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REVIEW

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Transitioning to a sustainable development framework for bioenergy in Malaysia: policy suggestions to catalyse the utilisation of palm oil mill residues

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Abstract

Background: The global commitment to climate change mitigation enforces the worldwide development of renewable energy sources. Therefore, various studies have investigated the growth of renewable energy in Malaysia, most commonly based on biogas and hydropower. In this article, the dynamics of Malaysia's renewable energy development is critically examined by using the latest official national reports and other reliable resources.

Results: The study reveals the influencing factors that shape renewable energy growth in a developing country endowed with substantial biomass resources, such as Malaysia. Likewise, it evaluates the evolution of renewable energy in the electricity sector. In 2017, renewable energy represented about 3.5% of the Malaysian electricity generation mix with 1122 MW of installed capacity. A closer look into the renewable energy resources, i.e. biomass, biogas, solar and small hydro power, revealed that over 47% of the grid-connected power generation came from solar photovoltaic (PV) energy. While solar PV capacity continues to accelerate, the development of other renewable resources, especially biomass, is seeing growth at a significantly slower pace. This article investigates the underlying causes of the skewed development rate as well as the potential strategies that may be adopted to promote a diversification of renewable energy resources. In light of this, introduction of a new national bioenergy policy is proposed, through which four essential programmes could be implemented: (i) enhanced bioenergy conversion efficiency and waste management, (ii) biomass co-firing in coal power plants, (iii) conversion of biogas to biomethane and bio-compressed natural gas (bio-CNG), (iv) large-scale biomass power plants. A total of 4487 MW of additional power could be connected to the grid upon successful implementation of a large-scale biomass power plant programme.

Conclusions: The establishment of a comprehensive and inclusive national bioenergy policy will lead towards a sustainable future of renewable energy development in Malaysia.

Keywords: Renewable energy, Biogas, Biomass, Co-firing, Electricity, Energy policy, Large-scale power plant

Background

It has become almost universally accepted, at least in the research community, that climate change and global warming represent one of the most pressing governance challenges of the twenty-first century [1]. The detrimental effects of climate change towards natural habitats and ecosystems can lead to mass species extinctions [2, 3] as

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well as disruption of human agriculture, food production, and water supply [4–6]. The extent of future climate change depends on the actions of the people and societies in managing the search for energy resources and reducing anthropogenic pollutions [7–9].

Because of this global commitment to climate change mitigation, the development of renewable energy is progressing at a diverse stage and pace in Southeast Asia, where it has attracted many investors and multinationals. Located near the equator, ASEAN-6 countries (Malaysia, Indonesia, Singapore, Thailand, Vietnam, and the Philippines) receive sunlight throughout the year, averaging more than 4.5 kWh/m^2 [10]. The International Energy Agency (IEA) in their landmark study estimated that there is a significant realisable potential for renewable energy in ASEAN countries totalling 1028 TWh encompassing solar, biomass, biogas, small hydro, geothermal, wind, tidal and wave energies [11]. Collectively, ASEAN-6 countries caters to more than 95% of the energy demand in South East Asia [12] and the energy consumption growth is expected to double [13] due to rapid industrialisation and urbanisation.

Despite having a high potential to deploy renewable energy technologies, funding and expertise are still scarce without effective energy policies in favour of renewable energy [10]. In an effort to create a better future pathway for renewable energy in the ASEAN region, new targets have been set during the ASEAN Plan of Action on Energy Cooperation (APAEC) from, 2016 to 2020 to increase the renewable energy contribution by up to 25% of the ASEAN energy mixture and 30% of the electricity generation mix by 2020 [14]. Until 2013, about 21% or 169.34 TWh of the electricity in the ASEAN region was generated from renewable energy sources, including large hydropower energy projects. Rising awareness, supportive government policies and the emergence of reliable and cost-competitive renewable energy technologies could boost renewable energy production in these countries, which makes it possible to deliver more affordable sustainable energy. Collaboration amongst all the ASEAN member states would undoubtedly allow them to form an economic powerhouse of their own. Currently, a multilateral electricity trade agreement among ASEAN member states, through the Power Integration Project, is at the negotiation stage [15], and upon agreement, will mark a momentous milestone in realising the ASEAN power grid aspiration.

All of these developments will be ineffective, however, if countries such as Malaysia fail to adequately diversify their electricity generation mix and effectively pursue domestic renewable energy sources such as biomass with its immense untapped potential [16, 17]. Malaysia produces more than 103 million tons of biomass, including agricultural waste, forest residues and municipal waste [18]. Agricultural waste represents 91% of the biomass amount, of which most is derived from palm oil mill residues. Malaysia is the second largest palm oil producer in the world with a total plantation area of 5.6 million hectares [19]. As an indication of the sheer volume of waste in the palm oil industry, the country had only 10 palm oil mills in 1960, but boasted 465 in 2018 for processing over 98 million tons of fresh fruit bunches (FFB), as shown in Table 1. The oil palm mills are spread all across Malaysia, and 76 of them are large-scale mills capable of processing more than 250,000 tons of FFB annually. The estimated installed capacity potential from biomass generated at the mills, comprised of empty fruit bunches (EFB), palm mesocarp fibres (PMF) and palm kernel shell (PKS) is between 2400 and 7460 MW [18, 20], while it is between 410 and 483 MW for biogas from palm oil mill effluent

Table 1 Processed FFB and palm oil mills in Malaysia

State	Total FFB processed by palm oil mills in 2018 (tons) [53]	No of palm oil mills	Major palm oil mills (FFB processing amount > 250,000 tons per year) [54]
Johor	1,586,8305	64	17
Kedah	1,329,859	6	2
Kelantan	1,421,809	11	0
Negeri Sembilan	3,529,664	16	1
Melaka, Perlis and Pulau Pinang	1,133,232	5	2
Terengganu	2,428,380	13	0
Pahang	14,079,377	71	2
Perak	9,824,589	47	11
Selangor	2,742,940	18	2
Sabah	24,952,356	131	30
Sarawak	21,052,976	83	9
Total	98,363,487	465	76

(POME) [18, 21] (considering 7200 operation hours of power plants annually).

Various studies have addressed the growth of renewable energy in Malaysia, most commonly on biogas and biomass [21–23], solar [24–26] and hydropower energy [27–29]. Some articles specifically reviewed the renewable energy policies and programs in Malaysia [22, 30]. In this study, the dynamics of renewable energy development in Malaysia is critically examined based on the latest official national reports and other reliable resources. It investigates the current challenges and opportunities to scaling up grid penetration of renewable energy technologies in the electricity sector as a direct response to the government's new target of increasing renewables share in the electricity generation mix to 20% by 2025 [31]. The economic and non-economic barriers that caused an imbalance in the development of renewable energy resources in Malaysia are investigated, and four strategic approaches are proposed to promote an effective and efficient exploitation of bioenergy in this country. In addition, several policy recommendations to support the establishment of a sustainable national biomass energy industry are presented and discussed. The study thus reveals the influencing factors that shape the renewable energy growth in a developing Asian economy such as Malaysia, endowed with substantial bioenergy resources.

Methodology: The article contains six main parts. It first begins with an overview of renewable energy in ASEAN countries ("Background" section), followed by a brief but necessary history of energy policy and renewable energy development in Malaysia since the 1970s ("History of renewable energy in Malaysia" section). Next, it evaluates the current challenges in developing and diversifying the renewable energy resources mixture ("Current challenges: diversification, development, and deployment" section). Based on a critical assessment of the current situation, it presents a conceptual framework to introduce a new vision for a sustainable bioenergy sector in Malaysia, as well as strategies to accelerate power generation from bioenergy ("New vision for bioenergy development in Malaysia" section). Finally, several policy recommendations are explored to ensure successful implementations of new initiatives ("Discussion of sustainability and policy recommendations" section) followed by a conclusion ("Conclusion" section).

History of renewable energy in Malaysia

Malaysia is a developing country that has transformed itself from a producer of raw materials in the 1970s into a country with an emerging multi-sector economy. Malaysia's GDP per capita in 2016 amounted to MYR 38,887 [32] and its economy continues to perform steadily with a projected increment of 40% by 2020, the third-highest amongst ASEAN economies [33]. Citizens in this middle-income country generally have good access to clean water, telecommunication, and electricity facilities with 4553 kWh electricity consumption per capita in the year 2016 [32]. The oil and gas (O&G) sector has long been the primary source of revenue for the Malaysian government over the last two decades with billions of dividends received from its state-owned O&G PETRONAS Company. As such, the national primary supply of energy continues to rely heavily on natural gas and crude oil. However, Malaysia's energy landscape is also experiencing transformation towards a more diversified mix of sources with an increasing share of renewable energy. Figure 1 shows Malaysia's electricity generation mix in terms of installed capacity in 2017 [34]. Natural gas and coal represented the majority, with 43.6% and 30.9% of shares, respectively, followed by large hydropower (17.8%), diesel (4.1%) and renewable energy (3.5%).

Malaysia has taken several initiatives to diversify the country's energy sources and revenue streams away from oil since the early 1980s, as shown in Table 2. Malaysia's first National Energy Policy in 1979 was aimed to pave the way for an efficient, secure and environmentally sustainable supply of energy in the future [35]. Later in the following year, the National Depletion Policy was established to conserve the country's resources by limiting the utilization of crude oil and gas. Since oil remained the main source for energy supply, the Four Fuel Diversification Policy of 1981 was formulated to balance the contribution of other resources which are gas, hydropower and coal into the energy mix. This started the rise of coal consumption, particularly in the electricity generation industry. By 2000, coal power generation began to escalate

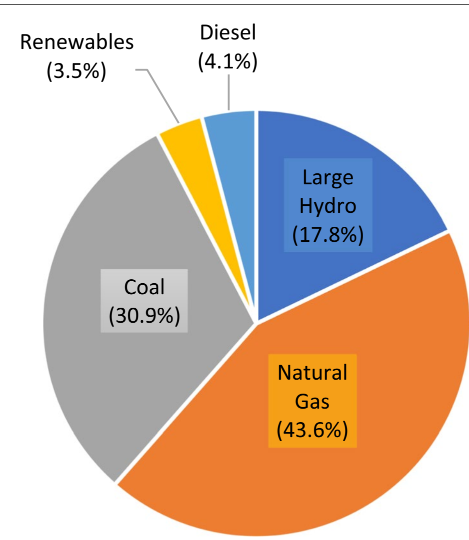


Fig. 1 Total installed capacity (MW) in 2017 by fuel type

Table 2 Chronology of Malaysia's energy policies and acts, and the related renewable energy initiatives (1979–2017)

Policy and act		Key initiatives, programs or activities
1979	National Energy Policy	Provide guideline for future energy sector development
1980	National Depletion Policy	Photovoltaic (PV) System for Rural Electrification Program (1980) Photovoltaic Grid Connected System Application (First introduce in 1998)
1981	Four Fuel Diversification Policy	Ensure energy security through diversification of energy sources
2000	Five Fuel Diversification Policy	Five Fuel Diversification Strategy (2000) Centre for Education, Training and Research in Renewable Energy, Energy Efficiency and Green Technology (CETREE and GT) (200) Small Renewable Energy Power (SREP) (2001)
2002	National Policy on the Environment	Con't Projects and Initiative: Biomass Power Generation and Generation Project (BioGen) (2002) Malaysia Building Integrated Photovoltaic Project (MBIPV) (2005)
2006	National Biofuel Policy	Biofuel programs: B5 biodiesel program B7 biodiesel program B10 biodiesel program B20 biodiesel program
2007	National Biofuel Industry Act	
2009	National Green Technology Policy	Green Technology Financing Scheme (2010)
2010	National Renewable Energy Policy and Action Plan New Energy Policy National Energy Efficiency Action Plan	Renewable energy incentive: Pioneer Status (PS) Investment Tax Allowance (ITA) Green Technology Financing Scheme (GTFS) Renewable Energy Business Fund (REBF)
2011	Sustainable Energy Development Act	Establishment of Sustainable Energy Development Authority (SEDA)
	Renewable Energy Act	Renewable energy programs: Renewable Energy and Energy Efficiency Scheme (2011) Feed in Tariff (FiT) Scheme (2011) Net Energy Metering Scheme (2016) Large Scale Solar PV Project (2016)
	National Biomass Strategy 2020	Development of biomass-based industries by capitalizing on the high-value opportunities available from biomass generated from agricultural, forestry, dedicated biomass crops and municipal waste
2017	National Green Technology Masterplan 2017–2030	Latest framework aligns strategic goals to MP11 target. To facilitate the mainstreaming of green technology encompassing the four pillars

rapidly in Peninsular Malaysia [36], which explains the gradual increase of coal supply into the energy supply mix. In the same year, the Five Fuel Diversification Strategy was formulated under the Eighth Malaysia Plan, in which the biomass, biogas, municipal waste, solar photovoltaic (PV), and small hydropower energies were recognised as potential renewable energy resources for electricity generation [37, 38]. Finally, renewable energy was introduced as the fifth fuel in the energy mixture in 2001 through the Five-Fuel Diversification Policy, as a key initiative to ensure the development of a sustainable energy sector and encourage the growth of renewable energy in Malaysia.

To promote renewable energy as the fifth fuel, the government launched the Small Renewable Energy Power (SREP) programme in 2001. Within the scope of this programme, small renewable energy power plants were regulated in order to contribute to the electricity grid network. However, this programme was not well-accepted and only managed to achieve 3% of its goal to install 500 MW of renewable energy capacity by 2005. One of the main reasons for the failure was the low rate of financial return, which failed to attract more investors to participate in SREP [39]. Additionally, a lengthy approval process, a low capacity cap, and lack of support from the electricity supply stakeholders are further reasons that the program fell short of achieving its goal [40]. The revenue obtained by the renewable energy facilities, especially the biomass power plants, was barely enough to cover the installation and operation costs. As a result, most facilities have had to find other sources of income to be financially viable. This tariff issue was revised several times by the government in 2006 and 2007. However, the solution only considered the biomass and biogas sectors.

In 2002, biomass-based Power Generation and Cogeneration (BioGen) for the palm oil industry project was launched. BioGen promoted the use of biomass and biogas waste from palm oil mills to replace some of the fossil fuels used in electricity production [41]. As an initiative to encourage the participation of private sectors in solar PV system investment, the Malaysia Building Integrated Photovoltaic Project (MBIPV) was launched in 2005 [42]. MBIPV has served to promote the integration of a solar PV system within the building designs and envelopes property projects where a total installed capacity of 213.6 kWp was reached at the end of the 5-year period of the programme [24].

Later in 2006, the National Biofuel Policy was launched to support the Five-Fuel Diversification Policy with the expectation that the stable prices of palm oil would have a spin-off effect on mobilising local resources and encouraging biofuel exports [43]. Unfortunately, this effort was also unsuccessful due to low global oil prices and the relatively high price of the main feedstock, namely crude palm oil, at the time. Besides that, some technical issues with biofuel emerged, such as being unsuitable for engines and causing clogs in the fuel lines, dampened public interest [42]. After 2 years, the Biofuel Industry Act of Malaysia was established to further facilitate biofuel usage by removing some of the administrative barriers. However, renewable energy continued to experience slow growth during this time.

In 2010, the government launched the National Renewable Energy Policy and Action Plan (NREPAP), which incorporates the elements of the planned energy, industry, and environmental policies to make it more convergent in nature [39]. The Green Technology Financing Scheme (GTFS) was established to assist and improve the utilisation of green technology for development, with the allocation of MYR 1.5 billion equivalent to almost USD 358 million at the time. The main highlights of GTFS were the government's intervention to bear 2% of interest or profit rate and to provide a guarantee of 60% of the financing amount.

Subsequently, in 2011, the Renewable Energy Act was established to introduce a feed-in tariff (FiT) and mechanisms for managing its implementation including the set-up of Sustainable Energy Development Authority (SEDA) to administer the overall process. The introduction of FiT overcame the various limitations of SREP and catalysed a rapid growth of renewable energy [44]. It lowers the investment risk with the guarantee that renewable energy developers will have access to the electricity grid network and gain long-term power supply contracts with the power utility company. A higher profitable margin among the new FiT tariffs, as shown in Table 3, has also raised stakeholders' interests [45].

Malaysia's SEDA has played a substantive and effective role in helping renewable energy project developers in gaining financial aid by engaging them with the local financial institutions through the Green Technology Financing Scheme (GTFS) [46] in addition to assisting in the application process between renewable energy developers and state governments. Workshops and seminars were also regularly conducted by SEDA to engage stakeholders in the periodic revision of the tariffs and guidelines to suit the latest renewable energy development in Malaysia, as well as the progression of global renewable energy technologies. The eligible renewable energy sources within this scheme are biogas, biomass, small hydropower, solar PV and geothermal energies. FiT duration varies according to the types of the renewable energy source. For biomass and biogas, the duration is 16 years, whereas for small hydropower (sometimes called "mini-hydro" or "pico-hydro") [47] and solar PV technologies 21 years are taken into account.

In 2011, the National Biomass Strategy 2020 was also established with the vision to develop a high-value biomass-based industry. However, the announcement had a polarising effect on palm oil mill owners and small biomass power plant developers, as an indication of the fact that the high-value industry has triggered the mill owners to demand relatively high prices for their biomass. Besides that, in view of the future growth of bioenergy industry in Malaysia, with higher value downstream industries, it has become more challenging for biomass power plant developers to secure a long-term feedstock contract supply with the millers. Additionally, to facilitate

Table 3 Tariff of renewable energy under Small Renewable Program (SREP) and Feed-in-Tariff (FiT) (excluding bonus FiT rates) schemes

	Type of resource				
	Biomass	Biogas	Mini hydro	Solar PV	Geothermal
Program/tariff rate (MYR/kWh)					
SREP, 2001	0.17	0.17	0.17	0.17	–
SREP, 2006	0.19	0.19	0.17	0.17	–
SREP, 2007	0.21	0.21	0.17	0.17	–
FiT, 2011	0.2687–0.3085[a]	0.2786–0.3184[a]	0.2400–0.2600[b]	0.4285–0.6682[b]	0.4500[a]

[a] Applicable 16 years since FiT commencement date

[b] Applicable 21 years since FiT commencement date

the mainstreaming of green technology, the Green Technology Masterplan (GTMP) framework was established to align strategic goals for the year 2017–2030 [48].

Current challenges: diversification, development, and deployment

In 2017, renewable energy represented 3.5% of the electricity generation mix with 1208 MW of installed capacity [34]. Thus, the power sector faced challenges related to diversification and future development. Out of the amount of renewable energy share, 591 MW is connected to the grid, most of which are operated by public licensees under the FiT program [49]. Figure 2 presents a 7-year review of the annual power generation by commissioned FiT renewable energy power plants from 2012 to 2018 [50]. Generally, the bulk of the power generation is derived from biomass and solar resources. However, in terms of the growth rate, solar power is the most rapidly accelerating renewable energy. In the beginning, solar energy only contributed 5% of the renewable energy mixture in 2012. However, in 2018, the solar PV share increased nearly 10 times to 47%, rendering it the highest share in the renewable energy generation mix with 430.5 GWh. In contrast, the share of biomass in the renewable energy generation mix shrank from 71% in 2012 to only 22% in 2018. Meanwhile, in terms of the capacity factor, biogas exhibited the highest amount that totalled 36.6%, followed by biomass (23.6%), small hydropower (13.4%) and lastly solar power energy (12.8%), as shown in Fig. 3. The capacity factor of biomass here is considerably low relative to the highest achievable capacity factor of a utility scale biomass power plant, which is 64.6% [51].

Many reasons contribute to the rise of solar power generation in the context of the FiT program. Among them are; (i) a premium FiT rate for solar power (the highest starting rate among renewables), (ii) the rapid technological advancement that increases the solar PV

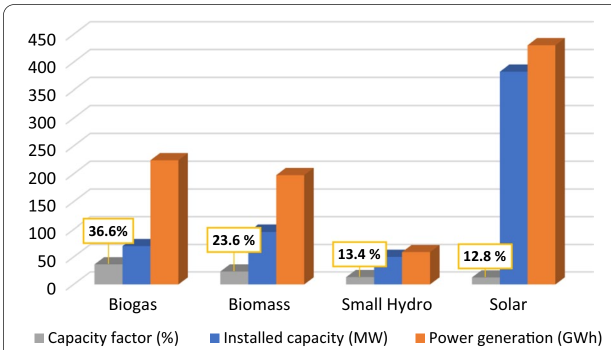
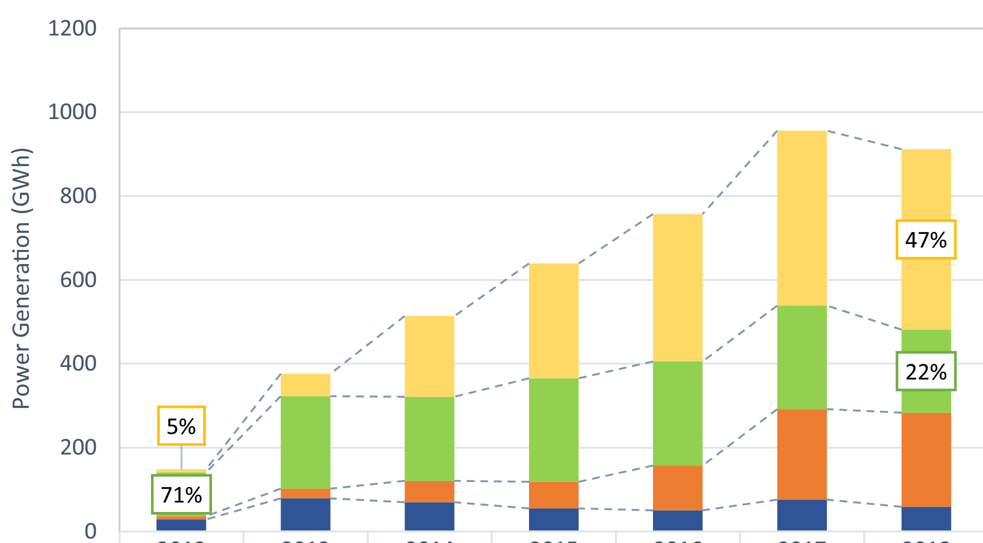


Fig. 3 Capacity factor, installed capacity and power generations of FiT-capacity installations in 2018. (Capacity factor is estimated based on 8760 h of plant operation)



	2012	2013	2014	2015	2016	2017	2018
Solar PV	7.5	54.1	192.82	274.47	350.7	417.05	430.51
Biomass	104.54	220.55	200.16	246.73	248.48	247.21	197.78
Biogas	7.56	22.77	51.27	63.34	107.11	215.81	224.43
Small hydro	28.68	79.05	69.58	54.97	50.28	75.55	58.95

Fig. 2 Annual power generation (GWh) from commissioned renewable energy installations under FiT program (2012–2018)

system's efficiency and solar power density potential of solar PV [52], and (iii) a continuous decline in the cost of solar PV panels that increases its economic viability [53]. Meanwhile, other renewable resources experience a much slower progress. Small hydropower generation has been unstable over the years. There is a lack of effort to develop small hydropower projects since its application is only limited to small-scale decentralized power generation for remote or rural areas or localized industries [27]. While biomass, though abundantly available in Malaysia, failed to capture its energy generation potential mainly due to uncertainty of biomass feedstock supply and other technical, financial and policy barriers, as described extensively by many researchers [16, 20, 21, 39, 54–58]. On top of that, there exists a competing interest in EFB pellets for the export market. Furthermore, surveys of Malaysian energy consumers have noted that the lack of knowledge with regard to renewable energy is pervasive [59]. The lack of understanding of risks associated with renewable energy and green technologies among financial institutions have also led to low investment in the biomass energy sector.

In order to reach the new national target of increasing the share of renewable energy to 20% by 2025, an additional renewable energy capacity installation of 3991 MW is required to be injected into the electricity grid network [60]. The government is yet to disclose information on the projected share of each renewable energy resource in the electricity generation mix in meeting the said target. Nonetheless, solar PV has attracted more attention in recent years. Besides the Net Energy Metering (NEM) programme for rooftop solar energy, the government introduced a Large Scale Solar (LSS) programme in 2016. The capacity allocated for LSS of 1000 MW and is carefully capped at 250 MW annually (200 MW for Peninsular, 50 MW for Sabah), starting from 2017 to 2020 [61]. So far, three LSS projects with a total installed capacity of 32.5 MW have successfully been installed and commercially operated [60]. Altogether, the implementations of FiT, LSS, and NEM are expected to enhance the grid-connected renewable energy capacity to 1779 MW by 2020 and 3269 MW by 2030 [62].

While solar power offers a rather quick short-term solution to accelerate the renewable energy capacity installation, its capacity factor is the lowest amongst all the renewable energy sources. Likewise, high dependency on solar PV will lead to grid system instability due to the intermittent nature of solar power generation. Additional investments are therefore needed to ensure grid flexibility and reliability by implementing an energy storage technology, such as Battery Energy Storage Systems (BESS) [63]. Therefore, a highly dispatchable renewable electricity is critically needed to assist in balancing the volatile inflow of solar electricity to the grid [64]. Given the high availability and achievable capacity factor of biomass, it could play a central role in gearing up the share of renewables in the energy sector [65]. Biomass can also act as the base load for the national grid, slowly taking over the role of coal power plants while decarbonizing the energy industry along the way. Currently, subsidised natural gas, the cheap price of coal, and a stable supply of both fuels have kept them more economically attractive (for the moment) than renewables. Meanwhile, the bioenergy industry is currently facing a supposedly "*chicken and egg*" dilemma, in which the potential bioenergy developers are reluctant to commit unless there is enough funding and an efficient market; whilst on the other hand, the financiers are hesitant to fund a new bioenergy project unless there is a demonstration plant as 'proof-of-concept' and long-term feedstock supply contract to prove business viability and sustainability.

New vision for bioenergy development in Malaysia

Conceptual framework

The review of the historical development of renewable energy policies and initiatives serves as the baseline study for this work to discuss the potential energy policy shift towards a sustainable renewable energy development future in Malaysia. Essentially, Malaysia's renewable energy development could be categorized into three evolutionary phases which are; (i) Early Transition Phase (2000–2009), (ii) Acceleration Phase (2010–2019) and (iii) Sustainable Development Phase (2020–2029). Figure 4 presents the energy policies that set (and would set) the impetus for renewable energy development in each phase, which stretches about 10 years, as well as the associated milestones and key insights from renewable energy programmes. In the programme section of the first and second phases, the white box represents the allocated or targeted installed capacity while the blue box shows the achievement so far as in the installed capacity of power plants that have successfully reached commercial operation. Meanwhile, the programmes in the third phase are the proposed new initiatives to revitalise the bioenergy industry, which are linked to this article's policy recommendations and conclusion.

During the early transition phase towards renewable energy, the achievement rate (*which is regarded herein as the ratio between the allocated installed capacity of renewable energy power plant and the commissioned renewable energy power plant's installed capacity*) of the first renewable energy programme is only 3%. However, as the country moves on to the acceleration phase, the total installed capacity of renewable energy escalated from 15 to 719 MW after the FiT scheme was introduced. While the scheme is still running, the achievement rate as

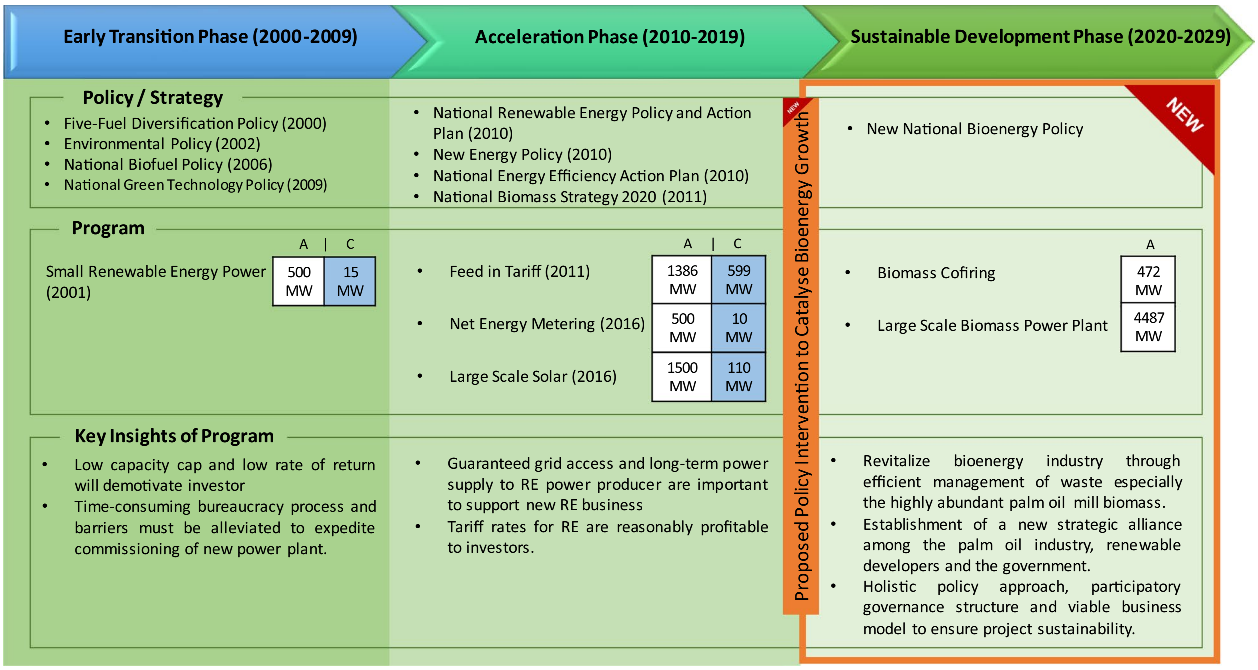


Fig. 4 Renewable energy development phase in Malaysia and proposed policy intervention to accelerate bioenergy share in the power mix. A (white box) = Allocated (or targeted) installed capacity, The targeted installed capacity for biomass cofiring is as projected by the authors, while for large scale biomass power plant, it is estimated based on the average of power generation potential of biomass described in Table 6. C (blue box) = Commissioned power plants 'installed capacity

of early 2019 is 43%. After all FiT quotas had been taken up, NEM and LSS programmes were introduced and to date, the commissioned power plants represent 2% and 7% of the allocated capacity, respectively.

Through chronological analysis, we also found that despite having many supporting policies and initiatives to spur bioenergy growth, the present power generation from biomass and biogas is still unsatisfactorily low. The bulk of biomass and biogas resources come from the palm oil industry which is one of Malaysia's leading commodities for international exports. Criticized by many international communities and environmentalists, the palm oil industry is perceived to threaten the biodiversity of Malaysia's rich tropical forests, especially with the relentless expansion of new plantations. As a corrective measure, the Malaysian government has taken a proactive step by introducing the Malaysian Sustainable Palm Oil (MSPO) certification scheme as an avenue to encourage the adoption of a systematic and integrated management plan towards achieving sustainable palm oil production.

The new sustainability certification aims to ensure that the oil palm plantations, independent and organised smallholdings, and palm oil mills use the best management practice that meets the internationally accepted standards thus avoiding further aggravation of the environment [66]. The MSPO standard (MS2530:2013 series) covers the entire supply chain and provides essential guidelines for the production of sustainable palm oil, which include; (i) implementation of waste and water management plans, (ii) monitoring of electricity usage, (iii) assessment of energy efficiency, and (iv) utilisation of renewable energy.

Presently, almost 70% of palm oil mills are MSPO certified [67]. However, compliance to the MSPO requirement is challenging to many of the millers, since in order to be certified, a certain set of new equipment such as scrubbers, biogas capture, and treatment devices has to be bought and installed in the plant. Besides monetary issues, the knowledge gap is also critical among the millers especially the smaller independent establishments [68–70]. Many of them have never invested in R&D, and therefore are not well informed of technology advancements in the oil extraction and/or renewable power generation (in this case biogas and biomass), nor do they have good access to industry experts and a proper technology transfer hub. As a result, they are susceptible to heightened business risks and income losses when equipment breaks down or the system experiences downtime.

Going forward, it is reasoned that the policymaker should observe the development of a sustainable national bioenergy policy which will assist in transforming the palm oil industry effectively. A well-thought-out action plan should be established to ensure the millers get the support they need to efficiently convert palm oil biomass into energy and thus revitalise bioenergy growth in this country. Four programs are proposed to catalyse bioenergy generation; (i) enhanced bioenergy conversion efficiency and waste management, (ii) biomass co-firing in existing coal power plants, (iii) biogas conversion to biomethane and/or bio-compressed natural gas (bio-CNG), and lastly, (iv) large scale biomass power plant.

Enhanced bioenergy conversion efficiency and waste management

When looking at Malaysia's waste sector as a whole, some 20,000 tons of waste are produced every day, contributing to 12% of national greenhouse gas emissions, mainly caused by carbon dioxide and methane [71]. Methane emissions from landfills represent the largest source of emissions at 700 Mt CO_2eq, followed by incineration at 40 Mt CO_2eq. The waste sector is certainly in a unique position to contribute towards electricity generation while at the same time mitigating Malaysia's contribution to climate change.

Traditionally, palm oil mills in Malaysia have made use of a proportion of their residues in their integrated industrial processes. The types of biomass residues are in the form of EFB, PMF, PKS, and POME, as described previously in introduction section. PMF and PKS are the most preferred solid fuels to feed low-pressure steam boilers as they have higher energy content and lower moisture compared to EFB, and their smaller sizes make them much easier to handle. In contrast, EFB is typically only used for mulching, or simply discarded in open areas. In some of the mills visited, there is already a huge pile of EFB, taking unnecessary space on site and producing unwanted sludge leachate as well as spontaneous combustion. In certain cases, biomass power generation alone is not enough to support the energy demand of the mill. Therefore, biogas is captured from POME to provide power-on-demand.

Presently, though most mills use onsite co-generation, the amount of palm oil mill residues produced still far exceeds the palm oil industry's demand. Unfortunately, only a handful of mills currently generate surplus electricity for the grid or employ efficiency improvements in their process. A significant number of mills still rely on outdated energy conversion technology, utilising aging boilers with an average conversion efficiency of less than 10%. Moreover, Francis calculated that the average conversion efficiency of biomass resources into energy at palm oil mills was only at 3%, yet this could easily be increased to 20% if those mills used their by-products to produce electricity for in-house use [72].

To capture this potential, the efficiency of biomass waste management and combustion at the mill could be substantially improved. Indeed, there have already been innovations within Malaysia that have improved the performance and efficiency of palm oil operations. At the Bell Palm Oil Mill in Johor, they have accelerated the speed of anaerobic digestion from the industry standard of 30 days to 14 days [73]. Moreover, the mill shred and combust EFB and palm fronds in a 10 MW biomass power plant to exclusively export power to the grid. Combusting both EFBs and palm fronds ensures that the by-products associated with pruning can be harnessed to produce energy rather than discarded. Both of these by-products have high energy content, about 15 gigajoules per ton for palm frond and 18 gigajoules per ton for EFB [21]. Rather than combust these directly, the new system shreds and dehydrates them to lower their moisture content below 50%, which also lessens the amount of leachate they create when burnt. By using only organic inputs from palm oil plantations, the combustion process creates fertiliser and soil conditioner rather than hazardous ash that is sold to local farmers. At a later stage, such efficiency efforts from palm oil operators could be further integrated with demand-side management and other efficiency and conservation practices across other sectors in Malaysia [74].

Biomass co-firing in existing coal power plants

Co-firing is a fuel-blending practice in which one or more alternative fuels are used to supplement a base fuel such as coal. Generally, there are three techniques for blending the fuels; (i) direct firing—supplement fuel is fed directly into the pulverisers; (ii) indirect firing—supplement fuel is gasified first and the syngas is burnt in the furnace; and (iii) parallel firing—supplement fuel is burnt in an external hot gas generator and exhaust gas is fed into the furnace or burnt in an external boiler, and the steam is used for heating.

For biomass co-firing in coal power stations, palm oil biomass may be regarded as the most plentiful local supply of combustible solid fuel. In 2018, around 20 million tons of crude palm oil was extracted from 98 million tons of fresh fruit bunches (FFB) [75, 76], trailed by a huge amount of crop residues along its supply chain. Among the palm oil biomass at the mill, EFB is the most abundantly available, covering 22% of the FFB on wet basis [21]. However, this fibrous material is also saturated with water; the moisture content in EFB is around 67% [21], which requires thermal pre-treatment to remove the moisture before combustion. On top of that, before EFB can be transported to the power plant, it must be densified to EFB fuel pellets in order to increase its bulk density for a more efficient transportation, handling and combustion.

The biomass fraction during co-firing is typically less than 5% in terms of energy [77]. Based on the Malaysian Palm Oil Board (MPOB)'s directory and our previous research, there are currently at least 103 palm oil mills surrounding 6 coal power plants in Malaysia, as shown in Table 4. The estimated total annual FFB production by these palm oil mills is 11.4 million tons. If EFB was collected and co-fired in all the coal power plants, the thermal substitution potential is estimated to be about 5% that is equivalent to 472 MW of the power generation potential. Other research studies suggested the blending of oil palm residues with a small fraction of rice and logging residues. They estimated that co-firing 12 million tons of the biomass mix at the four existing coal plants in Peninsular Malaysia could produce 330 MW of electricity and reduce annual feedstock costs as well as GHG emissions by about USD 24 million and 1.9 million tonnes of CO_2, respectively [78].

For direct co-firing of coal with raw EFB, the capital cost could be as low as USD 500/kW of the installed capacity. In contrast, the current investment cost to build a CHP medium-scale biomass plant (10–50 MW) ranges between 3550 and 6820 USD/kW [79]. If the plant deploys a biomass-fired stoker boiler or circulating fluidized bed boiler, the payback period could be as long as 6.7 and 9.7 years, respectively, which from the general cost justification point of view makes the investment grossly infeasible [80]. However, the costs of logistics to collect biomass from the supply points could be huge, since oil palm mills are scattered throughout the country, mainly in rural areas. Therefore, strategic management of the biomass supply chain is essential to reduce the overall feedstock cost. A dedicated biomass processing facility should be brought into play, to serve as a collection and redistribution hub, hence ensuring an efficient logistic chain and matching of demand and supply. Furthermore, the new facility location should be strategically located at the centre of the identified palm oil mill clusters.

Co-firing can be performed in stages since a coal power station usually has more than one installed boiler. The risk of co-firing affecting the boiler's performance could be further reduced if it was operated at a low level of fuel substitution. However, careful attention should be paid towards the ash handling system, especially the fly ash filtration device, such as the electrostatic precipitator (ESP). When biomass feedstocks are low due to seasonal availability, the power plant can still run at 100% despatched load using coal maintaining its high efficiency and availability. On the other hand, biomass plants would be forced to reduce their output and hence lowering the efficiency or shutdown of boilers. Financiers will be more convinced to invest in co-firing as it offers low cost and risk with a shorter payback period. Furthermore, there are no requirements to build a new power plant and no additional downstream costs for grid connection and grid reinforcement since these facilities are already in place at the existing coal power stations [81]. The Biomass Energy Plant in Lumut was reported as the first Malaysian biomass-coal co-firing power plant to be registered as a Clean Development Mechanism (CDM) project [18]. Moreover, there is also an interest to convert expiring coal-fired only power stations to deploy biomass co-firing as a means of extending its operational lifetime.

Conversion of biogas to biomethane and bio-compressed natural gas (bio-CNG)

When organic matter is broken down anaerobically by bacteria, gases are naturally produced as by-products. These gases are collectively known as biogas, which is mainly composed of methane (60–65%), CO_2 (25–50%), and trace quantities of other gases. The raw biogas could be produced by almost any kind of waste: (i) organic waste including municipal solid waste (MSW), livestock manure, sewage sludge from sewage treatment plants (STP) plus meat processing factories; and (ii) agricultural waste including vegetable farms, palm oil biomass and palm oil mill effluent (POME). Biogas is commonly harvested using an anaerobic digester, which is then stored in a vessel that can be used as fuel for vehicles or biogas engines to generate electricity.

The palm oil industry produces a considerable amount of methane that has still not been fully explored for electricity generation. Production of 1 ton of crude palm oil, generates 3 m^3 of palm oil mill effluent (POME) [82]. Furthermore, every ton of POME creates 12.36 kg of methane [83]. The power generation potential of biogas from POME in Malaysia is estimated to be 2376 GWh [63]. Researchers have a longstanding interest in harvesting biogas in palm oil mills through an anaerobic digestion process as the energy gained from the biogas can be used to offset the amount of energy needed for in-plant use [84–86]. It is also estimated that if POME in all palm oil mills was treated anaerobically, around 500 kilotons of biomethane could be produced annually [87].

Purified biogas or biomethane could be fed into natural gas pipelines to be distributed using existing gas grid networks [88]. In order to ensure that the gas is compatible with the gas grid and meets the conventional natural gas quality standards, the captured biogas should be subjected to purification and conditioning processes to remove most of the CO_2 and other undesirable contaminants to produce highly-purified biomethane [89]. The injection of biomethane into the natural gas grid in

Table 4 Palm oil mills surrounding coal power plants

No	Coal power plants	Location	Surrounding palm oil mills (within 100 km)	FFB processing capacity (ton/h)
1.	Sultan Azlan Shah	Manjung, Perak	1. Kilang Kelapa Sawit Lekir	100
			2. Kilang Sawit Changkat Chermin	60
			3. Pantai Remis Palm Oil Mill Sdn. Bhd	60
			4. KKS United Int. Enterprises (M) Bhd	100
			5. Kilang Sawit Felcra Nasaruddin	40
			6. Sri Intan Oil Palm Mill	60
			7. KKS Peladang and Perusahaan Minyak	20
			8. Awan Timur Palm Oil Mill	20
			9. Topaz Emas Sdn Bhd	60
			10. Temerloh Mill Sdn Bhd	45
			11. Tian Siang Palm Oil Mill	120
			12. Selaba Palm Oil Mill	40
			13. Kks Ganda	20
			14. Perak Agro Mills Sdn Bhd	30
			15. KKS TRP	60
			16. KKS Southern Perak	20
			17. Felcra Processing and Engineering	30
			18. Kilang Minyak Sawit Tanjung Tualang	40
			19. Gabungan Perusahaan Minyak Langkap Oil Palm Sdn. Bhd	60
			20. KKS Perak Motor Co. Sdn Bhd	54
			21. SYNN Palm Oil Sdn Bhd	60
			22. Tian Siang Oil Mill	120
			23. Central Palm Oil Mill	40
			24. ST Palm Oil Mill	30
			25. KKS Yee Lee Palm Oil Industries Sdn Bhd	60
			26. KKS Tali Ayer (Hilltop Palm Oil)	20
			27. KKS Chersonese	50
			28. KKS Trolak	30
			29. Elphil Palm Oil Mill	45
2.	Tanjung Bin	Tanjung Bin, Johor	1. KKS Bell Palm Industries Sdn Bhd	117
			2. KKS Ban Dung Palm Oil Industries Sdn Bhd	143
			3. KKS Chaah	147
			4. KKS Gunong Mas	156
			5. KKS Kekayaan	149
			6. KKS Ladang Tereh	139
			7. KKS Bukit Benut	98
			8. KKS Bukit Lawiang	109
			9. KKS Ulu Remis	85
			10. KKS Hadapan	71
			11. KKS Kulai	69
			12. KKS Tai Tak	91
			13. KKS Kim Loong	108
			14. KKS Simpang Waha	130
			15. KKS Lok Heng	138
			16. KKS Keck Seng (Refinery Factory)	103
			17. KKS Semenchu	140
			18. KKS Ladang Siang	135
			19. KKS Adela, Bandar Penawar	131

Table 4 (continued)

No	Coal power plants	Location	Surrounding palm oil mills (within 100 km)	FFB processing capacity (ton/h)
			20. KKS ADELA, Kota Tinggi	139
			21. KKS Kahang	161
			22. KKS Tenggaroh Timur 4	161
			23. KKS Bukit Besar	81
			24. KKS Paloh	N/A
			25. KKS Ulu Sebol	N/A
			26. KKS Sedenak	N/A
			27. KKS Telok Sengat	N/A
			28. KKS Jemaluang	N/A
			29. KKS Southern Malay	N/A
3.	Sultan Salahuddin Abdul Aziz	Kapar, Selangor	1. KKS Ulu Bernam	10
			2. KKS Sungai Tengi	54
			3. KKS Tennamaran	80
			4. KKS Kampong Kuantan	25
			5. KKS Tuan Mee	22
			6. KKS Bukit Kerayong	60
			7. KKS West Oil Sime Darby	80
			8. KKS East Oil Sime Darby	50
			9. KKS Seri Langat SDn Bhd	80
			10. KKS Eng Hong	60
			11. KKS Jugra Sdn Bhd	80
			12. KKS Seri Ulu Langat (SULPOM)	45
			13. KKS Fermanagh	30
			14. Kilang Sawit Meru	N/A
4.	Jimah	Negeri Sembilan	1. KKS Tenah Merah	30
			2. KKS Sua Betong Sime Darby	60
			3. KKS Bell Linggi	55
			4. KKS Sri Lingga	60
			5. KKS Pasoh	40
			6. KKS Serting Hilir	54
			7. KKS Prosper	65
			8. KKS Kok Foh	40
			9. KKS Jeram Padang	55
			10. KKS Ladang Pasir Besar	35
			11. KKS Supont and Leosk Sdn Bhd	65
			12. KKS Nam Bee	50
			13. KKS Diamond Jubilee	25
			14. KKS Kempas	60
			15. KKS Ulu Kanchong	N/A
			16. KKS Bukit Bujang	N/A
			17. KKS Classic	N/A
			18. Kilang Kelapa Sawit Muar Bhd	N/A
			19. K.K.S Bukit Pasir Sdn bhd	N/A
5.	Mukah	Mukah, Sarawak	1. KKS Balingian	45
			2. KKS Keresa Bintulu	30
			3. KKS Bau (BAPOM)	40
			4. KKS Seremas 2	35
			5. KKS Manis	90
			6. KKS Salca Serian	30

Table 4 (continued)

No	Coal power plants	Location	Surrounding palm oil mills (within 100 km)	FFB processing capacity (ton/h)
			7. KKS Palmgroup	45
			8. KKS Judan	40
6.	Sejingkat	Sejingkat, Sarawak	1. Felcra Jaya Samarahan Sdn Bhd	N/A
			2. KKS PH Lundu	28
			3. KKS Sempadi	40
			4. KKS TH Gedong	60

N/A not available

15 European countries has proven its interchange ability with natural gas [90].

The harvested biogas can also be upgraded for other potential applications such as bio-compressed natural gas (bio-CNG), which is an alternative fuel for natural gas vehicles (NGV). Gas Malaysia Berhad, Malaysia's leading natural gas distribution company, is now venturing into a bio-CNG distribution project which captures methane from POME to diversify its distribution business portfolio [91]. Since bio-CNG can be efficiently stored and transported in CNG cylinders, it will provide customers with a more cost-efficient means of gas distribution, especially those located in remote areas.

The benefits of harvesting and processing biogas are multi-fold. Other than generating energy and driving new economy, harvesting methane gas from POME disposal ponds will prevent the gas from being released into the atmosphere by significantly reducing on-site GHG emissions. If a crude palm oil mill is equipped with a 100% biogas capture system, the GHG emission could be reduced by 53.5% which is equivalent to 8.67 million tons of CO_2 per year [92].

Large-scale biomass power plants

Among all agriculture residues, palm oil residues namely EFB, PMF, and PKS demonstrate the highest rank of calorific values (MJ/kg) [20]. Therefore, it is only natural that many biomass-based power generation investors vested their interest in palm oil residues. Virtually all the biomass-based power plants rely on EFB as their main biomass fuel as illustrated in Table 5. The installed capacity normally ranges between 6 and 14 MW except for two power plants, Hartalega Biomass Energy, which is registered under a CDM project (43.6 MW) and Malaysia Newsprint Industries Sdn Bhd, which runs a cogeneration system in its paper mill (79.2 MW). At the moment, for biomass power plants in the context of the FiT program, there are currently 15 approved projects with a total installed capacity of 146.3 MW [93]. The capacity installation of all FiT projects is currently capped at a 30 MW limit unless permitted by the authorities. Generally, imposing a cap on renewable energy installed capacities is highly discouraged in many countries [94] since it will put constraints on renewable energy growth. However, as the current electricity market in Malaysia is still regulated by the government, a cap is deemed necessary to ensure that funding is adequate for FiT payments to utility companies.

Although the FiT program seems to work well for modular power generation systems such as solar systems, it greatly limits the economic feasibility of thermal power generation systems, such as biomass. Commissioning small biomass power plants would require high overhead costs, accompanied by a long payback period. Besides that, managing a large number of small biomass power plants would be significantly more complicated in view of energy security and sustainability. For small independent palm oil mills, it is simply not economical to build a new facility to harvest and generate energy from biogas. Going forward, developing a large-scale thermal power plant would be a sound decision, considering that biomass is abundant in this country and the levelized costs of energy generated will decrease tremendously via cost optimisation from economies of scale. Based on the availability of biomass, as discussed extensively in this paper, Malaysia is highly capable of building several large-scale power plants with an installed capacity between 700 and 2000 MW each. As shown in Table 6, a total of 2991 MW, 3739 MW or 4487 MW could be generated from palm oil mill biomass with boilers of 20%, 25% and 30% efficiency, respectively. Since obtaining a reliable fuel supply is a crucial factor to project viability, an integrated supply chain management should be established with several biomass processing hubs and diversified sources of fuel [16].

Discussion of sustainability and policy recommendations

This study has suggested that future emphasis should move from solar power to biomass and biogas, as they have huge potentials to accelerate the renewable energy share in the electricity generation mix, and if they are

Table 5 Biomass-based power plants in Malaysia

No	Plant name	Fuel type	Capacity (MW)
1	Bandar Baru Serting Biomass	EFB	13
2	Bell ECO	EFB	11
3	Bera Biomass	EFB	13
4	Bumbiopower (Pantai Remis)	EFB	11.5
5	Evergreen Intermerge Sdn Bhd	EFB	6
6	Felda Palm Industries	EFB	7.5
7	FNI Biofiel Sdn Bhd	EFB	10
8	Global Green Synergy Sdn Bhd	Palm oil	8
9	Gula Padang Terap Sdn Bhd	Bagasse	10.3
10	Hamparan Badai POM	EFB	6
11	Hartalega -Biomass Energy	EFB	43.6
12	Jerangan Bestari POM	EFB	6
13	Kembara Sakti POM	EFB	6
14	Leluasa Biomass Steam Plant (KLK)	EFB, PKS	11
15	Malaysia Newsprint Industries Sdn Bhd	Oil (agri waste)	79.2
16	Nilam Permata POM	EFB	6
17	QL Tawau Palm Pellet Sdn Bhd	EFB	5
18	Sahabat Biomass	EFB	7.5
19	50 Resources Sdn Bhd	EFB	7.6
20	Sunquest Biomass	EFB	6.5
21	Syarikat Cahaya Muda Perak (Oil Mill) Sdn Bhd	EFB	6.6
22	TSH Bioenergy	EFB	14
Biomass power plants under FiT program			
1	Cash Horse Biomass	EFB	12
2	FTJ Biomass	EFB/palm oil waste	12.5
3	IOI Bioenergy Sdn Bhd	Palm oil	10
4	Kina Biopower	EFB/palm oil	12
5	Maju Intan Biomass	EFB	12.5
6	Seguntor Bioenergy Sdn Bhd	EFB	13.5
7	Tenaga Sulpom Sdn Bhd	Palm oil	7
8	VibroPower Green Energy Sdn Bhd	EFB	12.5
9	Agni Power Sdn Bhd	EFB	13
10	Raub Energy Ventures (RE)	N/A	3.9
11	Majunaka Eco Energy	Rice husk	10
12	Meru Energy	EFB	8
13	Saluran Suriamas	EFB	7
14	DFB Bioenergy	N/A	10
15	Ajil Biofuel	Wood waste	2.4

not managed properly, the environment will be polluted through the emission of harmful gases during natural decomposition. To catalyse this development even further, this paper offers several strategic approaches to unravel a new chapter of the sustainable development phase of renewable energy through emphasis on bioenergy. The first two approaches for increasing the efficiency of waste-to-energy generation and biomass co-firing are the low hanging fruits that do not require massive costs to be incurred and require minimal modification to the operating system; hence it should be of priority for the short-term bioenergy development plan. Meanwhile, the latter two approaches of bio-CNG production and large-scale biomass power plants will require an intensive policy framework planning and strategic alliance among the key stakeholders, as well as huge investment costs in order to be implemented, they could serve for long-term planning of the bioenergy industry.

Table 6 Power generation potential of palm oil biomass (MW)

Estimated potential energy by biomass type					Power generation capacity (MW) for 7200 h operation		
Biomass type	Produced[a] (Million tonnes)	Dried[b] (Million tonnes)	Calorific value[b] (MJ/kg)	Total energy available (Million MJ)	Boiler efficiency		
					20%	30%	40%
Palm mesocarp fibre (PMF)	13.20	8.32	19.06	158,539	1223	1835	2447
Palm kernel shell (PKS)	5.38	4.73	20.09	95,096	734	1101	1468
Empty fruit bunches (EFB)	21.52	7.10	18.88	134,053	1034	1552	2069
Total					2991	4487	5983

[a] Estimated based on the amount of FFB produced in 2018 which is 97.8 million tonnes [74] and typical biomass fraction as described by [21]

[b] Estimated based on typical biomass moisture content and calorific value as described by [21]

Sustainable development is commonly defined as *"the simultaneous pursuit of economic prosperity, environmental quality and social equity"* [95], *or "development that meets the needs of the present without compromising the ability of future generations to meet their own needs"* [96]. The pathway towards sustainable development of renewable energy can only be achieved through a holistic policy approach that will trigger the right economic and investment decision adjustments. The proposed programmes will offer several economic, environmental, and social advantages, as follows:

a Economic aspect: The economics of biomass power generation are critically dependent upon the availability of a secure, long-term supply of an appropriate biomass feedstock at competitive costs, and an economic merit. Since biomass fuel could be sourced locally in Malaysia and many ASEAN countries, the size of the installed capacity will have more impact on overall costs. Increasing the capacity would leverage the total investment costs needed; (i) capital expenditure (CAPEX), which includes major and auxiliary equipment and construction costs, along with planning and (ii) fixed operation and maintenance (O&M) costs which include labour and scheduled maintenance. Based on our interview with several power plant operators, large-scale power plants of capacities above 1000 MW will require about 250 technical and non-technical staff, while a small scale of 10 MW will require about 30–50 personnel. That translates into a 95% higher efficiency (about 5 times the manpower of small scale, compared to 100 times gain in terms of the generation capacity). Hence, the larger the plant's capacity, the lower the specific (per kW) CAPEX and fixed O&M costs, due to the impact of the economy of scale. Consequently, large-scale power plants will exhibit much more attractive investment opportunities and commercial advantages. It should be noted that for biomass co-firing, there is no requirement to build a new power plant infrastructure or additional downstream cost for grid connection since these facilities are already in place at the existing power station. Therefore, minimal investment is needed.

b Environmental aspect: Over 99% of the emissions from industrial wastewater treatment and discharge derived from palm oil mill effluent (POME) [62]. Enhanced bioenergy conversion and waste management programmes will therefore significantly minimize the amount of open degradation of POME. Besides that, by practicing an appropriate waste management system and using more efficient equipment, more energy could be generated and in-house energy consumption would be optimized, thereby producing a higher amount of excess power to be injected into the grid, which would ultimately reduce the nation's consumption of fossil fuels and, ultimately, GHG emissions.

c Social aspect: Malaysia's palm oil industry has supported the local economy and livelihood of many of its citizens, particularly in the rural areas for decades. The establishment of large-scale biomass power plants will create a higher demand for biomass, due to an abundance of new job opportunities for the local people. The local community in the rural areas can also participate in economic activities, especially in biomass collection and processing centres, which would further eradicate poverty and reduce migration of rural people to urban cities and sub-urban areas. Furthermore, an increasing number of millers and the public's participation in renewable energy projects would create *relational trust*, which is defined as "truthfulness, mutual appreciation, and creating shared values among involved actors" [97] resulting in higher acceptability and unwavering support of the stakeholders towards green technology.

To ensure successful deployment of the proposed programmes, below are given several policy recommendations, as summarised in Fig. 5:

a Strategic alliance and development of a demonstration plant: The current limitations in harnessing bioenergy could be overcome by engaging and managing key stakeholders. Stakeholder engagement sessions with government agencies, palm oil agencies and millers, industrial and R&D experts, as well as energy providers and financiers are important to gather critical information, create mutual understanding and facilitate collaboration. Seminars and roadshows should be conducted to raise awareness and gauge readiness toward bioenergy industry transformation. Radical change of mindset among small renewable energy developers to a large “National Biomass Energy Corporation” should also be advocated. Establishing a new strategic alliance among the Malaysian Palm Oil Industry (MPOI) and the government, as well as renewable developers, would enable strong industrial and political relations and establish mutual trust. The organizational formats and governance structure of the newly established alliance should also be participatory and community-focused so as to ensure the sustainability of future project deployment [98]. As a proof-of-concept, a demonstration plant should be developed through shared investment and expertise. This could assist in building trust among local actors as well as fostering innovative technology development and mutual and reflective learning [48]. A detailed and comprehensive feasibility study should be conducted to identify pain points and assess the risks and opportunities; consequently, develop a viable business model that would satisfy and balance the expectations of each major player and all other parties concerned.

b Revision of pricing mechanism, policy reform and incentives for facility upgrade: It is proposed that the current FiT tariff for biomass and biogas should be reviewed to increase their competitiveness in the renewable energy market. One possible solution could be to reform policy so that subsidies for natural gas are reduced and then recycled into the FiT scheme with new incentives for biomass and biogas. One study concluded that “utilising a recycling plan in which additional revenues from subsidy reforms are re-allocated to finance the “FiT framework” contributes significantly to the production of renewable energies within the power generation sector in Malaysia [99]. The combined policy is anticipated to further expand the range of feasible FiT financing substantially and produce negligible negative macroeconomic effects.

As for large-scale biomass power plants, a new pricing mechanism should be established to offer a fair and competitive price, which is appropriate with the calculated risk. Besides that, the terms and conditions in the Renewable Energy Power Purchase Agreement (REPPA) should be revised for the benefit of infrastructure, profit and loss sharing among multiple shareholders, and not just the developer. By involving the millers in REPPA, they would have vested interest in bioenergy production and there-

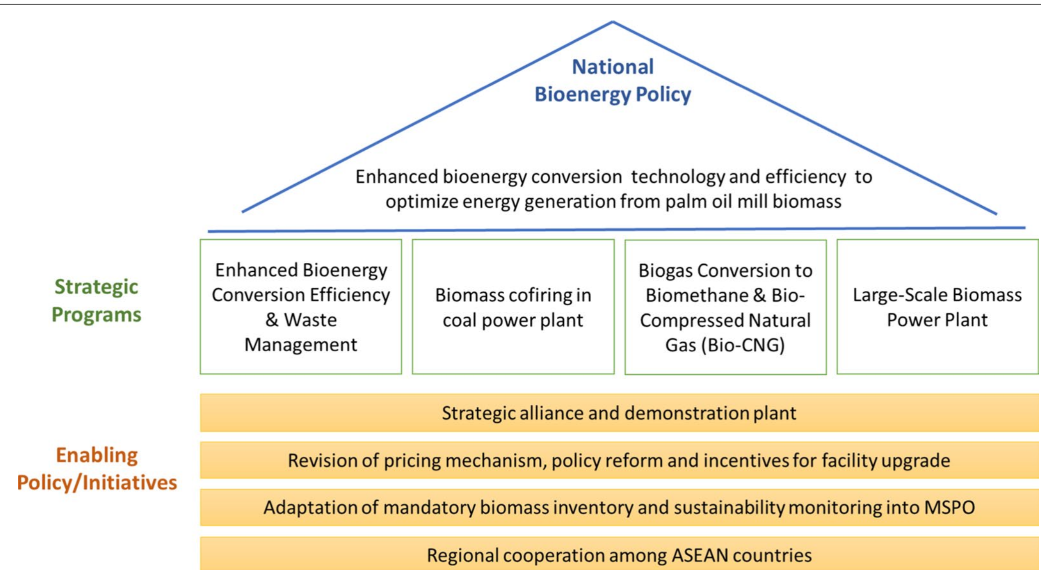


Fig. 5 Proposed strategic programs and recommended enabling policy and initiatives for a sustainable bioenergy development in Malaysia

fore more prepared and willing to cooperate with the developers in a long-term biomass supply agreement. In order to promote energy efficiency and consumption of alternative fuels, new incentive mechanisms should be structured to encourage utilities to strengthen energy system performance and upgrade infrastructure. Likewise, in order to further promote bio-CNG consumption in the transportation sector, the government could include the provision of mandatory use of bio-CNG, such as implemented on B5 biodiesel blend mandated in the Malaysian Biofuel Industry Act 2007 [68].

c Adaptation of mandatory biomass inventory and sustainability monitoring into MSPO: The current MSPO still lacks more specific requirements with regard to proper disposal of waste [100]. Therefore, a provision related to waste management, in particular for palm oil mills analogous to that of 'Environmental Quality (Scheduled Wastes)' Regulations 2005 [101] should be adapted into MSPO. As a result, the waste volume production could be monitored while its potential end-use could be regulated in order to optimize the utilisation of local bioenergy resources. Besides that, sustainability monitoring should be conducted regularly, at least once a year to ensure continuous compliance with MSPO. Furthermore, anti-bribery and corruption policies should be included in the legal compliance.

d Regional cooperation among ASEAN countries: Cooperation among ASEAN countries is essential so that synergies can be obtained to enable an optimal and efficient use of existing resources, capital, technology, know-how, infrastructure, etc. A common understanding that energy security is an imminent challenge for emerging countries must be established. Moreover, a change of mindset among the policymakers from the 'national energy market' to 'regional energy market' is vital. Improving the renewable energy infrastructure and widening pipeline connectivity to neighbouring countries, such as building gas interconnection from Malaysia to Singapore and Thailand, will create new trading opportunities and activities in a liberalized energy market. Consequently, it will lend ASEAN countries larger bargaining power.

Conclusion

In this paper, we have analysed the current development of renewable energy as a result of government policy. In addition, renewable energy evolution in Malaysia over three major phases is explored by introducing an early transition, acceleration, and sustainable development framework. The FiT scheme along with the National Renewable Energy Policy can be regarded as a successful initiative to escalate the capacity installation of renewable energy in the national grid. We have found, however, that financial and technical factors contributed to varying penetration rates of renewable energy resources into the national grid; which boosted the share of solar power, but unfortunately contracted the share of other resources, particularly biomass and biogas. While the diffusion of solar power is welcomed, overreliance on solar power solely generates risks in the resiliency and reliability of renewable energy supply due to necessary additional investment for grid stabilization. Given the current scenario, it is clear that going forward, a holistic approach considering economic, environmental and social dimensions is critically needed to invigorate renewable energy growth in this country. The efficient management of palm oil biomass will significantly increase bioenergy generation and decrease the demand for high-carbon fossil fuel-based energy. To promote both energy transition and transformation of the palm oil industry, Malaysian policymakers are encouraged to establish a clear and appropriate policy based on an effective coordination and collaboration with key stakeholders. The establishment of a comprehensive and inclusive national bioenergy policy will lead towards a sustainable future of renewable energy development in Malaysia.

Abbreviations

APAEC: ASEAN Plan of Action on Energy; ASEAN: Association of Southeast Asian Nations; Bio-CNG: Bio-compressed natural gas; CAPEX: Capital expenditure; CDM: Clean Development Mechanism; CHP: Combined heat and power; CNG: Compressed natural gas; EFB: Empty fruit bunch; FFB: Fresh fruit bunch; FiA: Feed-in Approval; FiT: Feed-in-Tariff; GHG: Greenhouse gas; GTFS: Green Technology Financing Scheme; GTMP: Green Technology Masterplan; LSS: Large-scale solar; MBIPV: Malaysia Building Integrated Photovoltaic; MPOB: Malaysian Palm Oil Board; MPOI: Malaysian Palm Oil Industry; MSPO: Malaysian Sustainable Palm Oil; MSW: Municipal solid waste; MYR: Malaysian Ringgit; NEM: Net energy metering; NGV: Natural gas vehicles; O&G: Oil and gas; O&M: Operation and maintenance; PKS: Palm kernel shells; PMF: Palm monocarp fibre; POME: Palm oil mill effluent; PV: Photovoltaic; REPPA: Renewable Energy Power Purchase Agreement; SEDA: Sustainable Energy Development Authority; SREP: Small Renewable Energy Power.

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Authors' contributions

This paper is a collaboration among Malaysian researchers from different institutions, who are: SFS, MEMR, AAR, AHS, TARTA, and a world-renowned researcher, BKS. SFS is an aspiring author who is leading as the first-author, responsible for the overall content and structure. MEMR is responsible for data collection and validation. AAR is responsible for providing information on industrial perspective of renewable energy, thermal substitution of biomass to coal, etc. AHS is a bioenergy expert responsible for the national biomass strategy in the policy recommendation section. TARTA is an energy industry expert responsible for giving insightful idea on the way forward for Malaysian electricity supply industry in the policy recommendation section. BKS is an energy social science expert responsible to critically analyse the review paper and give his take on energy efficiency and waste management in the policy recommendation section. All authors read and approved the final manuscript.

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