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Review

The Role of Bioenergy in Malaysia's Low-Carbon Energy Transition: Trends, Challenges, and Policy Perspectives

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ABSTRACT: Malaysia's energy sector predominantly depends on fossil fuels, accounting for almost 81% of the nation's electricity generation, which is primarily derived from coal and natural gas. Given that Malaysia, a country with abundant natural resources, uses bioenergy as an alternative renewable energy source, it will be propitious to explore further. Malaysia, with an abundance of palm oil residues, municipal, and agricultural waste, can adopt a waste-to-energy pathway by turning the residues into an alternative feedstock for various bioenergy technologies. In this synthesis review, various studies published between 2015 to 2025, with support from national and international policy documents, were explored to evaluate Malaysia's bioenergy adoption for nations' green energy diversification. The study analyses the potential of local resource availability from various sectors that could support large-scale bioenergy production. The paper also examines current practices to denote the possibility of an energy mix by utilizing biomass waste for energy generation. This paper contributes to the understanding of the specific barriers hindering the shift to a strong bioenergy economy in Malaysia. These practical and infrastructural challenges are important to tap into fullest potential of indigenous organic biomass resources and realisation of a sustainable low-carbon energy transition vision of the country.

Keywords: Sustainable energy; Renewable energy; Waste-to-energy; Decarbonization; Biomass

1. Introduction

Energy is the most powerful matrix that influences the world's development, social development, and a nation's Gross Domestic Product (GDP). The International Energy Outlook 2023 (IEO2023) projected that current energy production would scale up 76% by 2050 to meet growing energy demand [1]. The World Energy Outlook (WEO) provides a holistic and integrated analysis that highlights the energy demand driven by global population growth, rapid urbanization, industrial development, transportation, and the rapid advancement of technology, which plays an essential role in the profound surge in energy demand [2,3].

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This energy shift trend is profoundly mirrored in Southeast Asia, especially Malaysia. As a developing nation and a key player within the regional energy transition, it is the second-largest producer of petroleum and ranked the fifth-largest exporter of liquefied natural gas (LNG) worldwide. Figure 1 shows a comprehensive view of Malaysia's national energy demand, which has grown more than tenfold from 9143 ktoe in 1994 to 104,596 ktoe in 2004. From 2019 to 2020, energy demand declined during the COVID-19 pandemic, followed by a sharp rebound in the post-pandemic period. This exponential increase is directly reflected in Malaysia's rapid industrial growth, economic demand, and population growth, which placed the country as a critical case study [4].

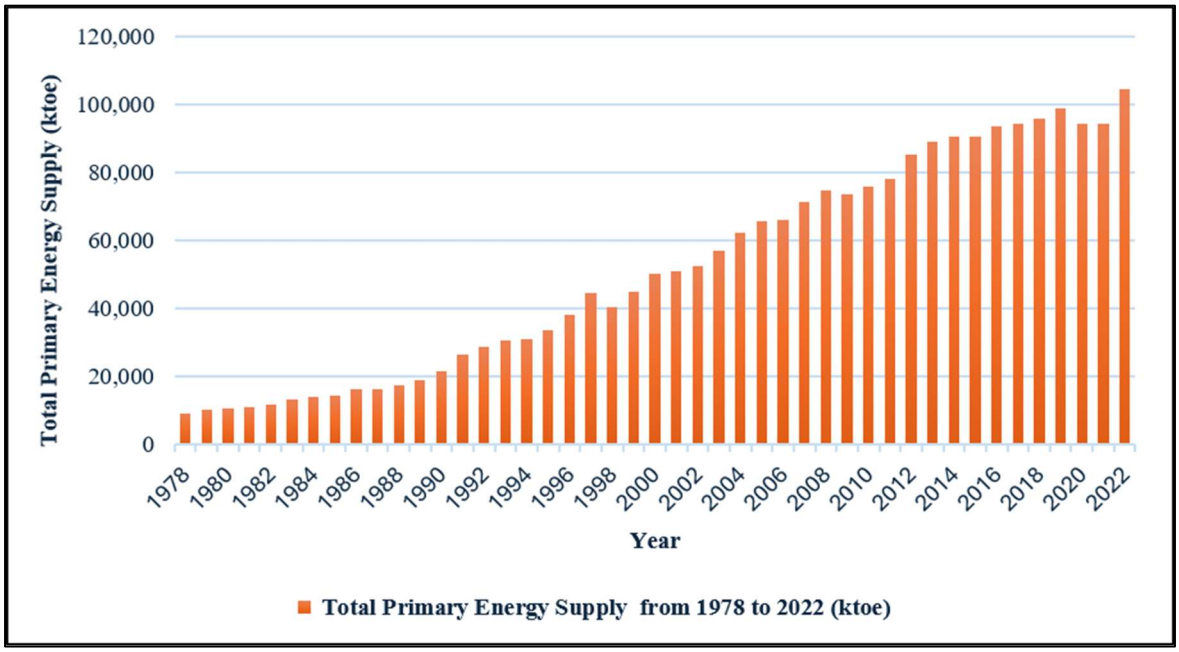


Figure 1. Malaysia's Total Primary Energy Supply from 1978 to 2022 (ktoe).

1.1. Malaysia Energy Diversification

The most pressing issues with the surging global energy demand are ensuring a secure energy supply that meets the needs and mitigating its profound environmental footprint. Current global energy production and consumption account for 77% of the greenhouse gas emissions (GHG) associated with energy activities worldwide [5]. These intensifying emissions on 2024 had begun to undermine the threshold limit of 1.5 °C as in established in the Paris Agreement and accelerated global mean temperature. Combating this serious form of climate change requires a fundamental, rapid transformation of the energy system by shifting the focus to diversifying clean energy. A successful energy transition hinges on supportive and actionable policies, innovative technology development, and the deployment of renewable energy infrastructure [6]. Beyond limiting greenhouse gas emissions, low-carbon energy has the potential to offer low-cost resource, flexible, stable, and high-quality green energy with lower environmental impacts compared to conventional energy [7].

For instance, Malaysia has exemplified its actionable, movable climate action strategies through its National Determined Contributions (NDC) and National Energy Transition Roadmap (NETR) to pave the path for its energy transition plans. Malaysia has set an ambitious target to reduce its carbon intensity by 45% by 2030, including phasing out coal-fired power plants and increasing renewable energy adoptiono up to 70% by 2050 [8,9]. Malaysia Renewable Energy Roadmap (MyRER) also aims to leverage the country's abundant natural resources to build a long-term, sustainable, and low-carbon energy system transition [10]. The core strategy is to systematically increase the share of solar energy, bioenergy, hydropower, and new

technology and solutions, including geothermal, onshore, and offshore wind by 2025 in the country's energy power system, with the current installed capacity being around 20%. In comparison, the target is 45% by 2030 and 70% by 2050 [11]. In Malaysia, as part of the energy mix, solar energy has gained huge market attention, and the installed capacity has grown significantly from 0.1 GW to 2.6 GW [9]. However, a closer examination of Malaysia's targets for phasing out coal from the power generation mix reveals a major shift in the country's energy existing source, given that Malaysia's main dependency is on coal-fired plants.

As a substitute for coal-fired power, Malaysia aims to increase existing bioenergy from biomass to foster low-carbon energy by adopting the Waste to Energy (WtE) concept. Malaysia set targets to build biorefinery capacity up to 3.5 billion litres by 2050 while expanding biomass and biogas power generation capacity to 1.4 GW by 2050 [9]. This demonstrates the country's commitment and proactive measures to consider bioenergy technology as a core part of their energy diversity and efforts in decarbonization.

1.2. Objective & Scope

This review paper aims to comprehensively analyse the evolving landscape of Malaysia's bioenergy sector, with a particular focus on its escalating importance as a crucial component of the nation's low-carbon energy diversification strategy. This study will examine the current trends and future projections of bioenergy, identify its inherent opportunities for sustainable development and energy security, and analyse the challenges hindering its widespread adoption in Malaysia. This paper will also analyse its underpinnings by examining Malaysia's national goals, policies, and support mechanisms aimed at fostering bioenergy as a pivotal means of building a low-carbon energy sector. The review period is from 2015 to 2025, focusing on peer-reviewed journal articles, policy reports, and national data. Inclusion criteria included relevance to Malaysia's energy transition and contributions to the low-carbon transition.

2. Overview of Malaysia's Current Energy and Bioenergy Development Trend

As a fast-developing country, Malaysia has significant indigenous fossil fuel resources, and its core energy production is highly dependent on them [12]. Based on the 2023 Statistical Review of World Energy, Malaysia's energy consumption has a 1.2% growth rate per annum from 2012 to 2022. Over these decades, energy consumption per capita has increased from 126.0 GJ to 149.5 GJ. This indicates rising demand for energy in Malaysia [13]. As of 2024, Malaysia's fossil fuel-based electricity consumption, comprising coal, natural gas, and oil, accounts for approximately 81% of the nation's electricity generation. The breakdown of the fossil fuel mix shows coal is the largest single source, accounting for approximately 44%, closely followed by natural gas at 37% [12]. Malaysia's current energy mix rate is as follows in Figure 2, highlighting a significant dependency on non-renewable energy sources and the proportion of renewable energy sources in Malaysia.

Malaysia's current power industry has a strong influence on the country's GHG emission rate. Malaysia's Fourth Biennial Update Report (BUR4) submitted under the United Nations Framework Convention on Climate Change (UNFCCC) reported that, compared to Malaysia's baseline year 2005, in 2019, the total GHG emissions from the energy sector had risen to 27.95%, and emissions from energy industries alone contributed 50.80% of the emissions, which was about 131,735.68 $GgCO_2eq$ [14]. According to data from Our World in Data (2021), the Electricity and heat sector is the largest single contributor, accounting for a significant 135.34 million tonnes of carbon dioxide equivalents ($MTCO_2$-eq). Apart from electricity generation, the transport sector is the second largest source, accounting for 50.57 $MTCO_2$-eq. Manufacturing and construction follow at 35.05 $MTCO_2$-eq, and Industry at 23.99 $MTCO_2$-eq [15]. This data collectively highlights the power generation sector, daily commutes, and Malaysia's industrial developments, raising concerns about the country's carbon emissions. Overall, the data reveal

that the relationship between energy consumption and sectoral emissions within the Malaysian context builds upon the foundation laid by these sectoral emission trends.

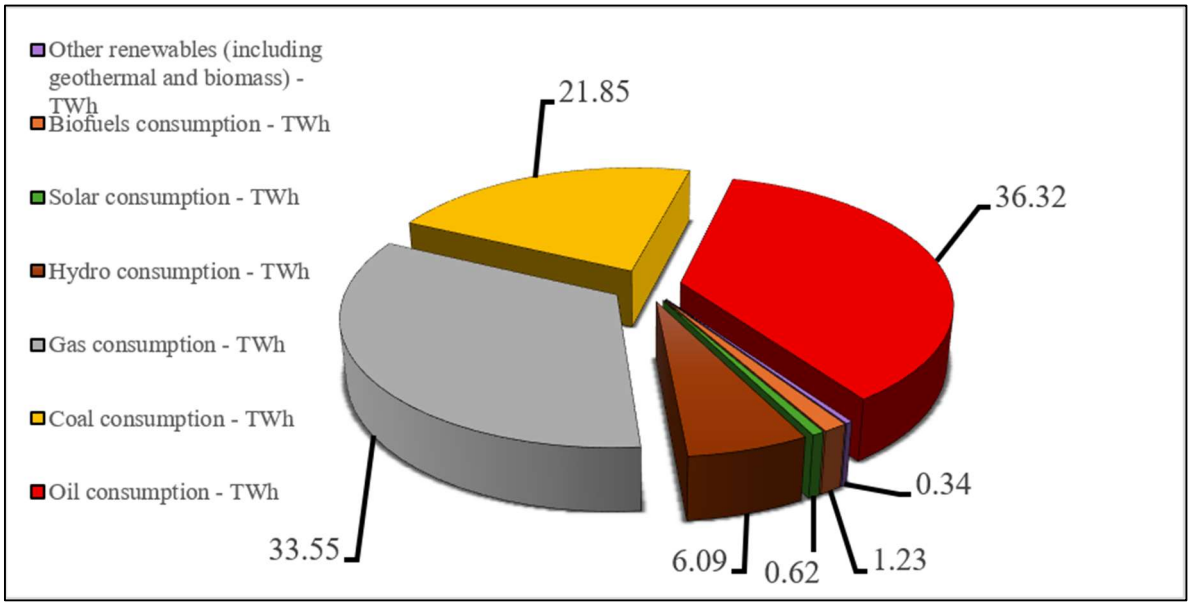


Figure 2. Malaysia's Total Primary Energy Supply from 1978 to 2022 (ktoe).

This review has drawn on both academic literature and official reports to evaluate the intersection of waste-to-energy technology, circular economy strategies, and nationwide decarbonization goals in Malaysia. Academic literature was retrieved through comprehensive queries in Scopus and Web of Science (WoS), leveraging main keyword strings that required core technological terms such as "Biomass", "Co-Firing", "Energy Transition", "Renewable Energy", "Bioconversion Technology", "Anerobic Digestion", "Biomass pyrolysis", "coal-cofiring", "Circular Economy", "Decarbonization", and "Malaysia". The academic literature search was primarily focused on peer-reviewed research articles, high-impact conference proceedings, and reviews published predominantly from 2010 to 2025 to capture recent technological advancements and the transformation of the decarbonization landscape in the energy sector, alongside the selected resource used to conduct a comparative depth analysis. Beyond this material, the evolution of the waste-to-energy approach is highly governed by regulations and standards. Thus, this study also retrieved grey literature to identify and include coherent analyses from a government-driven perspective and from the national energy sector. The paper also includes corporate disclosures and international outlooks as resources for the review. This includes the National Energy Transition Roadmap (NETR), Malaysia Renewable Energy Roadmap (MyRER), the National Biofuel Policy, and reports from bodies such as the International Energy Agency (IEA) and the U.S. Energy Information Administration (EIA), which were strictly filtered based on their explicit relevance to Malaysia's national energy development boundary, energy industrial structures, and demographic profile. Ultimately, 85 references, combining Scopus- and WoS-indexed publications with official national policies, present a balanced analysis of Malaysia's waste-to-energy and circular economy transition.

2.1. Evolving Waste-to-Energy Concept as Sustainable Energy Production in Malaysia

A recent study on energy security and energy demand suggests that countries can diversify their energy mix by incorporating fossil fuels and renewable energy sources, such as solar and wind energy, resulting in greaternergy efficiency [16]. The waste-to-energy (WtE) concept is a highly demanding approach within Energy Mix Diversification (EMD) that has the potential to offer dual benefits of sustainable waste management and generate renewable energy simultaneously. WtE primarily transforms municipal waste,

wet waste, food waste, agricultural waste, forestry residues, and other biomass solid waste into biofuels, bioproducts, and biogas for usable fuel, thermal heat, and electricity [17–19]. The waste is utilized as a valuable feedstock to produce green energy with minimal environmental impact.

WtE is a tangible pathway that embodies circular economy models by adding value to the waste and forming new raw material resources. The Circular Economy is a closed-loop concept that ensures resources are used, then reused, repaired, and repurposed as new products. This is the opposite of the comment practice, which is a linear model. In the linear model, waste is treated as an inevitable byproduct and mostly discarded in landfills. The circular concept is now highly encouraging for implementation in the energy and manufacturing sectors, enabling the recovery of byproducts or waste into valuable resources. This allows for reducing the reliance on non-renewable resources that are depleting [20]. Belmonte-Ureña et al. (2021) conducted a study to reveal the interlinkage among the Circular Economy, the United Nations Sustainable Development Goals (SDGs), and the discourse of turning waste into resources, such as energy, directly supporting different SDG goals. The concept of WtE has a strong relationship with Affordable and Clean Energy (SDG 7), Decent Work and Economic Growth (SDG 8), and Responsible Consumption and Production (SDG 12) [21].

In Malaysia, the WTE potential is reflected in the energy transition agenda, which is cited as an action measure. A focused study of Malaysia's palm oil industry highlights its capacity to yield significant bioenergy from biomass waste. The study indicates that biomass feedstocks derived from the palm oil industry can generate up to 63.5 Mtoe per year, which can be converted into multiple bio-products, such as biodiesel, biogas, and bio-pellets, using various technologies [22]. Yong et al. (2021) highlight the importance of Malaysia's organic waste recovery in solid waste management, noting that 80% of the country's waste ends up in landfills or dumpsites. Recovering the organic fraction of municipal solid waste can be used to produce biogas with the potential to generate 3941 MWh/day of energy, and 2500 t/day of biofertilizer through anaerobic digestion (AD) [23]. Another study conducted a feasibility study on energy recovery using sewage sludge within the Malaysian context. The study focused on alternative sewage waste management strategies within a circular economy framework, aiming to reduce waste from ending up in landfills. The life cycle cost analysis conducted in this study revealed that installing an anaerobic digester to produce biogas for electricity generation could be a beneficial investment, and the plant can operate at a 90% efficiency rate [24].

2.2. Malaysia Bioenergy Resource Availability and Its Potential

Upon exploring Malaysia's low-carbon energy action plans, it becomes clear that the country has targets to expand its bioenergy sector as an alternative to fossil fuels. This is mainly due to the nation's abundant biomass resources and its potential to develop different types of bioenergy from waste streams. The NETR plan's overview of the bioenergy sector framework is divided into three core pillars, which are biogas, biodiesel, and biomass-based energy [9]. In Appendix A, the NETR framework synthesizes these regulatory pillars alongside Malaysia's decarbonization roadmaps.

To accelerate its low-carbon energy transition, Malaysia is prioritizing the mobilization of its vast domestic feedstock resources, like biomass, as a reliable substitute for fossil fuels. Thus, it is crucial to examine the availability and potential of bioenergy production in Malaysia, as it plays a pivotal role in the energy transition to low-carbon energy sources. Various papers have addressed the abundance of biomass and solid waste resources in Malaysia that can be converted using multiple technologies to yield different forms of bioenergy with distinct applications. Below is an exploration of Malaysia's availability of varying biomass waste streams that can fuel different bioenergy technologies:

2.2.1. Municipal Solid Waste

In 2013, total MSW generated was 1.3 billion metric tonnes per year, equivalent to 1.2 kg of MSW per person per day on average. In Malaysia, the high organic content of MSW fractions collected from households

is 44.5% food waste, followed by 8.5% paper, and 5.8% garden waste. Other high-calorie value waste compositions include plastic waste, which accounts for 10%, along with materials such as glass, metals, wood, textiles, and rubber [25]. The organic material in this composition could be effectively converted into biogas, solid fuel pellets, and nutrient-rich digestate bio-fertilizer, offering a sustainable alternative to landfill dumping. The common approach is to convert MSW into green energy via thermochemical routes, including incineration, pyrolysis, and gasification. Apart from this, common practices in Malaysia include anaerobic digestion and landfill gas recovery, including methane extraction. Recent studies provide key evidence that commercial Malaysian food waste (CMFW) is a sustainable feedstock for biogas production. The study highlights the suitability and potential of Anaerobic Digestion (AD) application, with batch tests showing a maximum methane composition of 81% at an organic loading rate (OLR) of 1.92 g COD/(L·d). Another key finding was the high chemical oxygen demand (COD) of 230 g/L, indicating significant amount of organic matter from CMFW available for conversion into biogas [26]. This is a compelling case for addressing the untapped potential of Malaysia's MSW as a valuable bioenergy feedstock, with proven stability, allowing authorities to confidently explore the implementation of commercial-scale projects.

2.2.2. Agricultural Waste

Malaysia's agricultural industry plays a crucial role in the country's economic development, contributing 6.6% of the total National GDP in 2022. The oil palm sector plays a preeminent role, accounting for a significant 35.3% of this contribution in 2021. Nonetheless, the biomass waste produced by agricultural practices has consistently posed an environmental threat to the country [27]. In Malaysia's oil palm sector, the primary agricultural output harvests approximately 94.8 million tonnes of Fresh Fruit Bunches (FFB) annually. Processing this FFB generates massive volumes of organic biomass residues with potential for a circular economy model. The National Biomass Action Plan 2023–2030 has highlighted that Malaysia produces 182.6 million tons of biomass annually through agricultural activities, with the oil palm sector accounting for 85.17% of this biomass among all other agricultural operations [28]. Table 1 presents categories of biomass with high potential for clean energy production from various agricultural activities, along with their respective annual biomass generation rates.

Table 1. Agricultural Waste Generation derived from the various agricultural sectors [28].

Biomass	Biomass Sub-Category	Annual Biomass Generation (Tonnes)
Palm Oil	Empty Fruit Bunches (EFB)	7,300,713
	Palm Mesocarp Fibres (MF)	7,300,713
	Palm Kernel Shells (PKS)	4,427,835
	Palm Oil Mill Effluent (POME)	63,525,686
	Oil Palm Fronds (OPF)	59,593,762
	Oil Palm Trunks (OPT)	10,548,826
	Palm Kernel Cake (PKC)	2,465,176
Paddy	Rice Straw	1,307,315
	Rice Husk	534,356
Coconut	Coconut Husk	271,993
	Coconut Shell	72,531
Sugarcane	Sugarcane Top Sugarcane	5006
	Sugarcane Bagasse	7510
	Sugarcane Molasses	125

2.2.3. Wood Waste

Apart from agricultural and municipal waste, industrial byproducts from the timber industry, rubber plantation waste, and forest residue are significant biomass sources that can be recovered in Malaysia.

These resources are suitable solid fuel feedstocks for exploring the production of low-carbon energy, like direct-fired, pyrolysis, and gasification systems. The National Biomass Action Plan 2023–2030 suggests that these biomass waste categories should be transformed into fuel pellets or used to generate low-carbon energy [28]. Table 2 presents 2021 biomass generation quantities for different woody biomass categories. This further highlights the potential and provides a quantitative basis for developing these new energy systems. A Malaysia-centric Life Cycle Assessment study of WTE recovery of wood waste as fuel for a power plant concluded that a wood WtE plant has 96.1% lower GHG emissions than electricity from the national grid [29]. This shows Malaysia's potential to utilize wood biomass for bio-pallets and co-firing in its power plants. This can offer a positive impact on the environment by offsetting the GHG emissions from this sector.

Table 2. Wood Waste Generation derived from the timber industry [28].

Biomass	Biomass Sub-Category	Annual Biomass Generation (Tonnes)
Rubber Tree	Rubberwood Waste (Branches, twigs, leaves, roots)	212,120
Forest Residue	Log Production Residues	1,492,341
Wood-based industry	Production for sawn mills (Sawdust, offcuts, slabs, shavings, trimming, edging)	1,943,165

2.2.4. Current Trends and Future Projections in Malaysia Bioenergy Mix

Contextualizing the addressed feedstock, which is massively underutilized relative to current energy trends, is essential for long-term national projections. For centuries, this waste has been underutilized for energy production; thus, bioenergy development and its huge potential remain underexplored. As of the baseline year 2019, the report stated that Malaysia's bioenergy contribution to total energy supply was only 1%, while the future targets set in the NEP noted that the aim is for bioenergy to constitute 4% of the total primary energy supply by 2040 [30]. To address the resulting baseload capacity gap without compromising grid stability alongside reducing emissions, the trend is shifting from localized captive coal power to biomass resources from agricultural activities and MSW to support a large-scale, grid-connected system. This includes operating WtE processing facilities that use MSW as the primary feedstock, since MSW production is projected to double by 2025, according to a World Bank survey. In the initial stage, MSW was projected to generate about 2.2 billion tonnes per year by 2025; however, the amount predicted was surpassed by 2.3 billion tonnes in 2023. Waste generation is forecast to continue rising, reaching 3.229 billion tonnes by 2040 and 3.782 billion tonnes by 2040 [31]. This ensures that a WtE facility operating on MSW can secure an energy feedstock supply while enabling decarbonization by reducing coal's share in the energy mix. Alongside Malaysia developing mandates, the future co-firing of biomass with coal in existing power plants is targeted at a 15% blending ratio by 2027. The percentage-based increment from 5% to 15% ensures that the existing functionality of the coal power plant equipment is not jeopardized and that co-firing is sustainable and eligible for support, meeting existing building energy demand [9]. By aligning projected growth in waste generation with target capacity expansion, Malaysia aims to gradually shift bioenergy from a waste management solution to a core pillar of the national energy security framework.

2.3. Bioenergy Conversion Route and Technology Adoption in Malaysia

Malaysia, with various biomass resources, is currently exploring and implementing a range of bioenergy conversion technologies to enhance energy security, mitigate greenhouse gas emissions, and promote a circular economy. The diversification of conversion routes is key to ensuring the selection of biomass and appropriate technologies. This is also increasingly important for maximizing resource efficiency and improving overall system performance. Multiple papers have highlighted that bioenergy can be harnessed in

various conversion routes, each tailored to specific feedstock characteristics and desired end products [32–35]. Millinger et al. (2025) describe different biomass resources that can be converted through various conversion technologies, including anaerobic digestion for biogas production and gasification for synthetic natural gas (BioSNG) for low-carbon heat, power, and fuel applications [34]. Adopting technological advances in the bioenergy sector is essential for optimizing feedstock, enhancing the conversion process, and improving bioenergy yield. For instance, in the study mentioned, upgrading facility technologies, such as pyrolysis, direct combustion, and anaerobic digestion, can yield benefits beyond electricity. It can help to capture thermal energy for industrial heating [36]. Ultimately, all these studies show the bioenergy route leads to three main end-use applications such as transport biofuels, combustion for electricity and heat, and biomass-based green materials.

The type of bioenergy production and technology consideration is rooted in the availability of biomass and it's the form of it, either in solid, liquid, or gaseous form [37]. The Biochemical Conversion and Thermochemical Conversion technologies are the main approaches widely used. Thermochemical conversion processes use high temperatures, while biochemical methods involve enzymatic and microbial degradation of biomass [38]. As explored in Section 2.2 on Malaysia's available biomass primarily originates from agricultural activities, palm oil production, wood waste, municipal solid waste, and forestry residues. Based on the Malaysia NETR, Malaysia focuses on exploring these biomass wastes to produce low-carbon energy mainly through direct combustion, gasification, pyrolysis, and anaerobic digestion [9]. The subsequent sections will detail how these methods are being utilized in Malaysia to harness the country's abundant biomass resources.

2.3.1. Direct Combustion

Direct combustion, also known as direct burning, is a widespread and traditional practice for producing both electricity and heat energy. For daily activities, direct combustion is used for cooking and building heating, while electricity is generally generated through conversion technology using power from steam turbines [39]. Lignocellulosic biomass, like wood waste, livestock waste, municipal waste, and agricultural waste as a feedstock. Biomass based feedstocks generally undergo a drying and grinding phase to achieve the desired sizes before being fed into the combustor. Combustion will take place at high temperatures, producing combustible gases and solid char. The combustible gas then passes through water or steam systems where it is converted into steam, which rotates the turbine to transform the gas into steam, which rotates the turbine. This turbine is connected to a generator. The kinetic movement of the turbines and generators converts mechanical energy into electricity. These practices are commercial, being utilized primarily in mills like oil palm to produce energy for internal consumption [40]. In modernized technology, a combined heat and power (CHP) mechanism is often added to capture and utilize the thermal energy for heating purposes [41,42].

Coal power plants are now exploring the co-firing of coal with biomass waste, such as palm kernel, coconut shell, rice husk, wood biomass, municipal waste, and forestry residuals, to produce low-carbon energy. This is a steady initiative to retrofit the existing coal plant with biomass resources, aiming to meet the goal of coal phase-out in the future. Achieving optimal energy production from biomass blending requires adequate biomass treatment [43]. The pretreatments are designed to convert one or multiple types of biomass mixtures into pellets. Chemical treatment during the palletization process increases the density and homogenizing properties, thereby improving its combustion properties. This process addresses several core challenges in bioenergy, including the transportation of biomass to a power plant. The solid biomass pallet from biomass waste facilitates efficient transportation and storage [43–45]. In Malaysia, the co-firing approach has been actively explored and progressively added to practices, as mentioned in NETR and MyRER [9,10]. Table 3 below provides an overview of commercial applications of various biomass waste types available in Malaysia, along with their potential usage for energy production through direct combustion.

Table 3. Commercial Applications and Co-Firing Application in Malaysia Power Plant.

Power Plant/Facility	Capacity	Biomass/Feedstock	Required Feedstock Amount/Feedstock Blend	Plant Configuration/Key Features	Environmental Impact/Benefits	Reference(s)
Tanjung Bin Power Plant (TBPP)	2100 MW (three 700 MW units)	Feedstock: Empty Fruit Bunch pellets used during the pilot project. Other biomass, such as wood chip pellets, rice husk pellets, and palm kernel shell blends, is under study.	Biomass blend: 2022—0.5% Biomass Co-Fired. In 2025 is expected to increase to 3% TO5%. By 2027, targeted to 15%	Boiler steam flow rate: 3226 t/h Reheating temperature of 600 °C	Enhance grid stability Expected to offset Carbon emissions equivalent (CO_2e) to 141,536,250 mature trees planted upon 15% blend of biomass.	[46]
Cypark SMART Waste-to-Energy Plant (Port Dickson, Negeri Sembilan)	20 MW to 25 MW	Municipal Solid Waste (MSW)	Capacity: 1000 tonnes MSW daily. Current Input: 600 tonnes MSW daily	The wet waste will be transferred to Anaerobic Bioreactor System (FABIOS)	Amount of Waste Recycled at SMART WTE Plan (Tonnes): Metal-101 Textile-121 Paper-75.5 Tonnes Plastic-304.4 Power produced enables power up 25,000 households within the vicinity.	[47–49]
FTJ Bio Power Sdn. Bhd. (Jengka, Pahang)	12 MW (10 MW for export)	Empty Fruit Bunches (EFB)	300,000 MT of EFB annually	60 tonne/h Boiler 1 × 12.5 MW Steam Turbine Integrated with Heat and Power (CHP) Fired Power Plant The plant is Grid-connected TNB infrastructure. Up to 10 MW can be transported to the national grid.	Had offset 43,560 $MTCO_2eq$ per year if fossil fuels (diesel)	[50–52]
Sahabat Empty Fruit Bunch Biomass Project (Lahad Datu, Sabah)	7.2 megawatts (MW) of electricity & 16 metric tonnes (MT) of steam per hour	EFB	120,000 tonnes/year	7.5 MW turbine generator plant facilities with boilers, water demineralization plant, cooling tower, air pollution control devices, and EFB storage yard	The plant obtained Certified Emission Reductions (CER) of 72,380 tCO_2eq from January 2006 to December 2009. Electricity produced can power up to 4000 houses. 1500 homes within the complex to access clean, renewable electricity from the plant at a lower cost.	[52,53]

2.3.2. Biochemical Conversion Technologies

In addition to direct combustion, bioenergy can be produced through biochemical conversion techniques such as anaerobic digestion, aerobic digestion, hydrolysis, composting, or fermentation [54]. Biochemical conversion processes use microorganisms to break down organic matter in biomass into its simplest form and are particularly well-suited to high-moisture biomass. The biochemical conversion ideally takes longer period to yield than thermochemical conversion, and organic matter digestion occurs in the absence of external heat. This process produces end products such as biogas and biofuels [54–57]. Biochemical conversion technology for biogas and biomethane is broadly explored, and it has been identified that globally, biogases have the potential to meet more than one-quarter of global natural gas demands [58]. In a study, biofuels were categorized into conventional fuel and advanced biofuel. Conventional biofuels, such as sugar and starch-based ethanol, oil-crop biodiesel, and biogas from anaerobic digestion, primarily use food-related feedstocks and have a mature market presence. In contrast, advanced biofuels utilize waste from agricultural biomass, forest residue, and dedicated energy crops, leveraging emerging technologies that are still under development or demonstration. WtE technologies, particularly biochemical conversion processes within the advanced biofuels segment, are gaining commercial importance because they offer lower lifecycle greenhouse gas emissions and avoidompetition with food production resources, positioning them as crucial for sustainable low-carbon energy transitions [59].

Anaerobic digestion (AD) is a biological process in which microorganisms act as catalysts to decompose organic matter in an oxygen-free environment to produce biogas. Upon complete breakdown or organic matter, Biogases are a mixture of 50–70% methane (CH_4) and 30–50% carbon dioxide (CO_2) that forms [60]. The biogas generated is a renewable energy source that can be used to generate electricity and heat. This gas can also be upgraded to biomethane with the current technological advancements in dual-fuel engines. This gas is a notable replacement for natural gas for electrifying domestic, commercial, and industrial applications [61].

Among different technologies, AD is widely adopted in Malaysia for treating Palm oil mill effluent (POME), MSW, landfill leachate, and wastewater treatment waste to produce biogas. It plays a huge role in Malaysia's energy transition by converting the organic waste stream into clean energy. To boost biogas adoption, SEDA has established a Feed-in Tariff (FiT) scheme since 2011. This has driven growth in independent renewable energy production and supply to the national grid and infrastructure. In a report, SEDA had mentioned that the allocation of biogas began with a total 60 MW allocation in 2011, and 30.89 MW of power was supplied through the biogas plant. This power capacity grew to 55.83 MW in 2017, and in 2021, it reached 119.74 MW under operation with 60 biogas plants in commissioning, while the 95.58 MW biogas plant is under construction [62]. This shows a steady scaling of a biogas-based electrical energy mix capable of supporting Malaysia's ambitious renewable energy targets.

Focusing on biogas development in Malaysia, a study focuses on biomethane production as an advanced AD technology at landfill sites to explore its potential for injection into the natural gas grid as a viable option, with the condition of injection pressures at 20 psig. The study mentioned that this supports strategic planning toward Malaysia's ambitious renewable energy target of 30% by 2025 through enhanced landfill gas grid injection [63]. Exploring advanced technology to improve existing practices within the AD process, indicating sustained effort to keep the momentum toward Malaysia's 2050 carbon neutrality commitments.

2.3.3. Thermochemical Conversion

Adopting the low-carbon energy era, Malaysia is also showing interest in tapping deeper into biofuel resources to diversify its existing energy mix, ensure a steady supply, and reduce demand for fossil fuels. Malaysia's palm oil biofuel blend began at 5% (B5) and reached 7% in 2019. Malaysia expanded its target for biofuel blending to 10% (B10) and aimed to achieve 20% (B20) by 2020. This was delayed nationwide,

but petrol stations in Sarawak, Labuan, and Langkawi do offer a 20% biofuel blend. The upcoming national target, as outlined in the National Energy Transition Roadmap (NETR), aims to implement a 30% (B30) palm biodiesel and 70% fossil fuel blend for heavy vehicles by 2030, while also exploring advanced biofuels technology and Sustainable Aviation Fuel [9]. A study examines the transformation that biofuel mandates can bring, demonstrating that blending mandates increase biofuel consumption, which in turn correlates with reductions in transport-sector emissions. Apart from that, depending on the car segment, the blend reduces GHG emissions by 16–21% compared to petrol [64]. The country needs to transform its energy mix while reducing the current dominance of fossil fuels.

This is where thermochemical conversion via pyrolysis and gasification plays an essential role in turning biomass waste into valuable fuels. Pyrolysis is a thermal decomposition process that occurs in the absence of oxygen, and its output varies with temperature. This process can convert biomass into biochar, gases, and liquids. A study suggests that a slow heating rate of 400 °C, combined with a long residence time, can produce 35% char, 35% gas, and 30% liquid. If the temperature is set to 500, the proportions will be 50% biofuel production, 20% biochar, and 30% gas. Current technological advancements, specifically fast pyrolysis, produce biofuels as a key product, with a bio-oil yield of up to 75% by weight [65]. The techno-economic investigation on the pyrolysis of oil palm wastes (OPW) provides compelling evidence for its use in WtE applications. Their empirical model revealed that bio-oil is the primary product of pyrolysis, with yields consistently exceeding 50% for palm kernel shells (PKS), empty fruit bunches (EFB), and oil palm fronds (OPF). While biochar and gas are also produced, bio-oil's high market value makes it the most significant product. The economic analysis further supports this, showing that OPF-based pyrolysis, in particular, yields a high profit of $17 million per year and a favorable ROI of 22% [66].

The gasification process is a combustion process that converts biomass, in the presence of oxygen, into a gaseous fuel called syngas. This is achieved through a partial oxidation process at high temperatures, typically ranging from 700 °C to 1500 °C, with a controlled amount of a gasifying agent, such as air, oxygen, steam, or a mixture of these. The syngas produced is a valuable mixture of combustible gases, primarily carbon monoxide (CO) and hydrogen (H_2), which can be used for various applications, including electricity generation, heat production, and as a chemical feedstock for synthesizing fuels and other chemicals.

3. Underlying Opportunities and Challenges in Bioenergy as Low-Carbon Future

Malaysia's NETR plans and other outline policies demonstrate the government's determination to reduce GHG emissions, while advancing low-carbon energy production. Besides that, Malaysia is beginning to show significant interest in transforming existing waste into valuable feedstocks to power bioenergy technology, while offset carbon emission. The widespread adoption of bioenergy in Malaysia unlocks the nation's potential to build sustainable energy resources, reduce dependency, and build more green skills and green jobs within the community. However, fossil fuels now have a competitive advantage over bioenergy, as the fossil fuel industry and technology are more mature and already have substantial investment. In this study, both opportunities and the shortcomings that need attention will be further explored.

3.1. Leveraging Malaysia's Pivotal Bioenergy Opportunities

The recent uptake of bioenergy offers a multi-dimensional solution for Malaysia by supporting the nation's goal of reducing carbon intensity by 45% relative to GDP, while establishing a new business model through the circular economy concept. Transforming waste into feedstocks helps establish a new sustainable foundation for the long-term economy of agricultural, food processing, poultry, and timber-based businesses. In a study exploring the concept of Circular Economy within different companies, it shows that practice like recycling builds new revenue streams while helping to reduce material costs in producing new or similar products [67]. Apart from it, this promotes sustainable waste management by

improving the segregation practices and resource recovery methods. For example, many studies exploring waste reduction in the wood processing sector, such as a study on Malaysia's engineered wood products (EWP) sector, highlight wood waste recycling and reclaimed wood waste, which help in recovering a significant number of raw materials. This enables the business to stay current with global trends in building sustainable wood products made from recycled materials [68].

The switch to bioenergy in Malaysia will be a major economic opportunity aligned with the national energy transition roadmap (NETR) announced in 2023. The government is estimated to invest RM1.2 trillion to RM1.3 trillion by 2050, which would amount to around RM220 billion of GDP and generate about 310,000 green jobs. It is through value chain development with an emphasis on bioenergy, especially biomass and biogas, that can aid significantly in this employment creation, covering feedstock production to technological production and maintenance services [9]. New programs include higher feed-in tariffs for biogas production, green finance schemes through Development Financial Institutions, and the introduction of a carbon tax by 2026, to be applied to the iron, steel, and energy sectors, further encouraging bioenergy adoption [69]. A significant degree of international cooperation has occurred in Malaysia's bioenergy developments, particularly between Malaysia and Japan, resulting in necessary technology and knowledge transfer collaborations. The agreement worth RM1.34 billion was signed between Malaysia and Japan at Expo 2025 Osaka [70].

3.2. Challenges in Malaysia's Bioenergy Industry Development

One of the vital implementation barriers is the poor integration of bioenergy, primarily due to the logistical and collection center of biomass across different regions, challenges in transporting biomass to power plants, the complexity of decentralized biomass plants connecting to power grid systems, high capital expenditure, total investment cost, construction cost, and operation and maintenance (O&M) costs associated with it. This obstacle acts as a roadblock to Malaysia's venturing into bioenergy technology, along with technical obstructions and economic uncertainty hindering overall development.

The Malaysian government has continually developed extensive financial frameworks to accelerate bioenergy development through the NETR framework. The ambitious goal of the government under the NETR of having a 70% RE capacity by 2050 would need an investment of at least RM53 billion to upgrade the grid, to add RE capacity, and to increase energy storage [9,10]. Beyond these obstacles, Malaysia continues to struggle with financial and incentive allocation. Current available government incentives, such as the Green Investment Tax Allowance (GITA) and Green Income Tax Exemption (GITE), indicate good policy intention but are inadequate towards the mobilization of capital required to achieve what NETR intends to do. As we deeply look into GITA incentives for bioenergy development, place entire 3, offering a 100% investment Tax Allowance on capital expenditure (CAPEX), but a limited 70% set-off of statutory income over five years only. Comparing the first-tier Green Hydrogen, which does not fully receive a potential incentive period up to 10 years. This tiered structure may lead to low investor interest, and energy developers may focus on bioenergy. The heavy upfront payment and perceived risks are proving a barrier to SME borrowing, even though they play such an important role in the palm oil industry [71].

Apart from this, Malaysia's bioenergy sector faces complexity with logistics, especially in collecting, storing, and transporting the feedstocks due to the dispersed tropical agricultural regions. Various general studies have often cited the spatial fragmentation of biomass sources, especially from oil palm and rubber plantations, which are often owned by smallholders. A unique study has highlighted an underlying issue in bioenergy development that addresses the moisture content of the biomass feedstock, which is also a challenge. The analysis explored combining multi-feedstock scenarios using Palm Pressed Fiber, Empty Fruit Bunches, Oil Palm Fronds, and Trunks. The study concludes that combining feedstock activity has the potential to reduce sourcing distances; however, it does not inherently reduce costs. The cost can be influenced heavily by the dependence on effective moisture management. Thus, Malaysia is not merely a

matter of long-distance hauling due to fragmentation, but fundamentally an economic and technical problem of transporting excess moisture [72]. Future policy and infrastructure planning must start building a strategy to decentralize pre-treatment solutions to address this core cost driver. This effort will enable the scalable and sustainable integration of Malaysia's abundant biomass resources.

There is further discouragement in a project in the form of regulatory fragmentation and the high cost of connecting with the grid. In the case of palm oil mills, strict requirements are in place, requiring them to have biogas installations. However, progress is slow because the grid connection remains immature, and the primary grid connection is far from the factory, discouraging the export of excess biogas. These circumstances contribute to the underutilization of biomass resources, so it is necessary to revise the approach and create a consistent, policy-based, actionable strategy to modernize grid infrastructure and financial instruments. In this manner, the country can accelerate its goal of developing low-carbon energy through bioenergy, effectively reducing its carbon emission rate.

4. Formulation of Bioenergy Policy, Framework, and Roadmap in Malaysia

Malaysia's Biomass energy is being driven through multiple government policies, frameworks, and roadmaps. Mohd Shaharin Umar, Tania Urmee et al. (2018) highlighted the importance of establishing guidelines to foster sustainable development within the biomass industry [73]. In this study, the evaluation of policies related to low-carbon energy, with the focal sector of Malaysia Bioenergy, is outlined and explored.

Malaysia is one of the signatory countries to the 2015 Paris Agreement, an initiative that aims to limit global temperature rise to well below 2 °C, while pursuing efforts to limit it to 1.5 °C further. Ranked as the world's 24th largest GHG emitter with a total share of 0.77% the country has taken crucial steps in submitting the nation's NDC to the UNFCCC, showcasing its sustainability stewardship in its decarbonization journey. Upon the release of the country's NDC, Malaysia proactively published the country's Low-Carbon Energy Transition targets and strategies through the National Energy Transition Roadmap (NETR). NETR is primarily intended to communicate publicly the nation's targeted commitments to achieve net-zero emissions by 2050. Below are some key targets that were specified in Malaysia's NDC and NETR with the motive of championing the low-carbon energy sector [9,70].

- FY2030: According to Malaysia's NDC, the country set an ambitious goal to reduce carbon intensity by about 45% by 2030 against the country's GDP, relative to the 2005 baseline level.
- FY2050: Based on NETR Malaysia, the country aims to achieve net zero emissions by integrating a 70% share of renewables as part of the energy mix, with the baseline of 2019, by 2050.
- FY2050: Malaysia also targeted a 32% reduction in GHG emissions from the energy sector by 2040, relative to the baseline of 2019.

Further dive into Malaysia's target to reduce energy-based emissions and initiating low-carbon energy production. NETR has set key targets and milestones, including [9]:

- Raising RE installed capacity up to 31% by 2050.
- Establishing RE share at 40% by 2035, followed by an increase up to 70% by 2050.
- Energy savings target of 22% by 2050 through energy efficiency measures.

Apart from the targets, the bioenergy-related strategy focuses on holistic, both short- and long-term, sustainability and a market-driven approach, as summarized in the Table A1 in Appendix A.

The summarized table reveals that the evaluation of Malaysia's bioenergy policy and frameworks begins with a clear focus on liquid biofuels, driven by a confluence of economic and energy security concerns. The early B5 and B7 biodiesel mandates, while a step toward renewable energy integration, served as a powerful market-stabilization tool for the palm oil industry, effectively creating a captive domestic demand for its primary product [74]. The significant shift in increasing bioenergy adoption receives close attention in the National Energy Policy (DTN) 2022–2040 and the National Energy

Transition Roadmap (NETR). This framework moves away from a singular focus on biofuels toward a more holistic, circular-economy approach that recognizes the broader potential of biomass and biogas for power generation and waste management. However, there was no progress report or specific study communicating effectiveness and target achievement, respectively, for future transparency.

5. Conclusions

This review paper has shown that Malaysia has significant potential for bioenergy as a low-carbon technology, but this potential can be fully tapped only after addressing key supply chain, economic, and technological challenges outlined in this study. Leveraging Malaysia's annual generation of over 182.6 million tonnes of agricultural biomass from the oil palm sector, along with forestry residues and municipal waste, has created significant opportunities for bioenergy development [28]. Eventually, this can help increase Malaysia's share of total primary energy supply from 1% in 2019 to the targeted 4% by 2024 [30]. The NETR flagship lever under Bioenergy development has focused on building 1.4 GW of bioenergy generation capacity and 3.5 billion litters of biorefinery production by 2050 [28]. This targeted expansion directly aligns with the ambitious goal of coal phase-out by 2040 under the National Energy Policy [30].

In the future, bioenergy development in Malaysia needs to adopt a resource-centric approach that improves biomass processing facilities, feedstock storage systems, standardized storage systems, and transportation to refineries or power plants. By establishing this logistics and supply chain system, we will overcome current supply chain fragmentation in transport and ensure reliable feedstock quality and delivery, enabling utility power plants to run smoothly. Apart from this, it incorporates systems-level integration methods that address market failures, supply chain shortcomings, and the need for technological innovation, all of which require constant attention in the development of bioenergy. Policies such as the economic transition to RE, financial regulation, investment in energy infrastructure, and promoting collaboration between industry and academia are key to creating an enabling environment that sustains bioenergy growth. Future efforts need to establish clear communication on NETR and other green energy targets, progress, and amendments to build transparency in this green energy sector. Nonetheless, bioenergy development must be undertaken through concerted efforts across policy, technology, finance, and market levels, with viable monitoring and evaluation systems in place to ensure its effectiveness and realize the national ambitious goal of low-carbon energy development. This will not only bring meaningful changes to Malaysia's net-zero ambitions towards 2050 but also deliver long-term economic and social sustainability for the energy sector and the surrounding community.

Appendix A

Table A1. Malaysia's Bioenergy Policy and Frameworks.

Policy/Framework/Roadmap	Purpose	Target(s) Mentioned	Progress/Status Mentioned	References
National Biofuel Policy (2006)	To introduce the biodiesel industry in the Malaysian fuel sector. This involves researching the blending of a gradual percentage of biofuel, mainly from crude palm oil, into diesel fuels. Examining relevant technologies, establishing commercialization, and increasing awareness of biodiesel usage among Malaysians. This policy also considers the export of biodiesel as part of the strategy.	Short Term: Establish B5 diesel mix. Medium term: Establishing biofuel mandates. Long-term: Expanding into B7 diesel mix. Upcoming: In 2025, as continual progress, B30 biofuel requirements were targeted as a future goal.	• The B5 and B7 mandates were achieved in 2008 and 2015, respectively. • This helped stabilize Crude Palm Oil (CPO) prices.	[73–76]
Malaysian Biofuel Industry Act 2007 (ACT 666) (2007)	This is the foundational legislation and guidance established for the biofuel industry in Malaysia. It mainly mentions the mandatory use of B5 diesel, a licensing system for activities relating to biofuel production, storage, transportation, and export.	N/A[*a]	Subsequent changes and amendments were made to strengthen the Act.	[77,78]
Green Technology Master Plan (GTMP) (2017–2030)	GTMP builds upon the Eleventh Malaysia Plan (2016–2020) to outline a strategic plan for green technology development in Malaysia. It aims to create a low-carbon and resource-efficient economy.	Aspirational RE capacity targets Install RE capacity of 20% by 2020, 23% by 2025, and 30% by 2030 with the baseline of 2016. Coal Plant Phase Out. No coal-fired power plants were established in post-2020.	N/A[*b]	[79]
Malaysia Renewable Energy Transition Roadmap (MyRER) (2021)	To facilitate Malaysia's decarbonization of the electricity sector, we will formulate strategies to achieve specific renewable energy (RE) targets with milestones by 2035 and 2050. The targets are set with the aim of maintaining affordability and system stability.	Overall Target: The RE share in the national installed capacity mix is projected to reach 31% by 2025 and 40% by 2035. Biomass and Bioenergy specific targets: 2025 Target: Bioenergy (Biomass and Biogas) is targeted to contribute 862 MW to the renewable energy capacity mix.	Low deployment levels and systemic challenges in achieving these targets are a concern. New business models are being introduced to replace the FiT system.	[10]

		2035 Target: Bioenergy's contribution is projected to increase to 998 MW. 3.5 billion liters of biorefineries by 2050. 1.4 GW of bioenergy power by 2050.		
National Energy Policy (DTN) (2022)	DTN is to provide a framework for Malaysia's energy transition. It is to enable Malaysia to take progressive steps towards cleaner energy. It integrates circular economic solutions and mass production of bioenergy beyond just biofuels.	There are no specific bioenergy development targets. DTN provides the overarching policy direction to ensure Malaysia achieves low-carbon energy.	N/A[*b]	[30]
Fourth Biennial Update Report (BUR4) (2022)	BUR4 was developed to comply with reports to the UNFCCC as a signatory. It includes up-to-date data on the country's situation, GHG inventory, mitigation actions, and both obtained and needed aid.	• It outlines the progress of mitigation policies, including increased RE share and energy efficiency measures. •The targets are as referred to the National Biomass Action Plan 2023–2030	N/A[*b]	[15]
National Energy Transition Roadmap (NETR) (2023)	• To focus on a circular economy solution and mass production of bioenergy beyond just biofuels. A framework that represents an essential strategic step in Malaysian energy goals.	Targets are outlined as follows: Increase RE capacity to 70% by 2050. Reduce energy sector GHG emissions by 32% by 2050 (relative to the 2019 baseline) 3.5 billion liters of biorefineries by 2050. Increase biomass and biogas power generation capacity to 1.4 GW by 2050 Development B30 biofuel requirements Development of next-generation biofuels such as Sustainable Aviation Fuels (SAF). Developing potential biomass clusters with a centralized plant to improve economies of scale and ensure a more reliable supply of feedstock. Emphasizes capitalizing such as used cooking oil (UCO) and municipal solid waste, as a source for bioenergy • The roadmap encourages the exploration of alternative bioenergy feedstock, such as bamboo or algae.	A key flagship prect is the biomass co-firing initiative at the Tanjung Bin Power Plant. In the first quarter of 2024, the construction and commissioning of a 2% biomass co-firing installation was completed. The plan is to progressively increase the co-firing ratio to 3% to 5% in 2025 and eventually reach the target of 15% by 2027. July 2024 by PETRONAS, Enilive, and Euglena to construct a commercial-scale biorefinery within the Pengerang Integrated Complex (PIC), Johor. Targetd to be to be operational by the second half of 2028.	[9,80–83]

First Biennial Transparency Report (BTR1) (2024)	To fulfill Malaysia's reporting obligations under the Paris Agreement's Enhanced Transparency Framework (ETF). It provides a more comprehensive and standardized update on the national GHG inventory and progress toward the NDC.	Aligned with the NDC target of a 45% economy-wide carbon intensity reduction by 2030 compared to 2005 levels.	This report marks the transition from the BUR to the new BTR format under the Paris Agreement. It covers GHG inventory data from 1990 to 2021 and aligns with the latest reporting standards.	[84]
Long-Term Low Emission Development Strategy (LT-LEDS) (2025)	To align Malaysia's development with the Paris Agreement and provide a roadmap for a low-carbon, climate-resilient economy. It articulates actionable programs and policies to deliver measurable GHG emission reductions.	Achieve net-zero GHG emissions by 2050.	The LT-LEDS is still being finalized.	[85]

N/A[*a]: (Not Applicable): Legislative acts that establish regulatory frameworks rather than quantitative targets. N/A[*b] (Not Available): Policy frameworks or reports where specific implementation progress data has not been publicly disclosed.

Statement of the Use of Generative AI and AI-Assisted Technologies in the Writing Process

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Author Contributions

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