Opportunities of biomass co-firing with coal for CO_2 mitigation in Malaysia: A spatially-explicit assessment

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Keywords: Spatial planning, optimization, co-firing, GIS-MILP.
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Abstract

Due to the rising concerns on climate issues, transitions from fossil fuels to renewable energy are highly promoted globally. Malaysia which has abundant sources of biomass is increasing their efforts to increase renewable energy in the current energy mix. Biomass co-firing with coal offers a promising route to less CO_2 emissions as biomass combusted has a lower carbon content than coal. This paper presents a study on the effects of implementing co-firing practice in existing power generation facilities based on economic and environmental aspects. Integration of both geographical information system (GIS) and mixed-integer linear programming (MILP) is performed to discover biomass availability which is to be supplied for energy use as well as to investigate the spatial relationship between supply and demand based on land-use and logistics aspects. Based on findings, cost factor of deploying co-firing technology is in the range of 59.17 to 60.01 USD/MWh for 5 to 24.6% co-firing rates respectively. Up to 1.31 million tonne of CO_2 can be reduced annually in Johor as resulted from this practice. Minimum difference in cost factor is achieved when dedicated fossil fuels scenario is compared to co-firing. This shows that co-firing technology is ready to be implemented in Malaysia with small incentives by government or even without incentives in certain co-firing scenario case. For rapid implementation of co-firing in Malaysia, it is to be suggested that this technology should be included in the current Feed-in-Tariff (FiT) program with a revised tariff to promote existing industrial players to deploy this technology.

Introduction

Malaysian dependency on fossil fuels for electricity production contributes to the rise of greenhouse gases (GHG) emissions over the years, especially carbon dioxide (CO_2). Among the fossil fuels, coal shares about 38% of total electricity generation mix, second highest after natural gas [1]. As the second largest producer of palm oil in the world, Malaysia is abundant with unutilized biomass. Biomass co-firing with coal offers a promising route to less CO_2 emissions as biomass combusted has a lower carbon content than coal. However, utilizing raw biomass as fuel leads to the degradation of boiler performance due to high moisture content and low heating value of biomass. Biomass pre-treatment helps to enhance its properties so that it can approaches to the same properties of coal. Current practices in Malaysia in the context of biomass utilization are on-site utilization for combined heat and power (CHP), small-scale power generation and agricultural purposes. This is supported by Feed-in Tariff (FiT) program which is monitored by Sustainable Energy Development Authority (SEDA) of Malaysia. However, co-firing is not included in FiT, suggesting that this is probably one of the reasons why co-firing is not been practiced yet in Malaysia asides from biomass quality aspect. Before large scale implementation of co-firing can be performed, it is important to study about its feasibility to be practiced in Malaysia. This study investigates the economic and environmental performances of such solution to be implemented in Malaysia based on different co-firing scenarios in real case study which is Johor.

The novelty of this study can be described into these following aspects. First, spatially-explicit modelling through combination of geographical information system (GIS) and mixed-integer linear programming (MILP) or collectively known as GIS-MILP is conducted for the management of cost-effective biomass supply, siting of densification facilities and assessing optimal co-firing scenario. Previous studies have been conducted in assessing the feasibility of biomass co-firing with coal [2-6] through the applications of GIS with linear programming (LP) or MILP. Most of these studies focused on assessing the biomass allocations to existing power generation facilities by leveraging spatially distributed biomass supply data and optimal logistics networks in order to achieve minimum cost of supply chain. It can be identified that lack of emphasizes have been done in the context of facilities siting for the pre-processing of biomass to enhance its properties for co-firing specifically using this combined method. Those who discussed [6-8] neglected the consideration of area screening to identify potential sites to build processing facilities. Constraint areas which resulted from factors such as elevations, slope, buffer zones, built-up areas and protected areas should be included in the assessment in order to prevent the selections of infeasible areas. Also, this can reduce computational time for the model to generate results. Second, the relationships between different co-firing scenarios with number, location and capacities of densification facilities has not been explored yet in a spatially-explicit manner. This is important to investigate the effects of different co-firing rates on the spatial distribution of biomass and land-use change in Malaysia. With all the research gaps identified, this study is motivated to fulfil them by performing spatial planning and optimization in providing a roadmap for energy and environmental management in Malaysia.

Methodology

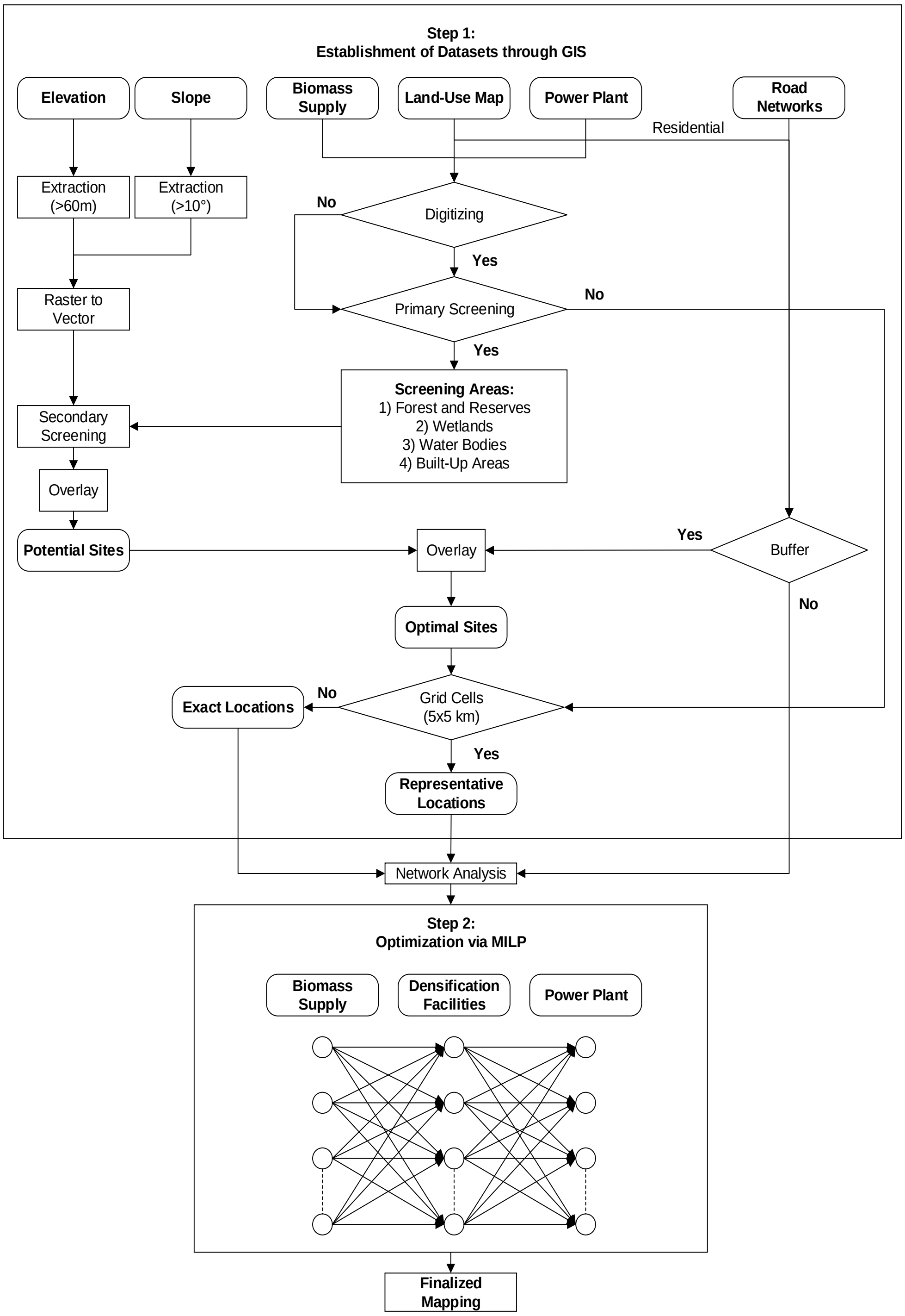

Fig. 1 Research framework

The method employed in this study consisted of two major steps and one intermediate step as shown in Fig. 1. The first step is the application of GIS to establish datasets needed by MILP. The data available may be in raster or vector form, depending on the sources of data. Digitizing is needed in the case where the data is in raster form (e.g: map, satellite, images). This is purposely to convert the data into a processable format that can be used in GIS. The major purpose of conducting the first step is to establish biomass supply data to fulfil co-firing demand by power plant and create final suitability map to locate potential locations to build densification facilities. This is achievable through the utilization of land-use map for the estimation of oil palm biomass availability and screening out the infeasible areas. Land-use map is retrieved from Malaysian Centre for Geospatial Data Information. It consists of forestry and reserves, wetlands, built-up areas, water bodies and agricultural areas.

Biomass included in this study are empty fruit bunch (EFB), oil palm trunk (OPT) and oil palm fronds (OPF). EFB sources are accounted from palm oil mills whereas OPT and OPF sources are accounted from oil palm plantations. As shown in Fig. 2, there are 65 palm oil mills in the state. The data is provided by SIRIM Berhad. EFB availability is reduced down by 62% [9-10] due to its applications for other purposes such as onsite power generation and agricultural purposes. Oil palm plantation area is extracted from land-use map for the estimations of OPT and OPF availabilities. The map is divided into 5x5 km grid to identify biomass yield per grid of plantation. The yield of OPT and OPF are 74.48 t/ha and 10.4 t/ha respectively [11]. This is with the conditions that only 50% of OPT can be extracted from plantations if only replantation program is scheduled and only 50% OPF can be extracted with 75% of oil palm trees aged 7 years are due pruning. Fig. 3 and 4 illustrated the spatial distributions of oil palm biomass in the state.

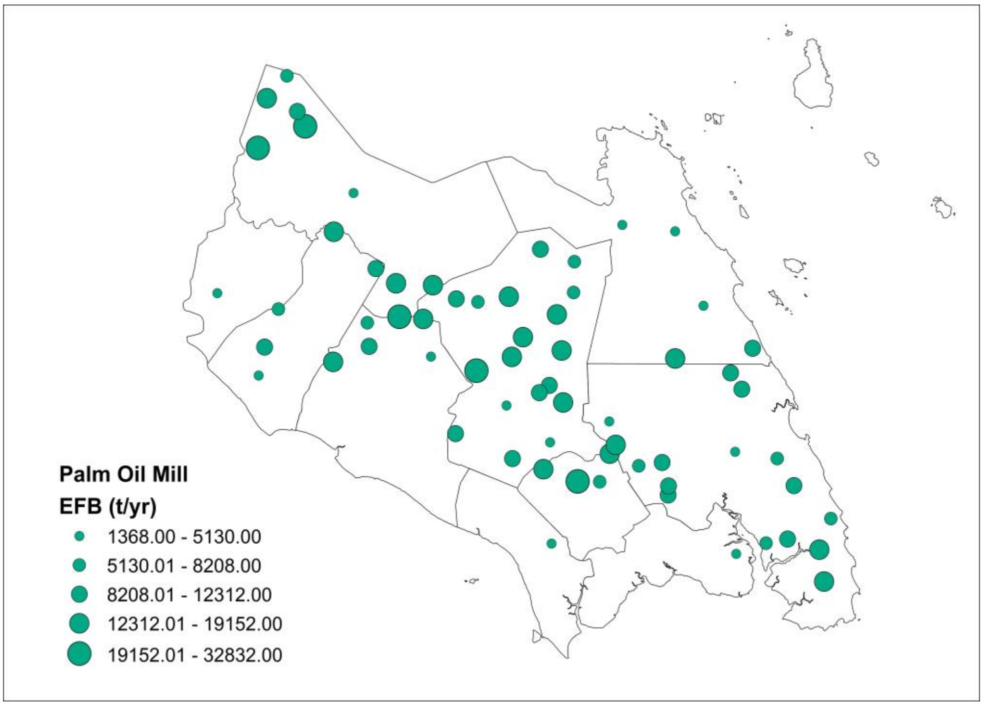

Fig. 2 EFB availability

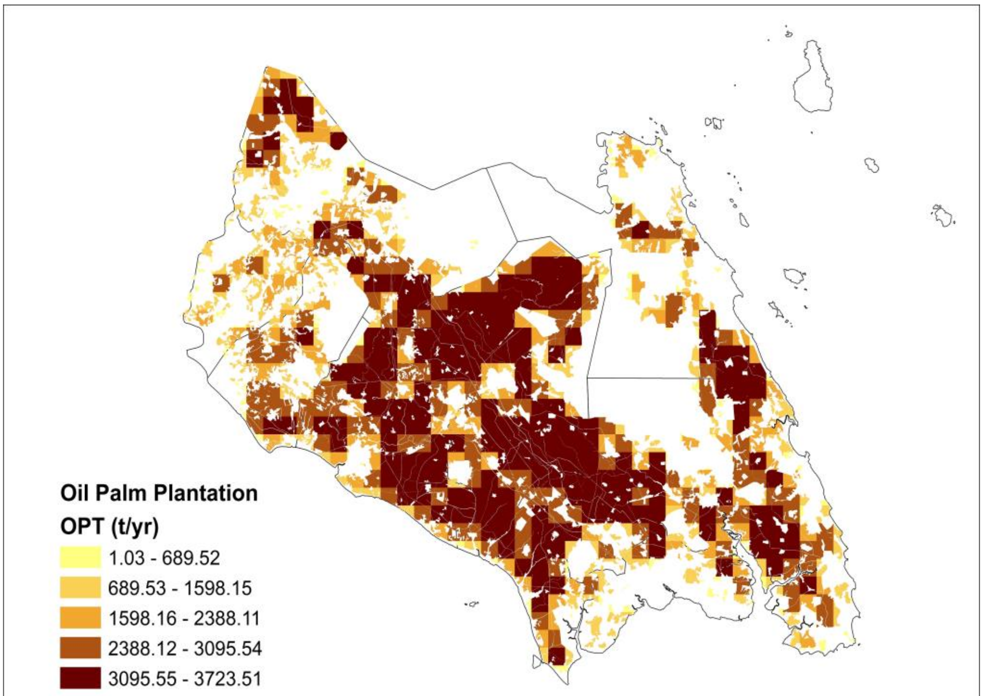

Fig. 3 OPT availability

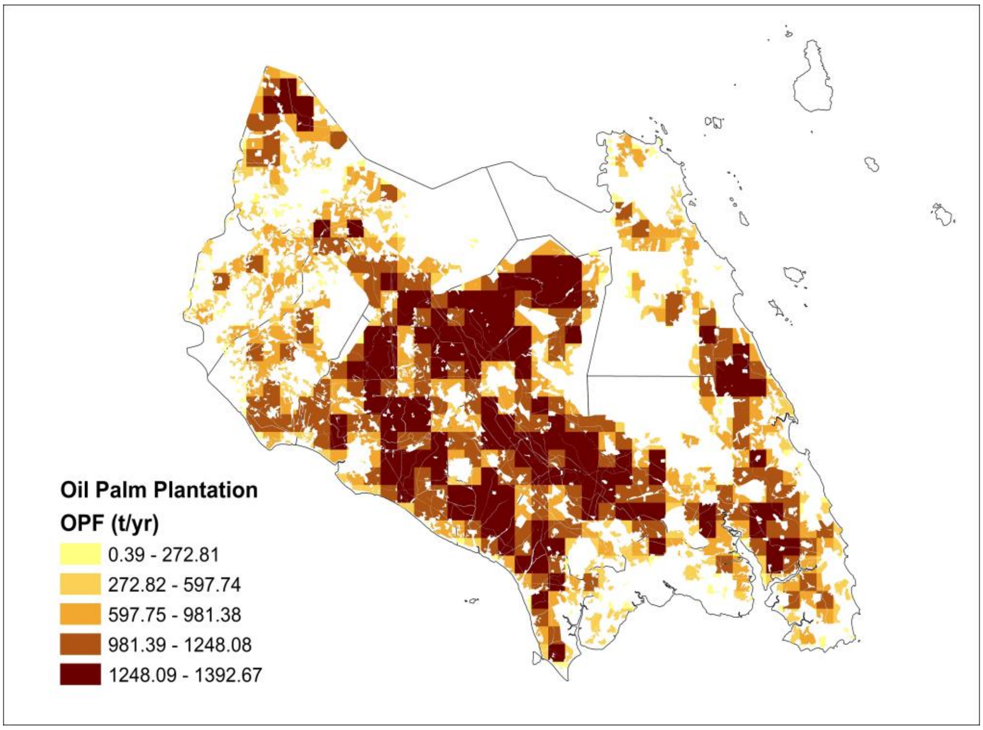

Fig. 4 OPF availability

To identify the final suitability map as shown in Fig. 5, series of screening processes are performed. Primary screening involved eliminating out protected and built-up areas from land-use map. Protected areas are consisted of forestry and reserves, national parks, wetlands and water bodies whereas built-up areas consisted of residential, commercial and recreational areas. After primary screening has been conducted, secondary screening is performed with the considerations of slope and elevation. Data for elevation and slope is retrieved from DIVA-GIS [12]. Areas which have slope higher than 10° [13] and elevation higher than 60 m [14] are excluded from the screened map in order to minimize cost of plant construction. In order to establish optimal sites, the suitability map is overlaid with transportation and residential buffers. This indicated that areas which are located within 1 km and 2 km from road and residential areas respectively are excluded from the suitability map. After overlay process, any area which is below than 1 km^2 in a grid is removed from the map to make sure area which is available for construction of facilities is large enough. After optimal sites are established, the map is assigned into grids of 5x5 km of same size. The centroid of the grids later is fixed based on area available per grid. Assigning map into grids is purposely to create representative locations for later analysis. These grids are not intended to be the exact locations, but rather generalized areas to represent the potential locations which will later be useful for network analysis purposes.

One of the key criteria in assessing the economic performance is transportation. Network analysis is performed by considering detailed road transportation networks (Fig. 6) in Johor state to find the optimal transportation route from each location to its destination. These distances are inputted to the optimization model for the calculation of transportation cost. For the supply of biomass to densification facilities and power plant, only transportation by truck is considered. Coal-fired power plant which has capacity of 3100 MW is located in Tanjung Bin, Johor. The data on capacity factor, availability factor, thermal efficiency of this power plant is acquired from Malakoff Corporation Berhad [15]. Transportation of coal to power plant which has a total distance of 4690 km is through direct shipment from Indonesia to power plant terminal. The transportation distance is estimated from Tenaga Nasional Berhad (TNB) [16] shipment contracts deal.

Secondly, optimization is conducted with the objective to maximize profit of the system. Biomass pre-treatment technology associated in this study is combined torrefaction and pelletization (TOP) process. This technology increases the energy content and reduces moisture content of biomass to the level approaching to that of coal. Besides, it helps to densify the biomass to ease the transportation process. The costs associated in this study are capital expenditures (CAPEX), operating expenditures (OPEX), raw material cost and transportation cost. CAPEX is accounted for TOP process only since these facilities are to be built while coal-fired power plant is already existed. Transportation cost is calculated using cost parameter which is based on volume instead of distance. This is due to the change in biomass volume affects the overall transportation cost. Overall, the biomass supply consists of 778 nodes, potential locations of densification facilities consist of 529 nodes and coal-fired power plant consists of 1 node. Binary variable is included in the MILP model in order for the model to restrict the selections of densification facilities at total number of 50 facilities or less. Asides from economical aspect, the model calculated the total emissions resulted from transportation, densification process and power generation activity. All the economic, environment and technical parameters which are required as input data for the MILP model are compiled as shown in Table 1. The software used for GIS and optimization are ArcMap and Generic Algebraic Modelling System (GAMS) respectively.

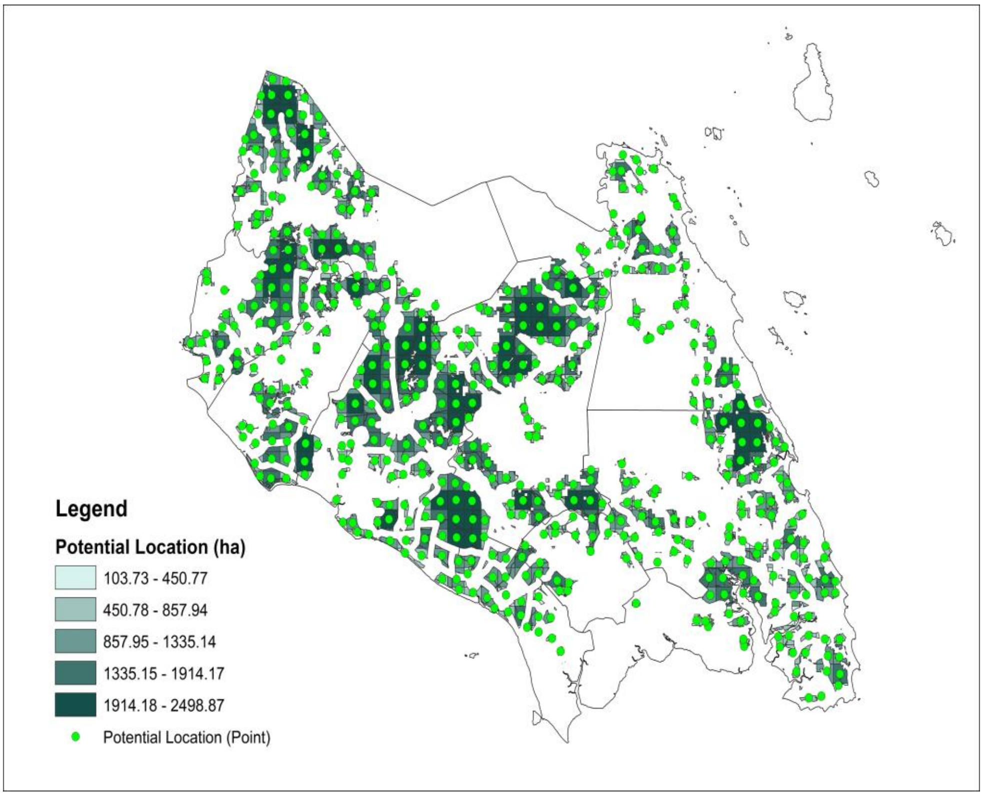

Fig. 5 Potential locations of densification facilities

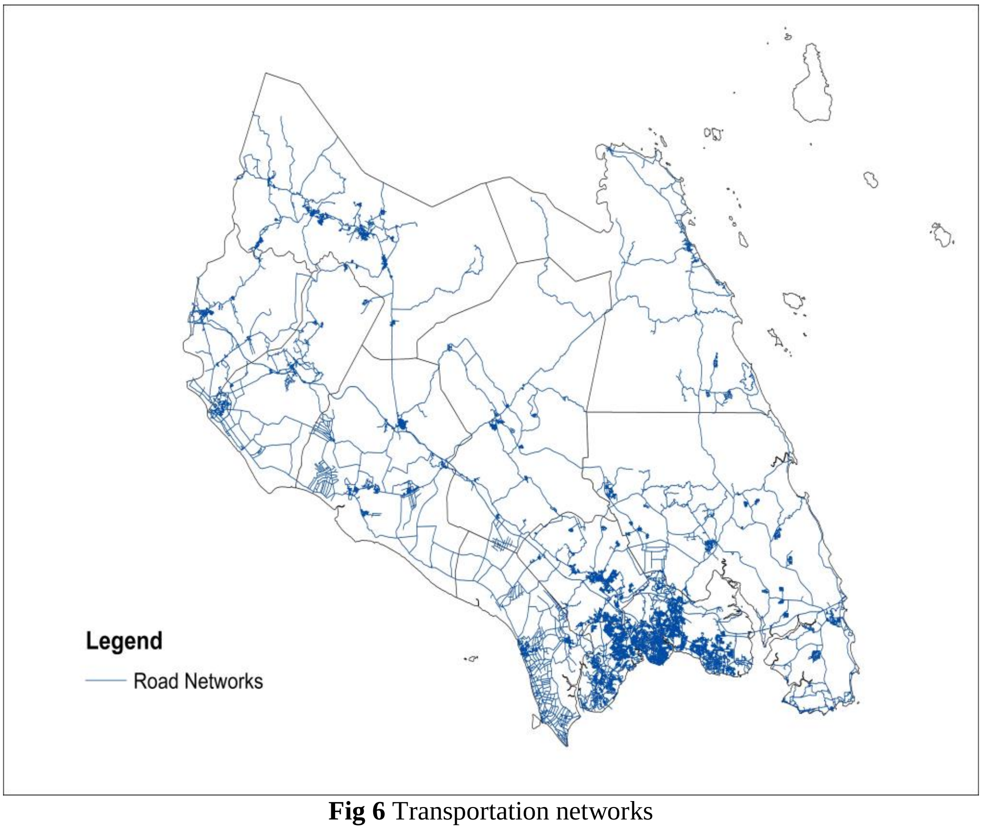

Fig 6 Transportation networks

Table 1 Economic, environment and technical input data

Economic			**Environment**			**Technical**		
Parameter	**Unit**	**Value**	**Parameter**	**Unit**	**Value**	**Parameter**	**Unit**	**Value**
CAPEX (TOP)	USD/t feedstock	35.91[a]	TOP	t CO_2/t feedstock	0.0390[k]	Biomass to TOP		
OPEX (TOP)	USD/t feedstock	22.63[a]				EFB	t/t EFB	0.6488[m]
OPEX (Power	USD/MWh	18.70[b]	Truck	t CO_2/ t.km	0.9000E-4[c]	OPT	t/t OPT	0.9037[n]
						OPF	t/t OPF	0.8370[o]
Truck	USD/m^3.km	0.03[c,d]	Shipping	t CO_2/ t.km	0.0350E-4[e,l]	Fuel to electricity		
Shipping	USD/t.km	13.91E-3[e]				EFB	MWh/t EFB	2.1395[m]
EFB	USD/t	13.00[f]	EFB	t CO_2/t	1.0006[m]	OPT	MWh/t OPT	2.2928[n]
						OPF	MWh/t OPT	1.9834[o]
OPT	USD/t	15.00[g]	OPT	t CO_2/t	1.6015[n]	Coal	MWh/t coal	2.1830[p]
						Volume before TOP		
OPF	USD/t	10.00[h]				EFB	m^3/t	2.8169[q]
			OPF	t CO_2/t	1.4947[o]	OPT	m^3/t	2.5126[r]
Coal	USD/t	82.51[i]				OPF	m^3/t	6.2500[o]
						Volume after TOP		
Electricity	USD/MWh	88.37[j]	Coal	t CO_2/t	2.0531[p]	EFB	m^3/t	1.3535[q]
						OPT	m^3/t	1.2073[r]
						OPF	m^3/t	3.0032[o]

a - [17], b - [18], c - [7], d - [19], e - [20], f - [21], g - [22], h - [23], i - [24], j - [25], k - [26], l - [16],
m – derived from [27], n – derived from [28], o – derived from [29], p – derived from [30], q - derived from [31], r- derived from [32]

Results and discussions

Various co-firing scenarios were developed consisting of 5%, 10%, 15%, 20% and 24.6% co-firing rates. 24.6% co-firing is selected as maximum co-firing rate based on maximum availability of oil palm biomass in Johor state which can be supplied for energy use. Table 2 shows the economic and environmental outputs resulted from running the GIS-LP model. It can be shown that at 5-20% co-firing rate, profit from electricity generation is slightly higher than base case profit at rate of USD 1.87-6.30 millions/yr. Although at 20% co-firing rate, the profit is still higher than base case, it can be shown that profit started to reduce beyond 15% co-firing rate. The economies of scale effects on 5 to 15% co-firing rates were likely to occurred due to sources of biomass pellets which are densely distributed (Fig. 7-9) near power plant location. At low percentage of co-firing rates, the model selected the nearest biomass supply and pre-treatment locations so that minimum cost of transportation could be achieved. Starting at 20% co-firing, the densification facilities started to scattered all over Johor state due to biomass supply is reaching to its maximum availability. This forced the model to find as many biomass sources as possible although the locations are far from power plant so that co-firing demand could be fulfilled.

As for CO_2 mitigation strategy, the utilization of biomass contributed to the reduction of CO_2 emissions at rate up to 1.31 million t/yr as resulted from implementing this technology. The reason on why CO_2 emissions is reduced as the co-firing rates increased is that the biomass substitutes a lower carbon content in energy mix than coal. Before pre-treatment of biomass, the carbon content in biomass is very much lower as compare to carbon content in the pre-treated of biomass. However, using the untreated biomass in existing boiler of coal-fired power plant, the efficiency will be going to reduce drastically although the amount of CO_2 mitigated will be much lower than current case. As for the readiness of this technology to be implemented in Malaysia, pre-treatment is needed so that the existing energy demand can be fulfilled without any degradations on the efficiency of power generation. The cost factor of deploying co-firing technology in existing coal-fired power plant is between 59.17-60.01 USD/MWh range. The difference is very small when cost factor of fossil fuels which is at 59.49 USD/MWh is compare to highest cost factor of co-firing. Although governmental incentives may highly promote the transitions of fossil fuels energy production to renewables, this results shows that certain portion of bioenergy substitution in existing coal fired power plant can be economically attractive. At maximum availability of biomass, trade-off between cost and emissions is at very minimum, suggesting that this technology should be ready to be implemented in Malaysia with small incentives from government. In future, biomass availability should be maximized in order to provide higher portion of biomass supply so that co-firing rate can be higher. This will lead to the pathway of less CO_2 emissions in the country.

Table 2 Economic and environmental results based on different co-firing scenarios

Scenario	Base case	Co-firing (5%)	Co-firing (10%)	Co-firing (15%)	Co-firing (20%)	Co-firing (24.6%)
Profit (USD/yr)	579,140,121	583,073,889	585,333,498	585,438,288	581,012,316	568,546,696
Total cost (USD/yr)	1,192,669,541	1,188,735,773	1,186,476,164	1,186,371,374	1,190,797,346	1,203,262,966
CO_2 emitted (t CO_2/yr)	19,007,690	18,776,466	18,545,242	18,314,442	18,104,361	17,697,572
CO_2 reduction (t CO_2/yr)	-	231,224	462,448	693,248	903,329	1,310,118
Number of facilities selected	-	49	49	49	50	50
Total production capacity (t/yr)	-	437,228	874,456	1,312,166	1,812,426	2,242,103
Cost factor (USD/MWh)	59.49	59.29	59.18	59.17	59.39	60.01

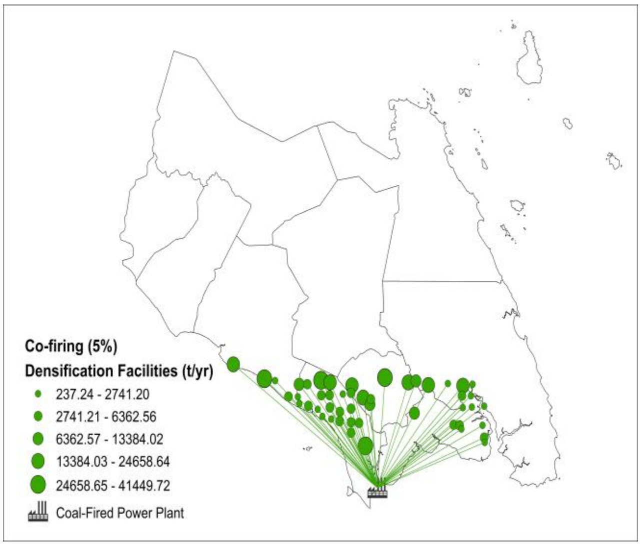

Fig. 7 Locations of densification facilities (5% biomass co-firing with coal)

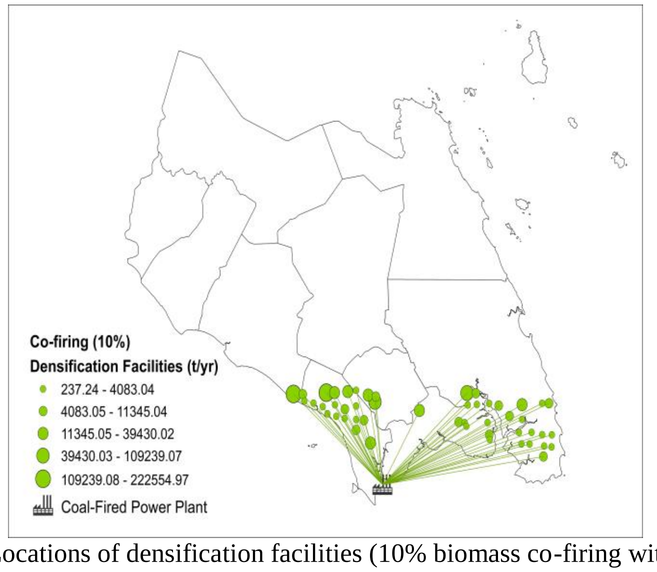

Fig. 8 Locations of densification facilities (10% biomass co-firing with coal)

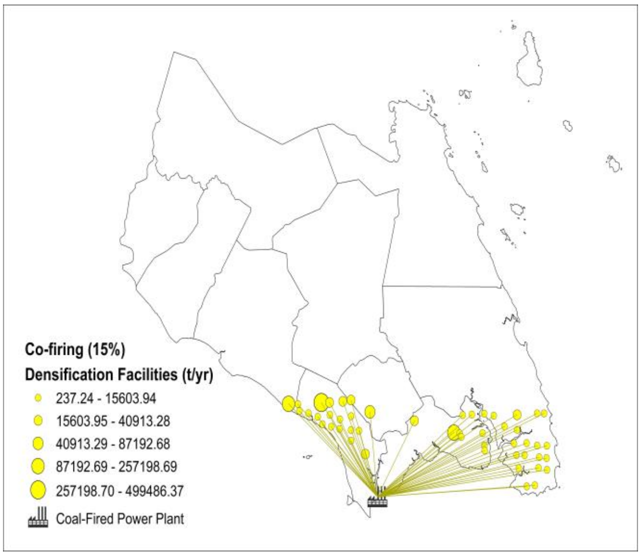

Fig. 9 Locations of densification facilities (15% biomass co-firing with coal)

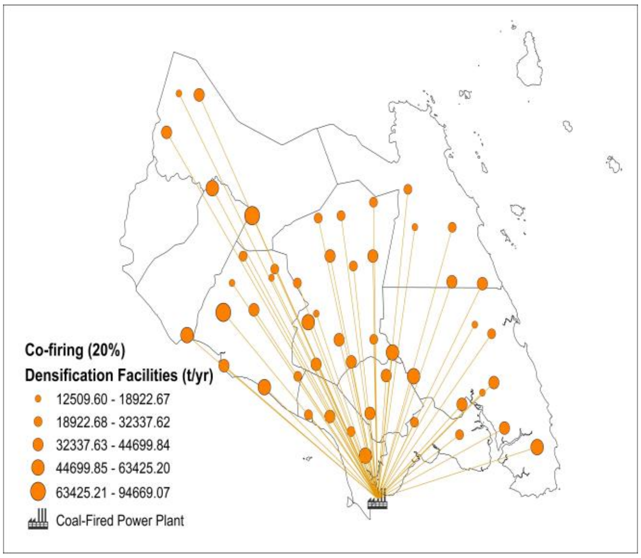

Fig. 10 Locations of densification facilities (20% biomass co-firing with coal)

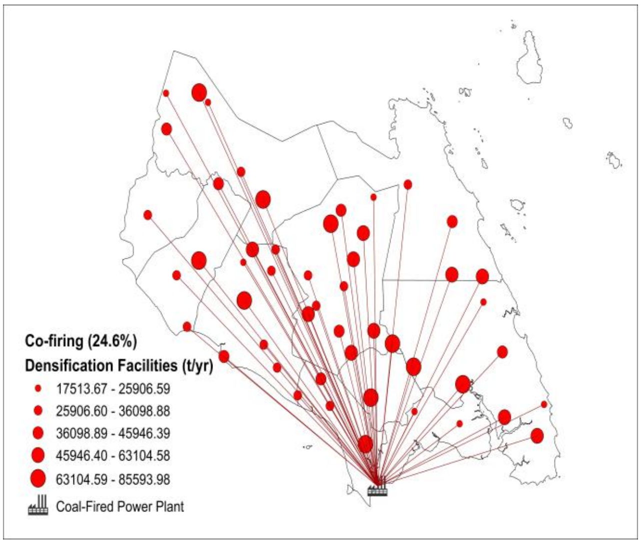

Fig. 11 Locations of densification facilities (maximum biomass utilization)

Conclusions

The results show that up to 1.31 million tonne of CO_2 can be minimized annually in Johor through co-firing practice. The cost factor of deploying co-firing technology in existing coal-fired power plant is between 59.17 to 60.01 USD/MWh range. The difference is very small when cost factor of fossil fuels power generation which is at 59.49 USD/MWh is compare to highest cost factor of co-firing technology. With these outcomes, it should promote the large scale implementation of bioenergy among industry. Governmental policies and incentives however are still needed for the rapid transitions from fossil fuels to renewables energy in Malaysia. It is to be suggested that this technology should be included in the current FiT program with a revised tariff since the maximum capacity of renewable energy facility under this program is still low. This model can be further extended by including technological selections of different co-firing technologies to improve the efficiency of combustion. The case study can be expanded by explicitly assessing the whole Peninsular Malaysia scenario rather than only Johor state.

Acknowledgement

The authors would like to thank Universiti Teknologi Malaysia for providing research funds under Vote No. Q.J130000.2546.14H46.

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