Clean Technologies and Environmental Policy (2018) 20:113–125
https://doi.org/10.1007/s10098-017-1461-7

ORIGINAL PAPER

An optimization study of a palm oil-based regional bio-energy supply chain under carbon pricing and trading policies

Ashkan Memari[1,2] · Robiah Ahmad[1] · Abd. Rahman Abdul Rahim[1] · Mohammad Reza Akbari Jokar[2]

Received: 16 August 2017 / Accepted: 9 November 2017 / Published online: 14 November 2017

Abstract

Biomass residues due to their low bulk density typically require frequent transportation from biomass plantations in rural areas to conversion bio-energy power plants. This issue contrasts with environmental protection strategies, especially when power plants are facing different carbon reduction policies that enforce them to emit less than a given specific carbon amount. Although several researchers have investigated bio-energy supply chains concerning environmental policies, the majority of studies have been devoted to strategic decisions over a single planning period. This paper presents a multi-period bio-energy supply chain under carbon pricing (carbon tax) and carbon trading (cap-and-trade) policies at the tactical planning level. A mixed-integer linear programming model was adopted to optimize the proposed regional oil-palm biomass-to-bio-energy supply chain planning model. The numerical results indicate that when carbon pricing is in place when carbon tax increases linearly, carbon emissions' reductions have a nonlinear trend, whereas both cost increase and carbon emissions' reductions have a relatively upward trend in the carbon trading scheme. This paper also presents the sensitivity analysis of the proposed model regarding cost, emissions' generation and supply chain performance. Finally, the paper recommends several significant practical implications and policy-making insights for managers and policymakers.

Keywords Bio-energy supply chain · Biomass · Carbon tax · Carbon trading · Optimization · Renewable energy

List of symbols

Indices

I	Number of palm oil mills
J	Number of CHP plants
T	Number of planning periods
K	Number of transportation modes
i	Index of sources, $i = 1, 2, \ldots, I$
j	Index of sinks $j = 1, 2, \ldots, J$
t	Index of planning periods, $t = 1, 2, \ldots, T$
k	Index of transportation modes, $k = 1, 2, \ldots, K$

✉ Ashkan Memari
ashkan.memari@utm.my

1 Department of Engineering, UTM Razak School of Engineering and Advanced Technology, Universiti Teknologi Malaysia, Jalan Sultan Yahya Petra, 54100 Kuala Lumpur, Malaysia

2 Department of Industrial Engineering, Sharif University of Technology, Tehran, Iran

Parameters

L_{ij}	Distance (in km, round-trip) between mill i and CHP plant j
D_{jt}	Demand (in tonnage) of empty fruit bunches in CHP plant j in period t
AEFB_{it}	Available empty fruit bounces at mill i in period t
H_{jt}	Holding capacity in tonnage at CHP plant j in period t
HC_{jt}	Holding cost per ton of empty fruit bunches at CHP plant j in period t
BC_j	Backlog cost per ton of empty fruit bunches at CHP j
$B_{jt}^{\max}$	Maximum allowed backlog in CHP plant j during period t
LC	Lorry's capacity
FC_k	Fuel consumption of transportation mode k per km (L/km)
FP_k	Fuel price of transportation mode k per litter
c_k	Carbon emission of transportation mode k (kg/(t km))
c_{hold}	Carbon emission from inventory holding

p Carbon price

E_{max} Maximum allowed carbon emissions per period (carbon cap)

Decision variables

EFB_{ijkt} Integer variable for the amount of empty fruit bunches shipped from mill i to CHP plant j through transportation mode k in period t

I_{jt} Integer variable for the amount of inventory at CHP plant j in period t

B_{jt} Integer variable for the amount of backlog at CHP plant j in period t

Objective functions

Z_1 Total logistics costs

Z_2 Total carbon emissions

Introduction

Energy generation from biomass sources is considered "carbon neutral" since biomass combustion releases the same amount of carbon dioxide (CO_2) captured by the plant during its growth (Cherubini et al. 2011). However, in conversion of biomass-to-bio-energy, there are greenhouse gases (GHG) emissions over its life cycle largely from the logistics activities (Yue et al. 2014). These emissions are originated mainly from frequent deliveries of biomass feedstock (which typically have low bulk density except wood logs) to bio-energy plants. Consequently, biomass supply and logistics play a fundamental role in environmental friendly renewable-energy generation.

Perhaps the ultimate way to delimit GHG emissions in the logistics sector can be achieved through technology change; however, it is still a long way to go. On top of that, using green technologies may end up with a very significant cost which is not economically viable for the current practice. To help accelerate the implementation of modern technologies, many countries are employing different mechanisms to reduce GHG emissions, which may consist of mandatory or incentive goals to mitigate carbon footprint. Carbon pricing (also known as carbon tax) and carbon trading (also known as cap-and-trade) are known as the most cost-effective mechanisms to reduce carbon emissions (Labatt and White 2011). The idea behind these schemes is to put a price tag on carbon emissions and create new funding opportunities to secure investment on developing green technology. There are already several active carbon markets; the Chicago Climate Exchange in the USA, New Zealand Emissions Trading Scheme (NZ ETS) in New Zealand, European Union Emission Trading Scheme (or EU ETS) in Europe, Montreal Climate Exchange in Canada and carbon trading scheme in Malaysia (Amran et al. 2013).

Malaysia has voluntarily agreed to reduce up to 40% of its emissions' intensity of GDP by the year 2020 compared to the 2005 level (Oh and Chua 2010). According to the Malaysia Energy Centre (MEC), although carbon pricing and carbon trading are relatively new in this country, various corporate sectors within the country could potentially benefit from carbon trading (Amran et al. 2013; Wong et al. 2016).

Despite the benefits of carbon mitigation mechanisms, economic and technical challenges barricade their employment. For instance, carbon emissions' mitigation can potentially lead to a complex and costly logistics of procurement and transportation. It must be noted that biomass logistic costs usually account for 20–40% of total costs (Cambero and Sowlati 2014) and restricting carbon emissions can increase them even more. Thus, a study of a biomass-to-bio-energy supply chain under carbon emission policies is critical for analyzing these challenges.

This paper focuses on the logistics network of oil-palm empty fruit bunches (the widely available and most abundant oil-palm residue in Malaysia). Lorries carry fresh fruit bunches from neighboring oil-palm plantation estates to the palm oil mills. Then, the empty fruit bunches are transported from mills to combined heat and power (CHP) plants. After some simple processes (such as pre-treatment and shredding), CHP plants use the oil-palm wastes as feedstock to generate heat and electricity. Local biomass power plants may then use the generated energy, and the extra power is sold to the national grid. Lorries do most of the transportation in this logistics network. Carbon emissions from the fossil-fuel combustion of these lorries are the largest carbon emission's source in this bio-energy sector due to frequent deliveries of biomass residues. The CHP operates 24/7 and requires a continuous supply of biomass not to mention the buffer stock to avoid a shortage of supply. In addition, carbon emission reduction is one of the main concerns in the planning of regional energy supply chain and should be minimized for a more sustainable energy generation. This problem is more challenging when external carbon emission limitations such as carbon policies are involved. This problem is addressed in this study.

The rest of this paper is organized as follows. In Sect. 2, the detailed review of relevant literature is presented. In Sects. 3 and 4, problem statement and the mathematical model formulations are described, respectively. The case study is then introduced in Sect. 5. Numerical results and policy insights are discussed in Sect. 6. Finally, the paper ends with concluding remarks and future research directions in Sect. 7.

Literature review

This paper is mainly related to two streams of literature, the research on (1) biomass-to-bio-energy supply chain optimization and (2) supply chain optimization under carbon emission policies. Each stream is elaborated in the following sections.

Biomass-to-bio-energy supply chain optimization

There is a comprehensive literature review devoted to the modeling of biomass/bio-energy supply chains. There is also an extensive research which specifically examined the literature on optimizing biomass-to-bio-energy logistics (Singh et al. 2010; Zhu et al. 2011; Zhu and Yao 2011). The key aspects of bio-energy supply chains (from biomass harvesting to conversion) and bio-fuel supply chains (from biomass procurement to bio-fuel distribution) with respect to the design; planning and management were addressed by Gold and Seuring (2011), Mafakheri and Nasiri (2014) and Yue et al. (2014). The associated decisions with respect to strategic, tactical and operational decisions in bio-energy/biomass supply chains were discussed by Iakovou et al. (2010) and Sharma et al. (2013). The solving methods and solution approaches were analyzed by De Meyer et al. (2014) and Mirkouei et al. (2017).

Several types of mathematical modeling have been proposed. A large body of literature has been devoted to strategic decisions of biomass/bio-energy supply chains through the implementation of mixed-integer linear programming (MILP). There is a recent modeling trend for optimizing biomass/bio-energy supply chains at tactical planning level dealing with the production planning and logistics problems through the implementation of MILP. Several researchers had a narrower focus on a carbon footprint problem within the biomass supply networks. For example, Lam et al. (2010a) developed a single objective MILP model to minimize the carbon footprint across a biomass supply network. They extended their study in their later work (Lam et al. 2010b) by focusing on resource planning and optimum process network of with P-graph approach. Čuček et al. (2010) developed a number of MILP optimization models to minimize the carbon footprint in a regional energy supply chain. Foo et al. (2013) developed a linear programming model to minimize carbon emissions. They considered several biomass supply scenarios for a regional oil-palm supply chain. Rudi et al. (2017) addressed an MILP model to optimize the biomass value chain with emphasis on feedstocks, technologies and outputs. They integrated location, capacity planning and transportation decisions to identify potential biomass conversion plants.

Although extensive research has been carried out on optimization of biomass and/or bio-energy supply chains, most studies within this field have only focused on strategic decisions, e.g., bio-energy supply chain network design. However, little attention has been paid to biomass and/or bio-energy supply chains at the tactical planning level. As there are many green requirements today relating to tactical decisions, this study aims to contribute to this growing area of research by exploring bio-energy supply chains at the tactical planning level.

Supply chain optimization under carbon emission policies

There is a growing body of literature that recognizes the importance of carbon policies on environment protection. Among different carbon mechanisms, carbon pricing (carbon tax) and carbon trading (cap-and-trade) are the most popular implemented policies. The idea behind both mechanisms is to put a price on carbon emissions, whether through taxing or trading in a market such that companies' emission performance improves and investment in low- or no-carbon technologies to make it more economically viable.

Several researchers addressed mathematical models to minimize the carbon footprint across supply chains under carbon pricing and carbon trading policies. Some of the optimization models have efficiently assessed carbon tax scheme through minimization of cost and carbon emissions (Fahimnia et al. 2013a, b, 2015; Santibanez-Gonzalez 2017). Some other efforts have been devoted to the optimization of supply chains under the carbon trading scheme (Diabat et al. 2013; Chen and Wang 2016). Recent rigorous modeling attempts in this context have compared the impact of carbon pricing and carbon trading on supply chain decisions (Jin et al. 2014; Zakeri et al. 2015; Memari et al. 2016a; Chen and Chen 2017; Mohammed et al. 2017).

There are also studies with a narrower focus on the biomass/bio-energy supply chains under carbon emission policies. For example, Giarola et al. (2012) developed an MILP model for bio-ethanol supply chain network design under the carbon trading scheme. Ortiz-Gutiérrez et al. (2013) addressed a multi-objective MILP model for bio-ethanol supply chain network design under the carbon trading scheme. They obtained different optimum solutions based on Pareto front. Marufuzzaman et al. (2014) developed two-stage MILP stochastic programming model for biodiesel supply chain network design. They investigated various carbon emission schemes, namely carbon tax, cap-and-trade, offset and cap to analyze the impact of carbon emissions on supply chain decisions. Quddus et al. (2017) proposed a stochastic MILP model to minimize cost and carbon emissions in pellet processing depots under supply uncertainty and carbon trading scheme.

According to the latest literature reviews on optimization of carbon emission across supply chains by Memari et al. (2016b) and Li and Haasis (2017) and optimization of biomass supply chains (Ba et al. 2016), the majority of attempts related to optimization under carbon emission polices have devoted to strategic decisions over single time period models, e.g., supply chain network design. Another stream of literature has been devoted to operational decisions mainly focusing on inventory management, e.g., lot-sizing or order quantity models. MILP is the frequently applied method for addressing both streams. The current study seeks to contribute to this body of knowledge in the following ways:

- A large body of the literature has highlighted the strategic and operational decisions over a single planning horizon. As there are many green requirements today relating to tactical decisions, our model was developed by considering tactical decisions, including inventory and transportation over multiple planning periods.
- The developed model and solution approach were employed to identify how carbon pricing and trading schemes affect the economic and environmental performance of an actual multi-period biomass-to-bio-energy logistics network at a tactical planning level.
- Finally, the numerical analysis of this research can provide important insights for managers and policymakers (from policy setting perspective).

Problem statement

This study addresses a supply chain network problem that consists of a set of palm oil mill sources ($i,\ldots, I$) which provide empty fruit bunches for a set of CHP plants ($j,\ldots,J$) over multiple time periods. Empty fruit bunches are carried from palm oil mills to CHP plants by lorries. The CHP plants use empty fruit bunches as the renewable-energy source to generate heat and power. The lorries can be operated using both diesel and palm biodiesel (transportation modes). The market price of diesel fuel is cheaper but emits more carbon to the environment where in contrast palm biodiesel is more expensive with lower carbon emission rate. Our objective is to find the optimum level of empty fruit bunches transported from the mills to CHP plants such that total logistics costs and carbon emissions are minimized where the carbon emissions in the whole supply chain network are limited by a carbon policy. This problem was investigated under carbon pricing and carbon trading schemes. The considered problem takes into account the following assumptions:

(1) The locations of palm oil mill sources and CHP plants are fixed.
(2) The capacities of the palm oil mill sources and CHP plants are known.
(3) There is no stock of empty fruit bunches at the CHP plants at the starting or end of the planning horizon.
(4) The lorries' capacity is fixed at 20 tons.
(5) The demand for empty fruit bunches is deterministic.

Model formulation

The input indices, parameters and decision variables used in the proposed model were presented in List of symbols. Considering the defined notations, the problem was formulated using mixed-integer linear programming (MILP). The first objective function [Eq. (1)] presents the total logistics costs excluding carbon emission cost over the T planning periods. It includes three components: transportation cost (component 1), inventory holding costs in stores of CHP plants (component 2) and backordering/shortage costs (component 3).

$$Z_1 = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{t=1}^{T} \left(\mathrm{EFB}_{ijkt}/\mathrm{LC}\right) L_{ij} \times \mathrm{FC}_k \times \mathrm{FP}_k + \sum_{j=1}^{J}\sum_{t'=1}^{t} \mathrm{HC}_j I_{jt'} + \sum_{j=1}^{J}\sum_{t'=1}^{t} \mathrm{BC}_j B_{jt'} \tag{1}$$

The second objective function [emission function, Eq. (2)] formulates total carbon emissions (equivalent emission-tons of carbon). This objective includes two components; carbon emissions from transportation (component 1) and carbon emissions in CHP stores (component 2).

$$Z_2 = \sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{t=1}^{T} \left(\mathrm{EFB}_{ijkt}/\mathrm{LC}\right) L_{ij} \times \mathrm{FC}_k \times c_k + \sum_{j=1}^{J}\sum_{t'=1}^{t} I_{jt'} c_{\mathrm{hold}} \tag{2}$$

Regarding the carbon policies in the carbon pricing scheme (carbon tax), the goal is:

$$\text{Minimize} \quad Z_1 + pZ_2 \tag{3}$$

while in the carbon trading scheme (cap-and-trade), the goal is:

$$\text{Minimize} \quad Z_1 + p(Z_2 - E_{\max}) \tag{4}$$

Equation (3) is considered to model the carbon tax policy. In this equation, for the amount of emissions generated a carbon tax of p is imposed. Equation (4) presents the carbon trading scheme. In this environment [Eq. (4)], CHP plants that emit more than their allocated emission allowances ($Z_2 > E_{\max}$) can purchase extra carbon allowances at a price of p. Otherwise ($Z_2 < E_{\max}$), they can sell their excess amount of carbon allowances to companies which maybe emitting more than their carbon caps. It should be noted that the value of $Z_2 - E_{\max}$ would be negative if $Z_2 < E_{\max}$. In this case, the negative value of carbon trading can be interpreted as an income source which can help to reduce its total logistics costs.

The model is subject to the following constraints:

$$\sum_{j=1}^{J} \mathrm{EFB}_{ijkt} \le \mathrm{AEFB}_{it} \quad \forall i, k, t \tag{5}$$

$$\sum_{i=1}^{I}\sum_{k=1}^{K} \mathrm{EFB}_{ijkt} + I_{j(t-1)} - B_{j(t-1)} = D_{jt} + I_{jt} - B_{jt} \quad \forall j, t \tag{6}$$

$$I_{jt} \le H_{jt} \quad \forall j, t \tag{7}$$

$$B_{jt} \le B_{jt}^{\max} \quad \forall j, t \tag{8}$$

$$\mathrm{EFB}_{ijkt}, I_{jt}, B_{jt} \ge 0 \quad i, j, k, t \tag{9}$$

Constraint (5) indicates that the total amount of allocated empty fruit bunches from the palm oil mill i to all CHP plants should not exceed its availability. Constraint (6) model the flow conservation at CHP plants. Constraint (7) ensures that the amount of inventories at CHP store should not exceed the holding capacity at each period. Constraint (8) limits the maximum allowed backlog in each period. Lastly, constraint (9) guarantees the nonnegativity values of decision variables.

The resulting model is an MILP with IJKT + 2 (JT) continuous variables (in this case 288 variables). The number of constraints is IKT + 3 (JT) excluding constraint (9), [in this case 124 constraints excluding constraint (9)].

Case study example

The considered case study in this research was formerly introduced in the study by Foo et al. (2013). The case study was based on actual palm oil mills, refineries and oleochemical plants in the northern part of Borneo Island in Malaysia. Figure 1 shows the approximate geographical location of the suppliers and consumers of empty fruit bunches.

Table 1 provides the available data for the considered supply chain. In this supply chain, 11 palm oil mills provided empty fruit bunches for the oleochemical plant (C1) and the palm oil refinery (C3). These two plants experience energy deficit and to generate electricity for the plants' usage; the CHP plants were built in these plants. Besides, an existing mill (C2) was also planned to have a CHP plant (C2 was the same plant as S8). The desired electricity outputs for each CHP plant and their corresponding empty fruit bunch demand are given in Table 1.

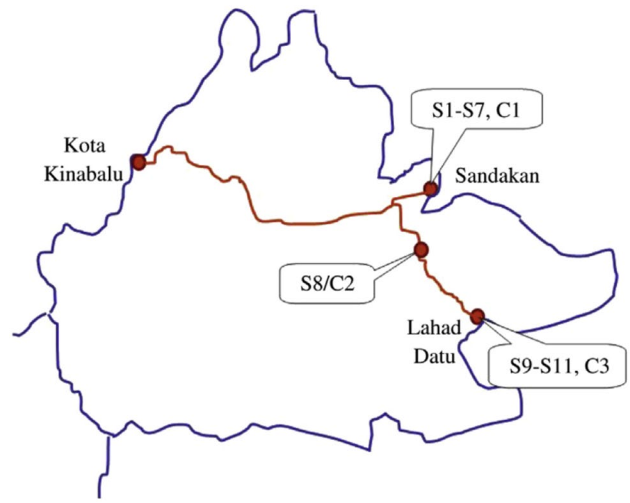

Fig. 1 Considered logistics network

For every MW of power output, 20 kt/y of empty fruit bunches is required at each CHP plant. The electricity demands for each plant in subsequent periods (four planning periods were considered) were generated at random normally with ± 2 MW standard deviation based on the available data. Since the palm oil mills and CHP plants are located in remote areas, the only available transportation mode is conventional lorries. The lorries can be operated with both diesel and palm biodiesel. The diesel fuel is cheaper (the current price in Malaysia is RM 2.2 per liter), whereas palm biodiesel is more expensive (the current price in Malaysia is RM 3 per liter). The consumption fuel rates for both diesel and palm biodiesel (Yee et al. 2009) are presented in Table 2.

The actual distances between the sources of the empty fruit bunches and CHP plants are given in Table 3.

Results and discussion

The MILP model presented in Sect. 4 was coded in CPLEX 12.7.1 for analyzing the results. All calculations throughout this paper were performed on a PC with Intel® Core (TM) i5-7200U CPU 2.50 GHz, RAM 4.00 GB. The model was run under two different environmental policies namely (1) carbon pricing and (2) carbon trading. The first scenario used Eq. (3) with the objective to monitor total logistics costs ($Z_1 + pZ_2$), while carbon price (p) varies over a practical and small range of RM 0–RM 1.00 per ton of carbon emissions. In the second policy (carbon trading), the objective [Eq. (4)] is to monitor total logistics costs ($Z_1 + p(Z_2 - E_{\max})$) by adopting a grandfathering concept. The grandfathering level (carbon cap) ranges from 100% (no carbon emissions reduction) to 70% reduction. The desired

Table 1 Suppliers and consumers of empty fruit bunches data

Palm oil mills	Empty fruit bunches capacity (kt/y)	Consumers	Desired power output (MW)	Empty fruit bunches requirement (kt/y)
S1	90	C1	12	240
S2	75	C2	10	200
S3	80	C3	10	200
S4	85			
S5	82			
S6	86			
S7	92			
S8	78			
S9	80			
S10	88			
S11	84			

Table 2 Fuel efficiency and emissions by fuel type

	Diesel	Palm biodiesel
Fuel consumption (L/100 km)	11.5	12.0
CO_2 emissions (g CO_2/km)	309	191
CO_2 emissions (kg CO_2/L)	2.2583	1.3950

Table 3 Distance (in km) between suppliers and consumers

	C1	C2	C3
S1	11.9	65.7	164
S2	9.9	69.9	168
S3	12.3	66.5	165
S4	12.3	66.5	165
S5	11.9	65.7	164
S6	8.0	77.8	176
S7	8.0	77.8	176
S8	75.6	0	98
S9	172	96.2	1.9
S10	170	94.5	5.5
S11	168	92.5	7.1

carbon price which forces the company to reduce its carbon emissions below a specific percentage of grandfathering level (carbon cap goal) was also determined through a trial-and-error procedure.

Analysis of the numerical results

Tables 4 and 5 present the numerical results for carbon pricing and carbon trading scenarios, respectively. Table 4 shows the numerical results of the carbon pricing scheme for various carbon taxes ranging from RM 0 to RM 1.00 per ton of carbon emissions in intervals of RM0.10. In this table, each row presents a fixed carbon price. The total carbon emissions (final column) and total logistics costs (sixth column) and their related components are also provided in Table 4. It must be noted that transportation and storage are two logistics operations that cause carbon emissions. For instance, when carbon price is RM 0, the total carbon emission is 1122.80 tons, and since the carbon tax is RM 0 per ton, there are no costs due to these carbon emissions (see the last cost component in Table 4).

Table 5 presents the results from the carbon trading policy. The total logistics costs and overall carbon emissions are presented for the considered grandfathering percentage (first column) or targeted carbon caps (second column). The baseline begins from the point that there is no carbon emission policy in place. In other words, the baseline is the situation with maximum carbon emission generation, which is 1122.80 tons in this case (see the first row in Tables 4 and 5). In the second row of Table 5, the percentage of grandfathering target (98%) indicates that the companies' overall carbon emissions should be reduced from 1122 to 1107 tons (0.98 × 1122), which is a new carbon cap for the company. The column of desired carbon price in Table 5 was obtained through a trial-and-error procedure by fixing the model at different carbon caps. This is the required price which encourages the company to reduce its carbon emissions lower than a specified cap. In this regard; an increment from RM 0.01 to RM 10 carbon price was considered until the targeted carbon emission goal was achieved.

The column "number of allowances traded" was specified by the model and showed the amount of traded carbon allowances in the carbon market, while the emission remained under the specified carbon emission goal. The amount of traded allowances was obtained by taking the carbon cap (E_{max}) from total generated carbon emissions (Z_2). It should be noted that negative numbers in Table 5

Table 4 Numerical results for carbon pricing scenario

Carbon price	Cost components (RM)				Total logistics cost	Emission components (*t*)		Total emission
	Transportation	Holding	Backlog	Emission		Transportation	Holding	
0	889.32	120	0	0	1122.32	1086.20	35.88	1122.08
0.10	889.32	120	0	112.5	1121.82	1086.20	35.88	1122.08
0.20	889.32	120	0	224.41	1233.73	1086.20	35.88	1122.08
0.30	872.5	140	0	332.24	1344.74	1065.60	41.86	1107.46
0.40	911.68	140	0	403.64	1455.32	967.240	41.86	1009.10
0.50	915.01	140	0	500.75	1555.76	959.640	41.86	1001.50
0.60	915.01	140	0	600.9	1655.91	959.640	41.86	1001.50
0.70	915.01	140	0	701.05	1756.06	959.640	41.86	1001.50
0.80	915.01	140	0	801.02	1856.03	959.640	41.86	1001.50
0.90	915.01	140	0	901.35	1956.36	959.640	41.86	1001.50
1.00	915.01	140	0	1001.5	2056.51	959.640	41.86	1001.50

present the revenue that can be obtained from selling extra emission allowances.

Carbon tax scheme

The first set of analyses examined the impact of different carbon prices on total costs and emission. In this regard, various carbon taxes ranging from RM 0 to RM 1.00 per ton of carbon emissions in intervals of RM 0.10 were considered. Table 4 presents the model outputs for this scenario where each row in this table shows a fixed carbon price. The results obtained from the model included total logistics costs and generated carbon emissions. Total cost components constitute of transportation, holding, backlog and emission costs. The components involved in carbon emissions function are emissions from transportation and holding. For instance, when carbon price considered is RM0, the total generated carbon is 1122.80 tons, whereas there is no cost associated with emissions as the carbon price was considered RM 0 per ton (see the fifth column in Table 4).

The results obtained from the mathematical modeling are also shown in Figs. 2 and 3. As can be seen from Fig. 2, when the carbon price increased, the total logistics cost increases linearly and almost steadily. However, a nonlinear and erratic trend can be seen in the emission reductions. As shown in Fig. 2, emission reductions are a zero ton for the carbon price of RM0–0.20, while there is a slight jump when the carbon price is at RM 0.30 in emission reductions, and there is a fast lessening in emissions when carbon prices are from RM 0.30–0.50 per ton. After this point, the emission reductions were unaffected by the carbon price increase until it reached the last considered carbon prices of RM 1.00.

An example of the optimum EFB allocation under the carbon pricing scheme is presented in Table 6.

Figure 3 shows the performance of logistics cost and emissions lessening in the considered carbon price ranges. It should be noted that the values in the y-axis show the percentage of logistics cost increase and the emission percentage reduction for every carbon price when compared to the RM 0 carbon price. In this study, the RM 0 price is considered as a comparison baseline because the researchers believe that this viewpoint gives a better understanding of the carbon taxing effectiveness over the considered carbon prices range. In Fig. 3, it can be seen that it is only the logistics cost that grows because of the increased emission tax for the carbon price ranging from RM 0–RM 0.20 and RM 0. 50–RM 1.00, while there is no improvement in emission reductions. However, there is a nonlinear trend in the emission reductions. According to the results, there was a slight jump in emission reduction from RM 0. 20–RM 0.30 and from this point, there was a notable reduction in emissions until the carbon price reached RM 0.40, when another insignificant jump can be seen in emission lessening at the point RM 0.50 and carbon emission improvement remained unchanged until RM 1.00 per ton. In the price range of RM 0–RM 0.20 and RM 0.50–RM 1.00, it was only the logistics cost that rose because of the increased carbon emission tax with no improvement in carbon emission generation.

Carbon trading scheme

Table 5 presents the numerical results in the carbon trading scheme. These results are depicted in Figs. 4, 5 and 6. In Fig. 4, the performance of considered logistics network is shown in terms of logistics cost increase and carbon emission reduction. Each grandfathering goal was compared with baseline, which was 100% cap with RM 0 carbon credit price. As it can be seen in this figure, both cost increase and carbon emission reductions had a relatively upward trend. However, this trend was not steady and constant. For example, there was a rapid jump in logistics cost as the percentage of grandfathering was lowered from 88 to 70%. It

Table 5 Numerical results for carbon trading policy

Percentage grandfathering	Carbon cap	Desired carbon price (RM)	Cost components (RM)				Total logistics cost	Emission components (t)		Total emission	Amount of emission traded
			Transportation	Holding	Backlog	Emission trading		Transportation	Holding		
100	1122	0	889.32	120	0	0	1009.3	1086.20	35.88	1122	0
98	1099	0.22	872.5	140	0	+ 1.86	1014.4	1065.6	41.86	1107	8.47
96	1077	0.40	911.68	140	0	− 27.16	1024.5	967.24	41.86	1009.1	− 67.89
94	1054	0.40	911.68	140	0	− 17.96	1033.7	967.24	41.86	1009.1	− 44.89
92	1032	0.40	911.68	140	0	− 9.15	1042.5	967.24	41.86	1009.1	− 22.89
90	1009	0.40	911.68	140	0	+ 0.04	1051.7	967.24	41.86	1009.1	+ 0.100
88	987	6	923.51	180	0	+ 13.72	1117.2	935.47	53.82	989.29	+ 2.28
86	965	34	899.26	150	1000	− 128.33	1920.9	916.38	44.85	961.23	− 3.77
84	942	75	882.64	130	3000	− 529.17	3483.5	896.07	38.87	934.94	− 7.05
82	920	100	825.04	130	9000	− 4487.40	5467.6	836.26	38.87	875.13	− 44.87
80	897	100	825.04	130	9000	− 2187.40	7767.6	836.26	38.87	875.13	− 21.87
78	875	100	825.04	130	9000	+ 12.59	9967.6	836.26	38.87	875.13	+ 0.12
76	853	111	717.84	130	21,000	− 9487.30	12,361	728.66	38.87	767.53	− 85.47
74	830	111	611.84	130	21,000	− 6934.30	14,333	728.66	38.87	767.53	− 62.47
72	807	111	717.84	130	21,000	− 4381.30	17,467	728.66	38.87	767.53	− 39.47
70	771	111	717.84	130	21,000	− 385.29	21,463	728.66	38.87	767.53	− 3.47

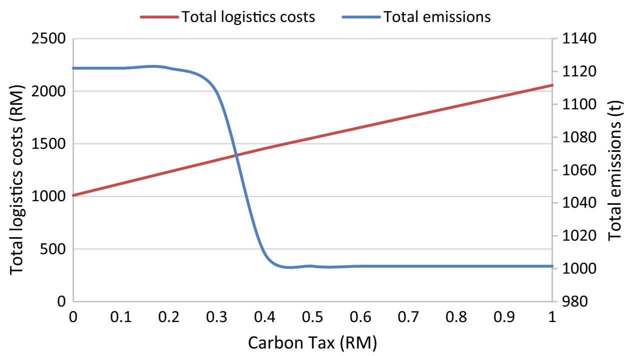

Fig. 2 Total costs versus total emissions

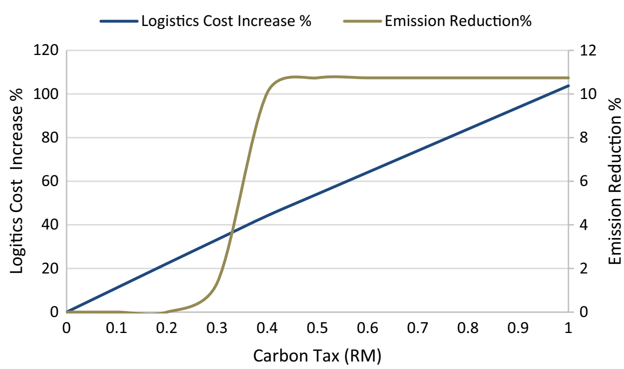

Fig. 3 Cost versus carbon emission's performance under the carbon tax policy

was apparent in this figure that lowering grandfathering percentage from a point may become impractical from the cost perspective. From the emission reduction viewpoint, it can be seen that while lowering the grandfathering percentage has an upward trend in emission's improvement, in some occasions, it may not necessarily lead to carbon emission reductions.

Furthermore, it can be seen from the results in Table 5 (depicted in Fig. 4) that inventory holding level increased when the grandfathering level became lower. Besides, tighter cap led to increase backlog level amount. For each carbon cap, the optimization challenge was to find a trade-off among holding, backlog, transportation and carbon trading costs (purchasing/selling). For each specific cap, the optimum answer consisted of distinct levels of these parameters. Depending on the carbon cap and carbon trading price, the optimum solution and the trend for carbon emission reduction can be erratic compared to the previous or next carbon cap.

Figure 5 illustrates the required carbon prices for achieving each grandfathering target. As mentioned earlier in Sect. 5, these fixed carbon prices were obtained based on a trial-and-error procedure. For example, in order to reduce emissions to 12% (88% grandfathering target), a carbon allowance price of RM 6.00 per ton was needed. It must be noted that in practice, the carbon allowance price is determined based on the demand and supply for allowances in the market. In addition, the actual carbon price in the market may highly depend on the performance of other companies participating in a carbon trading scheme (i.e., the availability of surplus carbon allowances to be sold or additional carbon allowances to be purchased). On the other hand, policymakers and governments can provide subsidies and effective carbon cap setup can also influence the real market of carbon price.

In this investigation, Fig. 4 shows that a 2 to 10% reduction of carbon cap from the baseline leads to a slight and steady rise. Nevertheless, a grandfathering below 90% will lead to a very large increase in carbon price and consequently, a substantial logistics cost increase. From this point, the company should invest in innovative technologies or logistics network restructuring toward its strategy for carbon emission mitigation.

Table 6 Allocation of EFB under carbon pricing policy (carbon tax: RM 0.20)

Sources	Period 1			Period 2			Period 3			Period 4		
	C1	C2	C3	C1	C2	C3	C1	C2	C3	C1	C2	C3
S1					80			80			80	
S2							60			60		
S3					80			80		20	60	
S4					80			20			80	
S5					80			80			80	
S6	60			80			80			80		
S7				40			80			80		
S8		40			80			60			60	
S9			80			80			80			80
S10			80			80			20			80
S11			20			80					40	40

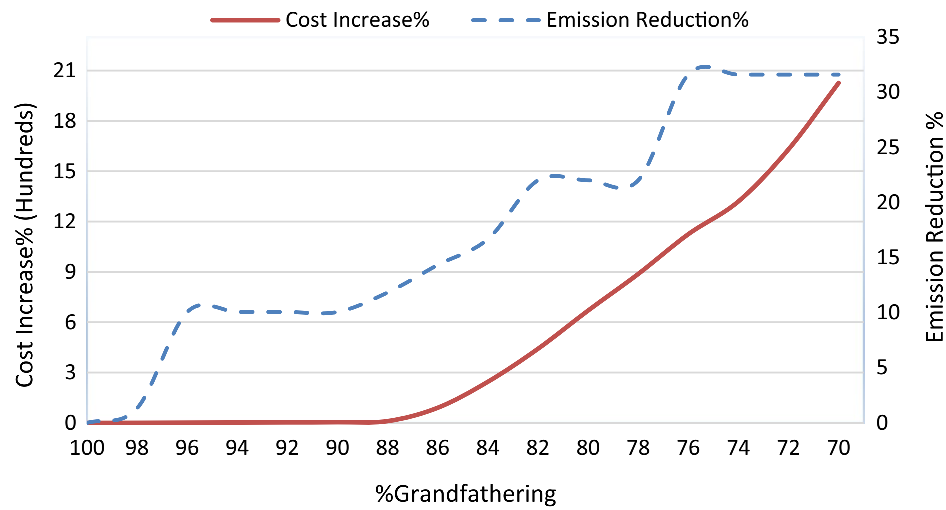

Fig. 4 Cost versus carbon emission's performance under carbon trading policy

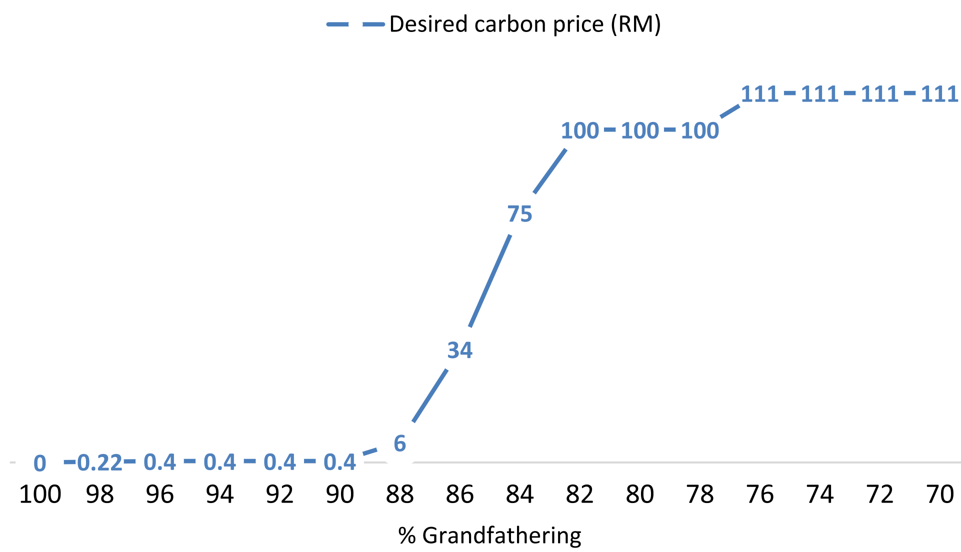

Fig. 5 Estimated carbon trading price for achieving each specific grandfathering target in the carbon trading policy

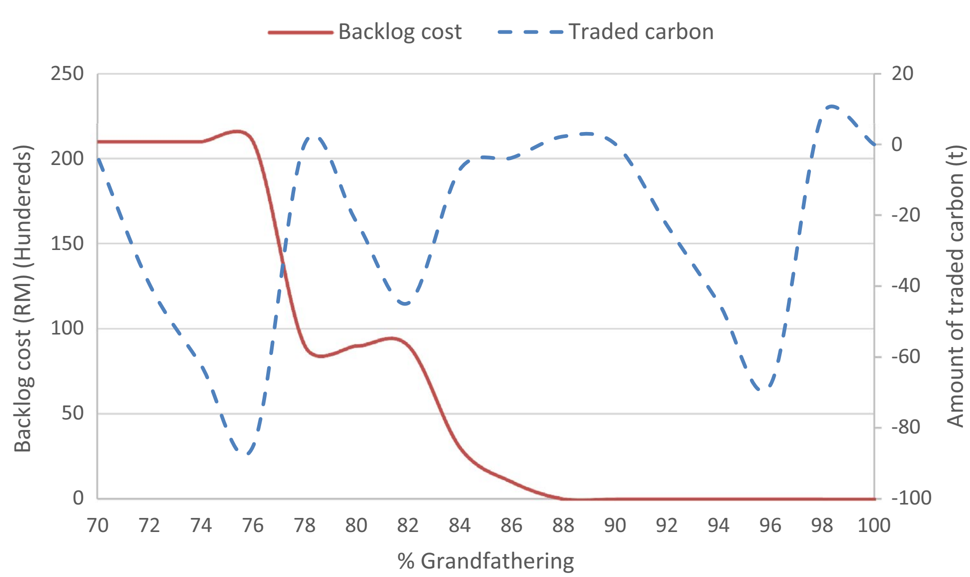

Fig. 6 Number of traded allowances versus backlog cost in the carbon trading policy

Figure 6 provides an overview of the amount of traded carbon allowances for each grandfathering goal. There was a very erratic and nonlinear trend in the number of traded allowances. There was a sharp decrease at 74 and 94% grandfathering level. Closer inspection of Table 5 at these points shows that these were due to major reductions in emissions from lorries using greener transportation fuel (palm biodiesel). These, however, increase transportation costs. It was also observed that in some instances (see, for example, the 76 and 98–100% grandfathering goals), the amount of allowances sold was almost close to the zero trading line. This analysis can give us a better perspective when compared to supply chain service level, which is one of the significant supply chain performance measures. Most commonly in literature, service level is considered as compensation and penalties paid to customers when back ordering demand occurred. In the case of this study, as can be seen in Fig. 6, there is a large jump in backlog cost after 88% grandfathering level. Consequently, it can be argued that by considering the logistics network with its current infrastructure and equipment, if the company's managers are willing to reduce carbon emissions greater than 12%, they have to either increase logistics costs to a considerable extent or sacrifice the company service level. In such situation, a decision might be a trade-off between investment for technology change or move toward alternative carbon emission reduction strategies. On the other hand, this situation might also lead to a conflict in organizational and policymaker viewpoints. For instance, as shown in Fig. 6, the 78, 88 and 90% grandfathering levels are the ideal policy situations from policymaker perspective since in all cases only below three allowances (rounded up) were traded, with 22, 11.8 and 10% emissions' reductions, correspondingly. However, from an industry practitioner perspective, the grandfathering levels of 78, 88 and 90% are led to 887.5, 10.69 and 4.2% into the overall logistics costs, respectively.

An example of the optimum EFB allocation under the carbon pricing scheme is presented in Table 7.

Overall, these results indicate that carbon trading scheme might be more effective than carbon pricing in terms of emission reduction. However, the percentage of grandfathering (carbon cap) is influenced by many other factors such as national economy situation, carbon reduction targets, positioning of firms, available alternative funds for new technologies, equipment and infrastructures. From the policymaker perspective, there might be more tendency to implement a carbon pricing (carbon tax) scheme because of its ease of execution and lower uncertainty level. In contrast, there is more flexibility for practitioners in the carbon trading scheme. The results of this study seem to be consistent with studies done by Diabat et al. (2013), Fahimnia et al. (2013b) and Santibanez-Gonzalez (2017) who found that the carbon trading scheme might be a more effective mechanism for achieving more carbon emission's reduction, even if the carbon price is set imperfectly.

Policy insights

Observation 1 Under the carbon pricing scheme, a higher carbon tax rate could significantly increase logistics costs without meaningfully reducing carbon emissions.

Under the carbon pricing scheme, it was observed that a higher carbon tax rate could significantly increase costs without substantially reducing carbon emissions or even in some occasions no reduction in emissions was found. This observation is shown in Figs. 2 and 3, while the corresponding results are reported in Table 4. For example, for the price ranges of RM 0–RM 0.20 and RM 0. 50-RM 1.00, it was only the logistics cost that increased because of the higher emission tax, where no improvement can be seen in the emission reduction. In this study, it is mainly due to the increase of tax rate when the higher tax rate is still cheaper

Table 7 Allocation of EFB under carbon trading policy ($E_{\max}$: 1022-ton, carbon price: RM 0.22)

Sources	Period 1			Period 2			Period 3			Period 4		
	C1	C2	C3	C1	C2	C3	C1	C2	C3	C1	C2	C3
S1					80			80			80	
S2							60			60		
S3					60			80		20	60	
S4					80			20				
S5					80			80			80	
S6	60			80			80			80		
S7				40			80			80		
S8		60			80			60			60	
S9			80			80			80			80
S10			80			80			20			80
S11			20			80					40	40

than shifting to lower carbon emission option (e.g., palm biodiesel, lower emission fuel in the case of this study or in other cases that may not cause shifting transportation mode or new lower carbon emission technology). Due to this reason, the tax can only increase total logistics cost without changing the emission reduction. Whether these findings are accurate for other industries and companies, they needed to be carefully assessed. The goal of setting carbon tax is to reduce emissions substantially; however, if the increased costs do not lead to further carbon emission reduction, then the efficiency of setting a certain carbon tax comes into question. Policymakers should be aware that to achieve maximum environment protection, carbon tax must be high enough to encourage companies to use new technologies and must be low enough not to affect profitability. A too high carbon tax may lead to unnecessary burden, while a too low carbon tax may lead to no emission reductions. In addition to the above-mentioned issue, a carbon tax should be stable. If organizations are sure that the carbon tax is steady, any revenue earned by the fixed carbon tax can be invested to enhance their emission reduction performance.

Observation 2 Under the carbon trading scheme, a higher carbon price is needed to reduce the percentage of grandfathering level (tightening carbon cap).

Under the carbon trading scheme, it was observed that when the grandfathering level was relatively low, the carbon price should be sufficiently high to compensate the additional costs caused by a tighter cap (i.e., shortage costs and costs of using lower emission technologies). The obtained results for "desired carbon price" presented in Table 5 confirmed that as we lower the carbon cap, the higher carbon price is required. This is mainly because a tighter cap removes the company's opportunity to meet some of its demands. Therefore, the possibility of being out of stock becomes higher. If the carbon price is not sufficiently high, then the company neither has an appropriate incentive to shift toward newer technology nor enough revenue (from selling carbon allowances) to compensate the extra costs due to a tighter cap.

Observation 3 Under the carbon trading scheme, a higher carbon price can help to invest in efforts to reduce carbon emissions.

Given a fixed carbon cap, it was observed that when carbon price was relatively low, the firm was mostly engaged in the buying of carbon. Consequently, higher carbon prices lead to higher carbon purchasing cost. However, when the carbon price is sufficiently high, the company becomes engaged in the selling of carbon allowances, since the company is encouraged to shift toward cleaner technologies and emit less carbon. In this case, higher carbon selling prices will also result in lower total costs as higher revenue is generated by carbon selling.

Policy recommendations

Carbon pricing and trading possess benefits and drawbacks. In general, carbon taxation is more comfortable to operate and may be more helpful from an uncertainty perspective, while carbon trading has more flexibility in response to variations of market conditions. However, this flexibility is also the origin of risks, uncertainties and political issues. A hybrid regulatory policy can make the best use of both benefits of the carbon schemes while avoiding their shortcomings. For example, a progressive carbon tax rate can be considered for small and medium companies, while a carbon trading policy may be a more efficient way to control carbon emissions of large companies. It can, therefore, be argued that the hybrid scheme makes proportional equity allocations in carbon emission rights among different companies, which may help economic development in certain areas.

Conclusion

This study analyzed the impact of carbon policies on a regional biomass-to-bio-energy supply chain network. An MILP mathematical model was developed to optimize the considered multi-echelon and multi-period logistics network under two well-known carbon policies, namely carbon pricing (carbon tax) and carbon trading (cap-and-trade) schemes. Under the carbon pricing scheme, this study determined the effect of different carbon taxes on cost and carbon emission performances. Under carbon trading policy, various analyses based on different carbon grandfathering levels and carbon prices were presented. The impact of traded carbon allowances against shortage cost was also evaluated. Consequently, different policy insights for policy makers were presented. In general, therefore, it seems that both carbon policies are very price sensitive. Policymakers need a careful investigation to determine strategies that maximize environmental protection that has less impact on the economic performance. In other words, the whole supply chain should be considered to find the right tax level and carbon selling price and cap level. This research has thrown up some questions that need additional investigation. A further study could assess the trade-off between carbon policies and technology change in a long-term period. In addition, the identified strategies, which are economically viable, scientifically sound and ethically defendable, have been an ongoing pursuit for many years. If the debate moves forward, a better understanding of new carbon policies should be developed.

Acknowledgements The authors would like to thank Universiti Teknologi Malaysia (UTM) and Ministry of Higher Education (MOHE) Malaysia under Fundamental Research Grant Scheme (FRGS) Vot 4F850 for financial support provided throughout this research. The first author is a researcher at UTM under the Postdoctoral Fellowship Scheme (PDRU Grant) for the project: "A Tuned NSGA-II for Optimizing JIT Distribution Networks" Vot No.Q.J130000.21A2.03E46.

References

Amran A, Zainuddin Z, Zailani SHM (2013) Carbon trading in Malaysia: review of policies and practices. Sustain Dev 21(3):183–192

Ba BH, Prins C, Prodhon C (2016) Models for optimization and performance evaluation of biomass supply chains: an Operations Research perspective. Renew Energy 87:977–989

Cambero C, Sowlati T (2014) Assessment and optimization of forest biomass supply chains from economic, social and environmental perspectives: a review of literature. Renew Sustain Energy Rev 36:62–73

Chen J-X, Chen J (2017) Supply chain carbon footprinting and responsibility allocation under emission regulations. J Environ Manag 188:255–267

Chen X, Wang X (2016) Effects of carbon emission reduction policies on transportation mode selections with stochastic demand. Transp Res Part E Logist Transp Rev 90:196–205

Cherubini F, Peters GP, Berntsen T, StrØmman AH, Hertwich E (2011) CO_2 emissions from biomass combustion for bioenergy: atmospheric decay and contribution to global warming. GCB Bioenergy 3(5):413–426

Čuček L, Lam HL, Klemeš JJ, Varbanov PS, Kravanja Z (2010) Synthesis of regional networks for the supply of energy and bioproducts. Clean Technol Environ Policy 12(6):635–645

De Meyer A, Cattrysse D, Rasinmäki J, Van Orshoven J (2014) Methods to optimise the design and management of biomass-for-bioenergy supply chains: a review. Renew Sustain Energy Rev 31:657–670

Diabat A, Abdallah T, Al-Refaie A, Svetinovic D, Govindan K (2013) Strategic closed-loop facility location problem with carbon market trading. IEEE Trans Eng Manag 60(2):398–408

Fahimnia B, Reisi M, Paksoy T, Özceylan E (2013a) The implications of carbon pricing in Australia: an industrial logistics planning case study. Transp Res Part D Transp Environ 18:78–85

Fahimnia B, Sarkis J, Dehghanian F, Banihashemi N, Rahman S (2013b) The impact of carbon pricing on a closed-loop supply chain: an Australian case study. J Clean Prod 59:210–225

Fahimnia B, Sarkis J, Choudhary A, Eshragh A (2015) Tactical supply chain planning under a carbon tax policy scheme: a case study. Int J Prod Econ 164:206–215

Foo DC, Tan RR, Lam HL, Aziz MKA, Klemeš JJ (2013) Robust models for the synthesis of flexible palm oil-based regional bioenergy supply chain. Energy 55:68–73

Giarola S, Shah N, Bezzo F (2012) A comprehensive approach to the design of ethanol supply chains including carbon trading effects. Biores Technol 107:175–185

Gold S, Seuring S (2011) Supply chain and logistics issues of bioenergy production. J Clean Prod 19(1):32–42

Iakovou E, Karagiannidis A, Vlachos D, Toka A, Malamakis A (2010) Waste biomass-to-energy supply chain management: a critical synthesis. Waste Manag 30(10):1860–1870

Jin M, Granda-Marulanda NA, Down I (2014) The impact of carbon policies on supply chain design and logistics of a major retailer. J Clean Prod 85:453–461

Labatt S, White RR (2011) Carbon finance: the financial implications of climate change. Wiley, London

Lam H, Varbanov P, Klemeš J (2010a) Minimising carbon footprint of regional biomass supply chains. Resour Conserv Recycl 54(5):303–309

Lam HL, Varbanov PS, Klemeš JJ (2010b) Optimisation of regional energy supply chains utilising renewables: P-graph approach. Comput Chem Eng 34(5):782–792

Li F, Haasis H-D (2017) Imposing emission trading scheme on supply chain: separate-and joint implementation. J Clean Prod 142:2288–2295

Mafakheri F, Nasiri F (2014) Modeling of biomass-to-energy supply chain operations: applications, challenges and research directions. Energy Policy 67:116–126

Marufuzzaman M, Eksioglu SD, Huang YE (2014) Two-stage stochastic programming supply chain model for biodiesel production via wastewater treatment. Comput Oper Res 49:1–17

Memari A, Rahim ARA, Absi N, Ahmad R, Hassan A (2016a) Carbon-capped distribution planning: a JIT perspective. Comput Ind Eng 97:111–127

Memari A, Rahim ARA, Ahmad R, Hassan A (2016b) A literature review on green supply chain modelling for optimising CO_2 emission. Int J Oper Res 26(4):509–525

Mirkouei A, Haapala KR, Sessions J, Murthy GS (2017) A review and future directions in techno-economic modeling and optimization of upstream forest biomass to bio-oil supply chains. Renew Sustain Energy Rev 67:15–35

Mohammed F, Selim SZ, Hassan A, Syed MN (2017) Multi-period planning of closed-loop supply chain with carbon policies under uncertainty. Transp Res Part D Transp Environ 51:146–172

Oh TH, Chua SC (2010) Energy efficiency and carbon trading potential in Malaysia. Renew Sustain Energy Rev 14(7):2095–2103

Ortiz-Gutiérrez RA, Giarola S, Bezzo F (2013) Optimal design of ethanol supply chains considering carbon trading effects and multiple technologies for side-product exploitation. Environ Technol 34(13–14):2189–2199

Quddus MA, Hossain NUI, Mohammad M, Jaradat RM, Roni MS (2017) Sustainable network design for multi-purpose pellet processing depots under biomass supply uncertainty. Comput Ind Eng 110:462–483

Rudi A, Müller A-K, Fröhling M, Schultmann F (2017) Biomass value chain design: a case study of the upper rhine region. Waste Biomass Valor 8(7):2313–2327

Santibanez-Gonzalez ED (2017) A modelling approach that combines pricing policies with a carbon capture and storage supply chain network. J Clean Prod 167:1354–1369

Sharma B, Ingalls R, Jones C, Khanchi A (2013) Biomass supply chain design and analysis: basis, overview, modeling, challenges, and future. Renew Sustain Energy Rev 24:608–627

Singh J, Panesar B, Sharma S (2010) A mathematical model for transporting the biomass to biomass based power plant. Biomass Bioenergy 34(4):483–488

Wong KY, Chuah JH, Hope C (2016) Carbon taxation in Malaysia: insights from the enhanced PAGE09 integrated assessment model. Carbon Manag 7(5–6):301–312

Yee KF, Tan KT, Abdullah AZ, Lee KT (2009) Life cycle assessment of palm biodiesel: revealing facts and benefits for sustainability. Appl Energy 86:S189–S196

Yue D, You F, Snyder SW (2014) Biomass-to-bioenergy and biofuel supply chain optimization: overview, key issues and challenges. Comput Chem Eng 66:36–56

Zakeri A, Dehghanian F, Fahimnia B, Sarkis J (2015) Carbon pricing versus emissions trading: a supply chain planning perspective. Int J Prod Econ 164:197–205

Zhu X, Yao Q (2011) Logistics system design for biomass-to-bioenergy industry with multiple types of feedstocks. Biores Technol 102(23):10936–10945

Zhu X, Li X, Yao Q, Chen Y (2011) Challenges and models in supporting logistics system design for dedicated-biomass-based bioenergy industry. Biores Technol 102(2):1344–1351