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Spatial optimisation of oil palm biomass co-firing for emissions reduction in coal-fired power plant

Muhammad Nurariffudin Mohd Idris [a, b], Haslenda Hashim [a, b, *], Nurul Hanim Razak [b, c]

[a] Faculty of Chemical and Energy Engineering, Universiti Teknologi Malaysia (UTM), 81310 UTM Johor Bahru, Johor, Malaysia
[b] Process Systems Engineering Centre (PROSPECT), Research Institute for Sustainable Environment (RISE), Universiti Teknologi Malaysia (UTM), 81310 UTM Johor Bahru, Johor, Malaysia
[c] Centre of Advanced Research on Energy (CARe), Faculty of Mechanical Engineering, Universiti Teknikal Malaysia Melaka (UTeM), 76100, Melaka, Malaysia

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A B S T R A C T

Due to the rising concerns on climate issues, the transitions of fossil fuels to renewable energy are highly promoted globally. Malaysia which has abundant sources of biomass, is maximising the efforts to increase renewable energy shares in the current energy mix. Biomass co-firing with coal offers a promising route to less greenhouse gas (GHG) emissions due to the zero net greenhouse effect of biomass combustion. This paper presents an integrated spatial optimisation model of biomass co-firing supply chain for existing power generation facilities through the integration of geographical information system (GIS) and mixed-integer linear programming (MILP). The model integrates spatial distributions of biomass supply, locations to build biomass pre-treatment facilities, location-allocation of supply and demand of biomass co-firing supply chain and economic and environmental sounds of biomass co-firing system. The optimisation of the whole supply chain system is conducted with the aim to minimise the overall cost and its emissions while determining the most optimal locations to build pre-treatment facilities to support co-firing power generation. Based on the findings, the cost factors of deploying co-firing technology in existing coal-fired power plant are between 56.61 and 61.65 USD/MWh for 10–50% co-firing rates as compared to the base case electricity generation cost which is at 56.29 USD/MWh. Minimum differences in cost factors are achieved when dedicated fossil fuels scenario is compared to several co-firing scenarios. Up to 8.83 × 106 t of CO_2 (equivalent to 46% of CO_2 reduction) can be reduced annually in Johor as a result of this practice. This shows that co-firing technology is promising to be implemented in Malaysia while achieving significant emissions reduction target with incentives supported by government.

1. Introduction

Severe fluctuations in fossil fuel prices and global environmental problems have greatly accelerated the efforts to develop renewable energy (RE). As the second largest producers of palm oil in the world, Malaysia has abundant sources of biomass that can provide sustainable resources for RE production. Malaysian oil palm industry is projected to achieve an increase of annual biomass production at 1.10×10^8 t by 2020 as compared to 8.30×10^7 t in 2012 (AIM, 2013). Despite the abundance of biomass, only 81 MW of solid biomass power plant is installed currently in the country (SEDA, 2017), leaving the rest of biomass untapped. Biomass co-firing with coal offers a promising strategy to effectively utilise the oil palm biomass in existing energy facilities and reduce the greenhouse gases (GHG) emissions due to the unique zero net greenhouse effect of biomass combustion. However, the consumption of raw biomass as fuel leads to the degradation of boiler performance as a result of the high moisture content and low energy density of biomass, contributing to the requirements of larger quantities of biomass to substitute the same amount of energy produced by coal.

The scattered spatial distributions of palm oil mills combined with other issues (i.e. small scale palm oil mill, seasonal, and local availabilities of biomass) contribute to the economic, environment, and logistic implications. Biomass suppliers typically come from small or medium sized plantations which are widely dispersed

* Corresponding author. Tel.: +607 5535578; fax: +607 5588166.
E-mail address: haslenda@utm.my (H. Hashim).

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Abbreviations

BAU Business as usual
CAPEX Capital expenditure
CPO Crude palm oil
EFB Empty fruit bunch
FFB Fresh fruit bunch
FiT Feed-in-Tariff
GHG Greenhouse gases
GIS Geographical information system
LP Linear programming
MF Mesocarp fibre
MILP Mixed-integer linear programming
OPEX Operating expenditure
OPF Oil palm fronds
OPT Oil palm trunks
PKS Palm kernel shell
POME Palm oil mill effluent
RE Renewable energy
TOP Combined torrefaction and pelletisation

Sets
b Type of biomass
i Biomass supply location
j Pre-treatment facility location
k Coal terminal location
l Coal-fired power plant location

Parameters
$Area_j^{facility}$ Available areas per grid of potential pre-treatment site *j* (ha)
$Area^{lu}$ Land use factor of pre-treatment facility *j* (ha/t.y)
$BA_{b,i}$ Availability of raw biomass *b* at source *i* (t/y)
BTE_b Torrefied biomass pellet *b* conversion to electricity (MWh/t)
CA_k Availability of coal at terminal *k* (t/y)
CF^{coal} Emission factor of coal (t CO_2/t)
CF_b^{cultiv} Emission factor of biomass *b* cultivation (t CO_2/t)
$CF_b^{harvest}$ Emission factor of biomass *b* harvesting (t CO_2/t)
CF^{luc} Emission factor of construction land use change (t CO_2/ha.y)
CF^{top} Emission factor of top process (t CO_2/t feedstock)
CF^{truck} Emission factor of transportation by truck (t CO_2/t.km)
CF^{ship} Emission factor of shipping process (t CO_2/t.km)
CTE Coal conversion to electricity (MWh/t)
$dist_{k,l}^{ccpp}$ Transportation distance of coal supply from coal terminal *k* to power plant *l* (km)
$dist_{j,l}^{cpp}$ Transportation distance of torrefied biomass pellet supply from pre-treatment facility *j* to power plant *l* (km)
$dist_{i,j}^{top}$ Transportation distance of raw biomass supply from source *i* to pre-treatment facility *j* (km)
$Elect_l^{target}$ Electricity generation target of power plant *l* (MWh/y)
n_b^{top} Conversion factor of raw biomass *b* to torrefied biomass pellet
P_b^{bio} Price of raw biomass *b* (USD/t)
P^{captop} Capital cost unit of TOP process (USD/t feedstock)
P^{carbon} Carbon price (USD/t CO_2)
P^{coal} Price of coal (USD/t)
P^{opcpp} Operating cost unit of electricity generation (USD/MWh)
P^{optop} Operating cost unit of TOP process (USD/t feedstock)
P_b^{plant} Price of biomass *b* cultivation and harvesting (USD/t)
P^{ship} Price of shipping (USD/t.km)
P^{truck} Price of truck transportation (USD/t.km)

Variables
C^{capex} Capital expenditures (CAPEX) (USD/y)
C^{carbon} Carbon cost (USD/y)
C^{opex} Operating expenditures (OPEX) (USD/y)
C^{plant} Biomass cultivation and harvesting cost (USD/y)
C^{rawmat} Raw material cost (USD/y)
C^{total} Total cost of the system (USD/y)
C^{transp} Transportation cost (USD/y)
CR_l Co-firing rate of power plant *l* (%)
$Elect_l^{bio}$ Electricity generation from biomass of power plant *l* (MWh/y)
$Elect_l^{coal}$ Electricity generation from coal of power plant *l* (MWh/y)
E^{cultiv} Emissions from biomass cultivation (t CO_2/y)
$E^{harvest}$ Emissions from biomass harvesting (t CO_2/y)
E^{luc} Emissions from construction land use change (t CO_2/y)
E^{tech} Emissions from technological activities (t CO_2/y)
E^{total} Total emissions of the system (t CO_2/y)
E^{transp} Emissions from transportation activities (t CO_2/y)
$F_{b,l}^{bcpp}$ Flowrate of torrefied biomass pellet *b* consumed in power plant *l* (t/y)
$F_{b,i,j}^{biotop}$ Flowrate of raw biomass *b* from source *i* to pre-treatment facility *j* (t/y)
$F_{b,j}^{btop}$ Flowrate of raw biomass *b* at pre-treatment facility *j* (t/y)
$F_{k,l}^{ccpp}$ Flowrate of coal from terminal *k* to power plant *l* (t/y)
F_l^{coal} Flowrate of coal consumed in power plant *l* (t/y)
F_j^{top} Production rate of pre-treatment facility *j* (t/y)
$F_{b,j,l}^{topcpp}$ Flowrate of torrefied biomass pellet *b* from pre-treatment facility *j* to power plant *l* (t/y)
L_j^{select} Binary coefficient for the selection of pre-treatment facility *j*

geographically, causing the processes such as loading, unloading, and transportation of biomass to be challenging and expensive. Biomass pre-treatment is essential to tackle these technical and logistical issues in order to enhance the biomass properties to the same properties as coal. Nonetheless, this does not eliminate the need for capital investments to build new pre-treatment facilities and transportation cost associated in supplying biomass to the plants. In order to address these issues, a spatial optimisation framework is developed to optimally determine the locations of centralised pre-treatment facilities for the cost-effective and

Table 1
Previous works on biomass co-firing supply chain planning.

Author	Method	Case study	Resource availability estimations	Biomass pre-treatment	Facility siting	Land use constraints	Network analysis	Policy supports
Hu et al. (2013)	GIS + LP	Taiwan	/	×	×	×	/	×
Lam et al. (2013)	MILP	Malaysia	×	/	/	×	×	×
Rozakis et al. (2013)	GIS + MILP	Poland	/	×	×	×	/	×
Delvin and Talbot (2014)	GIS + LP	Ireland	/	×	×	×	/	/
Griffin et al. (2014)	GIS + LP	Malaysia	/	×	×	×	/	/
Pérez-Fortes et al. (2014)	MILP	Spain	×	/	/	×	×	×
Roni et al. (2014)	GIS + MILP	United States	×	/	×	×	/	/

sustainable biomass co-firing supply chain planning in order to minimise the total cost and associated emissions.

Incorporating accurate geographical elements in bioenergy supply chain studies requires the need of geographical information system (GIS) in solving spatial decision problems, estimating resource availability, identifying optimal sites to build facilities, performing transportation network analysis and conducting sophisticated geographical analyses. In this study, integration of GIS and mixed-integer linear programming (MILP) through spatial modelling approach is conducted for the development of a conceptual framework which is inclusive of the management of cost-effective biomass supply, siting of pre-treatment facilities, assessment of various co-firing scenarios and policy supports development. Previous studies on biomass co-firing supply chain have been carried out to assess the feasibility of this technology to be implemented in various countries. Hu et al. (2013) studied the rice straw biomass resource utilisation for co-firing in Taiwanese energy industries, Rozakis et al. (2013) assessed the optimal allocation of straw biomass to major power plants in Poland for co-firing electricity generation, Delvin and Talbot (2014) developed the biomass transportation strategies with policy supports in meeting the co-firing energy regulations in Ireland, Pérez-Fortes et al. (2014) performed the optimal location-allocation of pre-treatment facilities to support biomass co-firing in Spain and Roni et al. (2014) developed a hub-and-spoke supply chain network design model for biomass co-firing planning in United States.

For the applications in Malaysian case study, Griffin et al. (2014) assessed the availability of biomass residues for co-firing in Peninsular Malaysia through a GIS-based linear programming (LP) model. Targeting the RE substitution at 330 MW, minimum cost of co-firing is achieved at 1.14×10^9 USD/y with a 6% decrease in the national GHG emissions as compared to the dedicated coal-fired case which is at 1.16×10^9 USD/y. Although providing a significant overview of co-firing energy realisation in Malaysia, consuming raw biomass at high co-firing levels without pre-treatment will causes the major degradation of power generation efficiency. It is important to consider pre-treatment technology for a realistic approach to adopt co-firing in the existing power plants. Lam et al. (2013) developed a transport cost model associated with supplying biomass for co-firing at a minimum total cost to coal-fired power plants in Peninsular Malaysia. This resulted in the overall transportation costs of 10.09×10^3 USD/h and 19.42×10^3 USD/h for the roadway and the railway transportation scenarios. Although providing an effective biomass transport supply strategy, the adopted euclidian distance and facility siting approaches may be improved with the considerations of detailed transportation networks and land use constraints through GIS approach for a more holistic representation of transportation planning.

To the best of our knowledge, there is a lack of emphasis on the context of biomass pre-treatment, GIS-based facility siting and policy supports in the biomass co-firing supply chain studies, specifically using the integrated spatial modelling approach. Spatial planning and optimisation should be investigated more widely in the co-firing studies by incorporating all the criteria shown in Table 1 in providing a more comprehensive and powerful decision support model. The primary objective of this paper is to develop a spatial biomass resource planning framework for the optimisation of biomass co-firing supply chain in providing a roadmap for sustainable energy and environmental managements in Malaysia. Using Johor as a case study, several specific objectives are outlined as follows. First, the estimations of oil palm biomass availabilities are conducted with the employment of GIS-based resource assessment. Second, the potential sites to build biomass pre-treatment facilities are identified with the considerations of various land use and accessibility constraints. Third, the optimisation of the whole supply chain system is performed with the aim to minimise the overall cost and its emissions while determining the most optimal locations to build facilities, the optimal co-firing rates and the optimal emissions reduction scheme. Fourth, the policy required to support co-firing implementation in the country is investigated.

2. Methods

A conceptual biomass co-firing supply chain planning framework with the integration of GIS and MILP consisting of resource availability assessment, suitability analysis of potential pre-treatment sites and optimisation is illustrated in Fig. 1. ArcMap 10.3 and GAMS 24.6.1 (CPLEX solver) are utilised as the platforms to conduct GIS analysis and optimisation works. Several assumptions are made to address the boundaries of this study. These are described as follows:

i) Oil palm biomass combustion is considered as CO_2 neutral.
ii) CO_2 emissions are accounted from several sources which are from biomass cultivations (i.e. fertilisations, pesticides, soil preparations), biomass harvesting (i.e. land use change, pruning), transportations by truck and shipping, constructions of pre-treatment facilities (i.e. land use change), pre-treatment process and coal combustion in power plant.
iii) Coal is assumed to be transported directly from coal terminals located in Javanese and Sumatra islands of Indonesia to the power plant terminals.
iv) Production rate of pre-treatment plants is specified at 100 kt/y.

2.1. Resource availability estimations

Due to the geographically distributed nature of biomass

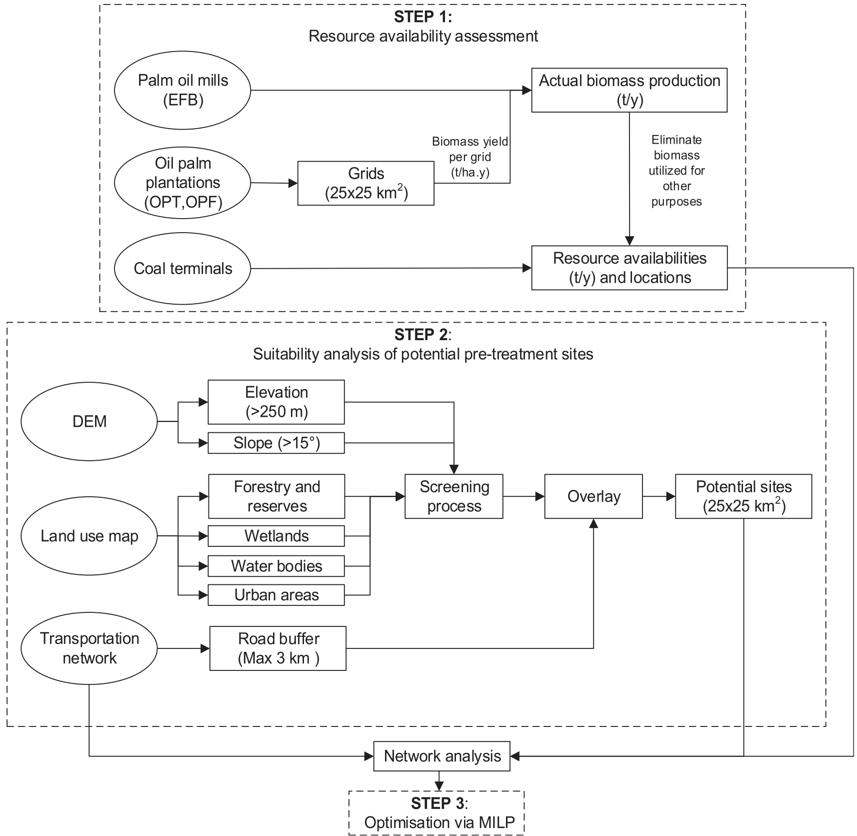


Fig. 1. Integrated GIS-based biomass resource assessment with spatial modelling approach.

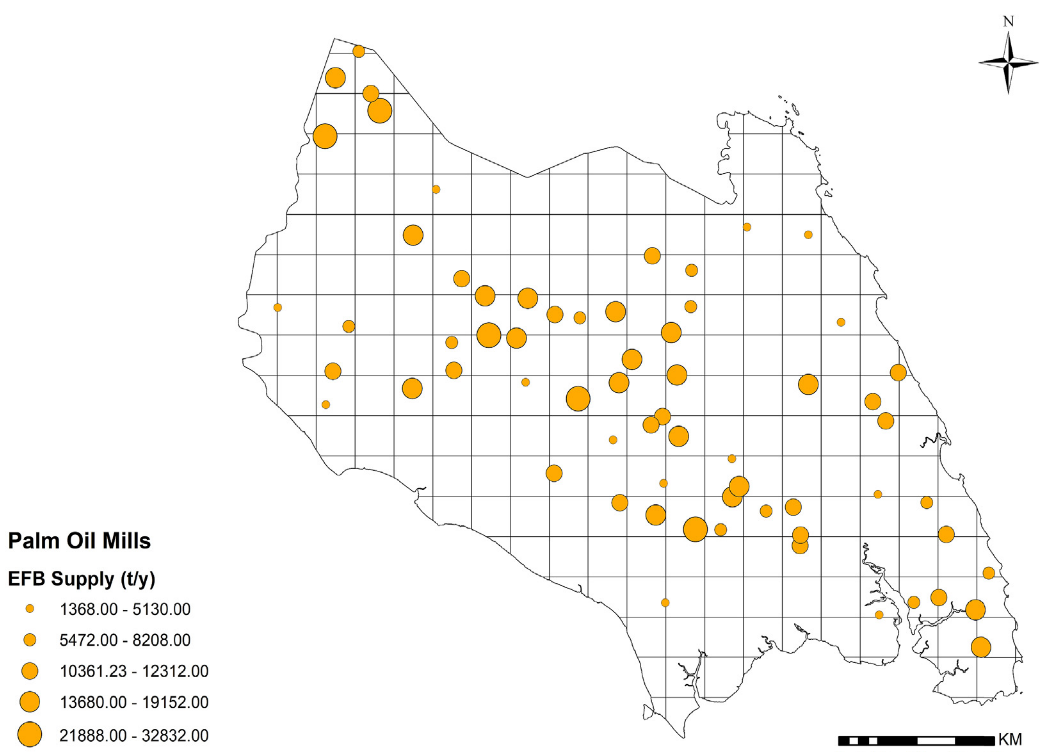


Fig. 2. Spatial distributions of palm oil mills in Johor (ETRC, 2014).

supplies, estimating the biomass availabilities and identifying its supply locations require the needs of GIS-based resource assessments. This approach is useful for the quantification of resource potentials from plantations and factories. Biomass types associated in this study are empty fruit bunch (EFB), oil palm trunk (OPT) and oil palm fronds (OPF). EFB sources are from process-based residues (palm oil mills) whereas OPT and OPF sources are from oil palm plantations. As shown in Fig. 2, there are 65 palm oil mills in Johor which primarily processing fresh fruit bunch (FFB) to produce crude palm oil (CPO). This contributes to the generations of several types of biomass such as EFB, mesocarp fibre (MF), palm kernel shell (PKS) and palm oil mill effluent (POME). Among these process-based solid biomass residues, only EFB is assumed to be available as fuel at 38% of its current availability (Aghamohammadi et al., 2016; Umar et al., 2014).

Land use map of Johor which consisted of several land classification types for the year of 2010 is retrieved from the Malaysian Centre for Geospatial Data Information (MaCGDI, 2010) as shown in Fig. 3. It displays several land classification layers such as forest and reserves, forest and wetlands, water bodies, agricultural areas, oil palm plantations, built-up areas and road networks. Among these layers, oil palm plantation layer is useful for the estimations of OPT and OPF availabilities. In Malaysia, the current practices of managing OPT and OPF biomass are by utilising them as top soil replacement or as fertilisers (AIM, 2013). The utilisation of these biomass for energy purposes is still low due to the need for major pre-treatment units, causing industrial players to prioritise process-based residues such as MF and PKS which have been slightly pre-treated after coming out of processing units. To estimate these oil palm plantation-based biomass, the map is divided into 25×25 km^2 grid square to identify the biomass yield per grid of plantation area. OPT and OPF can be collected in oil palm plantations at yields of 1.49 t/ha.y and 0.29 t/ha.y through replantation activities whereas pruned OPF can be retrieved annually at 3.9 t/ha.y (Loh, 2017). The life-cycle of oil palm tree considered in this study is 25 years. Figs. 4 and 5 illustrate the spatial distributions of OPT and OPF in Johor which are estimated from the oil palm plantation layer of the land use map.

2.2. Suitability analysis of potential pre-treatment sites

For co-firing technology to be technically feasible, the biomass to be consumed as fuel in coal-fired power plant must be pre-processed in order to enhance its combustion ability to the same properties as similar to coal. This can be achieved through the utilisations of several pre-treatment technologies such as grinding, shredding, drying, torrefaction and pelletisation in order to achieve the desired biomass quality for combustion. Combined torrefaction and pelletisation (TOP) is selected as the pre-treatment technology to upgrade the oil palm biomass for combustion in coal-fired power plants. TOP combined several processing techniques such as chipping, drying, torrefaction and pelletisation that increase the biomass energy content and reduce its moisture content. Table 2 shows the properties of each of the oil palm biomass before and after undergoing the TOP process.

Potential sites of centralised pre-treatment facilities are identified with the employments of multi-criteria spatial analysis technique which is inclusive of various land use and accessibility constraints in order to determine the optimal sites. To identify the candidate pre-treatment sites as shown in Fig. 6, a series of screening processes is conducted. First, the eliminations of several sensitive areas such as forest and reserves, wetlands, water bodies and urban areas from the land use map are performed. Second, areas with slopes higher than 15° and elevations higher than 250 m (Lovett et al., 2014) are excluded from the map. This is to prevent any difficulties associated in constructing the pre-treatment plants and also minimising the construction cost. Third, the current screened map is overlaid with the transportation buffers. This indicates that facility locations should be located at the maximum of 3 km away from road networks (Sahoo et al., 2016) to ensure the connectivity and smooth traffics for the transportation of biomass.

After the optimal sites are established, the map is assigned into grids of 25×25 km^2 of the same size. The purpose of assigning the map into grids is to create representative locations for later analysis. These grids are not intended to be the exact locations, but rather generalised areas to represent the potential locations which will later be useful for network analysis purposes. 234 potential

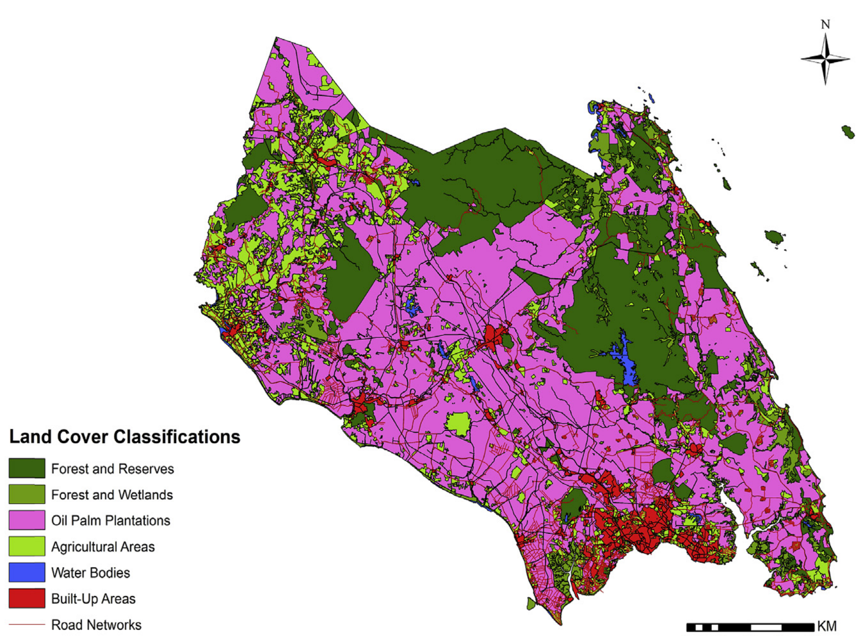


Fig. 3. Land use map (MaCGDI, 2010).

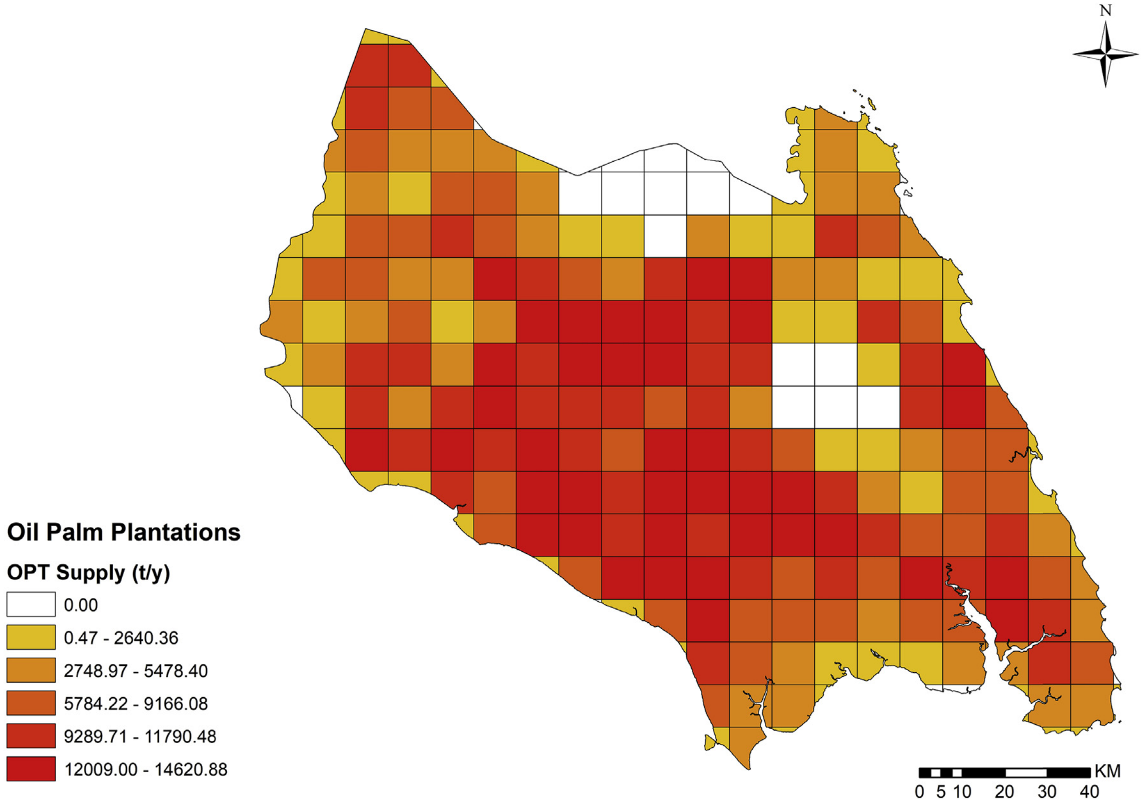


Fig. 4. OPT availability in oil palm plantations.

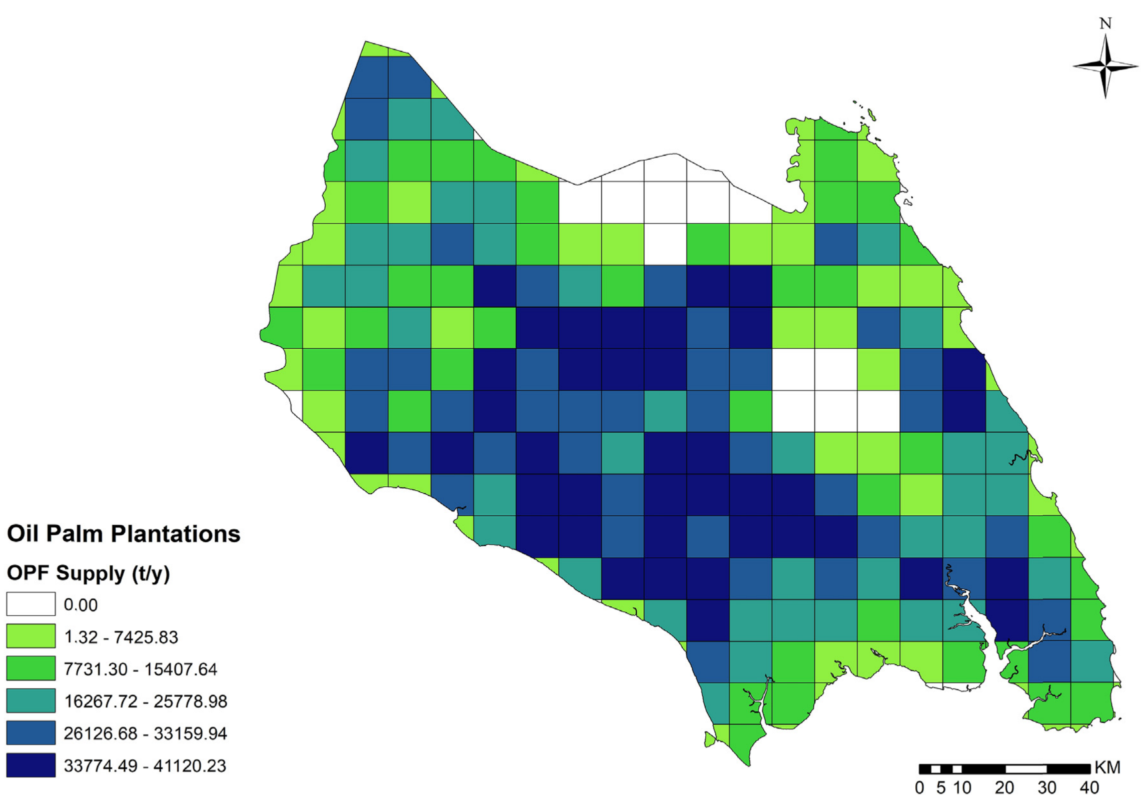


Fig. 5. OPF availability in oil palm plantations.

Table 2
Properties of biomass before and after TOP process.

Biomass	Lower heating value (MJ/t)	Moisture content (%wt)	References
Before TOP process			
EFB	14,800	38.40	Madhiyanon et al. (2013)
OPT	15,560	8.34	Nipattummakul et al. (2012); Loh (2017)
OPF	13,720	16.00	Guangul et al. (2012); Loh (2017)
After TOP process			
EFB	20,817	7.14	Madhiyanon et al. (2013); Uemura et al. (2011); Li et al. (2012); Chen et al. (2015); Kambo and Dutta (2014); Nunes et al. (2014)
OPT	22,309	1.11	Nipattummakul et al. (2012); Loh (2017); Li et al. (2012); Kambo and Dutta (2014); Nunes et al. (2014); Chin et al. (2013)
OPF	19,298	2.21	Guangul et al. (2012); Loh (2017); Li et al. (2012); Chen et al. (2015); Kambo and Dutta (2014); Nunes et al. (2014);

locations are identified after the employment of all the related GIS-based spatial analyses. These include the locations where the areas are not available for any construction activity denoted as having 0 ha of area in Fig. 6. The constraints of the optimisation model will later exclude these areas from the potential map by not selecting them as the locations to build the facilities. Among these identified potential locations, several pre-treatment facilities are to be built with the considerations of economic and environmental criteria through optimisation.

2.3. Network analysis and transportation

One of the key criteria in assessing the economic performance of the supply chain network is transportation. Network analysis is performed by considering detailed road transportation networks to define the optimal transportation routes from each location to their respective destinations. Network analysis can answer range of questions related to linear networks such as roads, railways, rivers, facilities and utilities. In this study, Network Analyst feature in ArcMap is used in the analysis of roadway transportation network by utilising the '*OD cost matrix*' function. Network Analyst enables users to dynamically model realistic network conditions, including turn restrictions, speed limits, connectivity, and traffic conditions, as well as allowing users to introduce customised parameters. This spatial analysis technique uses network data to calculate distances between points or nodes on the network. These distances are to be inputted into the optimisation model for the calculation of transportation cost.

For the supply of biomass to pre-treatment facilities and power plants (Fig. 7), same mode of transportation by truck is considered. Transportation price is assumed to be the same for all transportation activities conducted by truck due to the same type and capacity of truck considered. The transportation activities begin with the collections of biomass from oil palm plantations and palm

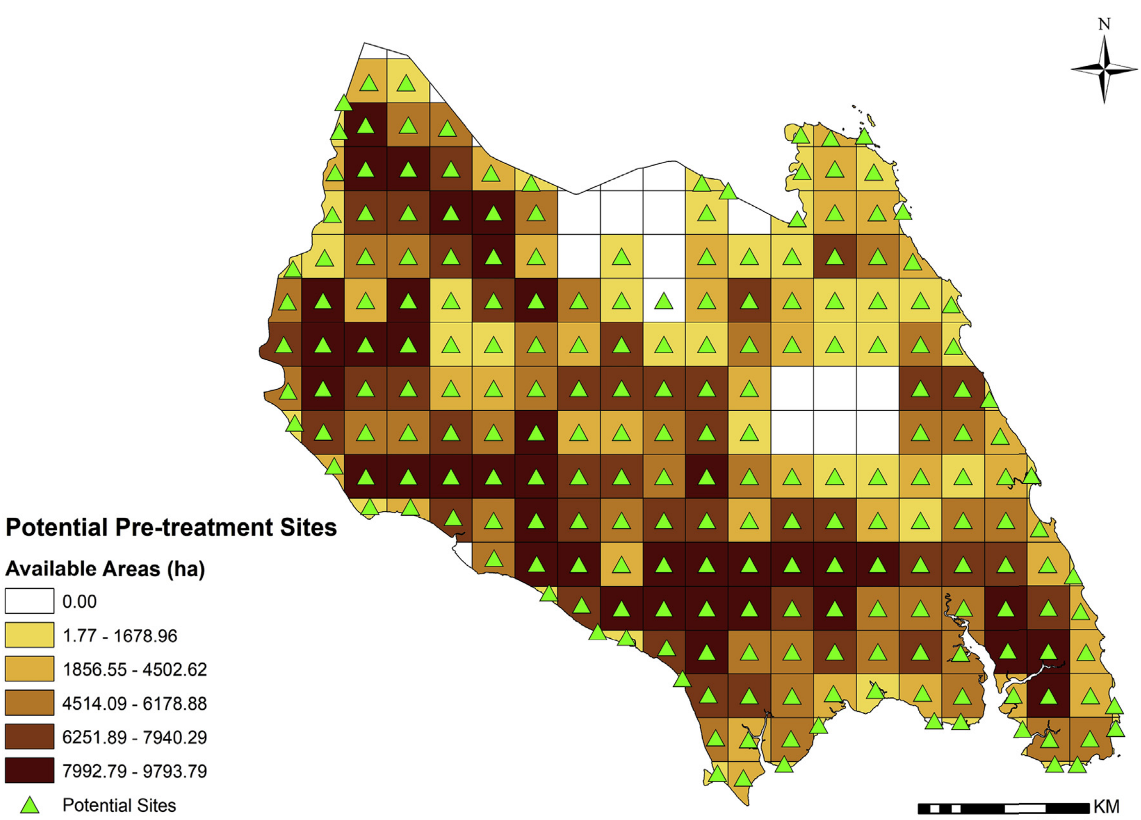


Fig. 6. Potential sites of pre-treatment facilities.

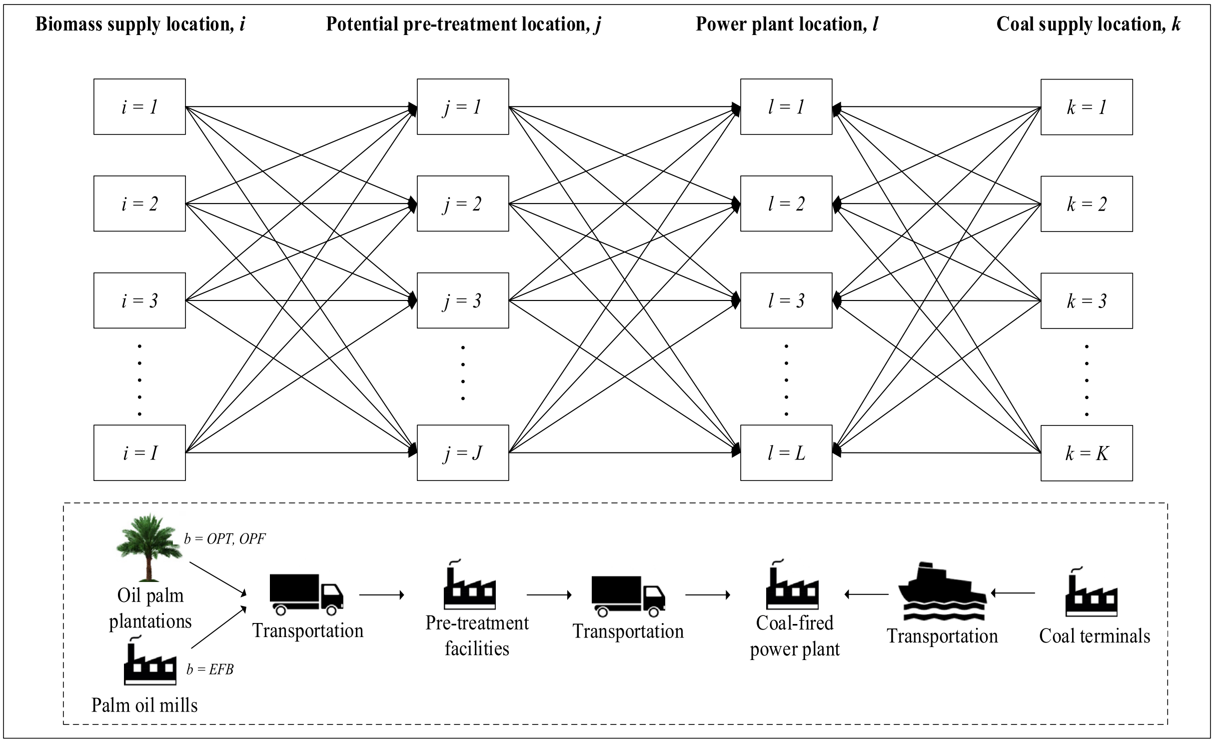


Fig. 7. Superstructure of the transportation network of biomass.

oil mills before transporting them to the pre-treatment facilities. The biomass pellets produced in the pre-treatment facilities are transferred to coal-fired power plant which is located in Tanjung Bin, Johor. The coal-fired power plant received coal supplies from Indonesian coal terminals (Table 3) through shipments. The capacity factor, thermal efficiency and operating days are specified at 83%, 37% and 330 days (Malakoff, 2016). Network analysis is conducted to determine the distances related in supplying the oil palm biomass to the pre-treatment facilities and power plants. For the coal supplies, euclidian distance approach is conducted to determine the marine transportation distances between Indonesian coal terminals and Tanjung Bin power plant.

2.4. Model formulation

A spatial biomass co-firing supply chain planning optimisation model is developed to assist the assessments of economic and environmental performances of co-firing in an existing power plant based on several scenarios considered. The model minimises the overall cost and the emissions of the supply chain system while determining the most optimal locations to build facilities, the optimal co-firing rates in coal-fired power plant, the optimal blends of fuels in each of the power plant and the optimal emissions reduction scheme. Superstructure representation of the whole supply chain and biomass transportations is illustrated in Fig. 7. Overall, the biomass supplies consisted of 299 locations, candidate pre-treatment facilities consisted of 234 locations and only one coal-fired power plant served as the demand. All of the economic, environment and technical parameters required as input data for the MILP model are compiled in Table 4.

Table 3
Indonesian coal terminals (Sourcewatch, 2012).

Coal terminals	State/Province	Annual capacity (t/y)
Muara Sabak	Sumatra	3,000,000
Muara Banyu Asin	Sumatra	3,000,000
Sungai Bankong	Sumatra	3,000,000
Suralaya	West Java	11,000,000
Tanjung Jati	Central Java	14,000,000
Tuban	Central Java	2,000,000

2.4.1. Material balance

In this work, set b represents the type of biomass, set i represents the biomass supply location, set j represents the pre-treatment facility location, set k represents the coal supply location and set l represents the power plant location. Different notations of flowrates are used to indicate the mass flow in or out of the system. These include biomass supply to pre-treatment facility ($F_{b,i,j}^{biotop}$), amount of biomass at pre-treatment facility ($F_{b,j}^{btop}$), production rate of pre-treatment facility (F_{j}^{top}), biomass pellet supply to power plant ($F_{b,j,l}^{topcpp}$), biomass consumed in power plant ($F_{b,l}^{bcpp}$), coal supply to power plant ($F_{k,l}^{ccpp}$) and coal consumed in power plant (F_{l}^{coal}).

Raw biomass to be supplied to pre-treatment facilities ($F_{b,i,j}^{biotop}$) and coal to be consumed in power plants ($F_{k,l}^{ccpp}$) are governed by their availabilities ($BA_{b,i}$ and CA_k). These are defined in Eqs. (1) and (2):

$$BA_{b,i} \geq \sum_{j} F_{b,i,j}^{biotop} \quad \forall_{b,i} \tag{1}$$

$$CA_k \geq \sum_{l} F_{k,l}^{ccpp} \quad \forall_{k} \tag{2}$$

Coal supply from terminal k to power plant l ($F_{k,l}^{ccpp}$) can be

Table 4
Economic, environment and technical parameters.

Parameter	Unit	Value	References
Economic parameters			
CAPEX (Pre-treatment)	USD/t feedstock	42.20	Agar (2017)
OPEX (Pre-treatment)	USD/t feedstock	10.10	Agar (2017)
OPEX (Power plant)	USD/MWh	13.94	Fout et al. (2015)
Transportation (Truck)	USD/t.km	0.20	Lam et al. (2013)
Transportation (Shipping)	USD/t.km	0.001391	Rentizelas and Li (2016)
Biomass (EFB)	USD/t	13.00	Do and Lim (2016)
Biomass (OPT)	USD/t	15.00	Ahmad et al. (2016)
Biomass (OPF)	USD/t	9.00	Gabdo and Abdlatif (2013)
Cultivation and harvesting cost (OPT)	USD/t	10.00	Zahari et al. (2015)
Cultivation and harvesting cost (OPF)	USD/t	10.00	Zahari et al. (2015)
Coal	USD/t	92.03	Coalspot (2017)
Environmental parameters			
Emissions (Pre-treatment)	t CO_2/t feedstock	0.0390	Bergman (2005)
Emissions (Truck)	t CO_2/t.km	0.000595	Paolucci et al. (2016)
Emissions (Shipping)	t CO_2/t.km	0.000025	Nealer et al. (2012)
Emissions (Coal combustion)	t CO_2/t feedstock	2.0531	Reddy and Vinu (2016)
Emissions (Cultivation (OPT))	t CO_2/t	0.0205	Rivera-Mendez et al. (2017); Loh (2017)
Emissions (Cultivation (OPF))	t CO_2/t	0.1055	Rivera-Mendez et al. (2017); Loh (2017)
Emissions (Harvesting (OPT))	t CO_2/t	0.0043	Rivera-Mendez et al. (2017); Loh (2017)
Emissions (Harvesting (OPF))	t CO_2/t	0.0222	Rivera-Mendez et al. (2017); Loh (2017)
Emissions (Construction land use change)	t CO_2/ha.y	0.3400	Rasid et al. (2013)
Technical parameters			
Biomass to torrefied pellet (EFB)	t/t	0.6488	Madhiyanon et al. (2013); Li et al. (2012); Nunes et al. (2014)
Biomass to torrefied pellet (OPT)	t/t	0.9037	Nipattummakul et al. (2012); Li et al. (2012); Nunes et al. (2014)
Biomass to torrefied pellet (OPF)	t/t	0.8370	Guangul et al. (2012); Li et al. (2012); Nunes et al. (2014)
Torrefied pellet to electricity (EFB)	MWh/t	2.1395	Madhiyanon et al. (2013); Uemura et al. (2011); Chen et al. (2015); Kambo and Dutta (2014)
Torrefied pellet to electricity (OPT)	MWh/t	2.2928	Loh (2017); Kambo and Dutta (2014); Chin et al. (2013)
Torrefied pellet to electricity (OPF)	MWh/t	1.9834	Loh (2017); Kambo and Dutta (2014); Chen et al. (2015)
Coal to electricity	MWh/t	2.1830	Reddy and Vinu (2016)
Land use (Pre-treatment)	ha/(t/y)	0.0001084	Cheng and Hammond (2017)

summed up to provide the sufficient fuel supply (F_l^{coal}) for electricity production as described in Eq. (3):

$$F_l^{coal} = \sum_k F_{k,l}^{ccpp} \quad \forall_l \tag{3}$$

Amount of biomass transported to pre-treatment facilities ($F_{b,i,j}^{biotop}$) can be summed up to obtain the flowrate of biomass b in pre-treatment facility j ($F_{b,j}^{btop}$) as written in Eq. (4):

$$F_{b,j}^{btop} = \sum_i F_{b,i,j}^{biotop} \quad \forall_{b,j} \tag{4}$$

The total production capacity of biomass pellets for each of the pre-treatment facility j (F_j^{top}) is resulted from the biomass ($F_{b,j}^{btop}$) conversion through TOP technology (n_b^{top}) as defined in Eq. (5):

$$F_j^{top} = \sum_b \left(F_{b,j}^{btop} \cdot n_b^{top} \right) \quad \forall_j \tag{5}$$

Biomass pellet b is transported to power plant l from pre-treatment facility j ($F_{b,j,l}^{topcpp}$) after the conversion of raw biomass ($F_{b,j}^{btop}$) by TOP process (n_b^{top}) as described in Eq. (6):

$$F_{b,j}^{btop} \cdot n_b^{top} = \sum_l F_{b,j,l}^{topcpp} \quad \forall_{b,j} \tag{6}$$

Biomass pellet b is consumed in power plant l ($F_{b,l}^{bcpp}$) after torrefied biomass pellet ($F_{b,l}^{bcpp}$) is transported from pre-treatment facility j. The consumption of biomass pellets in power plant is given in Eq. (7):

$$F_{b,l}^{bcpp} = \sum_j F_{b,j,l}^{topcpp} \quad \forall_{b,l} \tag{7}$$

The construction of pre-treatment facility (F_j^{top}) is restricted by the areas available per grid of potential site ($Area_j^{facility}$). This means that the total area needed for the construction of pre-treatment facilities must be always less than total available area in a grid. This is described in Eq. (8):

$$Area_j^{facility} \geq F_j^{top} \cdot Area^{lu} \quad \forall_j \tag{8}$$

2.4.2. Energy balance

The demand of power generation is based on achieving the base case electricity generation ($Elect_l^{target}$) using 100% coal as fuel. Two types of electricity generations are defined to illustrate the co-firing activities in power plant. These are electricity generation from coal ($Elect_l^{coal}$) and electricity generation from biomass ($Elect_l^{bio}$).

Electricity generations from biomass and coal are defined through the conversions of biomass pellet ($F_{b,l}^{bcpp}$) and coal (F_l^{coal}) to electricity based on their respective conversion rates (BTE_b and CTE) as shown in Eqs. (9) and (10):

$$Elect_l^{bio} = \sum_b \left(F_{b,l}^{bcpp} \cdot BTE_b \right) \quad \forall_l \tag{9}$$

$$Elect_l^{coal} = F_l^{coal} \cdot CTE \quad \forall_l \tag{10}$$

Electricity target ($Elect_l^{target}$) is equivalent to the summation of electricity generated from biomass ($Elect_l^{bio}$) and coal ($Elect_l^{coal}$) as given in Eq. (11):

$$Elect_l^{target} = Elect_l^{bio} + Elect_l^{coal} \quad \forall_l \tag{11}$$

Co-firing rate at power plant l (CR_l) is defined as the portion of electricity which is fulfilled by the electricity generated from biomass ($Elect_l^{bio}$). This is shown in Eq. (12):

$$Elect_l^{bio} \cdot (100) = Elect_l^{target} \cdot CR_l \quad \forall_l \tag{12}$$

2.4.3. Binary variables

The binary approach works by providing the values of '0' and '1' to the binary decision variable which is restricted by constraint. If '1' is given to the binary variable (L_j^{select}), the pre-treatment facility j is selected whereas if '0' is inputted to the variable, the facility will not be selected. Capacity of each of the pre-treatment facilities is specified at 100 kt/y production rate as shown in Eq. (13). The maximum number of facilities which can be selected is 234 (maximum number of potential pre-treatment locations) as given in Eq. (14). The binary approach can be described as below:

$$F_j^{top} = L_j^{select} \cdot (100,000) \quad \forall_j \tag{13}$$

$$\sum_j L_j^{select} \leq 234 \tag{14}$$

2.4.4. Economics

The economic objective function of this model is to minimise the total cost (C^{total}) of the system. The total cost is made up of raw material cost (C^{rawmat}), biomass cultivation and harvesting cost (C^{plant}), transportation cost (C^{transp}), capital expenditure or CAPEX (C^{capex}), operating expenditure or OPEX (C^{opex}) and carbon cost (C^{carbon}) as defined in Eq. (15):

$$Min C^{total} = C^{rawmat} + C^{plant} + C^{transp} + C^{capex} + C^{opex} + C^{carbon} \tag{15}$$

Raw material cost (C^{rawmat}) is defined by the flowrates of biomass ($F_{b,i,j}^{biotop}$) and coal (F_l^{coal}) multiplied by their respective prices (P_b^{bio} and P^{coal}) as given in Eq. (16):

$$C^{rawmat} = \sum_{b,i,j}\left(F_{b,i,j}^{biotop} \cdot P_b^{bio}\right) + \sum_l \left(F_l^{coal} \cdot P^{coal}\right) \tag{16}$$

Biomass cultivation and harvesting cost (C^{plant}) is calculated by multiplying the biomass feedstock ($F_{b,i,j}^{biotop}$) with its respective price (P_b^{plant}) as shown in Eq. (17):

$$C^{plant} = \sum_{b,i,j}\left(F_{b,i,j}^{biotop} \cdot P_b^{plant}\right) \tag{17}$$

Transportation cost (C^{transp}) is defined as the flowrates of raw biomass ($F_{b,i,j}^{biotop}$), biomass pellet ($F_{b,j,l}^{topcpp}$) and coal ($F_{k,l}^{ccpp}$) multiplied by their respective transportation distances ($dist_{i,j}^{top}, dist_{j,l}^{cpp}$ and $dist_{k,l}^{ccpp}$), ($dist_{j,l}^{cpp}$ and $dist_{k,l}^{ccpp}$) and respective transportation prices (P^{truck} and P^{ship}) as described in Eq. (18):

$$C^{transp} = \sum_{b,i,j}\left(F_{b,i,j}^{biotop} \cdot dist_{i,j}^{top} \cdot P^{truck}\right) + \sum_{b,j,l}\left(F_{b,j,l}^{topcpp} \cdot dist_{j,l}^{cpp} \cdot P^{truck}\right) + \sum_{k,l}\left(F_{k,l}^{ccpp} \cdot dist_{k,l}^{ccpp} \cdot P^{ship}\right) \tag{18}$$

CAPEX (C^{capex}) is accounted only for the investment of new pre-treatment facilities. Power plant is not entitled for CAPEX due to the existing capital of power generation facility considered in this study. C^{capex} is defined in Eq. (19):

$$C^{capex} = \sum_{b,j}\left(F_{b,j}^{btop} \cdot P^{captop}\right) \tag{19}$$

OPEX (C^{opex}) is accounted for both pre-treatment facilities and power plant. For pre-treatment plant, the operating cost is based on the flowrate of biomass feedstock ($F_{b,j}^{btop}$) multiplied by its cost factor (P^{optop}). For the operating cost of power plant, electricity generated from biomass ($Elect_l^{bio}$) and coal ($Elect_l^{coal}$) are multiplied with the operating cost factor of power plant (P^{opcpp}). C^{opex} is defined in Eq. (20):

$$C^{opex} = \sum_{b,j}\left(F_{b,j}^{btop} \cdot P^{optop}\right) + \sum_{b,j}\left(F_{b,j}^{btop} \cdot P^{optop}\right) + \sum_l \left(Elect_l^{bio} \cdot P^{opcpp}\right) \tag{20}$$

Carbon penalty (C^{carbon}) which will be imposed whenever CO_2 is emitted from any of the processes in the whole supply chain network can be described by the multiplication of the carbon price (P^{carbon}) and the total emissions of the system (E^{total}) as shown in Eq. (21):

$$C^{carbon} = E^{total} \cdot P^{carbon} \tag{21}$$

2.4.5. Environments

The environmental objective function of this model is to minimise the total emissions of the system (E^{total}) which are resulted from the emissions of biomass cultivation (E^{cultiv}), biomass harvesting ($E^{harvest}$) biomass pre-treatment (E^{top}), construction land use change (E^{luc}) biomass and coal transportations (E^{transp}), and technological emissions (E^{tech}). This is defined in Eq. (22):

$$E^{total} = E^{cultiv} + E^{harvest} + E^{luc} + E^{transp} + E^{tech}. \tag{22}$$

Emissions from biomass cultivation (E^{cultiv}) and biomass harvesting ($E^{harvest}$) can be calculated by multiplying the biomass feedstock ($F_{b,i,j}^{biotop}$) with their respective emission factors (CF_b^{cultiv}) and ($CF_b^{harvest}$) as described in Eqs. (23) and (24):

$$E^{cultiv} = \sum_{b,i,j}\left(F_{b,i,j}^{biotop} \cdot CF_b^{cultiv}\right) \tag{23}$$

$$E^{harvest} = \sum_{b,i,j}\left(F_{b,i,j}^{biotop} \cdot CF_b^{harvest}\right) \tag{24}$$

The emissions resulted from the construction land use change (E^{luc}) can be defined as the loss of CO_2 sequestration by crops in the plantations due to the construction of pre-treatment facilities as described in Eq. (25):

$$E^{luc} = \sum_{j} \left(F_{j}^{top} \cdot Area^{lu} \cdot CF^{luc} \right) \tag{25}$$

Emissions from the transportation activity (E^{transp}) are defined as the emissions from truck (E^{truck}) and shipping (E^{ship}) activities. These are described in Eqs. (26)–(28):

$$E^{transp} = E^{truck} + E^{ship} \tag{26}$$

$$E^{truck} = \sum_{b,i,j} \left(F_{b,i,j}^{biotop} \cdot dist_{i,j}^{top} \cdot CF^{truck} \right) \sum_{b,l,l} \left(F_{b,j,l}^{topcpp} \cdot dist_{j,l}^{cpp} \cdot CF^{truck} \right) \tag{27}$$

$$E^{ship} = \sum_{k,l} \left(F_{k,l}^{ccpp} \cdot dist_{k,l}^{ccpp} \cdot CF^{ship} \right) \tag{28}$$

Technological emissions (E^{tech}) are accounted for both emissions from TOP process (E^{top}) and power generation activity (E^{power}). These are shown in Eqs. (29)–(31):

$$E^{tech} = E^{top} + E^{power} \tag{29}$$

$$E^{top} = \sum_{b,j} \left(F_{b,j}^{btop} \cdot CF^{top} \right) \tag{30}$$

$$E^{power} = \sum_{l} \left(F_{l}^{coal} \cdot CF^{coal} \right) \tag{31}$$

3. Results and discussions

3.1. Spatial optimisation of oil palm biomass co-firing system

Spatial optimisation model developed is applied to a case study in Johor in order to minimise the total cost and emissions of biomass co-firing supply chain system. The two objective function scenarios are evaluated in comparison with the business as usual (BAU) scenario as shown in Table 5. The challenges faced in the biomass co-firing supply chain planning network are the infrastructure planning of pre-treatment facilities to supply the upgraded biomass to demand and its logistics. Johor has only one coal-fired power which has a capacity of 3100 MW located at southern coastal areas of the state. To replace portions of fossil fuels in this power plant, substantial amount of biomass is required. In the cost-minimisation scenario, co-firing technology is economically feasible at low co-firing rate which is at 1.13%, equivalent to a total 110.66 kt/y of total of oil palm biomass supply. This contributes to a slight reduction in the emissions of power plant due to the small amount of biomass substituting the fossil fuels. As shown in Fig. 8, only one pre-treatment facility is needed to supply the torrefied biomass pellet to power plant.

In the emission-minimisation scenario, co-firing rate is achieved at 52% representing the maximum utilisation of oil palm biomass in Johor at 6.13 × 10^6 t/y after the considerations of biomass utilisations for other purposes. This leads to a substantial emissions reduction in the supply chain system at 45.89% equivalent to 8.83 × 10^6 t CO_2/y. The main reason behind the significant emissions reduction is due to the maximum reduction of coal usage in power plant. Coal is the main contributor to the high emissions in the power plant. Substituting high amount of coal with biomass replaced the existing fossil fuels emissions with the zero net emissions of biomass combustion. To support the supply of biomass to power plant at minimum emissions scenario, 51 pre-treatment facilities are built in order to enhance the properties of biomass for co-firing as illustrated in Fig. 9. Although having a good performance in reducing the emissions, there is a trade-off in the total cost of the supply chain system resulting in the incremental cost at rate of 11.19% equivalent to 1.28 × 10^8 USD/y. The increase in the total cost is caused by the increase of CAPEX and OPEX due to additions of pre-treatment facilities in the supply chain network as well as the increase in the supply cost due to the biomass cultivation, harvesting and transportation activities.

The spatial optimisation model is further tested for its performance through sensitivity analysis. Sensitivity analysis is performed to observe the effect of economic parameters variations on the overall cost fluctuations based on minimising the cost objective function. As shown in Fig. 10, coal price is the most sensitive parameter in the model. Although price of biomass is significantly lower if compared to coal, the other costs associated with supplying

Table 5
Cost and environmental minimisation scenarios.

Scenario	BAU	Cost-minimisation	Emission-minimisation
Co-firing (%)	–	1.13	52.00
Economic			
CAPEX (USD/y)	–	4,669,691	259,293,991
OPEX (USD/y)	284,071,550	285,189,178	346,130,065
Cultivation and harvesting cost (USD/y)	–	1,106,562	54,042,865
Raw material cost (Coal) (USD/y)	859,093,937	849,427,872	412,456,074
Raw material cost (Biomass) (USD/y)	–	1,659,843	66,933,772
Transportation cost (Truck) (USD/y)	–	872,147	135,297,355
Transportation cost (Shipping) (USD/y)	3,981,935	3,858,489	1,321,103
Total cost (USD/y)	1,147,147,423	1,146,783,782	1,275,475,226
Cost increase (%)	–	−0.03	11.19
Environment			
Emissions (Cultivation) (t CO2/y)	–	2268	447,276
Emissions (Harvesting) (t CO2/y)	–	476	94,099
Emissions (Construction land use change) (t CO2/y)	–	4	188
Emissions (Truck) (t CO2/y)	–	2595	402,510
Emissions (Shipping) (t CO2/y)	71,566	69,347	23,744
Emissions (Pre-treatment) (t CO2/y)	–	4316	239,632
Emissions (Coal combustion) (t CO2/y)	19,165,654	18,950,012	9,201,544
Total emissions (t CO2/y)	19,237,220	19,029,018	10,408,992
Emissions reduction (%)	–	1.08	45.89

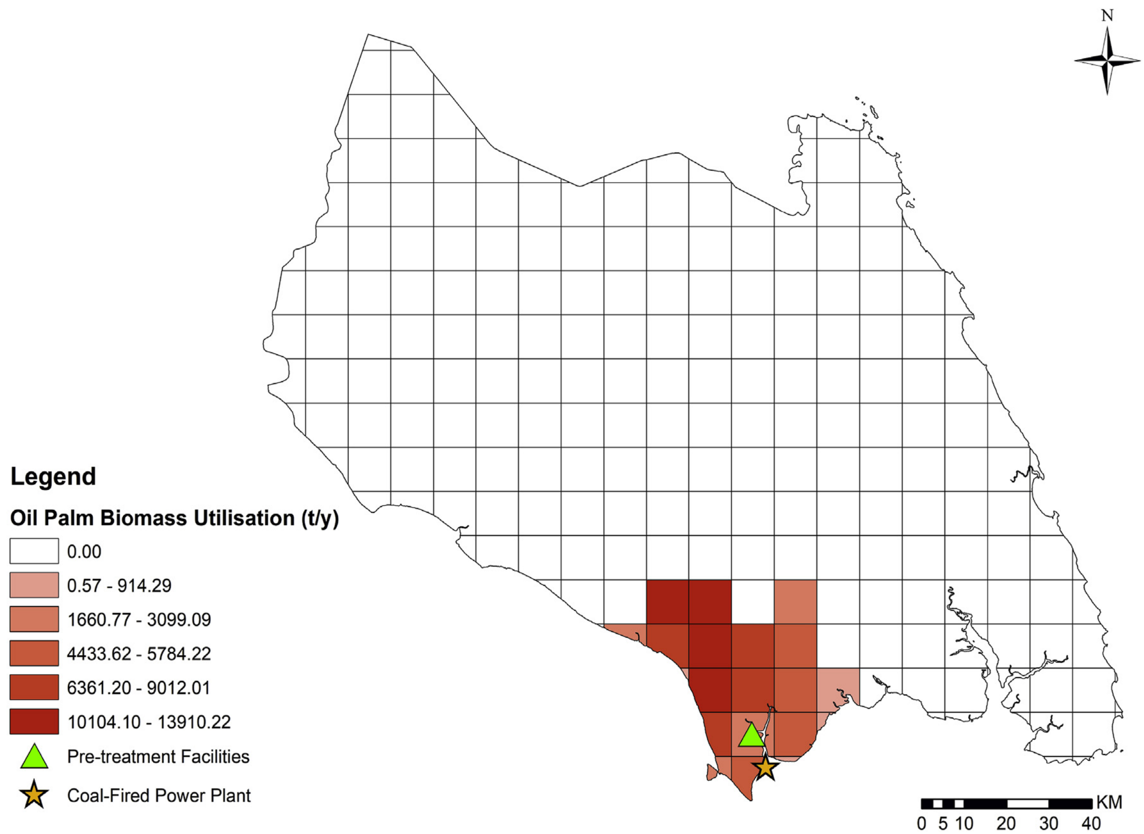


Fig. 8. Cost-minimisation scenario.

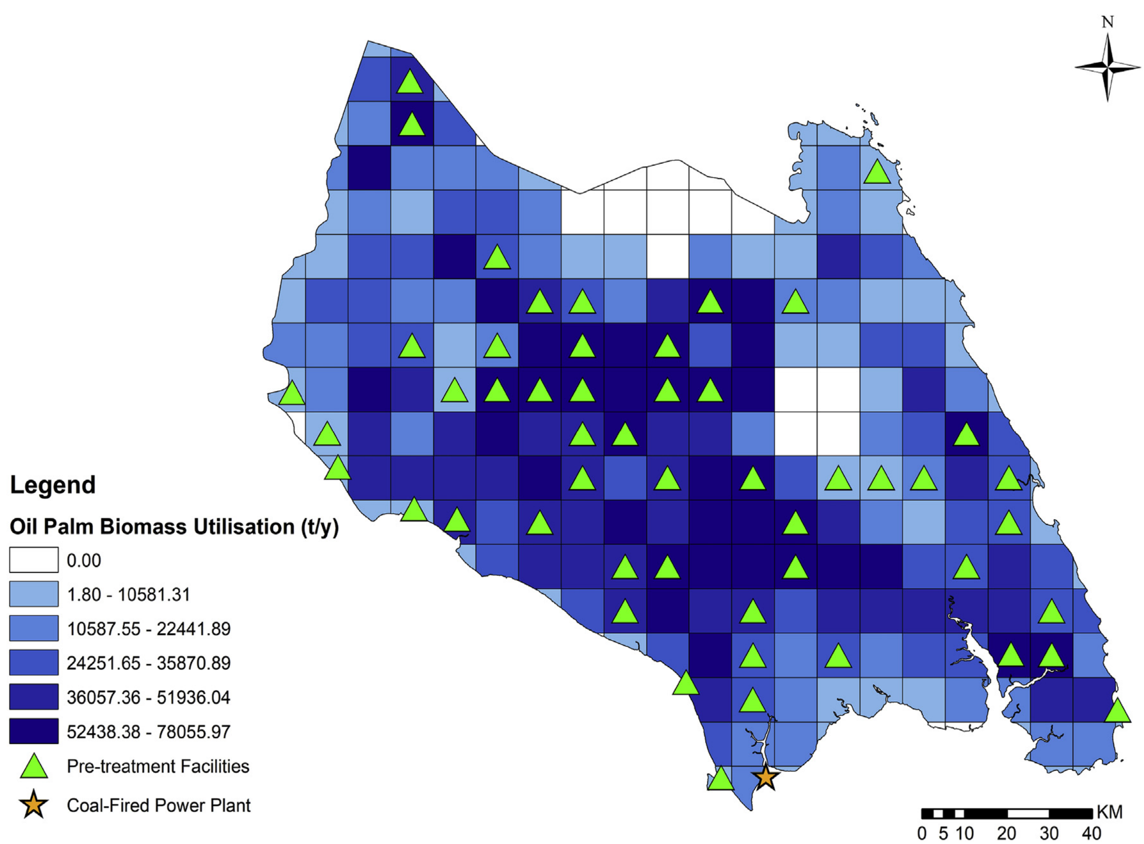


Fig. 9. Emission-minimisation scenario.

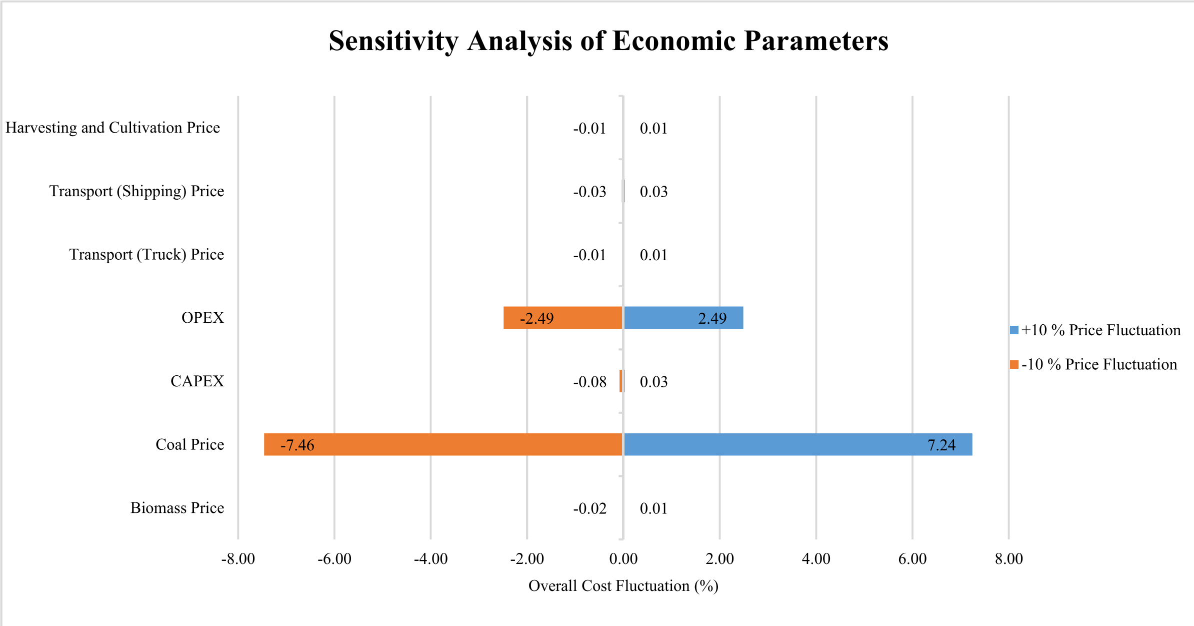


Fig. 10. Sensitivity analysis of economic parameters.

the biomass to the power plant such as CAPEX, OPEX, transportation, cultivation and harvesting costs contributing to the higher total supply cost if compared to the total coal supply cost. Reducing the coal price although at a very low rate may cause the model to not favour any of the co-firing modes. OPEX is the second most sensitive parameter due to the high operating costs of pre-treatment facilities and power plant. Operating cost of power plant is measured with a unit of USD/MWh which means that the cost is calculated based on the electricity being produced. Total OPEX is to be the same as long as the demand of electricity is not changing. Addition of pre-treatment unit contributes to the addition of more operating cost to the total OPEX, making this parameter sensitive to variations. The other economic parameters have a very low sensitivity to the fluctuations in the overall cost.

3.2. Economic and environmental assessments of various co-firing scenarios

Various scenarios are developed for the investigations of the economic and environmental performances of co-firing in the existing power plant consisting of BAU, 10% co-firing, 20% co-firing, 30% co-firing, 40% co-firing, and 50% co-firing scenarios. 50% co-firing is limited as the maximum co-firing rate to ensure the uniformness in the increment of the co-firing in the assessment. As shown in Table 6, the total cost of the system is increasing in line with the co-firing rates. The breakdowns of the total cost of biomass co-firing supply chain system are illustrated in Fig. 11. Coal purchased cost make up to the highest cost in each of the co-firing scenarios. As the co-firing increases, coal purchased cost is decreasing but the other associated costs continue to increase, contributing to the high overall costs if compared to the BAU scenario. The cost factors for deploying the co-firing technology in the existing coal-fired power plant are between 56.61 and 61.65 USD/MWh range. Although the difference is small when the cost factor of dedicated fossil fuels is compared to several co-firing scenarios, governmental incentives are still needed to promote the implementation of this technology in Malaysia.

Significant emissions reduction at rates up to 8.83×10^6 t annually can be achieved as a result of implementing this technology. The trends of emissions for each of the co-firing case are illustrated in Fig. 12. Majority of the emissions are contributed from the combustion process in the power plant. Emissions due to biomass combustion are considered to be zero due to the assumption of carbon neutrality of biomass. As the co-firing rate increases, substantial amounts of reduction are achieved due the substitutions of zero emission of biomass. This is supported by the

Table 6
Economic and environmental outputs of different co-firing scenarios.

Scenario	BAU	Co-firing (10%)	Co-firing (20%)	Co-firing (30%)	Co-firing (40%)	Co-firing (50%)
Total cost (USD/y)	1,147,147,423	1,153,600,025	1,169,018,392	1,191,559,783	1,219,639,759	1,256,222,662
Total emissions (t CO_2/y)	19,237,220	17,429,631	15,729,344	14,047,433	12,374,134	10,704,301
Cost increase (%)	–	0.56	1.91	3.87	6.32	9.51
Emissions reduction (%)	–	9.40	18.23	26.98	35.68	44.36
Electricity generated (coal) (MWh/y)	20,378,160	18,340,344	16,302,528	14,264,712	12,226,896	10,189,080
Electricity generated (biomass) (MWh/y)	–	2,037,816	4,075,632	6,113,448	8,151,264	10,189,080
Fuel consumed (coal) (t/y)	9,334,934	8,401,440	7,467,947	6,534,454	5,600,960	4,667,467
Fuel consumed (EFB) (t/y)	–	–	–	36,252	192,204	653,946
Fuel consumed (OPT) (t/y)	–	97,326	1,098,512	1,280,033	1,418,198	1,445,604
Fuel consumed (OPF) (t/y)	–	492,290	1,083,960	2,054,616	2,979,298	3,786,533
Number of pre-treatment unit	0	9	19	29	39	49
Cost factor (USD/MWh)	56.29	56.61	57.37	58.47	59.85	61.65

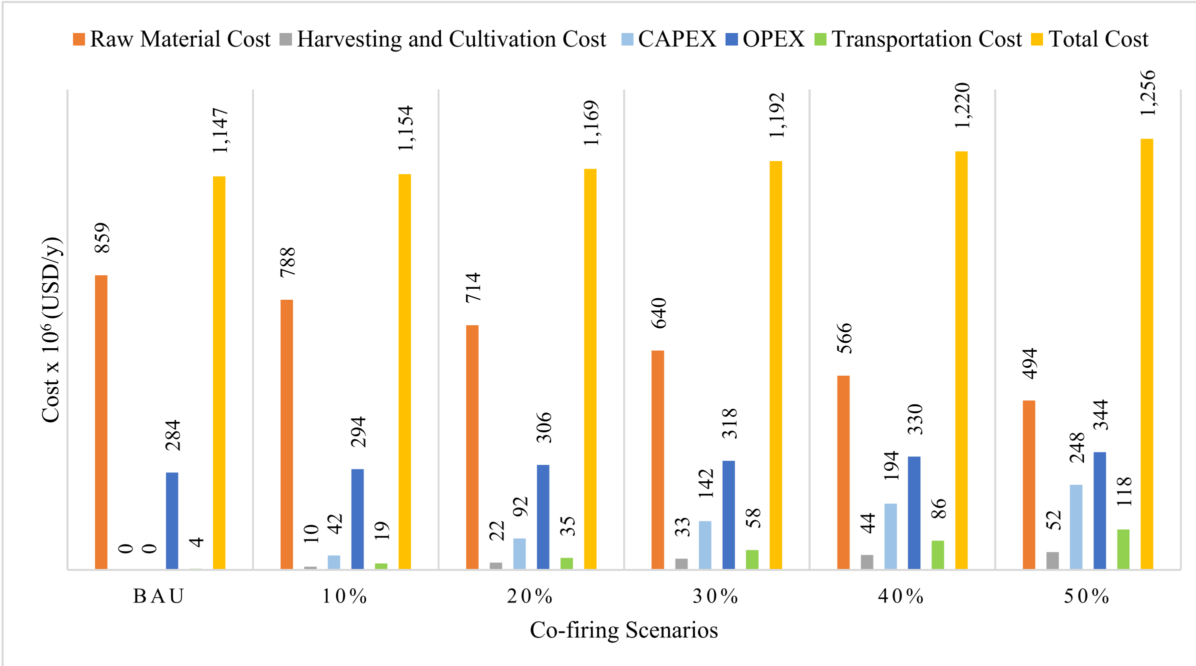


Fig. 11. Cost breakdown of electricity generation based on different co-firing scenarios.

gentle increase and further reduction in some aspects of the emissions. Emissions related to the biomass cultivation and harvesting, truck transportations and pre-treatment processes are increasing at the minimum rates while emissions due to the shipping process are decreasing due to the reductions in coal supplies. It can be concluded that the increase of biomass shares in fossil fuels energy mix provides substantial reductions of GHG emissions, however, contributing to the increased cost of the whole system.

Spatial distributions of pre-treatment facilities for each of the co-firing scenarios are illustrated in Fig. 13. The pre-treatment facilities selected are between the range of 9–49 facilities. This is in line with the constraint introduced in the MILP model where the maximum number of facilities which can be selected must be equal or less than maximum number of potential locations. It is shown that as the co-firing rate increases, the facility locations are becoming more scattered all over the state. With the increase of

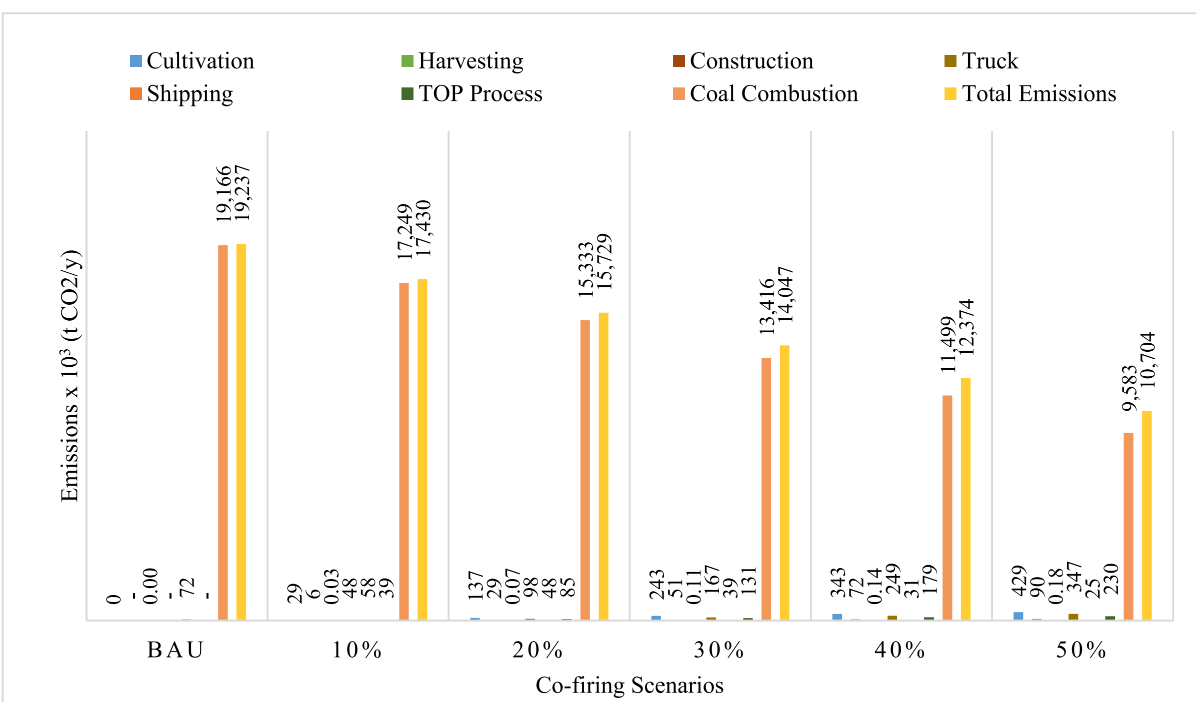


Fig. 12. Sources of emissions based on different co-firing scenarios.

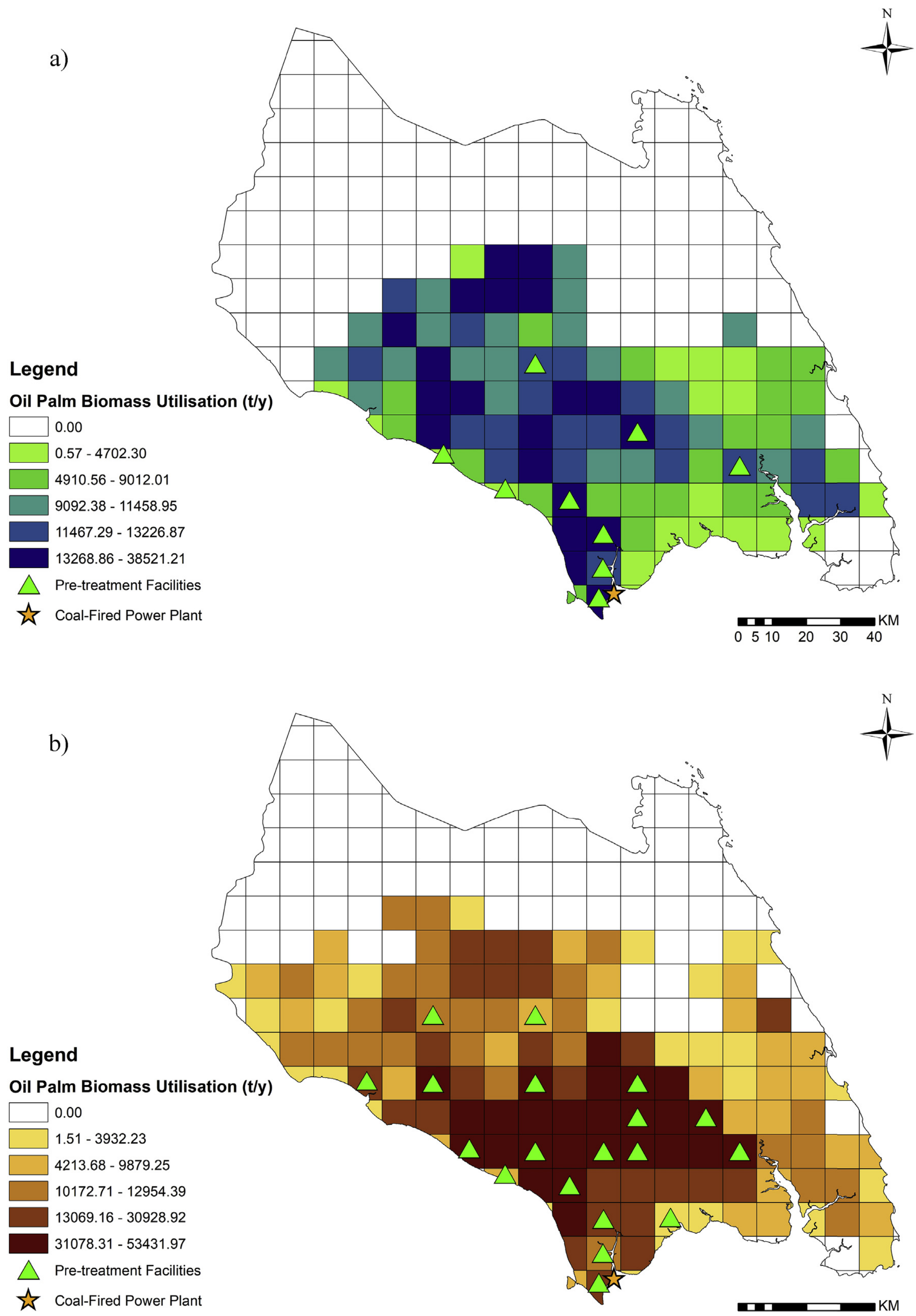
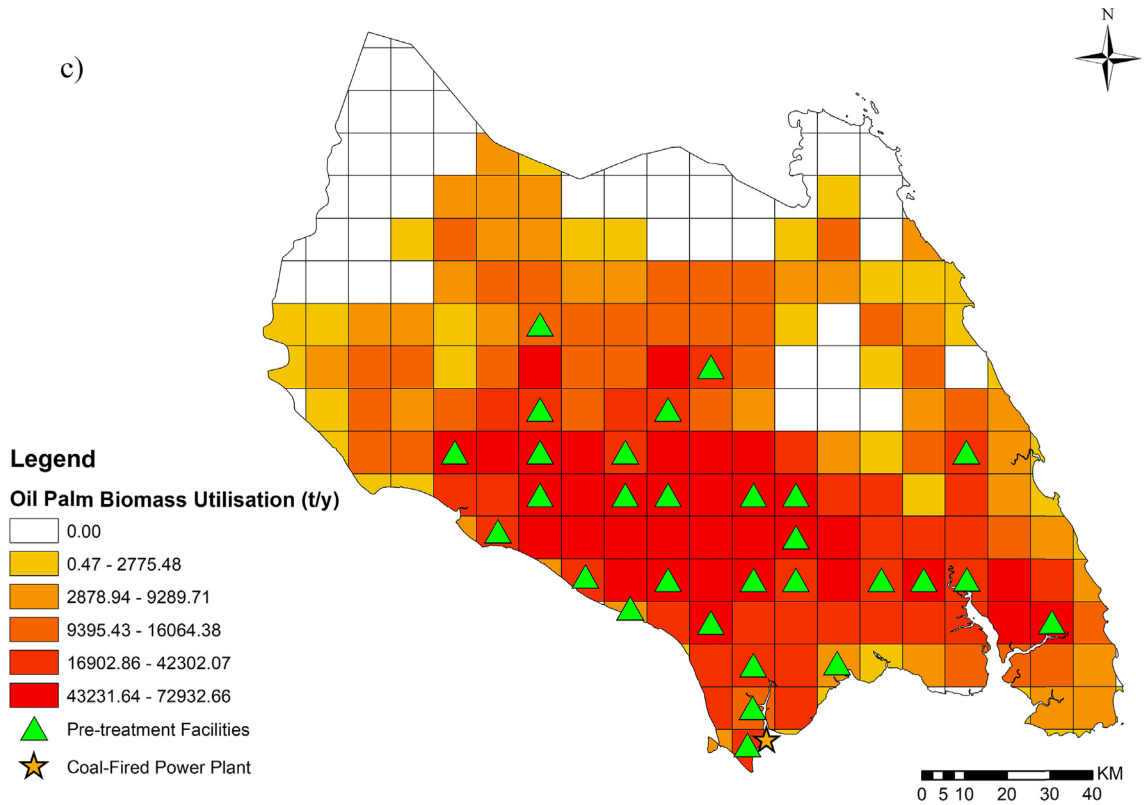


Fig. 13. Spatial distributions of pre-treatment facilities a) 10% co-firing b) 20% co-firing c) 30% co-firing d) 40% co-firing e) 50% co-firing.



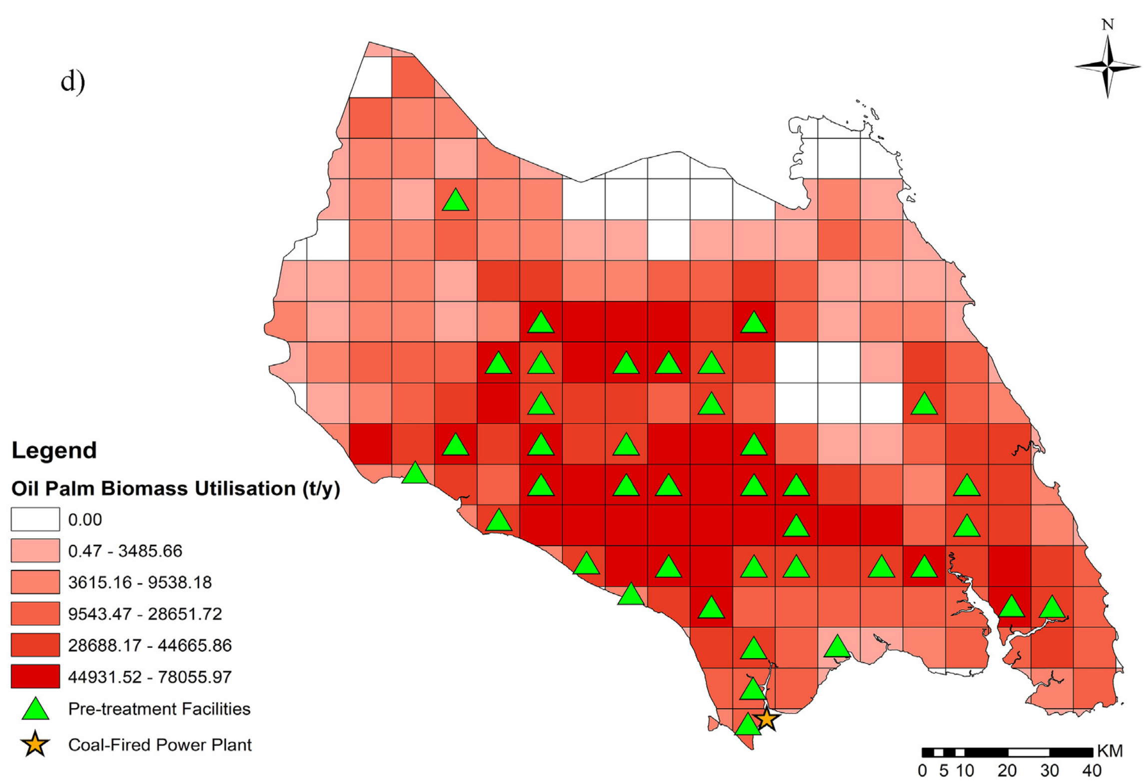


Fig. 13. (*continued*).

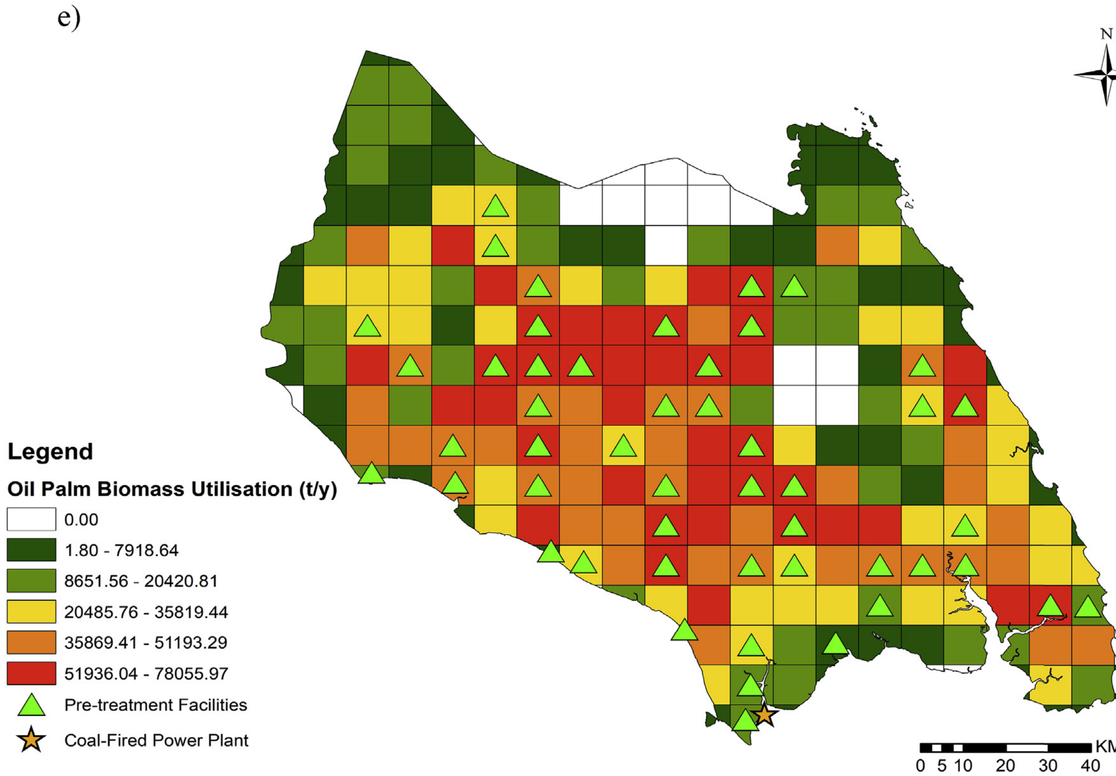


Fig. 13. (*continued*).

fuel demand in each of the co-firing scenario, the searches of biomass supplies are conducted in a more distributed fashion over the region in order to fulfil the demand. This leads to the increase of the biomass pre-treatment infrastructures since the demands to substitute portions of biomass in coal-fired power plant are increasing.

3.3. Policy supports for co-firing implementation

Over the past decades, co-firing has been successfully demonstrated in over 150 installations worldwide in various countries (Verma et al., 2017), yet there is no application of co-firing in Malaysia. Various action plans and policies have been developed by the Malaysian government to promote RE growths in this country. The current Feed-in-Tariff (FiT) program only targeted typical RE types such as solar photovoltaic, biogas power plant, biomass power plant, and small hydropower system. The subsidies given to each of the RE types are based on their respective capacities. For a dedicated biomass power plant for instance, up to a maximum of 30 MW facility is qualified for FiT (SEDA, 2017). Since the capacities of coal-fired power plants in Peninsular Malaysia are in the range of 1400–3100 MW (TNBF, 2016), co-firing at only small rates in these facilities constitutes to a capacity of more than 30 MW. This causes the ineligibility of biomass co-firing to be qualified for governmental incentives.

Fig. 14 shows the comparisons between the current incentives given by government in the form of FiT for biomass power plant. Average FiT given to power plant operators for this category is 68.70 USD/MWh. It can be shown that co-firing technology is economically feasible at any of the co-firing rates when current FiT is compared with the cost factors of co-firing electricity generations. All of the cost factors for each of the co-firing scenarios are less than the current FiT, proving that the current FiT provided is more than enough to breakeven the cost of electricity generations. It is to be suggested that co-firing should be included and reviewed under the FiT initiative to promote industrial players to adopt co-firing technology in their facilities in the future.

Another promising financial instrument which can be accelerating the co-firing power generation is the carbon penalty scheme. Carbon penalty is exerted to fossil fuels industries whenever they emit portions of GHG to the atmosphere. This forced the industries to operate in a more environmental friendly business to prevent any drastically profitable loss by adopting emissions reduction measures such as co-firing. Fig. 15 illustrates the correlations between incremental cost, emissions reduction and co-firing rates for each of the different carbon prices varies from 0 to 30 USD/t. The results indicate that the supply chain cost increases steadily and relatively linear as the carbon price increases. The reduction in emissions starts at the range of 0–1 USD/t carbon price and remains unchanged until reaching the 2 USD/t carbon price. After this point, emissions improvement continues to progress as the carbon prices are increasing. This trends show that carbon penalty scheme will acts a major instrument for the successful transitions from fossil fuels to RE through biomass co-firing. The best situation if the only goal is for effective emissions reduction, carbon price where the reductions of emissions are constantly progressing should be started at minimum of 2 USD/t.

3.4. Limitations of the study

This study assumed that torrefied pellets which exhibit coal-like properties, can provide a much higher share of biomass combustion in existing fossil fuels facilities. Pre-treatment of biomass is essential for the Malaysian case study due to coal-fired power plant locations which are situated in the coastal areas of Peninsular Malaysia. In this case, to achieve sufficient biomass supplies, biomass needs to be collected farther away from the power plant locations, contributing to the high transportation

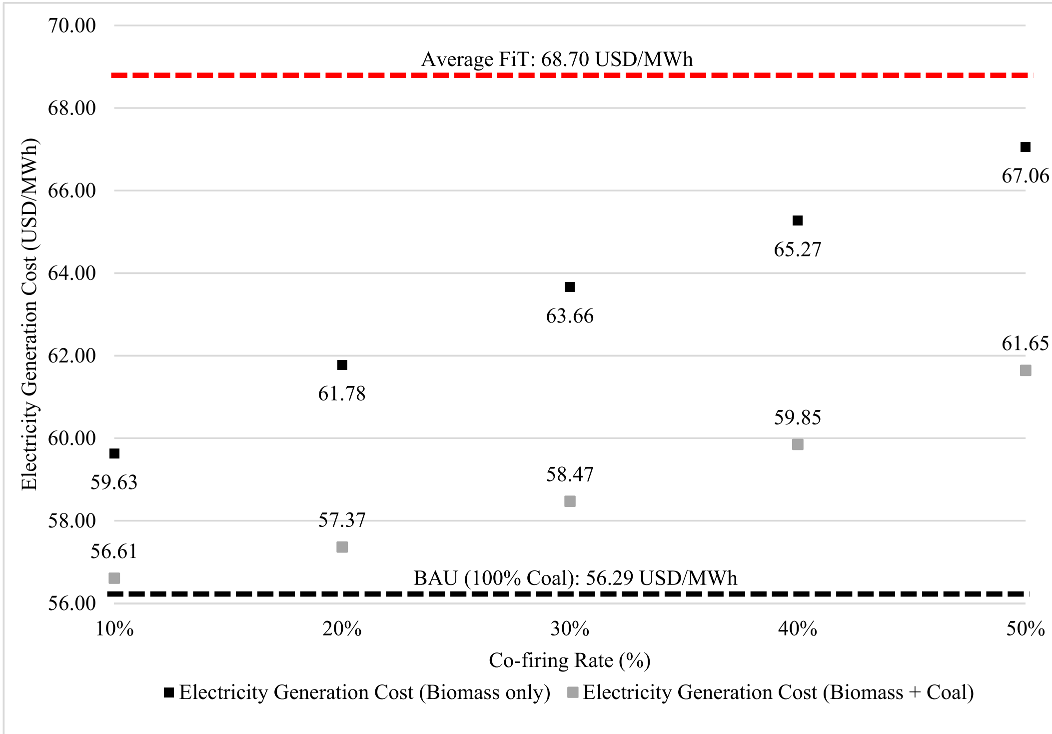


Fig. 14. Comparison of electricity generation costs with FiT.

cost. For this reason, pre-treatment reduced the transportation cost by densifying the raw biomass into the pelletised products so that more of them can be transported inside the transportation vessels. Only one pre-treatment technology is considered in this study to pre-treat the biomass before being consumed in power plant. Although TOP technology is one of the effective ways to increase the biomass energy content, considerations of other pre-treatment technologies which have lower costs and efficiencies such as drying, shredding and pelletisation may provide more optimal strategies to minimise the cost of the supply chain system while minimising its emissions.

The co-firing technology adopted in this study is direct co-firing

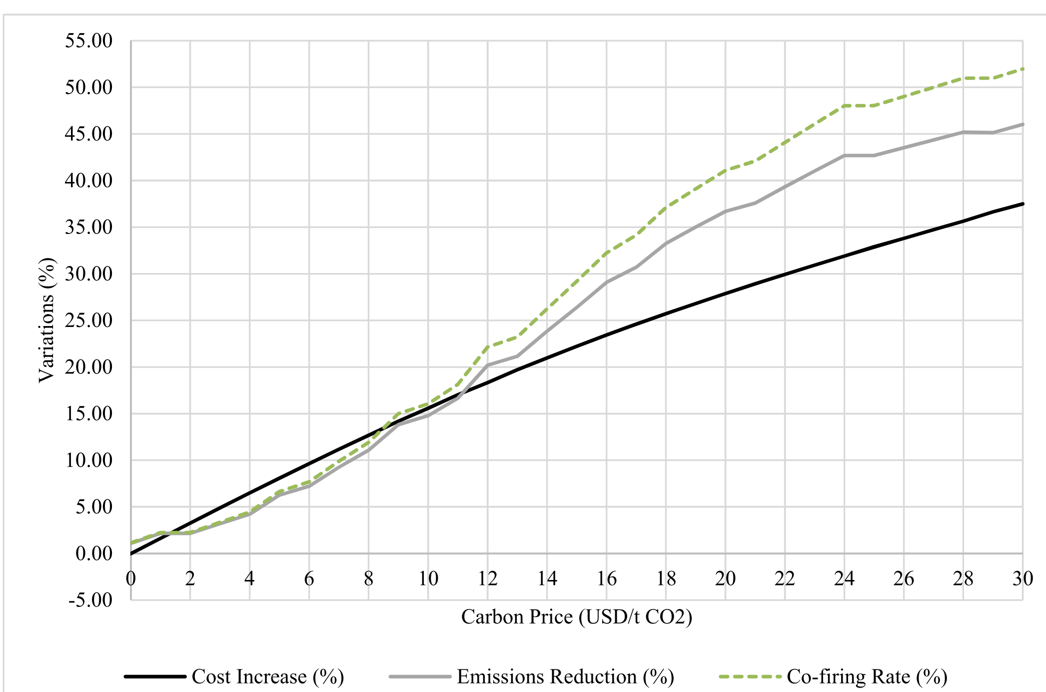


Fig. 15. Percentages of cost increase, emissions reduction and co-firing rate based on different carbon price.

which is widely used in the current practice due to its cost effectiveness. The advantage of direct co-firing is that capital investments can be maintained at a very minimum rate for the reason of existing facilities used for power generation activities. This study assumed that pre-treatment of biomass can support direct co-firing technology without affecting the efficiency of power generation. Other co-firing technology such as indirect and parallel co-firing have a much higher efficiency than the direct co-firing but the capital costs are intensive due to the addition of new processing units to the power plant such as gasification technology and new boiler. In the future, considerations of different co-firing technologies other than direct co-firing should be conducted to further allow much higher shares of biomass to be consumed in power plant. The higher the efficiency of the technology, the more efficient the co-combustion process is, resulting to the less CO_2 intensity due to the less amount of biomass being consumed to generate MWh of electricity. Nevertheless, the trade-off between the total cost and the emissions must be well investigated to ensure the optimal selection of technology.

The deterministic model has been successfully developed to evaluate the achievable co-firing rate based on the biomass availability while minimising the overall cost of electricity and the impact on emissions reduction. The current developed model has not been capturing the uncertainty factor such as the seasonal availability of biomass. Consideration of the seasonal availability of biomass is important to determine the amount of biomass that can be harvested at specific time period to be supplied for power generation activity. Acknowledging the shortcoming of the deterministic model, the next phase of our investigation will be developing the multi-period optimisation model by considering uncertainties in the model formulation.

4. Conclusions

A spatial optimisation model has been developed successfully to evaluate the economic and environmental performances of biomass co-firing in a coal-fired power plant. The geographical variabilities of biomass resources affected the overall supply cost structure very differently as compared to the dedicated coal-based electricity generation case. This indicates that the location factor has a substantial impact on the viability of biomass co-firing in power plant. It is vital to evaluate the locations of biomass pre-treatment facilities for sustainable biomass supply as well as minimising biomass transportation cost and total emissions thoroughly. The results showed that up to 8.83×10^6 t of emissions can be minimised annually in Johor through co-firing. The cost factors of deploying co-firing technology in existing coal-fired power plant are between 56.61 and 61.65 USD/MWh for 10–50% co-firing rates as compared to the base case electricity generation cost which is at 56.29 USD/MWh. Ineligibility of the FiT scheme renders biomass co-firing to be less competitive in the current power industry market. This shows that co-firing technology can only be implemented in Malaysia with incentives by the government. The implementation of biomass co-firing also can be supported through the introduction of carbon policy scheme in the country where energy industries need to pay for every GHG emitted to the atmosphere. This model can be further extended by the inclusion of technological selections of different pre-treatment and co-firing technologies to improve the efficiency of biomass transportation and combustion. The case study can be expanded to a larger regional scale context by evaluating co-firing feasibilities and its environmental implications for the whole Peninsular Malaysia case study.

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