It enables energy transfer to the gas phase, leaving solid biochar and liquid tar as by-products. Gasification offers versatile options for electricity and heat generation, serving as a substitute for natural gas, generating power with internal combustion engines (ICE) or gas turbines, and producing hydrogen-rich gases for fuel cells or chemicals. Agro-industrial activities, which often generate waste and byproducts, can benefit from proper biomass management, enhancing overall sustainability.

Agro-industrial activities generate significant amounts of waste and by-products worldwide while consuming substantial electrical and thermal energy. Mismanagement of these by-products poses challenges to the overall sustainability of the agro-industrial sector. This issue is particularly evident in the case of palm cultivation, which is highly concentrated in Asia, accounting for 55.8% of global production, followed by Africa at 43.4%. The Arab region contributes over 77% of global date production, approximately 6.6 million tons annually. Date palms (Phoenix dactylifera) have historical and cultural significance in Iraq, as the country is known for its long-standing tradition of date cultivation. The date harvest process generates by-products like fronds, empty fruit clusters, and fiber, which are produced on farms, as well as pits and pomace are produced during milling and date molasses production. Biomass gasification technology offers an efficient way to optimize and utilize these by-products, allowing the industry to become self-sufficient in electrical and thermal energy production, which, in turn, can lead to economic benefits. Additionally, this technology provides a gateway to new business models, potentially generating income through the production of syngas rich in hydrogen and combustible carbon monoxide. However, the advantages of gasification extend beyond economic gains. By enhancing the energy value of organic by-products that would otherwise become waste, this technology can also have positive environmental effects by addressing waste management issues and reducing environmental impact. This research centers on agricultural waste biomass, which is abundant but not fully harnessed in the realm of energy generation. Since the economies of developing countries heavily depend on forestry and agriculture, there is a growing interest in using biomass as an alternative energy source. In Europe, less than half of the available biomass is currently being utilized.

In addition to biomass energy, nuclear energy stands out as a prominent alternative energy source worthy of consideration in addressing the world's growing energy needs. Nuclear energy harnesses the power of nuclear fission to generate significant amounts of electricity, offering a relatively low-cost and low-carbon option compared to fossil fuels. However, it also presents unique challenges such as safety and security risks, nuclear waste management issues, and public perception concerns. Despite these challenges, nuclear energy has the potential to play a significant role in diversifying the energy mix and reducing greenhouse gas emissions. Its integration alongside biomass energy could offer a balanced approach to sustainable energy production, provided that stringent safety measures and effective waste management strategies are implemented.

In essence, this doctoral dissertation delves into the use of biomass gasification for generating combined heat and power as well as producing syngas on a large scale. It places particular emphasis on the use of agro-industrial waste from the date sector. The goal is to establish a robust scientific foundation and work towards potential commercialization, aiming to replace conventional systems for producing heat, electricity, and hydrogen that rely on fossil fuels. Moreover, these applications aim to contribute to an eco-friendly and sustainable energy landscape, in line with the Sustainable Development Goals established by the United Nations in 2015.

1.3 The State of Energy in the World

The world's energy consumption is projected to rise by 50% by 2050 because of rising energy demand. Globally, most energy consumption is attributed to oil, with coal, gas, and hydroelectricity following closely behind. Fossil fuels remain the primary components of the world's energy mix, accounting for 82.28% of total energy usage. Figure 1-1 illustrates the distribution of global energy consumption by source in 2022.

Recent years have seen a rise in interest in renewable energies due to the depletion of fossil fuels and rising global energy demand. In 2022, renewable energy sources comprised 40% of the total installed power capacity worldwide [6].

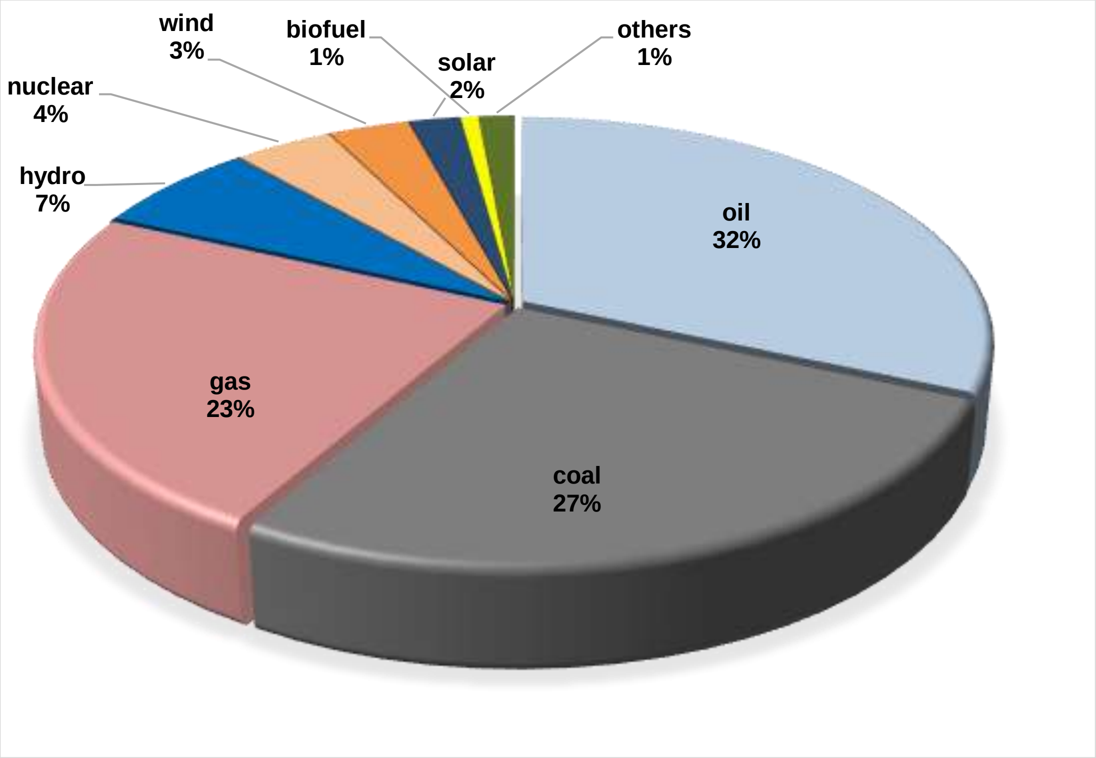

Figure 1-1 Global Primary Energy consumption by source 2022 [7]

Fossil fuels continue to be a part of Europe's energy mix despite efforts to transition to greener energy sources. Natural gas is considered a transition fuel due to its lower emissions compared to coal and oil. However, efforts are underway to decrease dependence on fossil fuels and transition to more sustainable alternatives where Europe has been making significant progress in renewable energy deployment. Countries like Germany, Spain, and the United Kingdom have been investing heavily in wind and solar power. Other renewable sources, such as hydroelectricity and biomass, also contribute to the energy mix in various European nations. Europe is a global leader in wind power capacity. Offshore wind farms have been established in the North Sea and the Baltic Sea, while onshore wind farms are prevalent in countries like Germany, Spain, and the United Kingdom. Wind energy plays a vital role in reducing greenhouse gas emissions and increasing energy independence [8]. Figure 1-2 shows the percentage of energy consumption in Europe by source[9], [10].

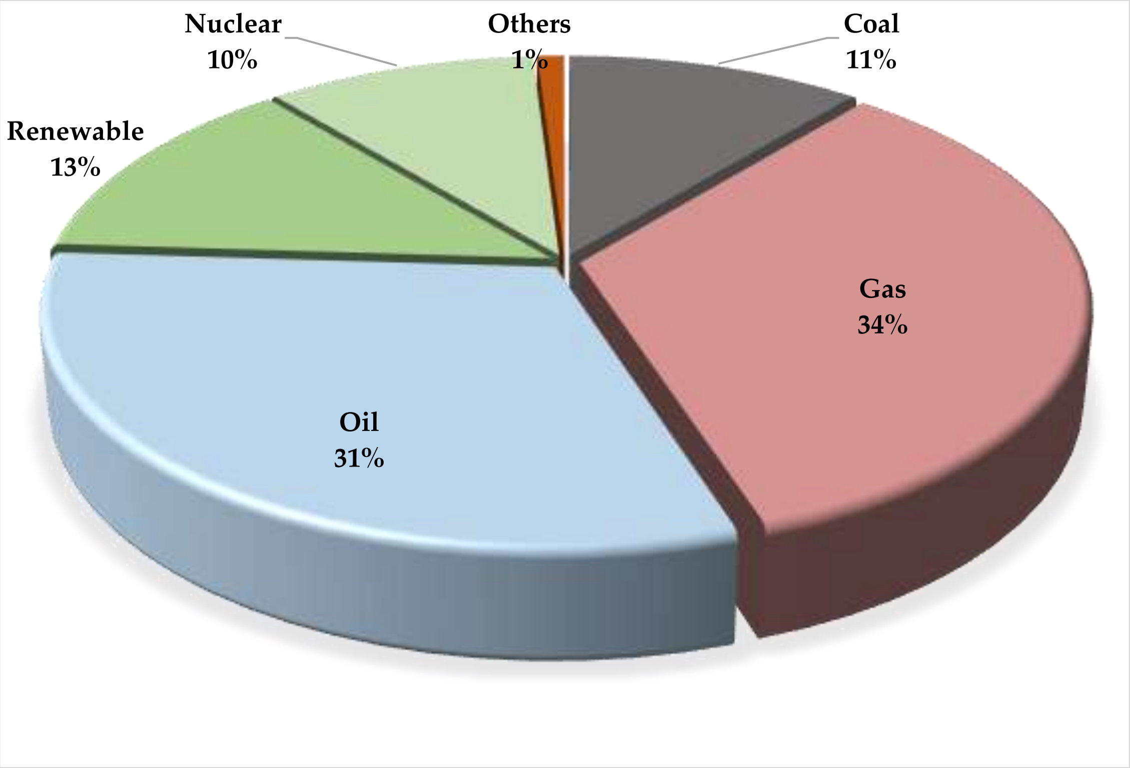

Figure 1-2 Primary energy consumption in Europe 2021 [9]

Iraq possesses a significant number of untapped energy sources, making it a country with great potential. Nevertheless, the energy resources currently accessible in Iraq are restricted to oil and gas, which serve as the primary fuels for power generation. The energy consumption in Iraq, as depicted in Figure 1-3 was predominantly driven by oil, which accounted for the majority at 70%. The remaining portion of the country's total energy consumption was supplied by gas (29%) and hydropower (1%) [11]. These energy sources are being harnessed to meet Iraq's growing energy demands and diversify its energy mix, with a growing emphasis on renewable energy development alongside traditional fossil fuel resources.

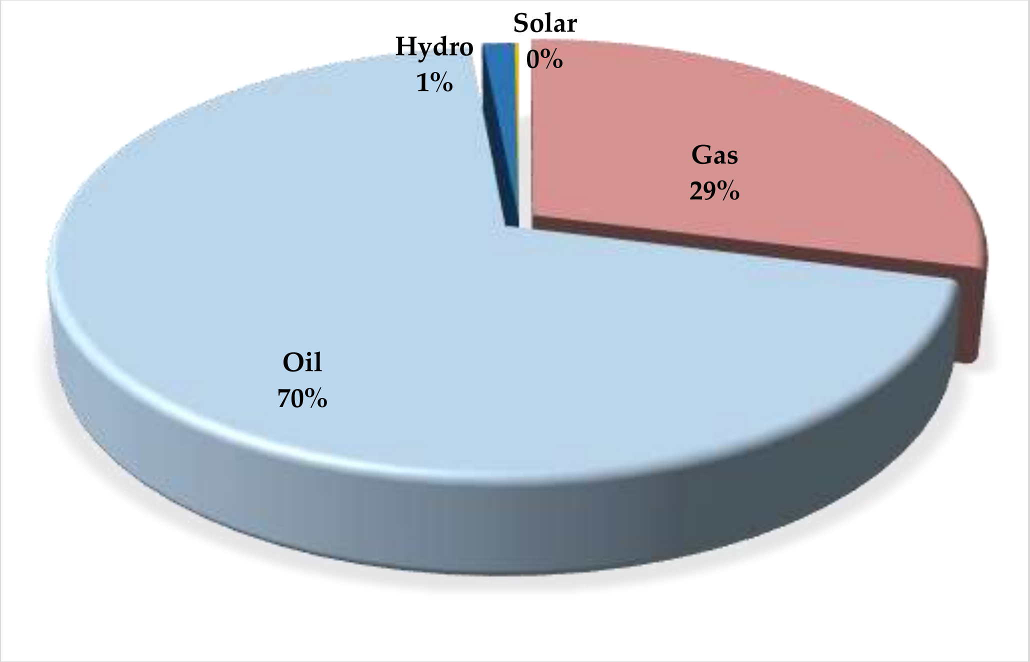

Figure 1-3 Primary Energy Consumption in Iraq 2022 [11]

1.4 The Renewable Energy Sector in Iraq

Iraq stands as one of the nations with tremendous potential for harnessing renewable energy. It can generate renewable energy from various sources, including hydropower, solar energy, biomass, and wind. Moreover, its vast desert regions make it an ideal location for renewable energy projects. However, its heavy reliance on oil as the primary energy source has hindered the exploitation of these resources. To ensure energy security and continuity, the government has formulated a comprehensive, long-term energy strategy. This plan aims to increase the contribution of clean energy sources in the power industry, thereby enhancing the role of renewable energy in electricity generation. Incorporating renewable energy sources in Iraq presents the opportunity to address the potential disparities in energy distribution, achieve continuous and sustainable energy supply, and reduce greenhouse gas emissions. As a result, researchers predominantly focus on designing and developing distributed energy resources based on renewable sources, particularly in rural areas. These resources include solar photovoltaic, wind turbines, diesel generators (DIG), biomass gasifiers (BG), fuel cells, and battery banks, among others, which are crucial for supplying the required loads [12].

The Renewable Energy Investment Program and the plan to increase the clean energy share to 33% by 2030 are examples of government efforts. Despite the potential, there are challenges to the widespread adoption of renewable energy in Iraq.

1.4.1 Solar Energy

Solar Energy: Iraq has vast solar resources due to its location in a sun-rich region. Solar power is increasingly being tapped into for electricity generation, particularly through the development of solar farms and rooftop solar installations. Iraq was one of the first Arab countries to express interest in solar energy utilization. In 1977, it introduced the first solar module. In 1980, it established a renewable energy research center and began working on several initiatives, including thermal conversion of solar energy, water desalination, and agricultural goods drying [13]. Due to its advantageous location in the world's solar belt, Iraq benefits from more than 3000 hours of bright sunlight annually, with an average daily sunshine time of 11–12 hours in the summer and 7-8 hours in the winter. Daily solar radiation averages around 5 kWh/m^2 [14], [15].

Nowadays Iraq wants to increase the number of renewable energy installations. At the end of 2022, the Federal Government Program was intended to generate 1000 MWp of solar energy. According to the Ministry of Electricity, 40% of Iraq's electricity will eventually come from geothermal, waste-to-energy, and wind sources. Iraq has set a goal of increasing renewable energy generation to 10 GW by 2030. In 2021, solar energy represented about 2% of the overall renewable energy in Iraq [16].

1.4.2 Wind Energy

Certain regions of Iraq have favorable wind conditions, particularly in the southern and western parts of the country. Wind farms are being established to harness wind energy and contribute to the electricity mix. Utilizing wind energy is not a recent development. It spans countless years of human existence on Earth wind energy is used by windmills and ships. In Mesopotamia during the reign of Hammurabi in 1700 B.C., machines first used wind energy. They have been able to use recycled waterwheels in irrigation to make use of wind energy [17]. Some of these waterwheels are still seen today on the Euphrates River. Recent years have seen a significant increase in the use of wind energy, which is also one of the technical advancements that have significantly altered the global energy landscape. Iraq is one of the most significant nations with good wind energy potential. The studies showed that Iraq's wind-dominated regions had an average energy density of 287.2 W/m^2 [18].

1.4.3 Hydro-Energy

Early in 1950, the Iraqi government began constructing dams to lessen the effects of flooding and to advance the nation's agricultural industry. In 1971, the first hydropower station named Dokan began to feed the national grid network. It used 84 MW of installed electricity at first, then raised it to 400 MW [19]. With a combined original capacity of roughly 2500 MW, Iraq has five major hydroelectric projects. It is hard for hydroelectric plants to produce energy continuously and steadily since so many elements impact them. The height of the water that has been stored in the dam, which is determined by the rate of rainfall, is one of the variables. Because dams in Iraq are also used for irrigation, drought years, which regularly occur in Iraq, cause the stored water to be used up more quickly [20].

1.4.4 Biomass Energy

Biomass and Waste-to-Energy: Biomass resources, such as agricultural residues and organic waste, can be utilized for energy production. Additionally, waste-to-energy technologies are being explored to convert solid waste into electricity or heat. Biomass is seen as a clean and sustainable energy source that will aid in biodiversity preservation, ecosystem sustainability, and environmental protection. The amount of combustible gas components, such as methane, carbon monoxide, and hydrogen, determines the biogas' thermal value. The entire area in Iraq that was under cultivation in 2021, including permanent pastures, permanent crops, and arable land, was around 1.25 M ha, additionally, forests made up an area of 220 ha, or roughly 1.3% of the country's total area [21]. Although there are many sources of biomass available, they are disposed of in ways that hurt the environment, so Iraq is considered one of the poorest countries in terms of using biomass to generate energy [22]. Given that each ton of crops generates 5 to 6 tons of garbage, agricultural wastes are regarded as the most significant sources of biomass [19]. Farmers typically burn agricultural wastes to get rid of them, but this has a negative influence on the biological elements and organic soil because it alters the characteristics of natural and chemical soil [20]. By building localized bioenergy stations based on biomass-specific resources, biomass resources might be seen as a feasible response to the energy deficit [22]. By using certain current and suitable technologies, biomass may also be used in gas or diesel plants. These facilities not only provide electricity but also aim to lessen the negative environmental consequences of garbage burning and generate new jobs [23]. Numerous thermodynamic conversion processes, including gasification technology and direct burning, may be used to turn biomass feedstock into fuel [15].

1.5 The Non-renewable Energy Sector in Iraq

Iraq is known for its significant oil reserves, and the non-renewable energy sector in the country primarily revolves around oil and natural gas. Here are some key aspects of the non-renewable energy sector in Iraq:

1.5.1 Oil

Iraq has abundant reserves of oil, and it is one of the world's major oil producers. The average daily Iraqi oil production was around 3.7 million barrels per day (bpd) [24]. Iraq's proven recoverable oil reserves were estimated to be 145 billion barrels, accounting for 8.4% of the world's total reserves and ranking second in the Middle East, according to the BP Statistical Review of World Energy for the Year 2020. Most of Iraq's electricity is produced by thermal and gas power plants. There has been a notable rise in the consumption of these primary energy sources in Iraq, as depicted in Figure 1-4 [25].

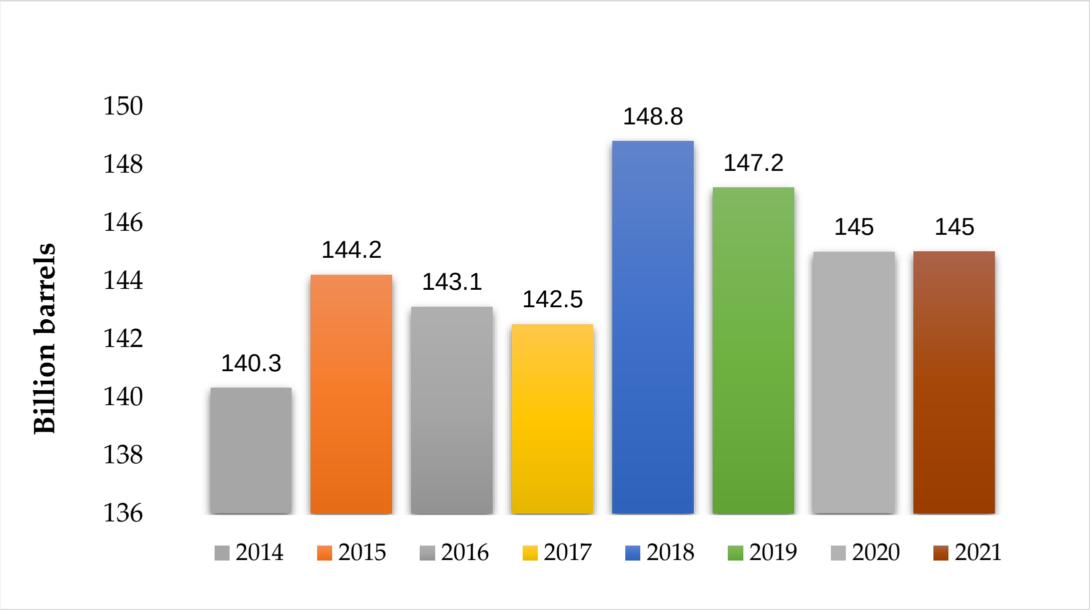

Figure 1-4 Oil production reserves in Iraq, (billion barrels)

1.5.2 Natural Gas

Iraq also possesses significant natural gas reserves. Natural gas is used for power generation, industrial purposes, and as a feedstock for petrochemical industries. Natural gas production has been increasing in recent years, driven by associated gas produced during oil extraction. Natural gas is currently considered the Iraqi economy's second most important raw material. Flaring of natural gas during oil production is a common practice, leading to environmental concerns and energy waste. At around 132 trillion cubic feet (Tcf), Iraq's proven natural gas reserves ranked 12th in the world as of the end of 2020. Most of this related natural gas is in the supergiant fields in the south and makes up around three-quarters of Iraq's natural gas reserves [2]. Iraq still faces challenges in capturing and utilizing its natural gas resources effectively [26].

1.5.3 Nuclear Energy

Nuclear Energy is considered A Powerful Player in the Global Energy Landscape. Nuclear energy has been a subject of both fascination and controversy since its inception. As the world grapples with the urgent need to transition to sustainable energy sources, nuclear power has emerged as a key player in the quest for a low-carbon future. Nuclear energy has established a significant presence on the global stage, contributing to the energy mix of numerous countries. Currently, over 440 nuclear reactors are operating in 30 countries, producing approximately 10% of the world's electricity. Prominent examples of nuclear energy adoption include the United States, France, China, and Russia [27]. One of the primary advantages of nuclear power lies in its ability to generate large amounts of electricity with minimal greenhouse gas emissions. Unlike fossil fuels, nuclear power does not produce carbon dioxide during the electricity generation process, making it an attractive option for nations aiming to reduce their carbon footprint.

Nuclear power plays a crucial role in mitigating climate change by providing a low-carbon alternative to traditional fossil fuels. The absence of direct CO_2 emissions during electricity generation positions nuclear energy as a key contributor to decarbonizing the global energy sector. Nuclear reactors offer a stable and consistent supply of electricity, making them ideal for providing baseload power – the minimum amount of electricity required to meet the constant demand. Unlike some intermittent renewable sources, such as solar and wind, nuclear power can operate continuously, ensuring a reliable energy supply. Nuclear energy contributes to energy security by diversifying the energy mix and reducing dependence on finite fossil fuel resources. This diversification helps nations maintain a stable energy supply and reduces vulnerability to geopolitical uncertainties affecting oil and gas markets [28]. Despite its advantages, nuclear energy faces challenges and concerns that have led to public skepticism. Issues such as the potential for accidents, nuclear waste disposal, and the proliferation of nuclear weapons have raised legitimate concerns among communities and policymakers. Addressing these challenges is essential to building public trust and ensuring the safe and responsible use of nuclear technology. Given that nuclear reactors contribute to approximately one-third of the world's carbon-free electricity, they play an indispensable role in advancing climate change mitigation objectives. This growth in the nuclear energy sector is a result of its notable efficiency and positive environmental characteristics [11].

While nuclear energy has proven itself as a reliable and low-carbon energy source, it exists alongside renewable energy technologies in the broader effort to combat climate change. The comparison between nuclear and renewable energy often revolves around factors such as cost, safety, and public acceptance. Renewable energy sources, including solar, wind, and hydropower, have gained popularity due to their clean and sustainable nature. These sources harness energy from natural processes without producing greenhouse gas emissions. However, they also face challenges such as intermittency, geographical limitations, and the need for energy storage solutions. The synergy between nuclear and renewable energy could provide a comprehensive solution to the world's energy needs. By combining the steady output of nuclear power with the flexibility and sustainability of renewables, countries can achieve a well-rounded and resilient energy portfolio.

In the pursuit of a sustainable energy future, nuclear power stands as a formidable ally alongside renewable energy sources. Its ability to generate large amounts of electricity with minimal carbon emissions makes it a vital player in the global energy landscape. However, addressing safety concerns, improving waste management practices, and fostering public acceptance is essential for unlocking the full potential of nuclear energy. A balanced approach that integrates nuclear and renewable technologies can create a resilient energy infrastructure capable of meeting the growing demands of our planet while minimizing environmental impact.

Iraq currently lacks an active nuclear power program. The nation has encountered various obstacles, such as political instability, conflict, and economic challenges, which have impeded the establishment of a robust and all-encompassing energy infrastructure, including nuclear power.

1.6 The State of Electricity Generation in the World and Iraq

The global electricity demand has been steadily increasing due to factors such as population growth, urbanization, and economic development. This trend is expected to continue as more countries and regions strive to improve their living standards and increase access to electricity. The state of electricity generation in the world is constantly evolving and can vary from region to region. Electricity constitutes a significant portion of the overall energy production, alongside transport and heating. The composition of energy sources, including coal, oil, gas, nuclear, and renewables, differs between electricity generation and the broader energy mix. Typically, the global electricity mix comprises a higher proportion of low-carbon sources such as nuclear power and renewable energy compared to the overall energy mix.

As we examine our present energy mix and investigate the sources we utilize, Figure 1-5 illustrates the breakdown of the electrical energy based on fuel or generation source. On a global scale, our predominant energy source is oil, followed by coal, gas, and hydroelectric power. Notably, other renewable sources are experiencing rapid growth.

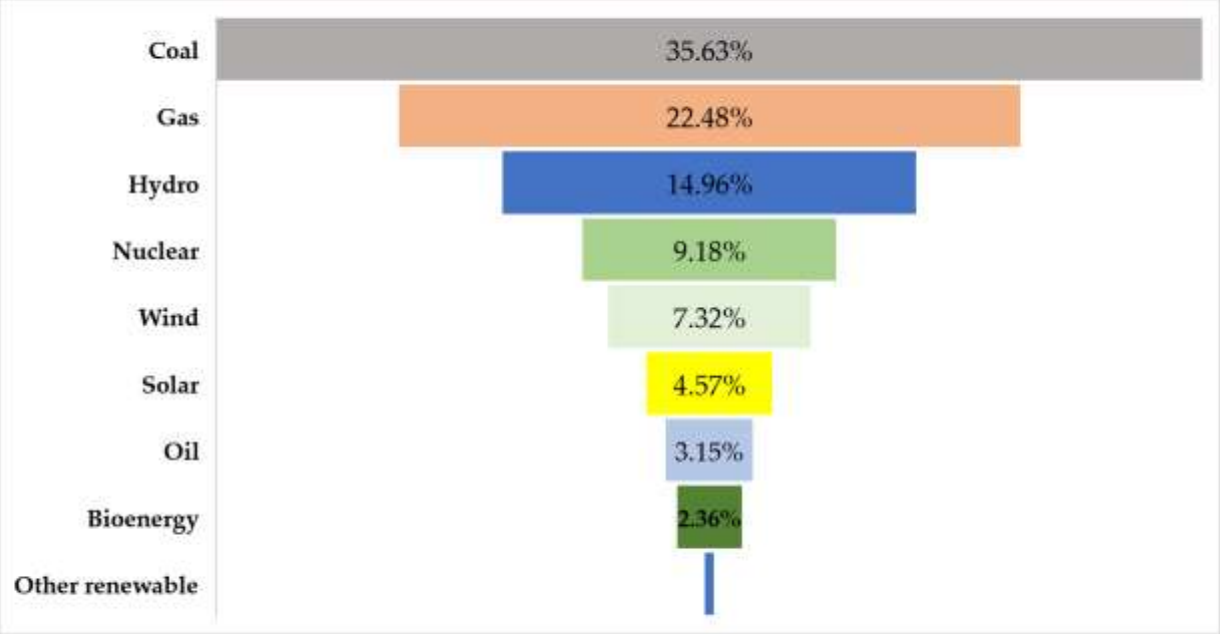

Figure 1-5 Global Electricity Production by Source 2022 [29]

The focus on cost-effective electricity generation has led to a growing interest in utilizing renewable energy sources. However, projections are indicating that by 2030, green energy sources such as solar power, wind power, hydroelectric power, geothermal energy, and biomass energy will contribute around 38% of the world's electricity production [30].

In the European Union (EU), fossil fuels continue to contribute significantly to the production of electricity. Coal, gas, and other fossil fuels collectively account for 39% of the region's electricity generation. Specifically, gas generates 20%, coal produces 16%, and other fossil fuels contribute 3.6%. Nuclear power retains its position as the primary source of electricity in the EU, constituting 22% of the energy mix. In the year 2022, solar and wind energy outpaced gas as the main contributors to the European Union's (EU) electricity production, constituting 22% of the total. Solar power accounts for 7.3%, while wind power contributes 15%. The remaining energy comes from hydro (10%), bioenergy (6%), and other renewables (0.2%), Figure 1-6 shows the percentage of Electrical energy generated in Europe by source in 2022 [31]. The production of bioenergy has experienced significant growth since 2000, increasing from 30 TWh to 167 TWh in 2022. During this period, its share in the EU's power mix rose from 1.2% to 6% in 2022. However, the pace of growth has decelerated, with only a 12% increase in production between 2015 and 2022. Since the signing of the Paris Agreement in 2015, the average yearly growth rate of bioenergy has been 1.6%, significantly lower than the sector's 11% average annual growth rate in the EU between 2000 and 2015. Despite the slowdown, the market share of bioenergy in the EU's power generation has slightly increased from 5.2% to 6% since 2015. Estonia stands out with the highest market share growth, as bioenergy in its power mix increased from 8% to 30% since 2015 [32]. Contemporary biomass utilization emerges as a highly promising option for clean energy.

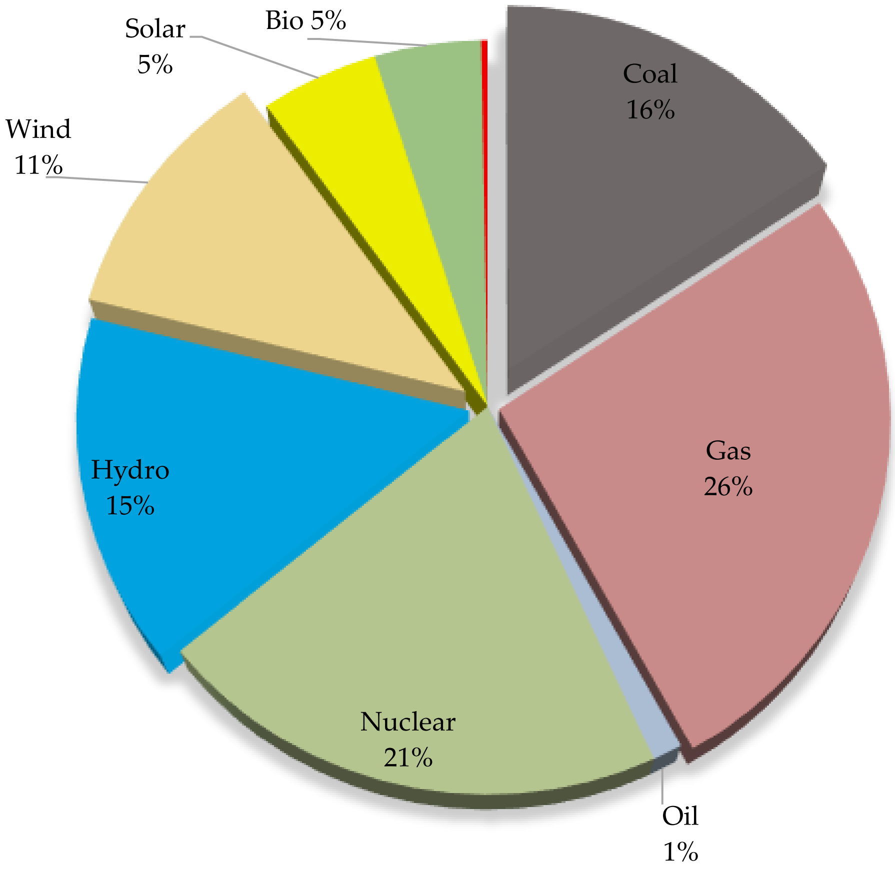

Figure 1-6 Electrical energy generated in Europe by source 2022 [30]

The EU's Energy Transition in Fast Forward following Russia's invasion of Ukraine, achieving energy independence within the EU has become a critical priority, prompting countries to expedite their shift toward renewable energy sources. According to a recent report by Ember [32], the transition made significant strides in 2022, as solar and wind power (22%) surpassed natural gas (20%) in electricity generation for the first time. Although there was a slight increase in fossil fuel electricity generation in the EU in 2022, Ember predicts a decline of up to 20% in 2023. If the EU can sustain this accelerated departure from fossil fuels, the future landscape of primary energy sources for electricity generation may feature a much larger presence of renewable and low-carbon energy sources. Iraq relies heavily on fossil fuels for over 94% of its power generation, posing a significant challenge due to unsustainable demand growth, inadequate investments, and lack of reforms in power generation, transmission, and distribution. This has led to a widening gap between electricity supply and demand. To address environmental concerns, renewable energy emerges as a key solution. The Iraqi government is actively formulating policies to develop the electricity sector, diversify energy sources, and attract investment in renewables, aiming to meet growing energy demand, enhance renewable energy's role, and ensure energy security. Iraq's diverse geographic resources position it favorably for renewable energy development.

In recent years, Iraq has made significant efforts to increase its share of renewable energy sources. Hydropower and solar energy are the most common renewable sources contributing to the energy mix in Iraq. The government has set a target to reduce emissions through renewable energy by 2025, and contracts have been signed with international companies to support solar energy projects. The Ministry of Electricity has presented a new plan to increase electricity production, which will be implemented soon. Accelerating the adoption of renewable energy sources and improving energy efficiency are crucial strategies to achieve 2050 Iraq's climate goals and meet the energy demands of future development. The government aims to determine the optimal energy mix, increase reliance on renewable energy, and enhance energy usage efficiency [21], [16]. Iraq possesses a significant foundation for renewable energy, including ample solar irradiance, favorable wind speeds in certain regions, geothermal potential through hot springs, and a vast amount of biomass. Adopting renewable energy sources for power generation in Iraq would not only enhance energy security but also lead to a substantial reduction in greenhouse gas emissions from the power sector. Currently, the power sector heavily relies on fossil fuel plants and highly polluting diesel generators, contributing to nearly half of Iraq's total emissions. Thus, transitioning to renewables would address these challenges and promote a more sustainable and environmentally friendly power sector. figure 1-7 shows the percentage of Electrical energy generated in Iraq by source 2022.

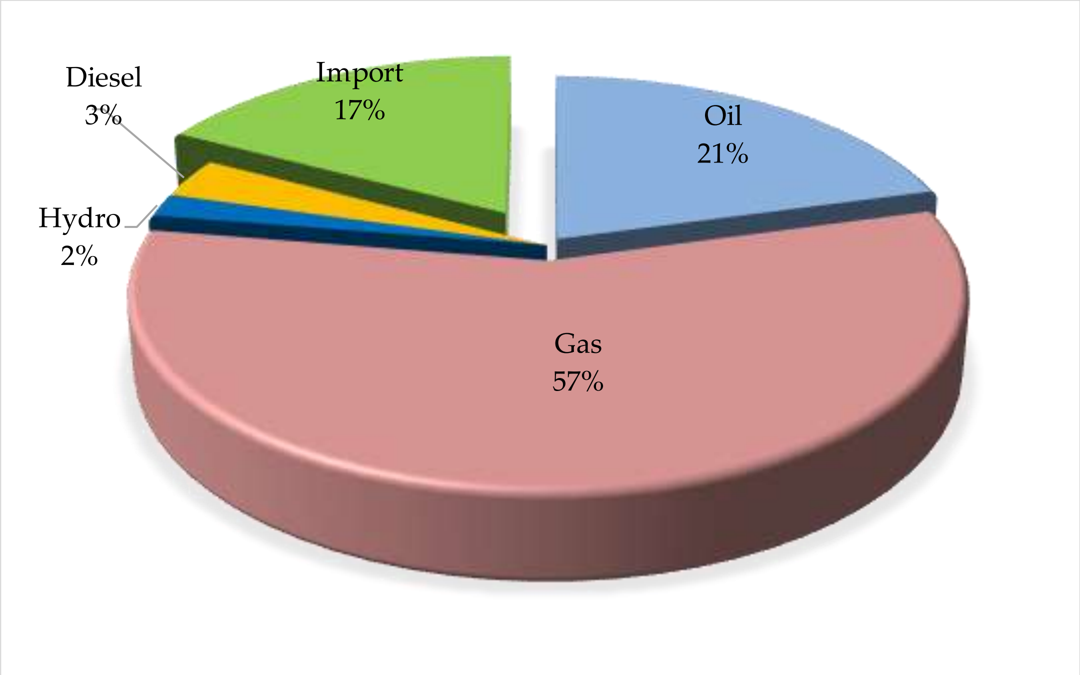

Figure 1-7 Electrical energy generated in Iraq by source [11], [33]

The Ministry of Environment initiated the Renewable Energy Investment Program in 2017, aiming to achieve a target of 2,695 MW by 2020. However, the target was not met, and the actual capacity reached by 2020 was only 220 MW. Nevertheless, in October 2021, the Ministry of Oil announced Iraq's ambitious plan to increase the share of clean energy to 33% of the power capacity mix by 2030. This goal will be facilitated by a substantial increase in solar capacity, with a specific target of 12 GW [34].

Table 1-1 Compares the annual generation of electricity 2022.

	World	Europe	Spain	Iraq
Fossil fuel	17,378.57 (TWh)	2,018 (TWh)	89 (TWh)	115 (TWh)
Coal	10,185	729	7	0
Oil	888.57	56	11	35.9
Gas	6,305	1,230	87	79
Renewable	7,758.71 (TWh)	1,692 (TWh)	126 (TWh)	3 (TWh)
Hydro	4,326	696	18	2.6
Wind	2,139	523	62	0
Solar	1,289.25	233	32	0.42
Nuclear	2,610 (TWh)	1,111 (TWh)	58.43 (TWh)	0 (TWh)

1.7 Biomass in Iraq

Even though Iraq has a lot of potential for biomass resources, particularly from agricultural waste and wood, the country only uses biomass energy on a small scale.

Agricultural waste is dumped every year in millions of tons in unexploited ways. However, recent technical advancements provide significant chances to increase the usage of biomass energy in Iraq.

Biomass is transformed into a variety of useful and adaptable energy sources, such as biofuels or syngas, which are two of the most significant biomass products. Gasification technology is the most common main treatment method that is utilized on a modest scale in the world. Combined heat and power systems are a significant choice to produce thermal and electric energy due to their exceptional energy efficiency, reduced environmental emissions, and relative independence from centralized power grids. CHP systems are thought to be the most efficient way to produce both heat and electricity. With the help of this technology, the network can more efficiently and concurrently provide the heat and power it needs. Cogeneration is another name for this method of producing electricity. Due to its flexibility and minimal infrastructure requirements, this idea has gained significant relevance compared to conventional power generation systems in huge thermal and hydro plants linked to the transmission network. All institutions, enterprises, and houses in Iraq utilize private generators since the country is experiencing a severe energy deficit. CHP offers a highly intriguing alternative for standalone systems, such as those that may be utilized in molasses production facilities, date canning facilities, and in many mills available in the cities, for the valorization of wastes, and which would supply the heat and electricity necessary for these plants. Researchers study how biomass can be converted to more usable forms of energy (electricity, heat, and transport fuels).

1.7.1 The Date Palm Sector in Iraq.

The historical and cultural importance of date palms (Phoenix dactylifera) in Iraq is underscored by the country's enduring practice of cultivating these trees. Dating back over 7000 years, this tradition has deep roots in Mesopotamia, the Arabian Peninsula, and North Africa. Beyond being a lucrative cash crop, date palms serve as a remarkably nutritious food source. This cultivation holds strategic significance across numerous Arab nations, including Egypt, Saudi Arabia, Iran, Algeria, Iraq, Pakistan, and Sudan. Iraq, known for its diverse types of date palms, has faced challenges due to environmental issues, political instability, and war. Nevertheless, it has emerged as a significant player in the palm agriculture sector. In 2021, Iraq ranked fifth in global date production, with 750,225 metric tons produced over 279,003 hectares [15].

Globally, there are over 120 million palm trees [35], with Iraq alone having 17 million. Egypt notably emerged as the frontrunner in date production, as illustrated in figure 1-8. The primary nations involved in cultivating date fruit, along with the proportions they contribute to global date production, were reported by the Food and Agriculture Organization (FAO) in its 2021 statistical data [15]. The palm industry generates waste, which could be harnessed for eco-friendly energy production, offering an opportunity for sustainable development [21].

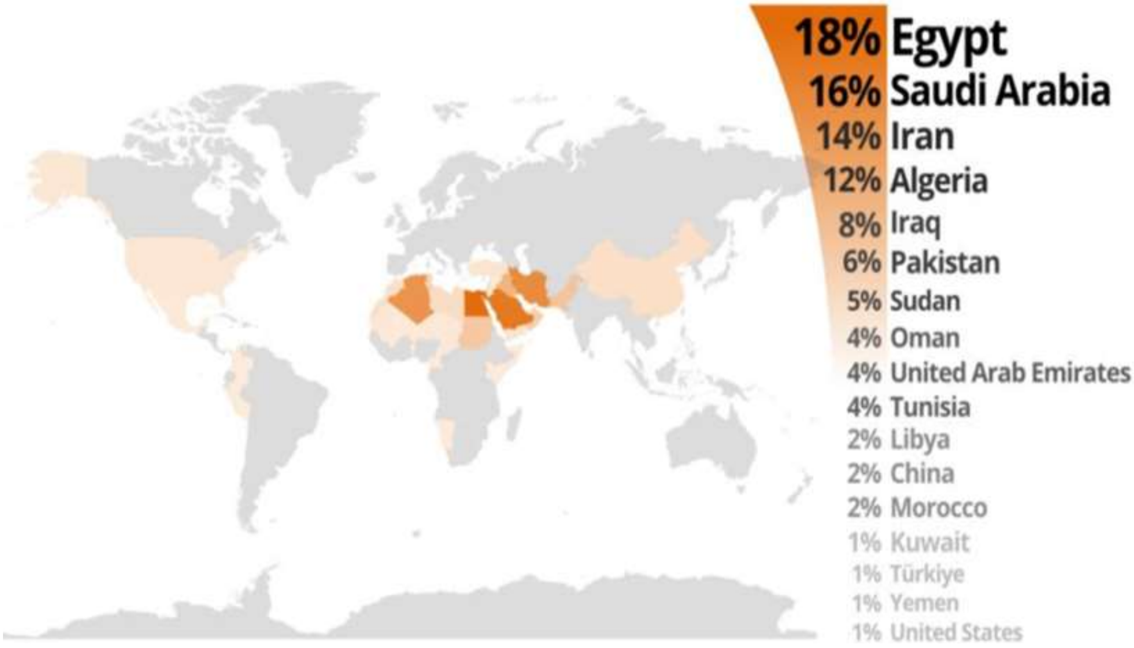

Figure 1-8. Dates Production by Country [36]

1.7.2 Concept of Biomass

Biomass refers to the organic matter derived from plants and animals, which can be used as a source of renewable energy or for various industrial purposes. This organic matter can include wood, crop residues, agricultural byproducts, and even certain types of waste, such as food scraps. The concept of biomass revolves around the idea of harnessing the energy stored in these organic materials, either through direct combustion, conversion into biofuels like ethanol and biodiesel, or other processes like anaerobic digestion to produce biogas. Biomass can be processed through a range of techniques, including thermochemical, biochemical, physical-chemical, and chemical methods [37]. Biomass is classified as a sustainable energy source because it involves using plants and crops that can be replanted and regrown, ensuring long-term viability. It represents an eco-friendly alternative to fossil fuels since it can mitigate greenhouse gas emissions. When biomass is burned, the carbon dioxide emissions are balanced by the carbon dioxide absorbed during plant growth. Legislative initiatives, like Directive

2009/28/EC of the European Parliament and the Council, have broadened the scope of biomass, recognizing it as feedstock rather than mere residue. This recognition has driven technological advancements in the biomass sector, particularly in renewable energy technologies, leading to rapid development.

Biomass finds applications in multiple sectors, including electricity generation, heating, and transportation fuels, offering a sustainable and environmentally conscious energy landscape. Biomass serves as a widely adopted fuel in numerous countries, especially for heating and cooking in developing regions. In industrialized nations, the use of biomass fuels for power generation and transportation is increasing, aiming to reduce carbon emissions resulting from fossil fuel combustion. Biomass stores solar chemical energy acquired through plant photosynthesis. Its applications range from direct combustion for heating to various processes that convert it into sustainable liquid and gaseous fuels. Sources of biomass energy include wood and wood processing waste, agricultural residues, components within municipal solid waste, animal manure, and sewage, as shown in figure 1-9.

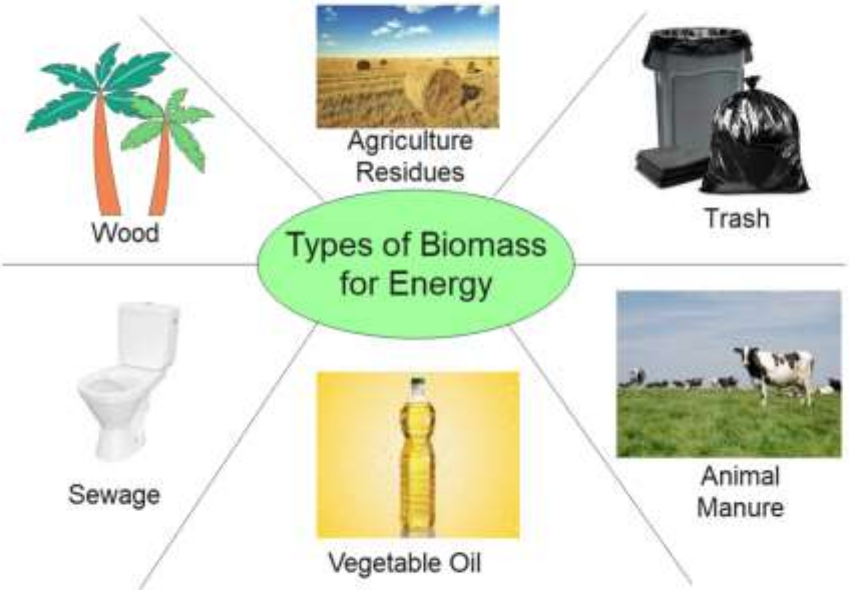

Figure 1-9 Biomass sources

Biomass energy boasts several advantages, serving as a consistent and readily available source of renewable energy that leaves no carbon footprint. Additionally, it diminishes our reliance on fossil fuels, presents a cost-effective alternative, and provides manufacturers with an additional income source. Moreover, biomass energy plays a role in waste reduction, minimizing the volume of materials in landfills. However, despite these benefits, biomass energy has its drawbacks, such as lower efficiency compared to fossil fuels, a lack of complete environmental cleanliness, potential contributions to deforestation, and the substantial space requirements of biomass plants.

Despite these drawbacks, ongoing research and innovation continue to be invested in the sector to make biomass energy more accessible, cost-effective, and a valuable replacement for conventional electricity and other energy sources. Biomass energy is a product of photosynthesis, which absorbs carbon dioxide from the atmosphere along with solar energy. During photosynthesis, plants utilize solar energy to convert water and carbon dioxide into sugars that can be stored. Figure 1-10 illustrates how scientists explore the transformation of biomass sugars into more practical forms of energy, such as heat, electricity, and transportation fuels. Biofuels are categorized into primary and secondary biofuels based on the type of biomass (processed and unprocessed) used, and secondary biofuels are further divided into multiple generations depending on the source or class of feedstock utilized.

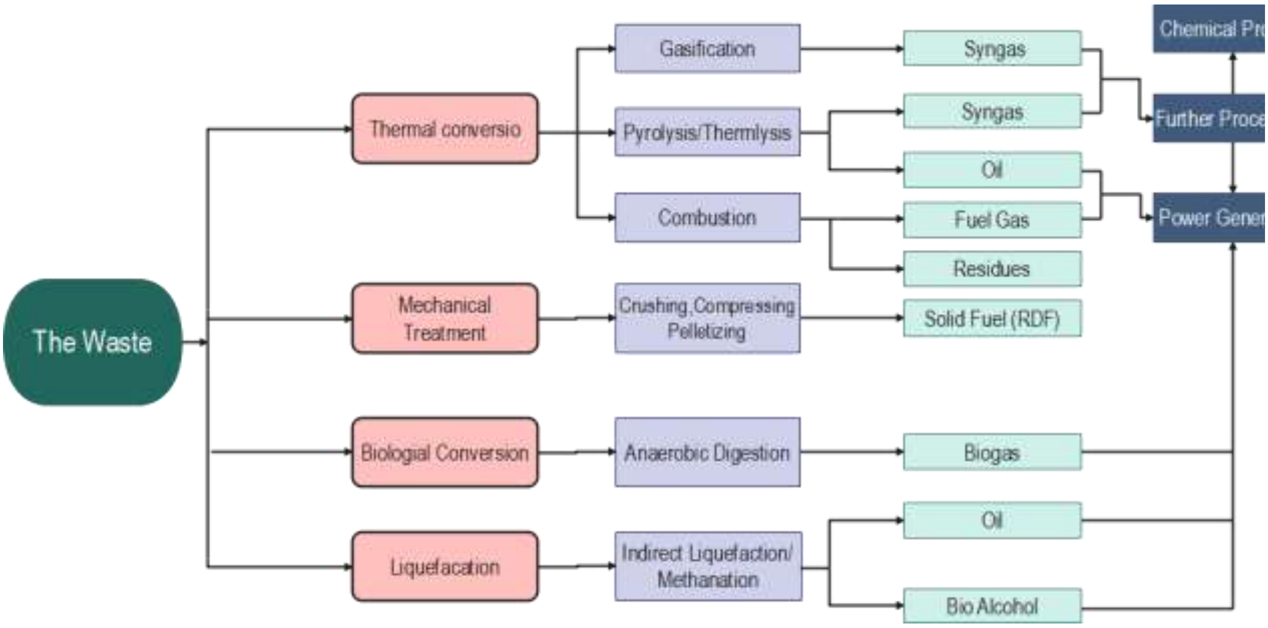

Figure 1-10 Various forms of energy from biomass [38]

1.7.3 Why Valorize the Residues of the Palm Sector in Iraq?

Fossil fuels, the primary energy source, have limited availability and significantly contribute to global climate change. International agreements like the United Nations Framework Convention on Climate Change and the Kyoto Protocol have spurred the development of national and European laws to reduce greenhouse gas emissions and promote renewable energy, especially in sectors like transportation and manufacturing. The EU initially aimed for 20% renewable energy in total consumption by 2020, with varying national targets. To address climate goals, there is a growing need for a substantial shift toward renewable energy sources and energy-saving practices. The EU has now set a binding goal of 40% renewable energy in the energy mix by 2030, up from the current target of 32%. Member states must enhance their efforts to achieve this ambitious objective [36].

One approach to meet climate goals is "distributed generation" (DG), involving decentralized electricity production, offering flexibility and reduced infrastructure needs. In regions like Iraq, facing energy deficits and relying on private generators, DG emerges as a promising alternative, particularly for facilities like molasses and date canning plants that can use waste for heat and power.

The Middle East, particularly Iraq, plays a crucial role in date palm cultivation, making the region a major producer and exporter of dates. However, the associated waste from this industry poses environmental challenges. The focus on utilizing palm residues in Iraq has emerged for various applications, emphasizing their potential as a renewable energy source. Traditionally, waste palm trees have been incinerated or discarded, causing environmental pollution in date-producing areas. While some countries use a fraction of palm waste for animal feed, a significant amount remains untapped. The biomass of palm trees, containing lignin, hemicellulose, cellulose, and having low humidity, is recognized as an excellent energy source for the Middle East and North Africa. Various thermal technologies and biochemistry methods can convert palm biomass into useful energy forms, including burning and gasification. Additionally, using palm waste as fertilizer not only reduces the environmental impact of agricultural waste but also enhances soil fertility. Overall, harnessing palm residues holds promise for sustainable energy generation and environmental improvement in the region.

Gasification is identified as a viable method for utilizing waste from date palm groves, specifically palm trunks, empty fruit bunches, and fronds, amounting to approximately 720 thousand tons annually just in Iraq. Presently, these leftovers are often burned in groves with limited economic value. Leveraging palm waste through gasification could create economic opportunities, supporting sustainability in the date palm industry. This approach has the potential to generate new income and job opportunities while contributing to broader sustainability goals.

1.8 Chemical- Physical Characteristics of Biomass

The engineering properties of biomass play a crucial role in determining the suitability of feedstock for any thermochemical application. These properties, which are essential for designing and operating downstream processes, encompass factors such as particle size, density, flow ability, heating value, moisture content, ash content, and color. They also have a substantial influence on the design of systems for storage, handling, fuel conversion, and transportation. Here, we provide an overview of the essential characteristics of the technologies under consideration in this thesis:

1.8.1 Bulk Density

It is a physical attribute that represents the total space occupied by a specific quantity or a collection of particles. This may be calculated utilizing the provided formula [39]:

$$P_{bulk} = \frac{\text{overall mass of the biomass particles}}{\text{a measured volume of organic matter particles}} \tag{1}$$

1.8.2 Moisture Content

The moisture content in biomass refers to the quantity of water present in each quantity of biomass, typically uttered as a percentage of the biomass's total weight. It indicates the proportion of water within the biomass material.

Moisture content in biomass is a critical parameter because it can significantly impact various processes, including combustion, gasification, and biochemical conversion. High moisture content in biomass can reduce its energy content, affect combustion efficiency, and make certain conversion processes less efficient. Therefore, understanding and controlling moisture content is important in biomass utilization and energy production. Heating value, as measured in MJ/kg, has been found to drop by approximately 66% as the moisture level in biomass rises from 0% to 40%.[40].

For certain agricultural residues, like husks and straws, moisture content can vary widely, ranging from below 20% to as high as 60%. Wood, a substantial source of biomass, typically contains moisture content in the range of 40% to 50%.

1.8.3 Temperature of Ignition

The temperature of ignition, often referred to as the ignition temperature or ignition point, is the minimum temperature at which a substance or material can catch fire and start to burn in the presence of an ignition source, such as an open flame, spark, or heat source. It is a crucial parameter in understanding the flammability and combustibility of materials.

The ignition temperature varies for different substances and materials and depends on their chemical composition and properties. Some materials have low ignition temperatures and can ignite easily, while others require higher temperatures to initiate combustion. Understanding the ignition temperature of a material is important for fire safety, industrial processes, and the design of combustion systems, as it helps in determining the conditions under which a material can undergo combustion and potentially become a fire hazard [39].

1.8.4 Heating Value

The heating value, also known as the energy or calorific value, is a measure of the amount of energy released when a given quantity of a substance or fuel undergoes combustion or another specific chemical reaction. It is typically expressed in units such as joules per kilogram (J/kg) or British thermal units per pound (BTU/lb) and represents the heat energy produced during the complete combustion of a specific amount of the substance.

Heating value is a critical parameter in understanding the energy content of different fuels and materials. It helps quantify the energy potential of a substance and is often used for comparing and selecting fuels for various applications, such as heating, electricity generation, or industrial processes. There are two types of heating values, including:

Higher Heating Value (HHV) or Gross Calorific Value (GCV): This value considers that the water vapor produced during combustion is condensed and the heat is recovered. It accounts for the latent heat of the vaporization of water in the combustion products [41]. Lower Heating Value (LHV) or Net Calorific Value (NCV): LHV does not consider the condensation of water vapor in combustion products. It assumes that the water remains in vapor form and does not release its latent heat [42]. The choice between HHV and LHV depends on the specific application and whether heat recovery from water vapor condensation is considered. Heating values are essential for understanding the energy efficiency and performance of combustion processes and for determining the energy content of fuels for various industrial and residential uses [43].

The Lower Heating Value (LHV) is calculated by deducting the heat linked to water vaporization from the Higher Heating Value (HHV). In LHV calculations, any produced water is considered vapor, and therefore, the energy needed to evaporate the water is not counted as heat. In contrast, HHV calculations presume that all water present in a combustion process remains in liquid form post-combustion. In contrast, LHV calculations assume that the water resulting from the combustion process is in a vapor state once combustion is completed. In LHV calculations, the latent heat from the vaporization of water in the fuel and reaction products is not accounted for as recoverable. Comparing fuels using LHV is beneficial when condensing combustion products is not feasible or when heat at temperatures below 150 °C isn't viable [44].

In most cases, empirical correlations are employed to estimate the calorific values of biomass. For example, in 2002, Channiwala and Parik developed a correlation for calculating HHV based on correlations for a range of fuels, including biomass liquid, coal, and gas, encompassing approximately 15 to 50 different fuels [45].

$$HHV\left(\frac{kJ}{kg}\right) = 349{,}1C + 1178{,}3H + 100{,}5S - 103{,}4O - 15{,}1N - 21{,}1Ash \qquad (2)$$

According to the elemental analysis of the biomass on a dry basis, C, H, S, O, N, and Ash are the mass percentages of carbon, hydrogen, sulfur, oxygen, nitrogen, and ashes. The following ranges are appropriate for this correlation:

- $0 < C < 92\%$; $0{,}43 < H < 25\%$
- $0 < O < 50\%$; $0{,}43 < N < 5{,}6\%$
- $0 < ASH < 71\%$; $4745 < PCS < 55.345$kJ/kg

The following equation may be used to compute the LHV of a solid fuel using the HHV [39]:

$$LHV\left(\frac{kJ}{kg}\right) = HHV - h_g\left(\frac{9H}{100} + \frac{M}{100}\right) \qquad (3)$$

H and M stand for hydrogen and moisture percentages, respectively, h_g uses the same units as HHV (2.260 kJ/kg) to describe the latent heat of water vapor.

Most frequently in European nations, LHV is used to define efficiency in medical processes. This will result in performance measured in terms of LHV being higher than it would be if the HHV were employed (as it is common in Canada and the US).

1.8.5 Ultimate analysis

Ultimate analysis, also known as elemental analysis, is a laboratory technique used to quantify the elemental composition of a substance, including carbon (C), hydrogen (H), nitrogen (N), sulfur (S), oxygen (O), and sometimes additional elements like chlorine (Cl) and others. It is valuable for understanding the properties of organic compounds. Furthermore, it plays a crucial role in combustion analysis, helping determine the elemental composition of fuels and combustion byproducts, which is essential for studying combustion processes and emissions.

Modern elemental analysis techniques typically involve advanced instruments such as mass spectrometers, combustion analyzers, and elemental analyzers. These instruments can accurately measure the quantities of each element in a sample, providing precise data for scientific research and industrial applications. The following formula can typically be used to represent the elemental analysis:

$$C + H + O + S + N + M + Ash = 100\% \tag{4}$$

where C, H, O, S, and N are the proportions of carbon, hydrogen, oxygen, sulfur, and nitrogen in the fuel, respectively. The term "ASH" stands for the fuel's ash content. The quantities for hydrogen (H) and oxygen (O) do not account for water content because M denotes moisture.

Ultimate analysis is a method to determine the elemental composition (carbon, nitrogen, hydrogen, oxygen, and sulfur) in organic samples. It's done using an ultimate analyzer, which employs static combustion. Excess oxygen is removed through copper scrubbing, converting oxides to elemental nitrogen, which is then measured against a helium reference. This analysis is crucial for understanding the composition of organic materials. Calculating the composition of the unknown sample can be done using the masses of these combustion products [46]. Costly elemental analysis is typical. The elemental analysis of fuel can be done using the following ASTM standards.

- Nitrogen: E-778
- Carbon, Hydrogen: E-777
- Sulfur: E-775
- Moisture: E-871
- Ash: D-1102

1.8.6 Proximate Analysis

Proximate analysis, a laboratory technique employed to ascertain the approximate composition of a substance, typically a solid sample like coal, biomass, or food, offers valuable insights into the major components of the sample, which are broadly categorized into four main parameters. Moisture content, expressed as a percentage of the total weight, quantifies the amount of moisture or water present in the sample, crucial for understanding its weight and energy content. Ash content, representing the inorganic or mineral content, is the residue left after complete combustion at high temperatures and is significant for assessing the quality of solid fuels. Volatile matter, the portion released as gas or vapor during moderate heating before complete combustion, is pivotal for understanding the combustibility and heating characteristics of fuels. Fixed carbon, the remaining solid carbonaceous material after volatile matter is expelled through heating, is a critical parameter for evaluating the energy content of fuels.

Proximate analysis is commonly used in various industries, including agriculture, energy, and materials science, to assess the quality and characteristics of different materials. It is particularly important in the evaluation of solid fuels like coal and biomass, as it provides information about their suitability for combustion and energy production. The analysis is conducted using the benchmarks in Ref [42]:

- Fixed carbon
- Moisture: E-871
- Ash: D-1102
- Volatile matter: E-872

The weight composition of the other compounds is subtracted from 100 to get the amount of fixed carbon, or "char." The analysis is often performed using controlled laboratory furnaces or specialist tools like thermogravimetric analyzers. LHV and HHV, as well as elemental (or ultimate) and proximal analyses, can be stated on many bases:

- The term “As received” has the moisture content of the biomass, usually at the point of delivery or harvesting [47]. The composition may be utilized with the greatest degree of validity for calculating combustion, evaluating efficiency, etc. On the other hand, the moisture level and all the other elements that affect it have an impact on the precise composition as received. Moreover, because it can be altered by drying procedures, the moisture content is the fuel quality criterion that can be changed the most simply. As a result, a sample's moisture content may change between the site of sampling, the delivery point, and the lab's final analysis location. The composition as received is therefore not usually a reliable indicator for comparisons between different biomass kinds, although being very helpful for real applications [40].

- The term "dry basis" composition (db) designates the biomass's composition without considering any water content. This is only true for laboratory samples; in "real-life" applications, all other kinds of drying always leave some moisture in the fuel, no matter how little. The dry basis, which is the normal manner in which most laboratories give their data, is an excellent starting point for evaluating the characteristics of various fuel kinds. many kinds Unfortunately, it does not account for fluctuations in the biomass's inorganic component, which may be brought on by the influence of the supply chain.

- The term "dry, ash-free" basis, sometimes known as "daf," describes the makeup of biomass that is free of all water and ash. Since it is hard of separating ash from the organic portion of biomass (which is what is done in combustion and laboratory applications), the dry, ash-free basis presents an even more advantageous scenario compared to the dry basis. Yet, this base enables direct comparison of the attributes of various biomass fuel types and the removal of all supply chain impacts [40].

- The majority of biomass contains more volatiles than coal. Herbaceous biomass generally exhibits a little grater volatile content than woody biomass or certain agricultural byproducts; generally speaking, the more volatile the biomass, the lower the lignin level. The volatile component of waste biomass can range from 60 to 80% of daf depending on the fraction, from 70 to 85 for herbaceous biomass, and from 60 to 85 for woody biomass [40].

1.9 Definition and Characterization of the Palm Residue

There are more than 5000 distinct varieties of date palm trees that are extensively cultivated in arid and semi-arid regions. Date palm plantations can be found across Asia, Africa, the Americas, and Europe, with respective proportions of 67.4%, 32.0%, 0.6%, and 0.04%. These date palm plantations collectively cover an area of over 1.381 million hectares (FAO, 2021), [48]. Figure 1-11 provides a visual representation of the global date palm cultivation area in 2021, highlighting the top-producing nations. In 2021, Iraq emerged as the world's largest land-based producer of palm dates, boasting a harvested area exceeding 279 thousand hectares (FAO, 2021).

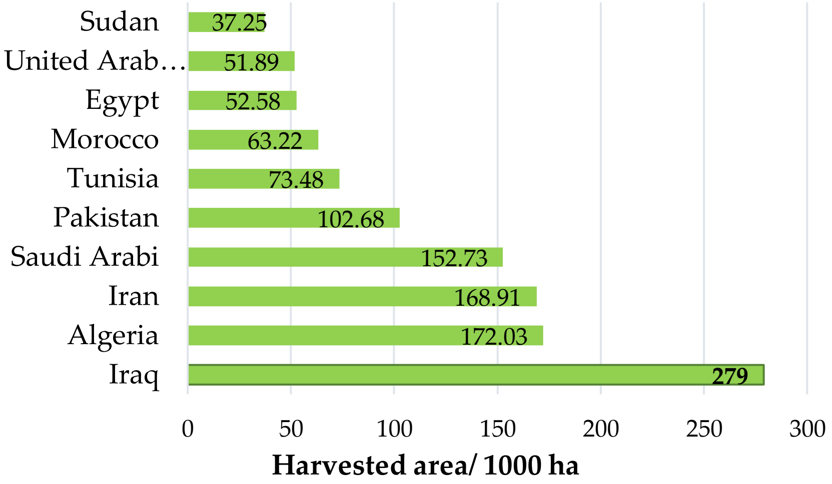

Figure 1-11 Date-harvesting areas globally in 2021 [48]

Given the abundance of date palm trees in the Middle East, especially in Iraq, this research focuses on the potential utilization of date palm waste for energy production. In Iraq, the land area dedicated to date palm cultivation has reached 279,003 hectares, yielding an annual date production of approximately 750,000 metric tons [21].The harvesting of dates results in various residues, specifically fronds, empty fruit bunches, and trunks, the management of which presents several challenges, as discussed later in this thesis. These so-called "other products" should not merely be considered as waste but rather as opportunities for various industrial applications, including power generation. Residue, in this context, refers to anything left over after a portion has been removed, divided, or labeled, or after the completion of a process. Furthermore, the processing of date fruits yields numerous by-products such as dibs, vinegar, alcohol, liquid sugar, bread yeast, and citric acid, illustrating the diverse range of products that can be derived. Among these, "Date Palm residues" stand out as one of the most abundant forms of biomass available in Iraq, generated in significant quantities on an annual basis.

Typically, palm date trees that yield dates need to undergo annual pruning. On average, each date palm tree produces approximately 35 kilograms of biomass residue annually, consisting of elements such as fronds, pits, empty fruit bunches, and trunks [49], [50]. Iraq generates a substantial annual quantity of around 700,000 tons of these residues, primarily composed of fibers and fronds. figure illustrates the regions with a high density of palm trees in Iraq. Throughout history, the cultivation of palm trees has been extensive in the country, with a notable focus on the southern regions due to their climate being conducive to palm growth. Areas such as Basra and its surroundings have gained recognition for their abundant palm groves.

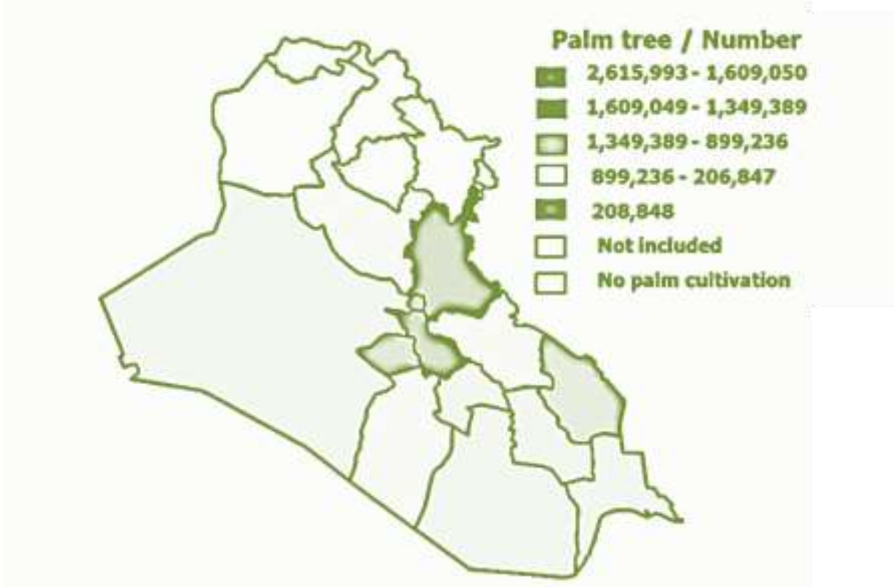

Figure 1-12 Palm tree concentration areas in Iraq [21]

The pruning of palm trees usually occurs in the spring, following the conclusion of the cold and rainy season. During this process, older fronds are trimmed, collected within each row of trees, in the most advantageous position, and promptly processed to prevent the potential spread of plant diseases. Managing the palm pruning material, which encompasses a significant volume of agro-industrial waste and byproducts, including leaves and palm fiber, poses environmental challenges [40], [51]. Currently, there are two predominant applications for this pruned biomass: Date palm leaves represent a valuable natural source of fiber that can be utilized in a wide range of industrial applications across various sectors [51], [52]. Alternatively, it is often burned in the field, which raises environmental concerns and represents a wasteful utilization of this resource.

1.9.1 Fronds

The cultivation of palm trees is on the rise globally, resulting in an increase in the generated waste from this activity. Date palms, aside from yielding edible dates, contribute to the environment through their rugged trunks and fronds. To maintain the appearance of date palms, it is necessary to trim them annually, a process that involves the removal of both the green and dry parts of the fronds, including their roots. Pruning is a vital aspect of palm tree cultivation as it enhances the palm's metabolic capacity. Date palm leaves typically measure between 3 to 6 meters in length (with an average of 4 meters) and have a lifespan of 3 to 7 years, which can vary based on the palm's variety, age, and environmental conditions. The maximum width of the frond midrib is 0.5 meters, although it is usually much narrower, tapering from the base upward [53], [54]. In contrast to other fruit trees, date palms do not naturally shed or drop dead or old leaves; instead, they are manually removed during cultivation. Considering their widespread availability in Iraq, as previously mentioned, date palm frond waste has been selected as a by-product of date palm cultivation. Given the dry climate of the region, there is less need for extensive pre-processing, as the biomass contains relatively low moisture content. The physicochemical characteristics of date palm waste can vary depending on factors such as the type of waste (e.g., fronds, empty fruit bunches, trunks), the age of the date palm, and environmental conditions. Palm fronds as in figure 1-13, which are the large, leaf-like structures of palm trees, exhibit various characteristics. Table 1-2 summarizes the results achieved in the relevant literature for palm date fronds. Notably, most studies have different values, which are reflected in the values obtained.

Table 1-2 Review of physicochemical characteristics of Palm frond (leaflets).

	[55]	**[56]**	**[57]**	**[58]**
		Proximate analysis		
Moisture (%wb)	7.1	5	5	8.50
Fixed carbon (%db)	9.7	7.7	5.2	7.64
Ash (%db)	15.2	10.8	11.7	11.58
Volatile matter (%db)	68.0	76.6	78.1	72.28

Ultimate analysis				
C (%db)	40.8	45.3	49.4	43.14
O (%db)	35.2	47.2	42.3	52.71
H (%db)	6.0	5.6	5.8	7.49
N (%db)	0.63	1.0	1.2	0.196
S (%db)	0.21	0.8	1.3	0.00
LHV (MJ/kg) (db)	19.0	17.9	19.66	-
HHV (MJ/kg) (db)	-	-	18.08	19. 09
Physical properties				
Bulk density (kg m-3)	312	298	298	-

Figure 1-13 Fronds of the palm tree

1.9.2 Empty Fruit Bunches

Empty Fruit Bunches (EFB) of date palm are a waste product generated during the processing of date palm fruits, predominantly from Phoenix dactylifera palm trees, renowned for their delectable dates. The harvesting and processing of these dates result in the separation of various components of the palm bunches, yielding EFB as one of the byproducts as shown in figure 1-14. EFBs from date palms share similar fibrous and stringy characteristics with other palm EFBs, often retaining remnants of date pulp, fibers, and moisture. In certain traditional agricultural practices, EFBs derived from date palms have been traditionally employed to enrich soil quality and enhance water retention when used as organic matter and mulch in date palm plantations. Their potential to bolster sustainable farming practices is recognized, and there is a burgeoning interest in discovering more eco-friendly and beneficial applications for date palm EFBs. Researchers are actively investigating potential uses such as biogas production, and composting, and harnessing them as a biomass source for energy generation. Responsible management and utilization of these EFBs are essential steps toward waste reduction and the advancement of sustainable practices within date palm cultivation. In date palm farming, EFBs are collected from the fields, with each palm tree typically yielding between six to ten empty fruit clusters. The most common method for disposing of the abundant EFBs is through burning. In the context of date palm cultivation and processing, finding beneficial uses for empty fruit bunches can help reduce waste and promote sustainable practices. EFBs have the potential for various applications. They can be processed into fiber and used in the production of paper, cardboard, and other paper products. EFBs can also be used as a source of biomass for energy generation, such as in the production of biogas, or as a fuel for boilers. Table 1-3 provides a summary of the findings documented in the pertinent literature regarding EFBs. Notably, most studies have different values, which are reflected in the values obtained.

Table 1-3 Review of physicochemical characteristics of Empty Fruit Bunches.

	[59]	[60]	[61]	[62]
Proximate analysis				
Moisture (%wb)	7 .68	2.44	16.86	
Fixed carbon (%db)	6.92	18.67	-	41.93
Ash (%db)	4.20	5.26	-	4.21
Volatile matter (%db)	81.20	73.63	93.96	53.85
Ultimate analysis				
C (%db)	43.49	48.48	42.96	50.25
O (%db)	52.73	43.74	48.32	41.06
H (%db)	7.51	7.14	6.24	7.0
N (%db)	0.188	0.64	1.19	1.69
S (%db)	0.00	0.00	1.29	0.00
LHV (MJ/kg) (db)	-	-	17.48	17.80
HHV (MJ/kg) (db)	19.21	-	17.95	-

Figure 1-14 Empty Fruit Bunches

1.9.3 Trunks

The trunk of a date palm, also referred to as the palm tree trunk or stipe, is a tall, cylindrical, and woody central stem that provides essential support to the date palm tree, serving as its structural backbone. The appearance of date palm trunks varies with age and species. As shown in Figure **1-15** 1-15. Young palms have slender trunks, while mature ones have thicker, sturdier ones, often covered in fibrous material for protection and insulation. Its average diameter is between 1 and 1.10 m [53].

Strongly with the clipped stubs of old leaf bases, date palm trunks provide lumber. In contrast to other decorative plants, the date palm's trunk is textured by the bases of the clipped leaves. One of the most appealing characteristics that highlighted the use of date palms as beautiful landscape trees is their cylindrical, textured trunk. The trunk of the date palm tree lacks a cambium layer and is made up of thick, fibrous vascular bundles that are bonded together in a matrix of cellular tissue that has been heavily lignified near the outside of the palm tree trunk. An extra fascicular cambium, which ensures lateral development of the palm tree trunk and results in a consistent and uniform palm tree trunk width throughout the palm's life, quickly vanishes [63], [48]. Table 1-4 provides a summary of the findings documented in the pertinent literature regarding Palm Trunk. Notably, most studies have different values, which are reflected in the values obtained.

Table 1-4 Review of physicochemical characteristics of Palm Trunk.

	[64]	[55]	[65]
	Proximate analysis		
Moisture (%wb)	4	10.0	18.1
Fixed carbon (%db)	10.24	11.5	8.1
Ash (%db)	3.25	4.2	20.2
Volatile matter (%db)	86.51	71.8	52.1
	Ultimate analysis		
C (%db)	38.78	42.8	38.1
O (%db)	52.23	45.5	55.6
H (%db)	5.70	5.8	5.2
N (%db)	2.90	0.21	0.8
S (%db)	0.39	0.12	0.3
LHV (MJ/kg) (db)		15.5	10.753
HHV (MJ/kg) (db)	16.70	-	

Figure 1-15 Trunk of the palm tree

1.10 Biomass Valorization Methods

The aim of valorizing biomass is to reduce waste, cut greenhouse gas emissions, and establish more sustainable energy and product sources by extracting value from organic substances like plant matter and agricultural residues. Various methods are employed for this purpose, depending on the type of biomass and desired product. Biomass valorization involves converting organic resources into valuable outputs such as biofuels, chemicals, and energy through technologies like direct combustion, gasification, pyrolysis, and fermentation [39]. Gasification offers several benefits, including higher process efficiencies compared to direct combustion systems, reduced CO_2 emissions, and the potential to revitalize rural economies by utilizing agricultural and forestry waste. This process could contribute to decreasing reliance on electricity and mitigating CO_2 emissions, particularly in the EU, which has one of the highest CO_2-emitting power sectors globally.

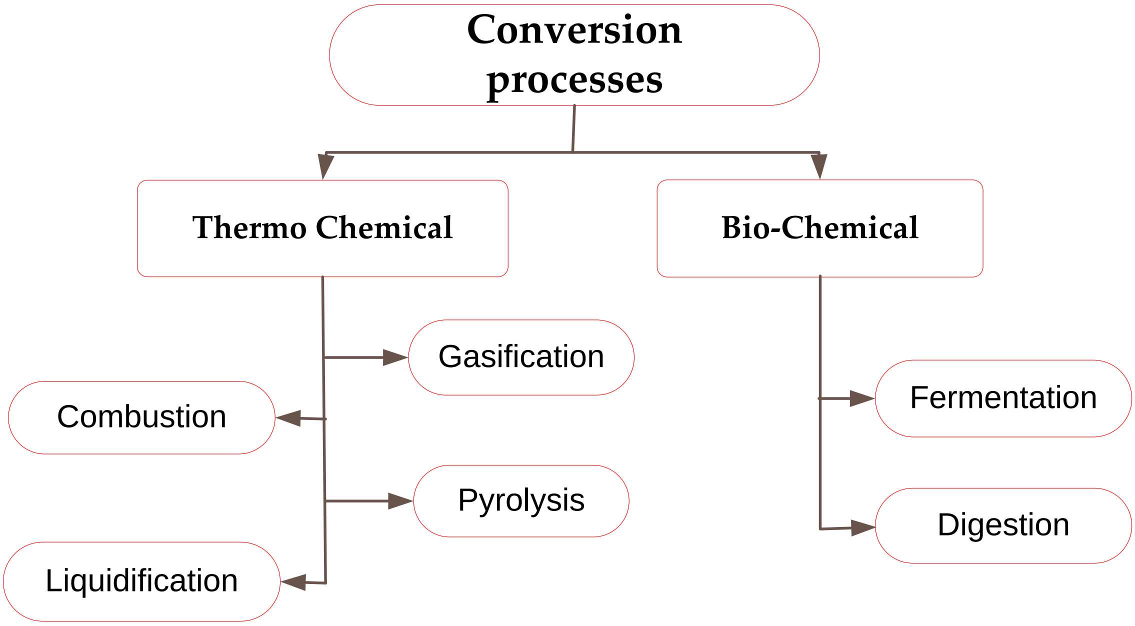

Figure 1-16. Biomass conversion technologies processes

This type of renewable energy source's enabling technologies is undergoing duration of rapid development. Studies are focused on enhancing the efficiency of various systems (such as boilers, motors, reactors, and power plants), mitigating the adverse environmental impacts of the utilized residues and technologies, boosting the market viability of the products, and facilitating new, sought-after applications through initial treatments like biofuels. Figure 1-16 shows the main biomass conversion process. Hence, the following processes will be discussed in the next sections as ways to produce energy from biomass:

1.10.1 Combustion

Combustion is a common and straightforward method of converting fuel into thermal energy by burning it in the presence of an oxidizer, usually air. The primary objective of direct combustion is to release heat, which can be harnessed for various applications, including heating, electricity generation, propulsion, and industrial.

If the moisture content is under 40% and the temperature is near 1000 ° C, it is an exothermic oxidation process with air [66]. The remaining biomass's LHV can be anywhere between 7,000 and 20.000 kJ/kg. The standard chemical formula for the direct burning of any biomass in the presence of air as an oxidizing agent is:

$$\begin{aligned} CH_aO_bN_cCL_dS_e + n_1H_2O + n_2(O_2 + 3.76N_2) \\ \rightarrow n_3H_2O + n_4CO_2 + n_5O_2 + n_6CO + n_7N_2 + n_8CH_4 + n_9NO_2 + n_{10}NO \\ + n_{11}HCL + n_{12}SO_2 + n_{13}C + n_{14}ASH + Thermal\ Energy \end{aligned} \quad (5)$$

The letters a, b, and c stand for the quantity of atoms in the chemical formula representing biomass, obtainable through its ultimate analysis. The moisture contents in kmols/s of biomass (n_1), air (n_2), and combustion products (n_3, n_4 ,…., n_{14}), accordingly, are given as n_1, n_2,..., n_{14}. Ash in biomass varies depending on the type of biomass. Nevertheless, alkali elements like Ca, K, Mg, Na, Al, Fe, and Si are typically found in ash.

Direct combustion can produce emissions, including greenhouse gases, particulate matter, and other pollutants. As a result, efforts are made to develop cleaner combustion technologies and to reduce emissions with more efficient combustion techniques and emission control systems, such as scrubbers and catalytic converters. Additionally, renewable, and low-carbon fuels, like hydrogen and biofuels, are being explored as alternatives to traditional fossil fuels to reduce the environmental impact of direct combustion [67].

1.10.2 Gasification

Biomass gasification involves transforming materials such as charcoal, wood chips, energy crops, forestry residues, agricultural waste, and other discarded substances into combustible gases under elevated temperatures (800–1000 °C). This conversion process relies on a gasifying agent, which can be oxygen-enriched air, pure oxygen, steam, or a combination of these. The resultant product from gasification is fuel gas, commonly referred to as producer gas, synthesis gas, or syngas, possessing a relatively low calorific value of approximately 4-6 MJ/Nm_2. Figure 1-17 illustrates the sequential stages of the gasification process for energy production. Producer gas can serve as a raw material for manufacturing chemicals like methanol [68].

An innovative approach is the biomass-integrated gasification/combined cycle, where gas turbines efficiently convert the gaseous fuel into electricity, achieving high overall conversion efficiency. By integrating gasification with combustion and heat recovery, a 40–50% conversion efficiency is ensured for power generation in the range of 30–60 MW. The syngas produced can further undergo conversion into hydrogen gas, potentially serving as a future fuel source for transportation [69].

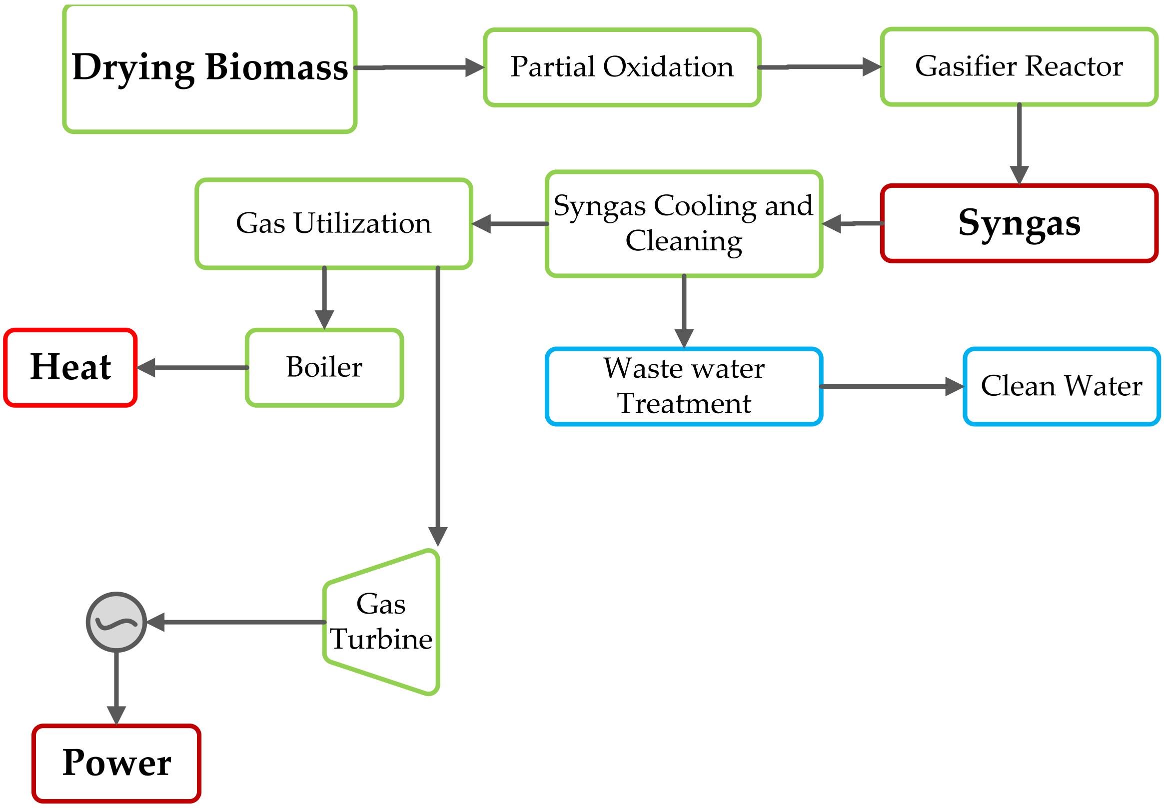

Figure 1-17 Power generation through the process of biomass gasification

1.10.3 Pyrolysis

Pyrolysis is a thermal decomposition process in which organic materials, such as biomass, plastic, and waste, are heated in the absence of oxygen (or with limited oxygen) to break down into simpler compounds and produce valuable products. It is essentially the opposite of combustion, as combustion involves the rapid oxidation of materials in the presence of oxygen, while pyrolysis occurs in a controlled environment without oxygen.

Pyrolysis produces three main products: Syngas (Synthetic Gas), Biochar, and Bio-oil or Pyrolysis Oil. Pyrolysis has many applications such as Bioenergy Production, Soil Improvement, Waste Management, and Chemical Industry. Pyrolysis can be an environmentally friendly technology, as it can reduce waste, lower greenhouse gas emissions, and contribute to carbon sequestration by converting organic materials into stable biochar. In the thermochemical process of pyrolysis, biomass is heated in a reactor at temperatures between 380 and 530 °C without the presence of oxygen [66], [70]. As a result, the contents are changed into three different fractions: coke, a solid fraction made of carbon, and liquid fractions made of aldehydes acids, tars, ketones, alcohols, water, and phenolic chemicals (primarily CO_2, CO, H_2, CH_4, H_2O, C_2H_6, C_2H_4, C_6H_6, C_2H_2). The pyrolysis products depend on heat ratio, the reactor's temperature, biomass residence time, and particle size [66], [71]. The lower heating value (LHV) of pyrolysis gas is contrasted with various fuel sources in Table 6 [39]. A flowchart illustrating the stages of the pyrolysis process for generating energy is presented in figure 1-18.

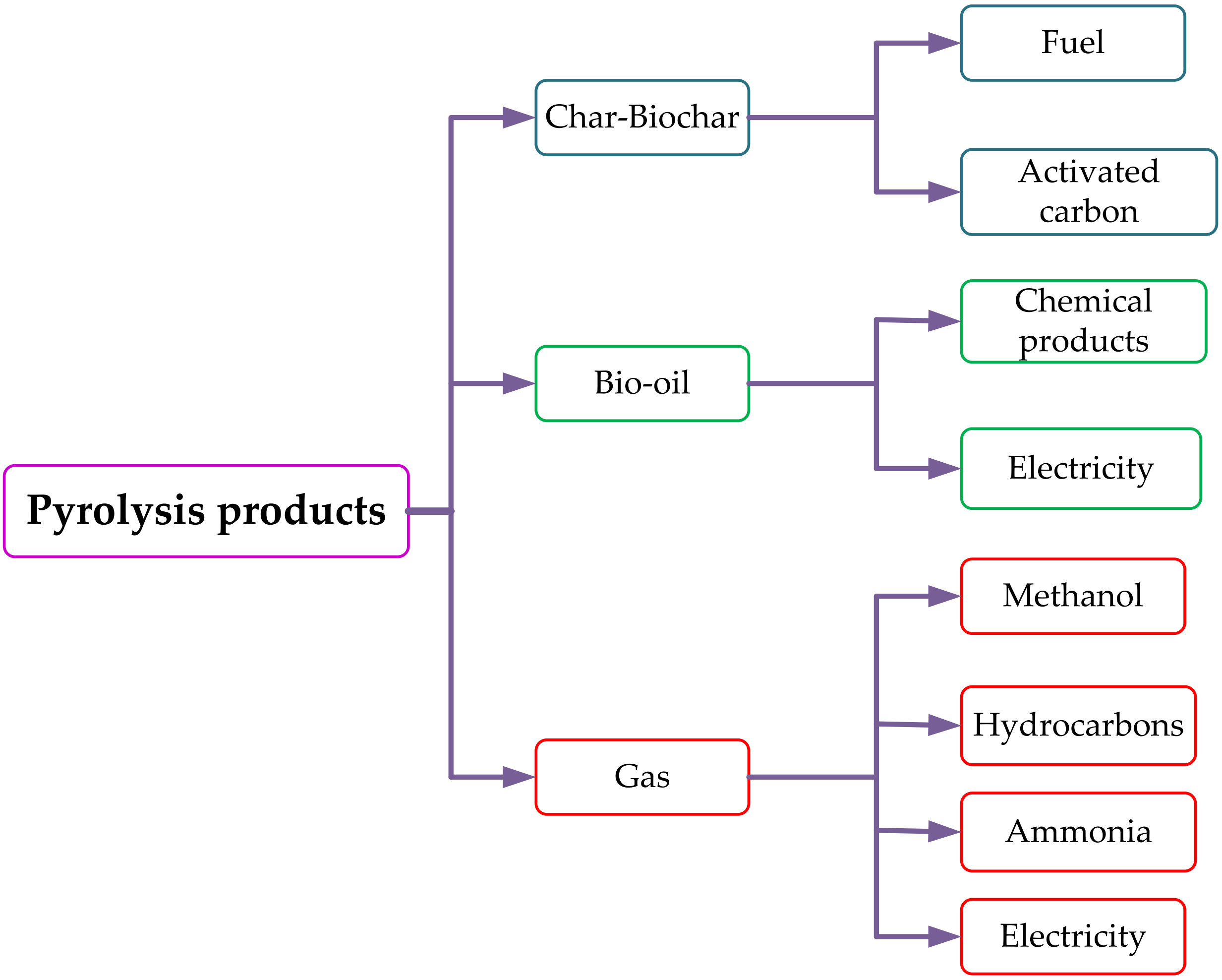

Figure 1-18 Block diagram of biomass pyrolysis

1.10.4 Anaerobic Digestion

Anaerobic digestion is a biological process that decomposes organic materials, including organic waste, agricultural residues, and sewage sludge, in the absence of oxygen. This process generates biogas, primarily composed of methane and carbon dioxide, which is a flammable gas. Anaerobic digestion can be applied to a wide range of biodegradable biomass materials, both primary and secondary. The residual product, called digestate, is nutrient-rich and serves as a valuable organic fertilizer. Anaerobic digestion systems can be categorized into suspended and fixed biomass systems. One of the significant advantages of anaerobic digestion is its positive environmental impact. It helps reduce greenhouse gas emissions by capturing methane that would otherwise be released during natural decomposition. Additionally, it contributes to renewable energy production. Furthermore, it plays a role in effective waste management by diminishing the volume of organic waste that ends up in landfills. This sustainable process aligns with the goals of environmental conservation and energy generation [72],[73].

1.10.5 Fermentation of Alcohol

Fermentation of alcohol is a biological process that involves the conversion of sugars into alcohol and carbon dioxide by the action of yeast or other microorganisms. It is an anaerobic process. It is a fundamental process used in the production of alcoholic beverages like beer, wine, and spirits, as well as in the manufacturing of biofuels, such as ethanol. The ethanol produced during fermentation can be used as an alternative to fossil fuels, primarily in the form of bioethanol. It can be blended with gasoline to reduce greenhouse gas emissions and reliance on non-renewable energy sources [72].

1.11 Gasification Technology

Biomass gasification is a flexible and eco-friendly method that transforms biomass raw materials into a burnable gas blend referred to as syngas (synthetic gas). This section explores the fundamentals of gasification technology, the types of reactors employed, and the specific considerations for electricity generation in distributed generation using downdraft gasifiers. Gasification represents an intricate thermochemical process wherein incomplete combustion of biomass occurs through a sequence of chemical reactions within a bed. This bed can either be stationary or mobile, a distinction we'll delve into shortly. The resulting gas, termed syngas, consists of components such as CO, H_2, N_2, CH_4, and others, exhibiting a heating value typically ranging from 4 to 10 MJ/m^3. This value is largely influenced by the type of biomass and the gasification agent employed [74]. Positioned between pyrolysis and combustion, gasification is a transitional process with a two-step endothermic nature.

In the first phase, intricate reactions occur at temperatures below 600°C, causing volatile components of the fuel to evaporate. Notably, this initial phase operates without requiring any oxygen. The volatile vapors produced encompass hydrogen, hydrocarbon gases, carbon monoxide, carbon dioxide, water vapor and tar. The process leaves behind ash and char (fixed carbon), which remain unevaporated. The second step involves gasifying the char through reactions with steam, oxygen, and hydrogen, requiring the combustion of some unburned char to generate the necessary heat for the gasification reactions that absorb heat. Gas, char, and tars represent the primary byproducts of gasification, and their composition and quantity are substantially influenced by factors such as the gasification agents, heating rate, pressure, temperature, and fuel properties (water content, composition, granulometry). Figure 1-19 illustrates the entire technological pathway, starting from the feedstock vessel and extending to the combustion chamber.

Gasification involves several key steps in the transformation of biomass or other organic materials. Firstly, feedstock preparation is essential, where biomass or other organic material undergoes processes, such as drying, grinding, and sizing to make it suitable for the gasification process. Subsequently, the prepared feedstock is subjected to gasification, where it is heated to high temperatures (typically between 700°C and 1,500°C) in a specially designed vessel known as a gasifier. The absence of sufficient oxygen or air prevents complete combustion, leading to the production of syngas. Following gasification, syngas cleanup becomes necessary to remove impurities like tar, particulates, and sulfur compounds to prevent equipment fouling and meet environmental standards. Once cleaned, the syngas can be utilized for various purposes, including electricity generation using gas turbines or engines, heat production for heating applications, and as a feedstock for chemical processes, producing products such as methanol or synthetic fuels. Additionally, hydrogen can be separated from syngas for use as a fuel or in industrial processes. The stages of the gasification process are illustrated in figure 1-20.

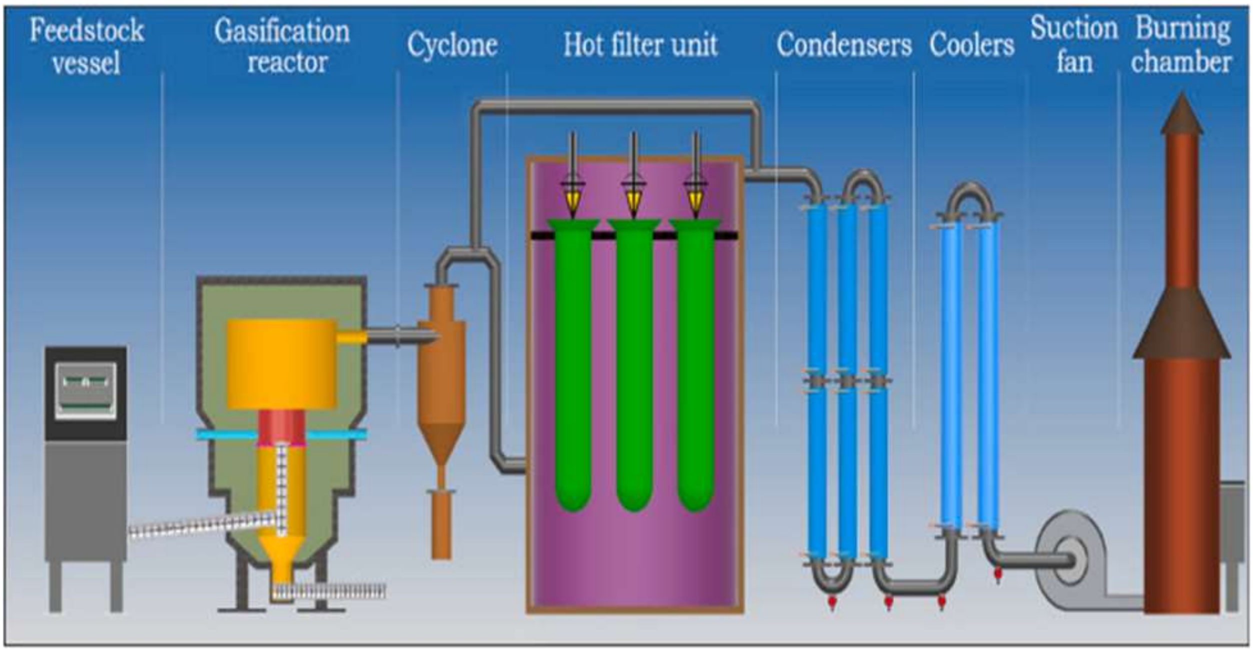

Figure 1-19. Gasification technology line [75].

Gasification holds numerous advantages as a sustainable and eco-friendly energy conversion method. The use of biomass, a renewable resource, emphasizes its role as a renewable energy source. Additionally, gasification distinguishes itself by generating lower carbon emissions when compared to conventional combustion methods, contributing to reduced greenhouse gas emissions. Its adaptability is further showcased through effective waste utilization, encompassing a diverse range of biomass feedstocks, such as agricultural residues and organic waste. Despite the versatility of syngas for various energy and chemical applications, including the utilization of different feedstocks like biomass, coal, and waste materials, the gasification process presents challenges. These challenges include the need for precise control to prevent tar formation and the substantial initial capital costs associated with gasification plants. Nonetheless, despite these obstacles, gasification remains a promising technology for the production of clean energy and the reduction of environmental impacts related to organic waste disposal.

Gasification can be categorized based on several factors. Firstly, consideration of the gasifying substance involves options such as air, oxygen, vaporized water, and carbon dioxide. Secondly, concerning the heat supply method, gasification can be classified as either direct or indirect. Finally, in terms of reactor type, the categorization includes fluidized bed gasifiers, entrained flow gasifiers, and moving bed or fixed bed gasifiers. These classifications provide a comprehensive framework for understanding the various dimensions and methods involved in gasification processes.

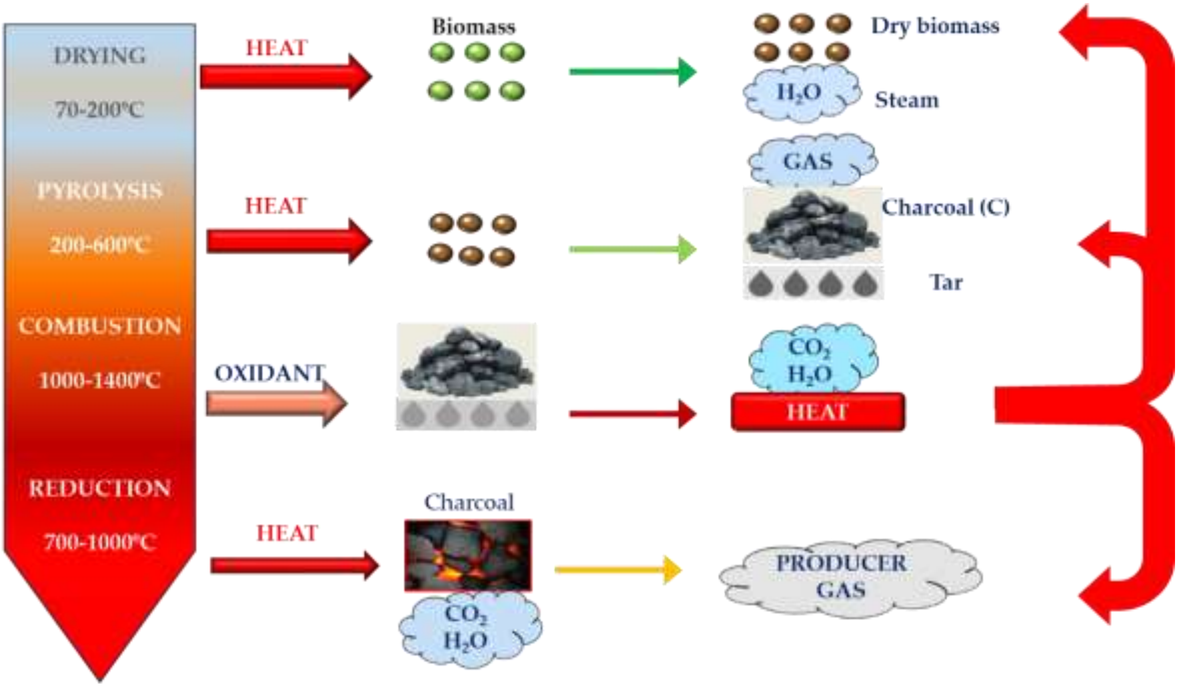

Figure 1-20 Processes of Gasification

Table 1-5 Compares the key performance indicators for each kind of gasifier.

Parameter	**Entrained bed**	**Fixed bed**	**Fluidized bed**
Biomass particle size	<0.15 mm	<51 mm	< 6 mm
Tolerance to coarse particles	Bad	Very bad	Good
Tolerance to small particles	Excellent	Limited	Good
Exit Temperature (°C)	>1,260	450 – 650	800 – 1,000
Raw material	Coal of high energetic value	Lignite and biomass	Lignite and excellent for biomass
Oxidant requirements	High	Low	Moderate
Reaction temperature (°C)	1800-2000	1000-1100	800-1000
Steam requirements	Low	Low-Moderate	Moderate
Status of the ashes	Wet	Dry	Dry
Gasification performance	80-85	75-85	80-85
Power ranges (MW)	50-1000	0.01-10	1-10
Residence times	Very low	Medium-Low	High
Main inconvenience	Producer gas cooling	Use of small particles. Tar (updraft)	C Conversion

1.12 Types of Gasifiers

Gasifiers are devices or systems used in the gasification process to convert various feedstocks into syngas, a mixture of carbon monoxide (CO), hydrogen (H_2), and methane (CH_4). There are several types of gasifiers, each with its characteristics and applications. The type of reactor utilized has a direct impact on the temperature, chemical reactions, and phases of the gasification process. The primary way in which the gas-solid medium (bed) and the gasifying chemical come into contact determines how the gasifiers are categorized. This allows us to divide gasifiers into three primary categories: fluid, entrained, and fixed or moveable bed. Each of them may be further separated into several types of gasifiers, as shown in figure 1-21. The most crucial operating parameters for each kind of gasifier are compared in Table 1.5 [39], There is a certain thermal power range output for each kind of gasifier. Fixed bed reactors are preferable to fluid bed gasifiers for intermediate powers (5 MWt to 100 MWt) in low thermal power plants (10kWt to 10MWt), but the entrained type is preferable for high installation powers (greater than 50MWt) [76]. The most common types of gasifiers and the power utilization span of several of these reactors are also shown in Figure 1.21. The main types of gasifiers include:

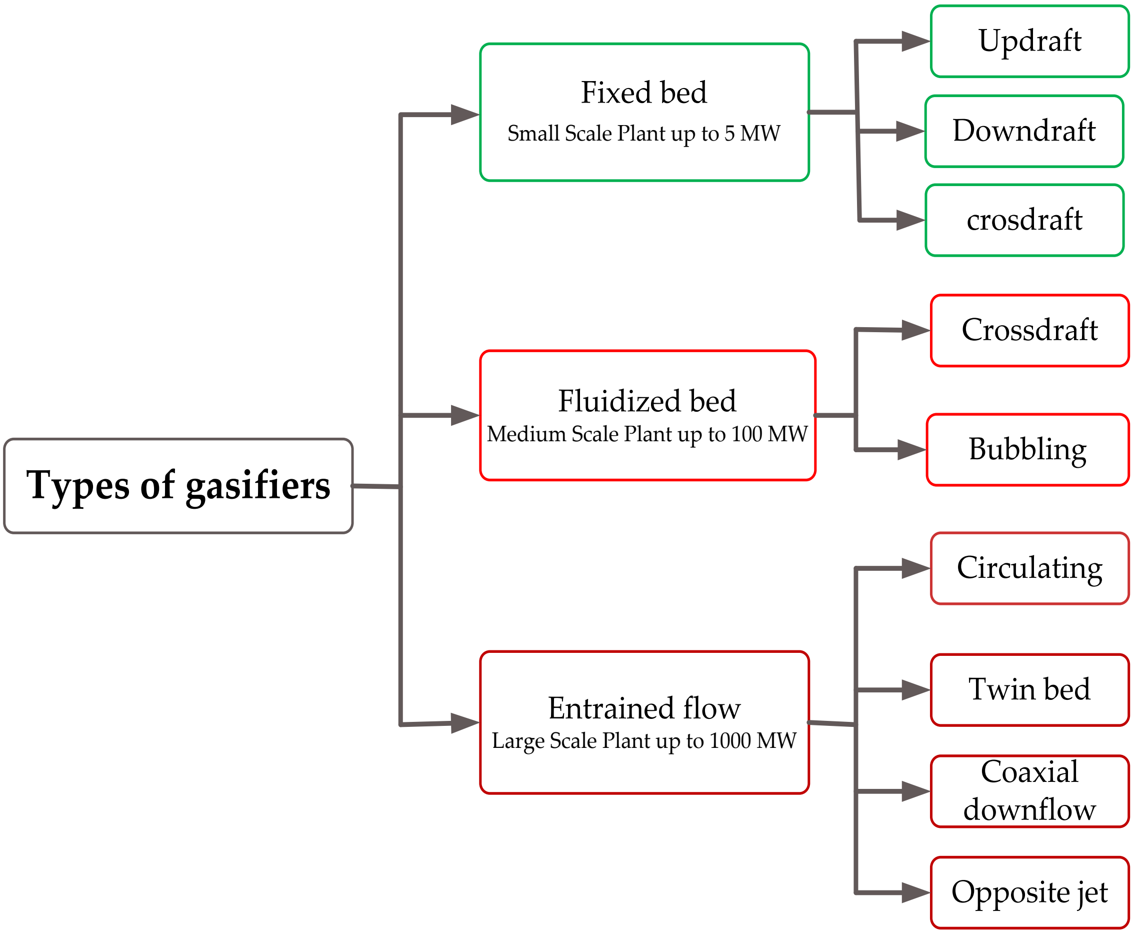

Figure 1-21 Types of Gasifiers

1.12.1 Fixed-Bed Gasifiers:

The top of the reactor is where the fuel is inserted in fixed-bed gasifiers. A variable height is used to inject the gasifying ingredient. The biomass fuel flows downward through the entire length of the reactor, earning it the term "moving bed gasifier" as well. These reactors are made for small-scale thermal powers because of their straightforward construction. Because of this, a significant number of fixed-bed reactor-based gasification facilities are currently in operation [77], [78], [79], and [80]. These gasifiers do not have consistent fuel distribution, temperature, or product gas composition over the whole gasifier section. According to figure 1-21 there are three different types of fixed bed gasifiers: updraft, downdraft, and cross draft. The attributes of each of them regarding the utilization of wood as an input fuel are summarized in Table 1-6 [81], [82], and [78].

Table 1-6. Characteristics of several fixed bed gasifier models.

Parameter (wood)	Updraft	Downdraft	Cross draft
C	25	6	0.5-1.0
Max. admissible moisture (%)	60	25	10-20
Max. fusion temp. (°C)	>1000	>1250	-
Average particle size (mm)	5-100	20-100	5-20
Application range (MW_t)	2-30	0.1-2	-
Gas exit temperature (°C)	300-400	700-800	1250
Tars (g/Nm^3)	30-150	0.01-3	0.01-0.1
LHV producer gas (MJ/Nm^3)	5-6	4-5	4-4.5
Gasification performance (%)	85-90	80-85	75-90

A) Updraft Gasifiers:

In updraft gasifiers, air or oxygen is introduced at the bottom of the gasifier, and the feedstock moves upward against the flow of gases. These gasifiers are simple but less efficient, and primarily used for small-scale applications. Updraft reactors were the initial gasifiers that were created. In these, the fuel bed goes downhill while the agent or gasifying medium (including oxygen, air, and/or water vapor) flows upward, resulting in a countercurrent flow of the generated solids and gas. As seen in figure 1-21, air enters the gasifier at the bottom and produces gas leaves at the top. The exothermic combustion reactions R4 and R5 occur as a result of the interaction between oxygen in the air (acting as the gasifying agent) and solid particles (char and ash) descending from the top of the reactor.

When there is not enough oxygen in the surroundings, reaction R5 quickly uses up the oxygen that is present before giving way to reaction R4, which releases the energy of a reasonable form (111 kJ/kmol). Hot gas that is created when CO, CO_2, and water vapor are combined with the gasifying agent or raw material rises to the top of the reactor and enters the reduction zone. At this time, the char predominantly generated at the top undergoes gasification primarily by R1 and R2, with R3 and R15 playing a secondary role. The temperature of the gases generated decreases because of the endothermic reactions R4 and R5, which provide the heat (energy) needed for their creation. Above the gasification zone, pyrolysis takes place. The decomposition of the entering biomass mad about low molecular weight gases, condensates (tar), and char is carried out by the remaining heat from the hot gases created in the preceding step. The gases from this zone combine with the rising ones created in the previous stages of reduction and combustion as the solid particles fall and char. The arriving raw material is dried after pyrolysis in the top zone while in proximity to the ascending hot product gas. Because of this, the pyrolysis and reduction zone byproducts combine to generate the final product gas.

However, they are discouraged for use with fuels containing high volatile content. Updraft gasifiers are especially suitable for biomass containing elevated levels of ash (up to 25%) and moisture (up to 60%). The gasification performance attained in these gasifiers is extremely high (90%), [78]. Also, they are best suited for direct applications of product gas combustion when cooling or cleansing of the gas is necessary. 400–500 ° C is the temperature at which the product gas leaves the reactor.

B) Downdraft Gasifiers:

Downdraft gasifiers introduce air or oxygen at the top and extract syngas from the bottom. This design allows for better combustion control and tar reduction, making them suitable for large-scale operations. In contrast to an updraft reactor, downdraft gasifiers have different zones where the gasification steps take place. At this point, the gasification agent is introduced into the reactor at a designated elevation, and the resulting gas exits the reactor from its bottom, descending alongside the solid particles. The biomass is dried and pyrolyzed in the earliest stages of the gasification process, as shown in figure 1-22. Low molecular weight gases, tars, and char that are pyrolysis products also acquire some oxygen (air) from the lower section, leading to a partial combustion of these products (referred to as flamed or flaming pyrolysis). Ashes and the by-this-point produced byproducts go to a location with abundant oxygen to produce the combustion stage. The char reacts quickly in this instance, yielding CO_2, CO, and enough energy for further reduction processes. This stage's temperature approaches 1200 ° C, [81], [82]. This makes it easier for the tar produced during the pyrolysis stage to thermally crack.

The last step of reduction involves the high-temperature gases resulting from the combustion (CO and CO_2), in addition to any remaining unreacted water vapor (originating from the biomass or the gasifying agent) and char. As CO and H_2 are generated through endothermic reactions in this area, the temperature decreases. The product gas's exit temperature, however, continues to be above 700 ° C, [78]. We may categorize downdraft gasifiers into two categories based on their structure and design: strangled and non-strangled (also known as open center) [81]. The key distinction is that the reactor part is strangled in the middle zone, which is where the combustion stage takes place. All the pyrolysis byproducts are forced to pass through that zone due to a decrease in the reactor section (at the level where the combustion stage is located), which facilitates the thermal cracking[1] of most of the tar [83]. Table 8 lists the key attributes of downdraft reactors along with their intended use and usage limitations.

C) Cross-draft gasifiers:

Cross-draft gasification represents one of the most straightforward gasification techniques, where the gasifier's configuration closely resembles that of an updraft gasifier. In this setup, the fuel is introduced from the top, and the thermochemical reaction progresses as the fuel descends through the reactor.

In this type of gasifier, the gasifying agent, typically air, is forcefully injected through the lateral zone, while the fuel is simultaneously fed from the top of the reactor (as shown in figure 1-22). The resulting gas is emitted from the opposing side to the air injection point. These reactor designs are primarily intended for gasifying low-ash coal. By injecting additional air near the injector, a region with an extremely high temperature exceeding 1500 °C is created, allowing for the combustion of some of the char [78]. This, in turn, facilitates the conversion of unoxidized char into carbon monoxide (CO). The heat generated by the rapid char combustion is transferred to the pyrolysis zone, assisting in the disintegration of incoming biomass. Cross-draft gasifiers are commonly employed in small-scale units. Moreover, the utilization of tar in small-scale (ICE) is highly advantageous due to its low production (0.01–0.1 g/Nm^3) and its rapid response to changes in load [81]. Additional characteristics of this fixed-bed reactor type are outlined in Table 1-6.

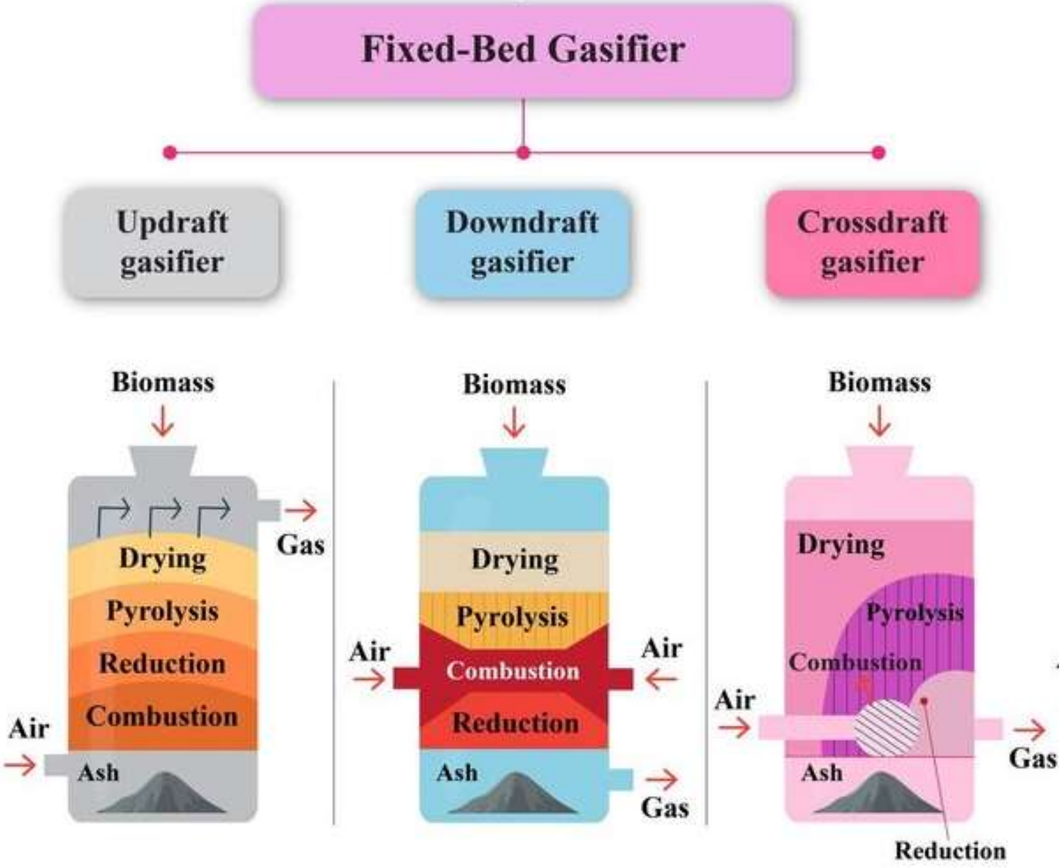

Figure 1-22 The most common types of gasifiers [84]

1.12.2 Fluidized Bed Gasifiers

A fluidized bed gasifier, often referred to as a fluidized bed gasification system, is a technology used for the conversion of solid biomass, coal, or other carbon-based materials into a gaseous fuel known as syngas (synthetic gas). It operates based on the principle of fluidization, which involves suspending solid particles (in this case, the feedstock) in an upward-flowing stream of gas (usually air or steam) to create a fluidized or "bubbling" bed of solids as shown in Figure 1-22

A. Bubbling Fluidized Bed Gasifiers:

These gasifiers use a bed of particles (e.g., sand or ash) that bubble as gas is passed through it. This provides good mixing and efficient gasification. They are commonly used in biomass and waste-to-energy applications.

B. Circulating Fluidized Bed Gasifiers:

In these gasifiers, the bed material circulates, providing even better mixing and improved temperature control. They are suitable for a wide range of feedstocks, including coal and biomass. These gasifiers run between 800-1,000° C and up to 10 bar of pressure to prevent subsequent agglomeration and melting of ash in the reactor walls [85], [81]. Fluid bed gasifiers suffer from the drawback of incomplete conversion of char particles because many of them end up in the fluid bed and often leave the reactor with the product gas. For this reason, the tiny char particles (not gasified) exiting the reactor are sorted in a cyclone and re-introduced from the bottom to increase the efficiency of carbon conversion present in the biomass. [78]. Another significant flaw is that biomass requires prolonged residence durations in the reactor due to its poor responsiveness to charge changes.

Temperature, pressure, and consistent product gas composition are the fluid bed's physical characteristics, which provide these reactors with an edge. They are quite versatile in the kinds of biomass that they may employ, but to have decent fluidization in the bed, the biomass must first be ground. The creation of tar is also not particularly substantial (1-50 g/Nm^3). Fluidized bed reactors may be divided into two categories: circulating and bubbling (circulating fluidized bed). The fundamental distinction between the two is found within the fluidized bed dynamics; specifically, the rate of fluidization in circulating fluidized bed gasifiers is substantially higher (3.5–5.5 m/s) than in bubbling bed gasifiers (0,5–1.0 m/s), according to [81], [78]. Advantages of fluidized bed gasification systems include efficient heat transfer, good mixing of feedstock and gasifying agents, and the ability to handle a wide range of feedstock types and sizes. The fluidized bed design promotes better combustion and gasification efficiency, reducing emissions of pollutants compared to some other gasification methods. Fluidized bed gasifiers are utilized in various industrial applications, including coal-to-syngas processes, biomass gasification for renewable energy generation, and waste-to-energy systems. They contribute to sustainable energy production and environmental benefits by allowing the conversion of carbon-based materials into useful energy forms while reducing greenhouse gas emissions and minimizing waste.

1.12.3 Entrained Flow Gasifiers

Entrained-flow gasifiers are advanced technology used for coal gasification. They efficiently convert coal fines and oxidants into syngas by operating at high temperatures, achieving remarkable carbon conversion rates of 98-99.5%. Additionally, they effectively break down tar and other liquid byproducts into hydrogen and carbon monoxide. Entrained-flow gasifiers are versatile, capable of handling various coal types, and are particularly suitable for high-power gasification facilities, typically exceeding 50MWt. These gasifiers operate at high pressures (20-70 bar) and temperatures above 1400°C [81], [78]. Figure 1-23 shows the entrained-flow gasifier.

The gasification process involves delivering the fuel and gasifying agent into the reactor, leading to combustion reactions. Water is often added to the fuel and gasifying agent at high pressures (around 70 bars) for ease of operation, resulting in a slurry-like mixture. However, the presence of excess water can increase the reactor's size. One distinguishing feature of entrained-flow gasifiers is their minimal tar production, very short residence time (typically seconds), high operating temperatures and pressures, and exceptional coal particle conversion performance. They are well-suited for producing synthetic gas with a high content of H_2, CO, and low CH_4. The gasifiers can be classified as either downstream reactors (inlet from the top) or opposing flows (lateral input), varying based on the fuel and oxidizing agent inlet area [82], [86].

The coal feed can be dry or in a slurry form:

- Dry Ash Gasifiers: These are often used in coal gasification processes. Finely ground feedstock is suspended in a high-velocity stream of gas and burned, creating syngas. The ash is collected as a dry powder.

- Slagging Gasifiers: In slagging gasifiers, the ash produced during gasification is kept in a molten state, forming slag. This design can handle a wide range of feedstocks and is used in applications like gasification of coal and biomass [87].

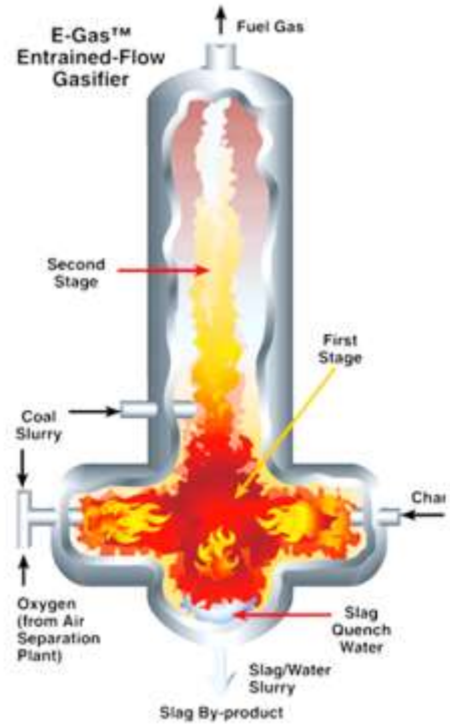

Figure 1-23 Entrained-flow gasifiers, [86]

1.12.4 Plasma Gasifiers

Plasma gasifiers are advanced gasification technology that uses a high-temperature plasma torch that can reach temperatures figure 1-24 of 10,000°C (18,032°F) or even higher, making it capable of breaking down complex organic and inorganic materials, to convert various feedstock materials, such as municipal solid waste, biomass, or hazardous waste, into valuable products, primarily syngas [88]. shows the plasma gasifier. Plasma gasification technology is complex and can be expensive to implement, but it offers an innovative approach to waste management and clean energy production, with the potential to reduce waste, minimize environmental impact, and recover valuable resources.

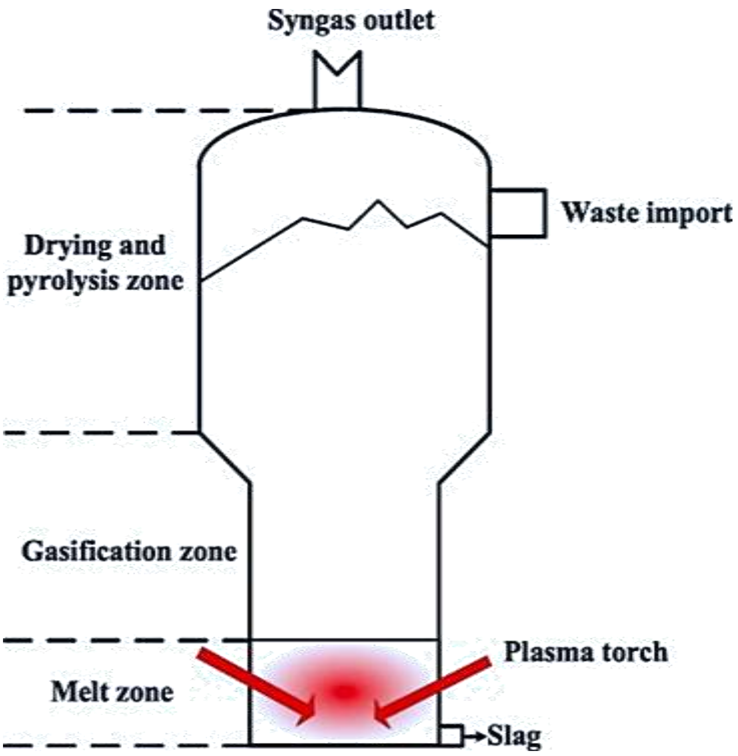

Figure 1-24 Plasma gasifier working principle diagram [89]

1.13 Power Generation Technologies Suitable for Biomass Sources.

1.13.1 Internal Combustion Machines

ICEs are machines that convert the chemical energy contained in fuel into mechanical energy through the process of internal combustion. These engines are commonly used in various applications.

ICEs play a significant role in transportation and power generation, providing a reliable source of mobile and stationary power. They are integral to various industries and are continuously evolving to meet efficiency and environmental standards.

1.13.1.1 Steam Turbines

A steam turbine is a mechanical device designed to convert the energy contained in high-pressure steam, typically in the form of water vapor, into mechanical energy. This mechanical energy can be employed to generate electricity or perform various mechanical tasks. This technology finds extensive use in power plants to produce electrical power.

Steam turbines are utilized as turbomachinery to generate electricity from fluid under high pressure and temperature, typically water vapor. Currently, the most widespread type of power plant fueled by biomass operates using the conventional Rankine cycle, as shown in Figure 1-25 a steam-powered plant fundamentally comprises the following primary components: a turbine (connected to an electrical generator), a pump (usually driven by an electric motor), a condenser (linked to a cooling tower), and a steam generator, often referred to as a boiler. Additional systems are integrated into the setup to facilitate fuel storage, transportation, and supply, as well as other supporting subsystems [90].

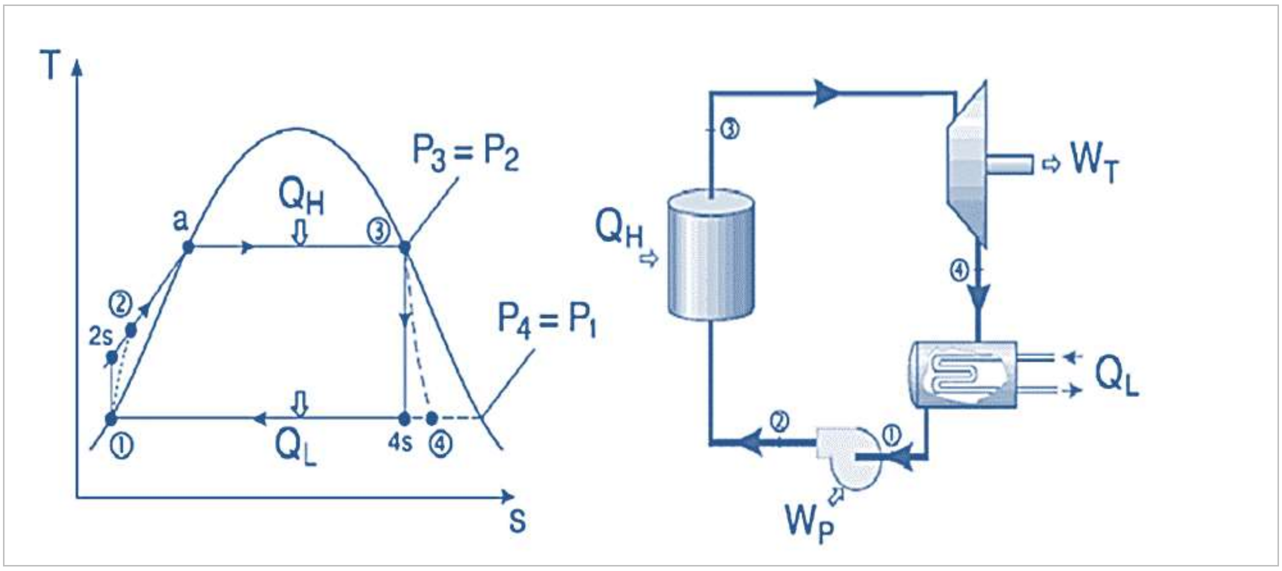

Figure 1-25 Simplified diagram of a steam plant [91]

1.13.1.2 Organic Rankine Cycle (ORC)

The Organic Rankine Cycle (ORC) is a thermodynamic process used for the generation of mechanical work and electricity. It is based on the Rankine cycle, which is a well-known thermodynamic cycle used in steam power plants. However, the key difference is that the ORC uses organic fluids, typically organic compounds with low boiling points, instead of water, to transfer heat and generate power. This makes the ORC suitable for applications where lower-temperature heat sources are available, such as in waste heat recovery or renewable energy systems.

The ORC is particularly useful for converting low-temperature heat sources (typically between 100°C and 300°C) into electricity. It has applications in a wide range of industries, including waste heat recovery from industrial processes, geothermal power generation, and solar energy systems. The choice of the organic fluid in the ORC depends on the specific application and the temperature range of the heat source, as different organic compounds have different boiling points and properties suited to different temperature ranges [92]. At present, Stirling engines and EFGTs are not technologies that have reached industrial-scale development. Most of the research in the literature centers around a small (CHP) prototype, which receive support from specific research and development (R&D) programs or funding from local governments [93], [94], [95].

1.13.1.3 Internal Combustion Engines

ICEs are devices that generate mechanical power by burning a fuel-air mixture within a confined space called a combustion chamber. This process is known as internal combustion because the fuel is burned inside the engine itself. ICES are widely used for various applications, including transportation, power generation, and industrial machinery. Two primary varieties of ICEs exist:

A) Spark-Ignition Engines (Gasoline Engines):

Spark-ignition engines are commonly used in automobiles and small equipment. They operate on the Otto cycle and use a spark plug to ignite a mixture of gasoline and air. Gasoline engines are known for their relatively high power-to-weight ratio and are used in vehicles where high-power output is required.

B) Compression-Ignition Engines (Diesel Engines):

Compression-ignition engines, also known as diesel engines, are widely used in heavy-duty vehicles, industrial machinery, and some passenger cars. They operate on the Diesel cycle. Diesel engines are known for their fuel efficiency and high torque output, making them suitable for heavy loads and long-distance transportation. ICEs can run on a variety of fuels, including gasoline, diesel, natural gas, and biofuels. They are a crucial component of modern transportation and power generation systems. In general, diesel engines tend to be more efficient than gasoline engines, which operate on the Otto cycle. Many ICEs employed for generating power, often referred to as stationary engines, are four-stroke engines [96].

At present, there are many use cases for utilizing biomass from ICE in electricity production, heat generation, and transportation.

- The syngas generated through biomass gasification can be employed in gas engines for Distributed Generation systems [97], [98]. Figure 1.26 depicts a gasification facility utilizing syngas produced from the gasification of biomass to power a gas engine [99]

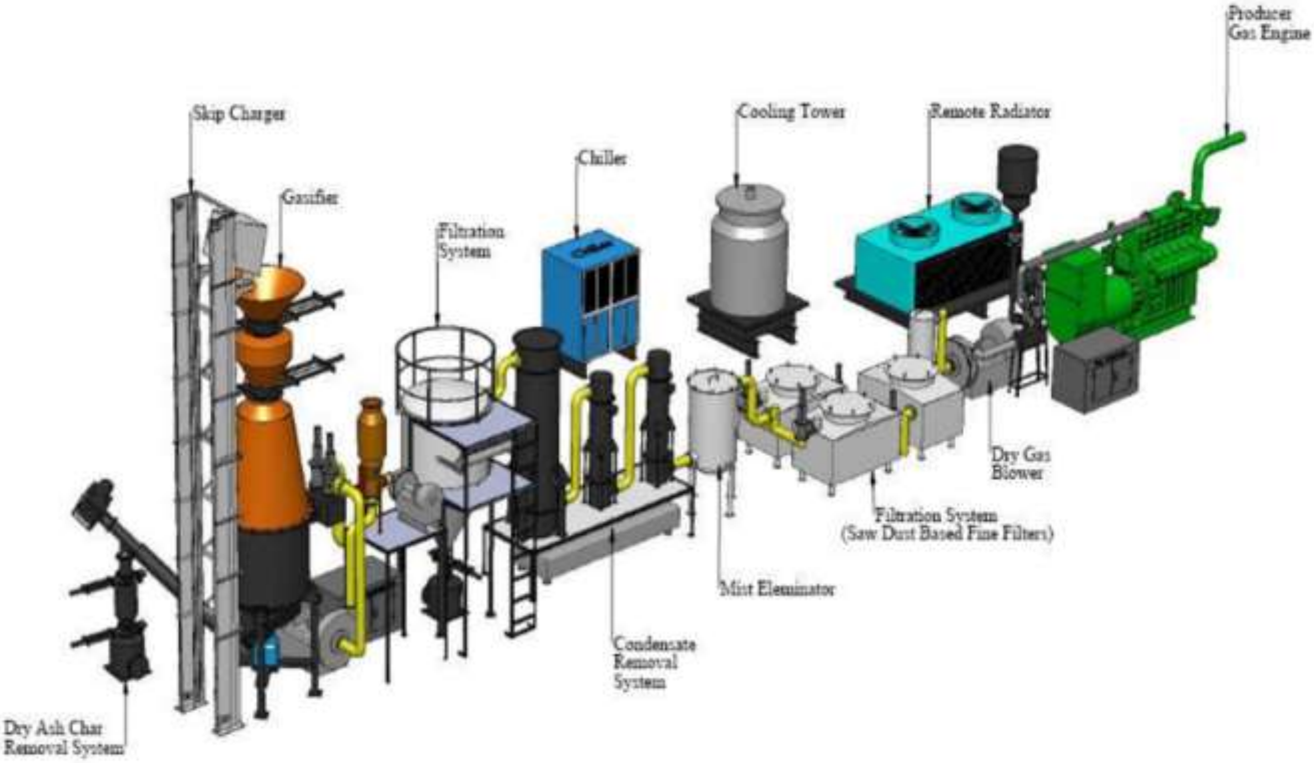

Figure 1-26 Unit gasification of biomass to power a gas engine [99]

Biogas produced through the anaerobic digestion of waste from landfills, agricultural farms, and sewage treatment facilities is utilized in ICE to produce on-site electrical and thermal energy in various applications [100]. Figure 1.27 illustrates a biogas plant in Styria, Austria, generated from the anaerobic digestion of manure. This facility is equipped with an internal combustion engine capable of generating 500 kilowatts of electricity and around 600 kilowatts of thermal energy [101].

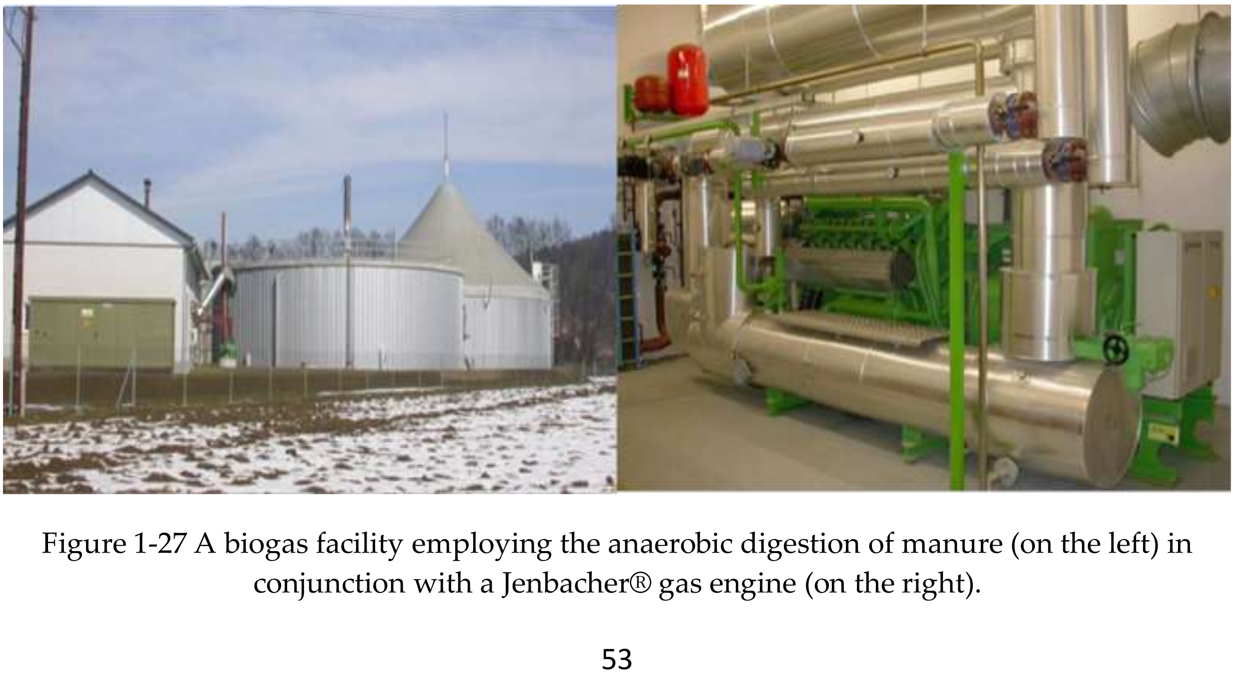

Figure 1-27 A biogas facility employing the anaerobic digestion of manure (on the left) in conjunction with a Jenbacher® gas engine (on the right).

- In the present day, biodiesel derived from sources like rapeseed and palm oil is employed in ICEs. These biofuels effectively reduce emissions that harm the environment while preserving the efficiency of conventional diesel engines.
- In certain regions, bio-alcohol, specifically ethanol produced through the fermentation of biomass, has been utilized for several years either as a partial or complete replacement for gasoline in ICEs using the Otto cycle. This type of fuel is commonly referred to as "gasohol." Otto engines require minimal adjustments to run on ethanol-gasoline blends or ethanol instead of gasoline. Additionally, bio-alcohol can also be mixed with diesel for application in diesel engines.

Generation units utilizing ICEs stand out for having the lowest initial costs among distributed generation (DG) technologies, yet they come with relatively high operational and maintenance expenses. Noteworthy drawbacks associated with ICEs include elevated maintenance costs attributed to their numerous moving parts. Furthermore, these engines produce higher levels of nitrogen oxide (NO_x) emissions compared to alternative DG technologies, although the use of fuels like natural gas, biogas, or gasified biomass can aid in mitigating these emissions. Another challenge lies in the generation of low-frequency noise by ICEs, a characteristic that can be more difficult to control compared to noise from other technologies. However, there are available mechanisms for mitigating and managing this noise issue.

Despite the noted disadvantages, this technology presents several attractive features. The initial investment required is notably economical, positioning it as the most cost-effective among Distributed Generation (DG) technologies. ICEs demonstrate commendable efficiency, with power conversion rates ranging from 28% to 42% of the lower heating value. Achieving cogeneration is feasible by harnessing heat from exhaust gases, especially given their temperatures often exceeding 400°C. Additionally, the highly modular nature of ICEs allows for versatile applicability, accommodating a broad spectrum of loads, from kilowatts to megawatts.

1.13.1.4 Gas Turbines

GT gas turbine, also known as a combustion turbine, is a type of heat engine that converts chemical energy from fuel into mechanical energy through a high-speed rotating shaft. Gas turbines are commonly used for various applications, including electricity generation, aviation (jet engines), marine propulsion, and industrial processes. Gas turbines typically operate based on the Brayton cycle principle [102], [103]. The process involves introducing ambient air into the compressor, where its pressure and temperature are elevated. The pressurized air moves to the combustion chamber, where it combines with fuel and undergoes combustion under steady pressure. Subsequently, the elevated-temperature gases enter the turbine and expand to reach atmospheric pressure, producing mechanical energy. In gas turbines, the temperature of the exhaust gases as they depart from the turbine is often notably higher compared to the temperature of the air exiting the compressor. As a result, the pressurized air leaving the compressor can be warmed by transferring heat from the hot exhaust gases through a counterflow heat exchanger, referred to as either a regenerator or recuperator. If the exhaust gases are released (not recirculated), the cycle is referred to as an open cycle. Traditional gas turbines are well-known for their large-scale electricity generation, typically on the order of hundreds of megawatts. Gas turbines are known for their high power-to-weight ratio, making them suitable for applications where weight and size constraints are critical, such as aviation. They are also valued for their efficiency, reliability, and the ability to start and stop quickly, which is crucial for some applications like power generation. Additionally, gas turbines are often used in combined cycle power plants, where their exhaust heat is used to produce steam and generate additional electricity, enhancing overall efficiency.

In this thesis, we will explore distributed generation technologies applicable to biomass fuel, particularly waste from the palm tree, within the broader context of gas turbine development. Our focus will be on two specific types of gas turbines: externally fired gas turbines (EFGTs) and microturbines (MTs).

1.13.1.5 Microturbines

Microturbines (MTs) are compact, highly efficient gas turbine engines designed for distributed energy generation and various applications. They typically range in power from 25 kilowatts (kW) to 500 kW, with some larger units capable of producing a few megawatts. Microturbines offer numerous advantages, including their high energy efficiency, low emissions, and the ability to generate both electricity and thermal energy.

Microturbines exhibit notable characteristics such as high-speed rotation, with turbine speeds reaching 120,000 rpm and generator operation at 40,000 rpm. Their ability to operate effectively at low combustion temperatures contributes to reduced nitrogen oxide (NOx) emissions, and their compact, lightweight design simplifies installation. With noise emissions of approximately 70 dB at a one-meter distance, microturbines are relatively quiet. The cost efficiency of microturbines is underscored by reasonable initial investment costs and lower maintenance expenses due to their minimal moving parts, sometimes limited to just the axis, resulting in fixed costs estimated between €800 and

€1,300 per kilowatt of electrical power (kW) [102], [104]. These versatile units, available in a power range of 25–200 kW, can be easily combined to generate higher power outputs. Figure 1-28 shows that.

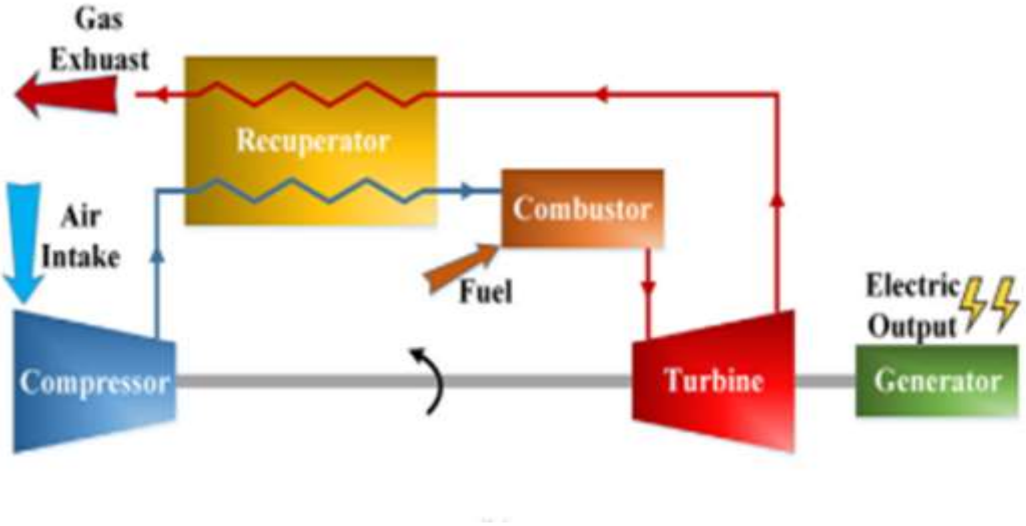

Figure 1-28 Basic diagram of a microturbine for decentralized power generation [105]

1.13.2 External Combustion Machines

External combustion machines, also known as external combustion engines, are a type of heat engine where the combustion of fuel occurs outside the engine itself. In these engines, a working fluid, often steam, air, or other gases, is heated by an external heat source, such as a burner or furnace. This heated working fluid then enters the engine where it expands and does mechanical work, typically by driving a piston or a turbine. External combustion engines are in contrast to internal combustion engines, where the combustion of fuel occurs within the engine, directly affecting the working fluid.

One of the most common examples of an external combustion engine is the steam engine, which was widely used during the Industrial Revolution to power locomotives, ships, and various industrial machines. While internal combustion engines, such as those found in most automobiles, have become dominant in many applications, external combustion engines are still used in some specialized and niche applications, particularly in power generation and certain industrial processes. These engines are often appreciated for their fuel flexibility and the ability to generate power from various heat sources, making them suitable for specific uses like steam turbines and Stirling engines [106].

1.13.2.1 Externally fired gas turbines (EFGT)

Externally fired gas turbines, also known as EFGT engines, are a type of heat engine used for power generation, operating on principles similar to traditional gas turbines with a notable distinction. In EFGTs, the combustion of fuel occurs externally within a heat exchanger rather than within the engine itself. Here's how they function:

Like standard gas turbines, EFGTs initiate the process by compressing atmospheric air. This compressed air is subsequently directed into an external heat exchanger. Inside the heat exchanger, the compressed air is heated by an external heat source, such as a burner, furnace, or another heat-producing apparatus. This external heat source supplies the high-temperature air essential for the combustion process. The high-temperature, compressed air is mixed with fuel and combusted within the heat exchanger, resulting in the creation of hot, high-pressure gas. The hot, pressurized gas generated through this external combustion process is then channelled into the turbine section of the EFGT, where it expands, propelling the turbine to generate mechanical work. The mechanical work harnessed from the turbine is utilized to drive an electric generator, producing electricity [107].

EFGTs are appreciated for their ability to utilize a diverse range of heat sources for combustion, making them versatile and suitable for various applications. They are commonly employed in distributed power generation, particularly in combined heat and power (CHP) systems, where waste heat from the external combustion process can be captured and used for heating or other purposes, enhancing overall efficiency.

One notable advantage of EFGTs is their potential for achieving high efficiency and low emissions since the external combustion process can be precisely controlled. Additionally, they can operate with a variety of fuels, including natural gas, biomass, and waste heat, depending on the specific application. Presently, this technology is experiencing significant growth and progress, offering numerous benefits compared to conventional internal combustion microturbines [108],[109][,[110]. Direct Utilization of Solid Biomass: EFGT technology allows for the direct utilization of solid biomass as an energy source without the need for prior conversion into biogas or syngas. In contrast, traditional internal combustion microturbines require the introduction of gaseous or liquid fuels into the system at combustion chamber pressure, incurring additional power consumption for fuel compression. EFGTs do not face this issue as their external combustion chamber can accommodate a wide range of fuels, including solid biomass.

Adaptation to Gaseous Fuels: Adapting conventional internal combustion microturbines originally designed for natural gas to operate with gaseous fuels of lower or moderate energy density, such as biogas or syngas, may require adjustments to the combustion chamber injectors. This entails research and development efforts by major manufacturers, presenting an obstacle to their use of biomass. For instance, Capstone® currently offers microturbine models operating using biogas generated from anaerobic digestion, known as CR (Capstone Renewable), available in modules ranging from 30 kW to 1 MW of electrical power [111]. However, there is no industrialist producing microturbines designed for syngas derived from biomass gasification.

Reduced Wear and Corrosion: In EFGT systems, the fluid that passes through the expansion turbine consists solely of air at high temperature and pressure. This design mitigates potential corrosion and wear effects on the turbine blades, which can be a concern in conventional microturbines. Concerning microturbines using biogas, the presence of hydrogen sulfide (H_2S) in the gas is a notable consideration. Insufficient gas cleaning for biogas may expose turbine blades to corrosion, diminishing their operational lifespan. Figure 1-29 illustrates the fundamental configuration of an EFGT powered by solid biomass [112]

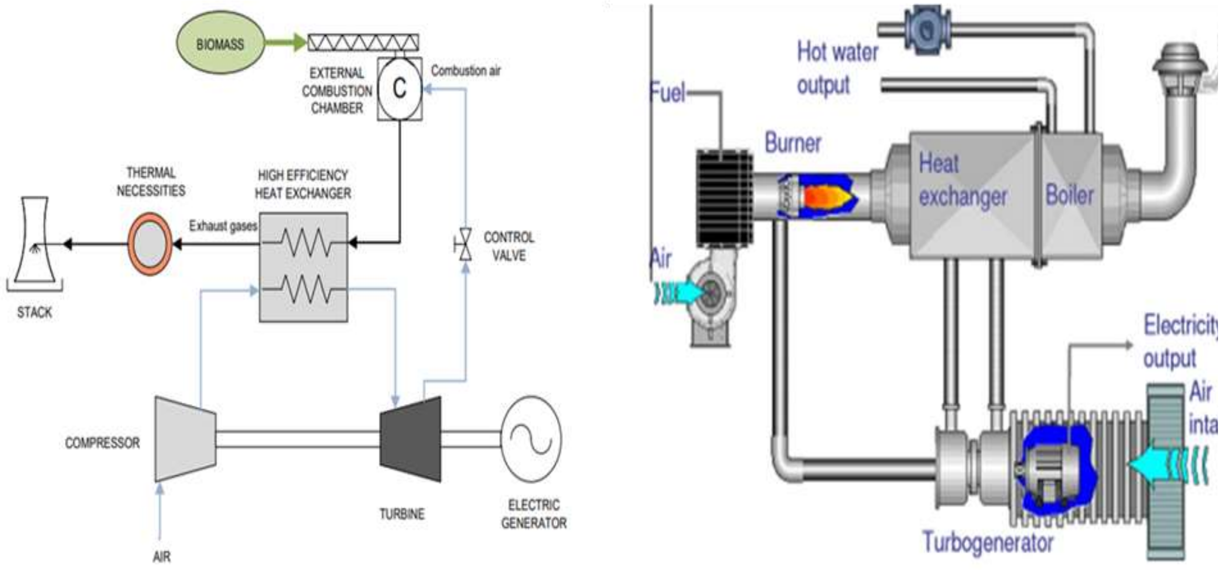

Figure 1-29 An Externally Fired Gas Turbine [112]

The primary challenge with this technology pertains to the efficiency of the heat exchanger. The system's operational temperature must not exceed approximately 100–150 degrees Celsius above the temperature of the incoming air to the turbine. Furthermore, the relatively low heat transfer coefficients of both flue gas and air necessitate the construction of larger heat exchangers to enhance heat exchange surfaces, thus increasing the overall cost of this technology. Nevertheless, there is potential for substantial advancements in EFGTs' development in the future, particularly with advancements in ceramic materials that can endure operational temperatures as high as 1200–1300 degrees Celsius [113],[108].

1.13.2.2 Stirling Engines

In an engine with external combustion, ignition of the fuel occurs outside the cylinders at a constant pressure. When air, hydrogen (H_2), or helium (He) is used as the working fluid, it follows the Stirling cycle, named after its inventor, Robert Stirling [114]. Heat is transferred from an external combustion chamber to the working fluid via a highly efficient heat exchanger called a regenerator. These engines outperform ICEs (such as Otto or diesel).

Key advantages of Stirling engines include the fact that they don't release working fluids (air, He, or H_2) into the environment, resulting in quiet and explosion-free operation. They are applicable in small-scale distributed generation (DG) and cogeneration (CHP) systems, offering high efficiency [115]. One of the main drawbacks of Stirling engines is their high initial investment cost per kilowatt of electrical output. Their commercialization and widespread use are still in the research and development phase. Currently, Stirling engines are developed based on experimental findings from pilot projects funded by diverse funding sources [116].

1.13.2.3 Fuel Cells

Fuel cells are electrochemical devices that generate electricity through a chemical reaction between a fuel and an oxidizing agent, typically oxygen. They are similar in concept to batteries but differ in that they require a continuous supply of fuel and oxygen to sustain their operation, making them ideal for continuous power generation. A single unit, often referred to as a cell or fuel cell, can generate a voltage of approximately 1.2 V. To achieve higher voltages, multiple cells are connected in series, forming what is known as a fuel cell stack. Additionally, a portion of the heat produced in this process can be utilized, making FC technology particularly appealing for combined heat and power (CHP) applications [117], [118].

The fundamental fuel cell (FC) unit comprises three essential components: the anode, responsible for fuel supply; the cathode, where the oxidizing agent, typically air, is introduced; and the electrolyte, facilitating the flow of ions from the anode to the cathode while impeding the movement of electrons and reactants. The electrochemical reactions occurring at the anode and cathode result in the flow of electrons through an external circuit, generating electricity. This process allows fuel cells to efficiently convert the chemical energy in the fuel into electrical energy. Fuel cells are known for their high energy efficiency, low emissions, and quiet operation. They can be used for a wide range of applications, including stationary power generation for homes and businesses, transportation (such as hydrogen fuel cell vehicles), and portable power sources. The most common types of fuel cells include hydrogen fuel cells (like PEMFCs and AFCs), solid oxide fuel cells (SOFCs), and molten carbonate fuel cells (MCFCs), each with their advantages and disadvantages. The choice of fuel cell type depends on the application and specific requirements[117], [119].

1.14 Combined Heat and Power

Combined Heat and Power (CHP), also referred to as cogeneration, is an exceptionally efficient technique for producing both electricity and practical thermal energy (heat) from a single energy source. This contrasts with the conventional practice of separately generating electricity and thermal energy, which tends to be less efficient. In a CHP system, the heat that is typically squandered in traditional power generation is harnessed and used for various purposes like space heating, cooling, hot water supply, or industrial processes.

CHP is a technology that achieves high efficiencies in the production of both electricity and thermal energy by employing various technologies and fuel sources. Through on-site power generation, it minimizes losses and efficiently utilizes excess heat that would otherwise go to waste. This surplus heat is redirected to serve facility needs, such as process heating, steam, hot water, or even chilled water. Figure 1.30 demonstrates that the conventional approach to generating distinct heat and power results in a standard combined efficiency of 45%. In contrast, Combined Heat and Power (CHP) systems can achieve efficiencies of 80% or greater. CHP systems can be installed at individual facilities or buildings, or they can function as part of a larger network, such as a district energy system, microgrid, or utility resource. In this capacity, CHP provides power and thermal energy to multiple end-users, enhancing overall energy efficiency and sustainability.

One notable advantage of CHP is its ability to deliver reliable power 24/7, even during grid outages, which makes it a resilient energy source. Additionally, it can be combined with other distributed energy technologies like solar photovoltaics (PV) and energy storage to further enhance energy reliability and sustainability [120].

Since its inception in the 1880s, (CHP) technology has evolved to become both the oldest and the most advanced method of power generation. Initially, CHP emerged as an inadvertent solution to address the challenges of waste heat stemming from conventional combustion-based power generation. While this approach was implemented, it did not achieve widespread popularity, primarily due to the low electricity prices in the 1980s. Nevertheless, it has experienced a renewed surge of interest in recent years, driven by the quest for sustainable energy solutions and the advancement of highly efficient power generation techniques. In recent times, CHP systems have witnessed progress in terms of energy sources, components, and various applications [92]. The most prevalent CHP system configurations are as follows:

- Utilizing a combustion turbine or reciprocating engine in conjunction with a heat recovery unit.
- Employing a steam boiler paired with a steam turbine.

The key components and features of a Combined Heat and Power (CHP) system encompass diverse technologies such as gas turbines, reciprocating engines, and steam turbines for electricity generation, all capable of being fuelled by natural gas, biomass, or coal. A defining characteristic of CHP is the recovery of waste heat generated during electricity production, which is harnessed for applications like space heating, hot water production, or other industrial processes. Renowned for their high efficiency, CHP systems maximize energy utilization by incorporating both electricity and waste heat, resulting in total energy efficiencies surpassing 80%. Not only do CHP systems enhance efficiency, but they also yield environmental benefits by reducing greenhouse gas emissions and air pollutants, making them environmentally friendly through optimized utilization of primary energy sources. Widely applicable across industrial facilities, commercial buildings, hospitals, universities, and district heating systems, CHP systems are particularly advantageous in locations with simultaneous demands for electricity and heat.

Overall, CHP is a sustainable and efficient way to meet energy needs while minimizing waste and reducing environmental impacts. It is an important approach for enhancing energy efficiency and reducing greenhouse gas emissions in many sectors. The field of combined heat and power (CHP) generation technologies is continuously progressing, offering a wide range of options, each with its unique strengths and weaknesses, encompassing various power capacities, electrical efficiencies, and applications. However, when operating in CHP mode, the overall energy conversion efficiency among the different options remains relatively consistent, typically falling in the range of 80% to 90%. Fuel cell technologies are an exception, as they may achieve lower CHP efficiencies, usually ranging from 65% to 75%, depending on the specific technology.

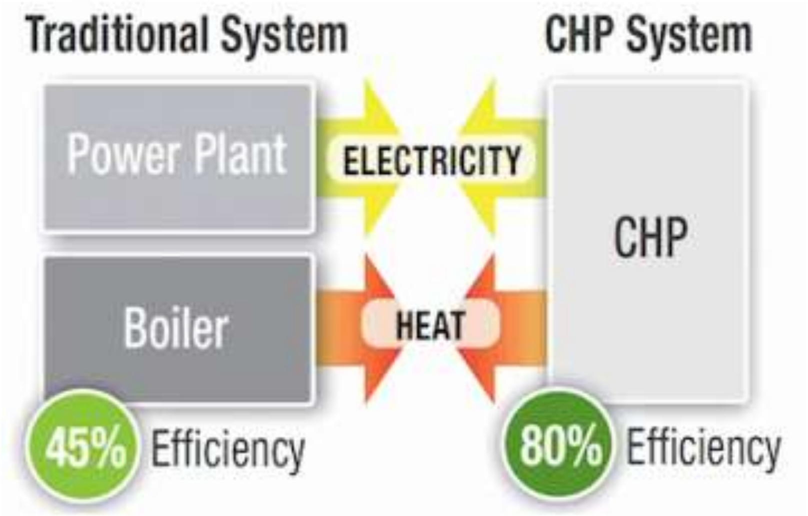

Figure 1-30 Combined Heat and Power (CHP) [121]

Regarding distributed power generation, ICEs and gas turbines are the preferred choices for integration with gasifiers, followed by organic Rankine cycles and steam turbines. ICEs and gas turbines are already commercially available with relatively low capital costs, rapid load response, and simple control systems. In contrast, advancements in technology are essential for Stirling engines and fuel cells to compete effectively, particularly in terms of improving their response to sudden load changes and reducing their high capital costs.

Distributed Generation (DG) entails the production of electricity in a decentralized fashion, where power generation is spread across various locations within the serviced area, typically in proximity to the energy consumer, who often happens to be the facility owner [122], [123]. This approach has gained significant significance in contrast to the conventional methods of electricity generation, which involve centralized thermal and hydro plants linked to the transmission grid.

In this thesis, we adopt the definition of distributed generation as suggested by Ackermann et al. [124]. According to this definition, distributed generation (DG) is defined as a power source generation directly linked to either the low-voltage grid or the power grid. This definition primarily focuses on the placement and linkage to the generator system. While this definition doesn't place any constraints on the technology utilized or the production capacity of these plants, in general, it can be observed that these facilities are smaller in scale compared to traditional generation systems, although the maximum capacity of generators within DG has been on the rise in recent years, reaching as high as 10 MW, 50 MW, or even 100 MW.

1.15 Thesis Structure

This research project is organized into four chapters, and this initial chapter serves as an introduction, setting the stage for the general approach. It outlines the significance of the topic under investigation, presents the working hypothesis, establishes the general objective, outlines specific objectives, and describes the methodological approach that will guide the research. The coherence of this thesis is justified because it does not adhere to a traditional structure but is instead based on a collection of publications (or thesis by articles), all following a coherent and justified line of argument while adhering to the requirements specified for a thesis consisting of a collection of publications by the University of Jaén's regulations. The first chapter also includes an in-depth analysis of the global significance of the energy and renewable energy sectors, particularly in the contexts of Europe and Iraq. Furthermore, it offers a comprehensive review of gasification technology for combined heat and power generation and syngas production. The introduction also covers various biomass utilization technologies, ranging from direct combustion to alcoholic fermentation, with a specific focus on gasification due to its pivotal role in this thesis. Chapter 2 explores Iraq's potential for biomass energy, focusing on waste from animals and crops like wheat, barley, rice, and sorghum, as well as residues from palm date trees. Chapter 3 delves into the generation of electricity from palm waste such as (fronds, empty fruit bunches, and trunk), using gasification, coupled with an externally fired gas turbine (EFGT), presented as a case study. fourth Chapter, a comprehensive overview of the findings is provided, followed by the primary conclusions that support both the core hypotheses of the study and the attainment of the various established objectives. Additionally, the chapter outlines potential future research projects derived from the obtained results.

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Chapter 2 MAIN RESULTS AND INTEGRATED DISCUSSION, CONCLUSIONS AND FUTURE WORK

2.1 The main result and integrated discussion

The works presented in the previous chapters have described a review of bioenergy potential from the agricultural sector in Iraq and the modeling of a system for the valorization of palm grove residues:

- Biomass gasification coupled with an Externally Fired Gas Turbine

The second chapter emphasizes the significant role that bioenergy, particularly biomass, could play in Iraq's energy landscape. Despite being a country with abundant biomass resources, including animal waste and agricultural crop waste, Iraq has yet to harness this potential for energy production. The findings reveal that if properly utilized, agricultural leftovers and animal wastes in Iraq could contribute substantially to the country's energy needs.

The research underscores that 10 million tons of dry agricultural leftovers can generate an impressive 115 PJ of energy annually. Furthermore, the study indicates that the country's 10 million cattle could potentially produce 72 million cubic meters of biogas per day, with a total annual energy potential of 946 TJ. These figures highlight the immense untapped bioenergy resources in Iraq.

However, the current practice of burning agricultural waste directly poses environmental risks. The study suggests redirecting these resources toward bioenergy generation. Geographically, the regions of Wasit, Qadisiyah, and Mosul are identified as the most feasible locations for harnessing this agricultural waste potential.

The research also sheds light on the underutilization of renewable energy sources, including wind, solar, and biomass, in Iraq's energy mix. Given the country's reliance on fossil fuels and the challenges in meeting rising electricity demand, transitioning to a more diversified and sustainable energy portfolio becomes imperative.

The potential of bioenergy not only aligns with environmental goals but also offers a viable solution to Iraq's electricity shortages. By implementing a long-term economic plan focused on sustainable bioenergy generation, Iraq could address its energy needs while contributing to economic development and environmental conservation. Ultimately, embracing the full potential of bioenergy sources emerges as a crucial step in shaping a sustainable and resilient energy future for Iraq.

The third chapter presents a promising and practical approach to addressing the challenges associated with fossil fuel usage for energy production by focusing on renewable energy sources, particularly biomass. The study specifically explores the feasibility of producing electricity from palm waste, including fronds, empty fruit bunches, and trunks, through a simulated Combined Heat and Power (CHP) system.

The simulation, conducted using Cycle-Tempo software, reveals that palm fronds are the most effective feedstock for gasification, demonstrating their potential to generate 390 kW of electric power with a commendable 19% electrical efficiency. The gasification process, carried out at 800°C using a downdraft fixed-bed reactor, produces syngas with a favorable molecular composition and a low heating value of 4.16 MJ/kg. The proposed technology exhibits a gasification efficiency of 77% and an overall CHP efficiency of 61%.

Comparative analysis with existing literature validates the efficacy of the proposed CHP system, emphasizing the satisfactory composition of syngas derived from palm fronds. The study underscores the significance of factors such as turbine inlet temperature, biomass flow rate, biomass moisture content, and compressor pressure ratio in influencing the system's performance.

Moreover, the developed CHP system demonstrates the capability to deliver not only 390 kW of electrical power but also 851 kW of thermal power. This highlights the system's potential to efficiently utilize palm waste for both electricity generation and heat production. The overall electric efficiency of approximately 19.57% positions this technology as a viable and sustainable option for energy production.

In summary, the research contributes to the growing body of knowledge on biomass utilization for energy generation, specifically showcasing palm waste as a suitable feedstock for gasification technology. The findings encourage further exploration and implementation of such systems to enhance the sustainability and environmental friendliness of electricity production.

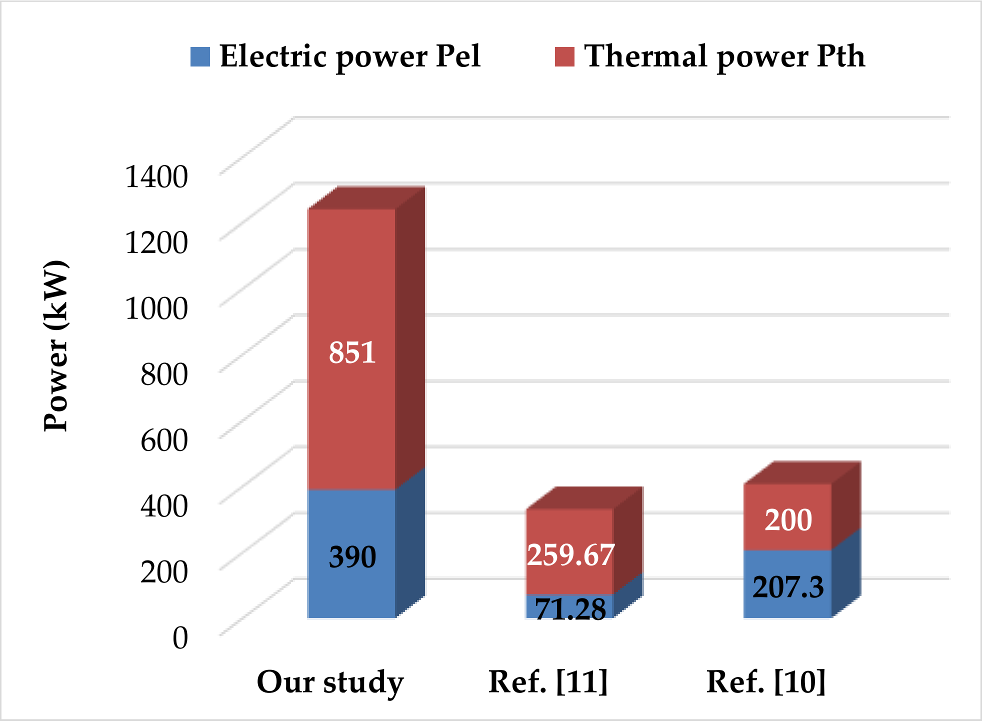

Figure 2-1 Comparison of power generation results with relevant research

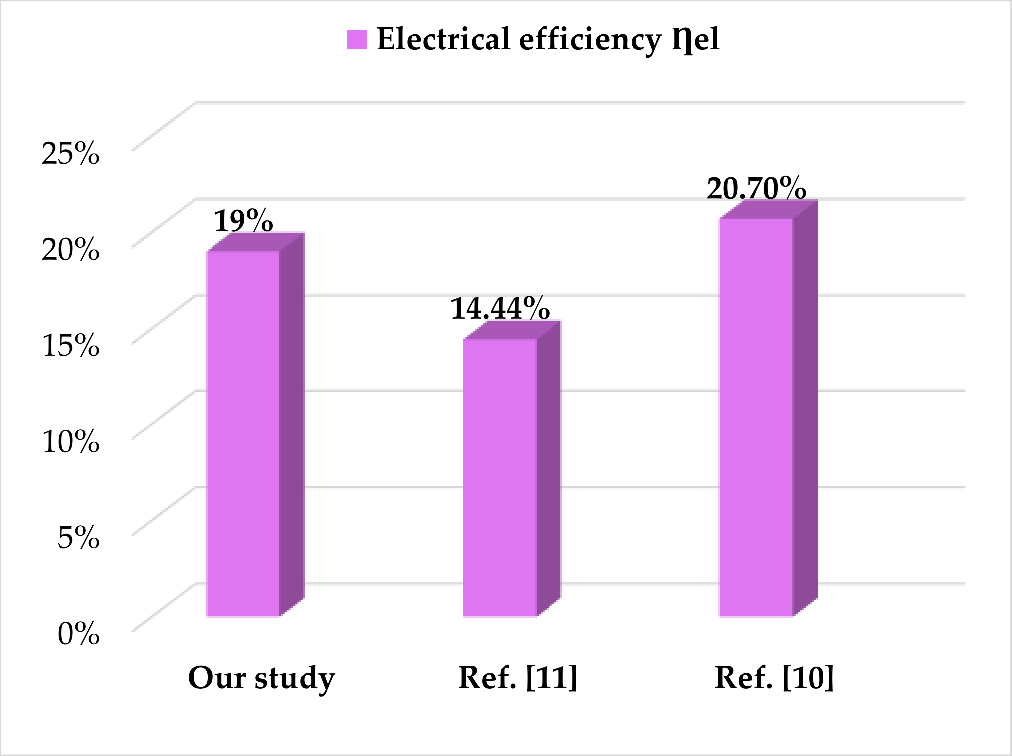

Figure 2-2 Comparison of electrical efficiency **results with relevant research**

2.2 The Conclusions

Iraq has significant biomass potential, particularly from agricultural and animal waste. This capacity positions Iraq to become a major bioenergy producer, highlighting the country's potential in the renewable energy sector. The thesis explores Iraq's potential for biomass energy, focusing on waste from animals and crops like wheat, barley, rice, and sorghum, as well as residues from palm date trees. It emphasizes sustainable management practices to enhance energy production and environmental preservation.

Biomass emerges as a pivotal renewable energy source, especially in generating hydrogen-rich syngas through gasification technology. Among various gasification methods, downdraft gasifiers stand out as viable options for small-scale power generation due to their capability to produce high-quality syngas with minimized particle and tar levels.

The study examines the best technologies suitable for valorizing the by-products of palm groves, particularly palm frond pruning, trunks, and empty fruit bunches. These by-products are prevalent in palm groves, and some, such as empty fruit bunches, are also transported alongside harvested dates to date molasses factories. Disposal of these residues at the factories presents more significant challenges compared to disposal at the groves, as it eliminates direct utilization options like soil spreading and imposes additional costs on factory operations. However, the study proposes exploring technologies capable of valorizing these by-products to fulfill the electrical and heat demands of the factories, thereby presenting a promising avenue for sustainable waste management and energy provision.

The thesis focuses on optimizing a Combined Heat and Power (CHP) system through gasification technology. The proposed techniques are compared with established optimization methods, encouraging investor engagement in biomass-dependent projects due to promising economic returns. The optimized configurations can serve as valuable guidelines for designing cost-effective electrification systems, particularly for biomass-utilizing facilities, including date molasses factories in Iraq.

2.3 Future work

Several aspects within this thesis still require attention, and it is worthwhile to highlight them in this section to inspire future research:

- Investigate methods for producing hydrogen from biomass, focusing on optimizing gasification processes to maximize hydrogen yield and integrating hydrogen production into CHP systems.
- Explore and develop new CHP systems using alternative technologies such as fuel cells, Stirling engines, etc.
- Create hybrid systems that combine biomass CHP with solar or wind to optimize energy production and reduce reliance on biomass alone.
- Investigate algae and other microbial sources of biomass, which offer high yield and lower land use compared to traditional biomass.
- Study strategies to reduce capital expenditures for CHP plants.
- Enhance the ability of biomass CHP plants to interact with smart grids, improving demand response capabilities and grid stability.
- Implement AI-driven predictive maintenance and operational optimization to improve CHP plant performance and reduce downtime.
- Validate the thermodynamic equilibrium model using specifications from commercial gasifiers and published experimental data, with an emphasis on conducting significant experimental tests.
- Model and simulate various gasifier reactors, including updraft and fluidized bed gasifiers, to determine the optimal gasification option.
- Address the challenges in commercializing biomass gasification technology for CHP generation by developing an upscaled biomass gasification plant for the palm sector. Focus on scaling up, designing, assembling, and operating these plants to advance the technology for broader adoption in the date molasses industry.
- Conduct research comparing different cogeneration technologies in terms of their economic and environmental aspects for applicability in biomass gasification of palm waste.
- Perform experimental analysis on the potential reuse of ash generated during the gasification process, exploring its application as fertilizer to enhance soil quality.

PERSONAL INFORMATION

Hend Dakhel Skhaal Alhassany, a PhD student enrolled in the Renewable Energies Doctoral Program at the University of Jaén, holds a bachelor's degree in Nuclear Engineering from the University of Baghdad (2007) and a master's degree in Heat Transfer and Heat Engineering from the Technical University of Tambove, Russia (2017). Fluent in English, Russian, Arabic, and Spanish, her research currently centers on the conversions of biomass for combined heat and power (CHP). She has co-authored five publications in international peer-reviewed scientific journals indexed in the Journal Citation Reports (JCR) within the realms of renewable energy and energy efficiency.

Professional Experience

- Work in the laboratories of Tambov State Technical University, Faculty of Engineering, for low-emission fuel generation.
- Supervising the sewage treatment project in Karbala Governorate.
- Supervising the project of remote sensing systems for river and lake water in Iraq.
- Supervising the drinking water filtration station project.
- Oversaw and managed multiple mechanical engineering projects, primarily aimed at developing infrastructure.
- Consultant engineer in the Iraqi Engineers Syndicate.
- Head of the Projects Follow-up Committee in Karbala Governorate.
- Practicing my profession as an engineer by specialty since 2008
- Current research focuses on using thermochemical processes to convert biomass into combined heat and power (CHP) and produce hydrogen.
- Co-authored six papers published in international, peer-reviewed journals listed in the Journal Citation Reports (JCR).
- - Research contributions span the area of renewable energy.

RESEARCH PUBLICATIONS

- **Alhassany, H. D**., Abbas, S. M., Tostado-Véliz, M., Vera, D., Kamel, S., & Jurado, F. (2022). Review of bioenergy potential from the agriculture sector in Iraq. Energies, 15(7), 2678.
- **Dakhel Alhassany, H.,** Malik Abbas, S., Vera, D., & Jurado, F. (2023). Generating electricity from palm waste by gasification technique coupled with externally fired gas turbine: a case study. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 45(1), 1150-1167.
- Abbas, S. M., **Alhassany, H. D**. S., Vera, D., & Jurado, F. (2023). Review of enhancement for ocean thermal energy conversion system. Journal of Ocean Engineering and Science, 8(5), 533-545.

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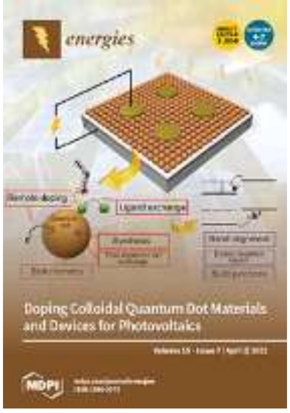
- Malik Abbas, S., **Dakhel Alhassany, H.**, Vera, D., & Jurado, F. (2023). Techno-economic viability analysis of a downdraft gasification system for hydrogen production from date molasses waste in Iraq. Biofuels, Bioproducts and Biorefining.

Scientific contributions

The research output generated throughout the doctoral program is compiled in the subsequent five publications, encompassing a collection of research articles referenced in the text and published in global scientific journals.



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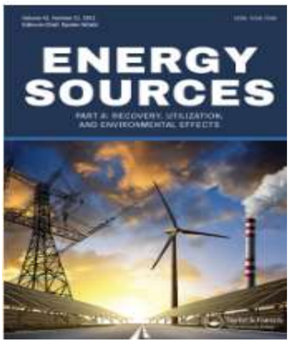

Dakhel Alhassany, H., Malik Abbas, S., Vera, D., & Jurado, F. (2023). Generatng electricity from palm waste by gasification technique coupled with externally fired gas turbine: a case study. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 45(1), 1150–1167. https://doi.org/10.1080/15567036.2023.2176569