CHEMICAL ENGINEERING TRANSACTIONS

VOL. 81, 2020

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Petar S. Varbanov, Qiuwang Wang, Min Zeng, Panos Seferlis, Ting Ma, Jiří J. Klemeš

ISBN 978-88-95608-79-2; **ISSN** 2283-9216

DOI: 10.3303/CET2081184

Modeling Near-Term Bioenergy Strategy to Meet the Emission Target: Production of Solid Biofuel to Scale Up Co-Firing

Muhammad Nurariffudin Mohd Idris, Haslenda Hashim*

School of Chemical and Energy Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Skudai, Johor, Malaysia
haslenda@utm.my

The present work presented the application of a spatio-temporal techno-economic supply chain model for the modeling of near-term bioenergy strategy to meet the emission target through the co-firing of biomass with coal. Multi-level solid biofuel production capacities for the purpose of scaling up the maximum co-firing share in coal plants were incorporated into the studied supply chain configuration. Scenarios related to the near-term CO_2 emission target were developed and analyzed. The findings have shown that higher commitment of emission reduction will impact the choices of the biomass pre-treatment technologies and the scales needed. Co-firing is capable of contributing toward the achievement of more ambitious emission reduction than the targeted but highlighting the need for policy to financially supporting the near-term deployment.

1. Introduction

As coal is expected to dominate the electricity generation mix of Malaysia in the next few decades (IEA, 2015), meeting the near-term Nationally Determined Contribution (NDC) remains challenging at the country's level if the necessary shift toward renewable-based economy is not promptly taken into action. One of the promising strategies to mitigate greenhouse gas (GHG) emission resulted from coal-based electricity generation is through the substitution of coal with biomass in the existing power plants. Despite the large-scale availability of coal power plants that can be leveraged to increase the renewables share of the country's energy mix, there are several limitations hindering the implementation of this strategy. These include the technical limitation of maximum co-firing share in the coal plants (Truong et al., 2019), the limited availability of processing/collection facilities to mobilize biomass use at the national scale (Nurariffudin et al., 2018), the scatterly distributed sources of biomass (Furubayashi and Nakata, 2018), and the lower energy value and high moisture content of raw biomass which are unattractive for co-firing (Khorshidi et al., 2014).
Previous assessments have been made to address several of the issues mentioned in the most recent years: Cutz et al. (2019) presented a techno-economic evaluation done in a multi-country scale to examine the cost-effectively way to transform coal-fired boilers into co-firing; Truong et al. (2019) examined the opportunities to mitigate the CO_2 emission of Vietnam's coal plants through the deployment of multiple co-firing technologies under the influence of carbon price; Furubayashi and Nakata (2018) evaluated the costs and the CO_2 emissions of biomass pre-treatment technologies for the co-firing of waste wood biomass in Japan's coal plants; Nurariffudin et al. (2018) developed an integrated resource planning framework to investigate the location-allocation of biomass supply facilities for co-firing. However, no study has been made dynamically to investigate the impact of multi-level production of solid biofuel from local biomass resources for the purpose of scaling up the maximum co-firing share of the coal plants to meet the NDC's emission target. This study was conducted to address the aforementioned research gap through the application of a spatio-temporal techno-economic supply chain model for modeling and scenario analysis. Aside from its aim to inform near-term policies, this study also presented a harmonized techno-economic and logistic dataset related to the production of solid biofuel from the selected oil palm biomass, which will be useful in the future for studies related to energy planning and bioenergy

Paper Received: 13/06/2020; Revised: 22/06/2020; Accepted: 23/06/2020
Please cite this article as: Idris M.N.M., Hashim H., 2020, Modeling Near-Term Bioenergy Strategy to Meet the Emission Target Production of Solid Biofuel to Scale Up Co-Firing, Chemical Engineering Transactions, 81, 1099-1104 DOI:10.3303/CET2081184

supply chain. Findings from this study are expected to improve the understanding on the implementation of fuel switching strategy at the national scale, and highlight the important role of co-firing to meet the emission target.

2. Method and input datasets

The modeling framework adopted in this study was based on the BeWhere Malaysia model (IIASA, 2020), integrated with the supply chain configuration for biomass co-firing. The framework consists of the following modeling procedures: the spatial analysis for identifying the feedstock availability, potential facility locations, coal plant locations, demand projections, and land availability constraints; the network analysis for establishing the transport cost networks between the spatial grids; the input and output data processing of the techno-economic and emission parameters; the optimization work using Mixed-Integer Linear Programming (MILP); and the scenario analysis. A spatial resolution of 0.25° (25 km x 25 km) was applied, consisting of 560 spatial grid points that cover both Peninsular Malaysia and Malaysia Borneo region and a short-term planning period with a time-step of 2 y was employed in the model from 2020 to 2030. The supply chain configuration incorporated in the model includes the flow of resources from the supply to the intermediate processing, from the intermediate processing to the main processing (co-firing plants) and from the main processing to the demand. The model's objective is to minimize the total cost of the energy supply chain:

$$min\ Cost_{supplychain} + Emission_{supplychain} Price_{CO_2} \quad (1)$$

where $Cost_{supplychain}$ refers to the total cost of the supply chain, $Emission_{supplychain}$ refers to the total emission of the supply chain, and $Price_{CO_2}$ refers to the carbon price.

The biomass types considered in this study were empty fruit bunch (EFB), oil palm frond (OPF) and oil palm trunk (OPT); the solid biofuel production technologies considered were drying (50,000 t/y, 100,000 t/y, 150,000 t/y), pelletization (100,000 t/y, 250,000 t/y, 500,000 t/y) and torrefaction (100,000 t/y, 250,000 t/y, 500,000 t/y); the feeding technology considered for co-firing was biomass co-milling; and the transport modes considered were truck (90 % load factor) and shipping (80% load factor). Coal-based electricity generation cost and CO_2 emission factor at 74 USD/MWh and 0.87 t/MWh were used as the reference fossil fuel cost and emission. The maximum co-firing share of each coal plant unit was limited by the type of biomass used: maximum of 5 % (dried biomass), 20 % (pelletized biomass) and 40 % (torrefied biomass) of the coal plant capacity can be substituted based on the limitations outlined by Khorshidi et al. (2014). The spatial distribution of the combined biomass availability is illustrated in Figure 1, the lower heating value (LHV) and the moisture content (MC) of each biomass states are presented in Table 1, the solid biofuel production technology cost information consists of capital expenditure (CAPEX), fix operation and maintenance (O&M) cost, and variable O&M cost is compiled in Table 2, and the biomass price, the transport cost and the transport emission factor are outlined in Table 3. All cost parameters were adjusted based on 2017's monetary value and all emission parameters were based on CO_2 equivalent unit. Other process-based emissions such as SO_2 and NO_2 were not accounted in the modeling.

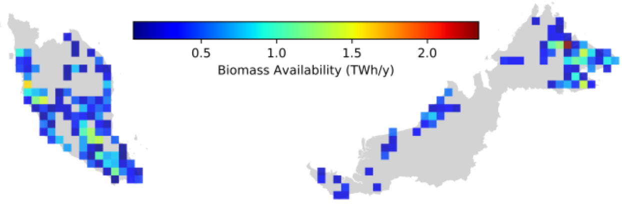

Figure 1: Spatial distribution of the combined biomass availability (EFB, OPF and OPT) in Malaysia

Table 1: LHV and MC of each state of biomass (raw, dried, pelletized, torrefied). Noted that energy yield for conversion to each state of biomass was based on the MC value assumed

	Raw biomass			Dried biomass			Pelletized biomass			Torrefied biomass		
	LHV (MJ/t)	MC (%)	Reference	LHV (MJ/t)	MC (%)	Reference	LHV (MJ/t)	MC (%)	Reference	LHV (MJ/t)	MC (%)	Reference
EFB	6,228	67	Loh (2017)	15,102	20	Calculated	16,990	10	Calculated	19,440	3	Uemura et al. (2011)
OPF	4,557	71	Loh (2017)	12,574	20	Calculated	14,146	10	Calculated	24,403	3	Matali et al. (2017)
OPT	4,191	76	Loh (2017)	13,974	20	Calculated	15,721	10	Calculated	21,232	3	Chin et al. (2013)

Table 2: Solid biofuel production technology cost information

	Size 1 (MW)	Size 2 (MW)	Size 3 (MW)	CAPEX 1 (USD /MWh)	CAPEX 2 (USD /MWh)	CAPEX 3 (USD /MWh)	Fix O&M 1 (USD /MWh)	Fix O&M 2 (USD /MWh)	Fix O&M 3 (USD /MWh)	Variable O&M (USD /MWh)	Calculated based on:
Drying (EFB)	26	52	79	0.828[a]	0.673[a]	0.596[a]	0.244[a]	0.198[a]	0.175[a]	3.58[b]	[a]Chai and Saffron (2016); [b]Adams et al. (2013)
Drying (OPF)	22	44	65	0.994[a]	0.808[a]	0.715[a]	0.293[a]	0.238[a]	0.211[a]	4.30[b]	
Drying (OPT)	24	49	73	0.895[a]	0.727[a]	0.644[a]	0.264[a]	0.214[a]	0.190[a]	3.87[b]	
Pelletization (EFB)	59	147	295	1.158[c]	0.879[c]	0.714[c]	0.523[d]	0.397[d]	0.323[d]	5.25[b]	[c]Agar et al. (2013); [d]Batidzirai et al. (2013); [b]Adams et al. (2013)
Pelletization (OPF)	49	123	246	1.390[c]	1.056[c]	0.858[c]	0.628[d]	0.477[d]	0.387[d]	6.31[b]	
Pelletization (OPT)	55	136	273	1.251[c]	0.950[c]	0.772[c]	0.565[d]	0.429[d]	0.349[d]	5.68[b]	
Torrefaction (EFB)	68	169	338	1.698[c]	1.290[c]	1.048[c]	0.767[d]	0.583[d]	0.473[d]	4.99[b]	[c]Agar et al. (2013); [d]Batidzirai et al. (2013); [b]Adams et al. (2013)
Torrefaction (OPF)	85	212	424	1.353[c]	1.028[c]	0.835[c]	0.611[d]	0.464[d]	0.377[d]	3.97[b]	
Torrefaction (OPT)	74	184	369	1.555[c]	1.181[c]	0.959[c]	0.702[d]	0.534[d]	0.433[d]	4.57[b]	

Table 3: Biomass supply cost and emission information. Noted that the datasets for the calculations of truck-related cost and shipping-related cost were adapted from How et al. (2016) and Rentizelas and Li (2016).

	Biomass price (USD/MWh)		Loading/unloading cost (USD/MWh)		Transport cost (USD/MWh/km)		Transport emission (kg CO_2/MWh/km)	
	2020	2030	Truck	Ship	Truck	Ship	Truck	Ship
EFB (Raw)	7.81	8.20	1.44504	3.86315	0.04728	0.00108	0.06685	0.00405
OPF (Raw)	8.21	8.62	1.97517	5.28040	0.06463	0.00148	0.09137	0.00553
OPT (Raw)	8.93	9.38	2.14770	5.74163	0.07027	0.00160	0.09935	0.00601
EFB (Dried)	-	-	0.59594	1.59318	0.01950	0.00045	0.02757	0.00167
OPF (Dried)	-	-	0.71575	1.91349	0.02342	0.00053	0.03311	0.00200
OPT (Dried)	-	-	0.64405	1.72179	0.02107	0.00048	0.02979	0.00180
EFB (Pelletized)	-	-	0.52972	1.41614	0.01733	0.00040	0.02450	0.00148
OPF (Pelletized)	-	-	0.63621	1.70084	0.02082	0.00048	0.02943	0.00178
OPT (Pelletized)	-	-	0.57247	1.53045	0.01873	0.00043	0.02648	0.00160
EFB (Torrefied)	-	-	0.46296	1.23768	0.01515	0.00035	0.02142	0.00130
OPF (Torrefied)	-	-	0.36880	0.98594	0.01207	0.00028	0.01706	0.00103
OPT (Torrefied)	-	-	0.42390	1.13324	0.01387	0.00032	0.01961	0.00119

3. Results and discussions

Three main scenarios were developed in providing the basis to the overall analysis, namely: EMT – the scenario where unconditional CO_2 emission reduction target based on the Malaysia's NDC (MESTECC, 2018) is defined at each planning period in the model; EMT_CUM – the scenario where the EMT targets are defined cumulatively in the model based on the total CO_2 emission reduction commitment from 2020 to 2030, EMT_MIN – the scenario where the minimization of the total emission is defined as the objective function of the model.

Figure 1 presents the trends of electricity generation from co-firing for each scenarios. Both of the NDC's related scenarios (EMT and EMT_MIN) have shown the importance of biomass pelletization in contributing to the substantial portions of co-fired electricity generation on top of coal. This can be translated to an increase of co-firing capacity from 7 TWh in 2020 to 28 TWh in 2030 in the EMT scenario, and contrast trend can be observed in the EMT_CUM scenario where the co-firing capacity increases at the minimal rate from 18 TWh in 2020 to 21 TWh in 2030. Since the target in the latter scenario was defined cumulatively, the model optimizes the annual co-firing capacities to acquire less system cost compared to the former scenario. As the maximum generation capacity of co-firing plant is higher in EMT than EMT_CUM, higher co-firing share is required in the former, contributing to the utilization of torrefied biomass as boiler fuel starting from 2026. Maximum potential of co-firing capacity that can be deployed at the national level is shown in the EMT_MIN scenario where up to 41 TWh of co-firing capacity can be implemented by 2030. This scenario highlights the important role of torrefied biomass utilization for co-firing in meeting more ambitious emission reduction target. The co-firing capacity shares contributed by each of the existing coal plants are illustrated in Figure 2.

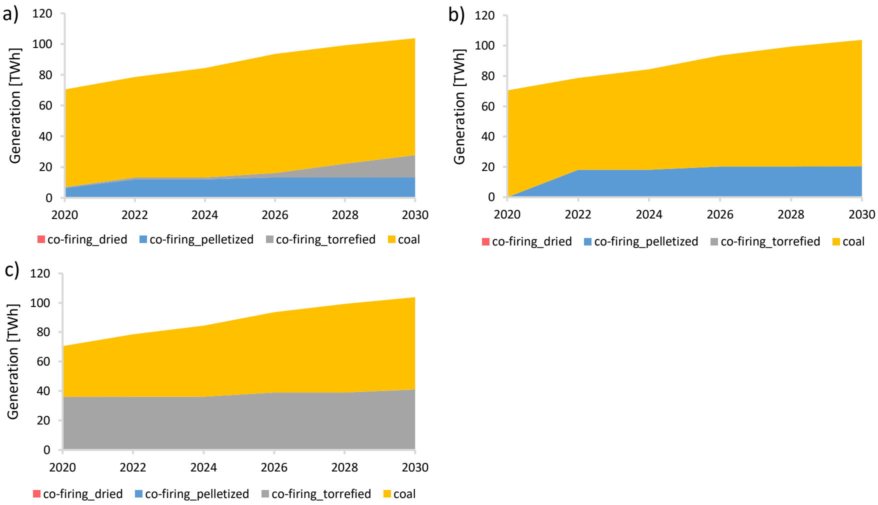

Figure 1: Electricity generation trends for each scenario: a) EMT, b) EMT_CUM, c) EMT_MIN.

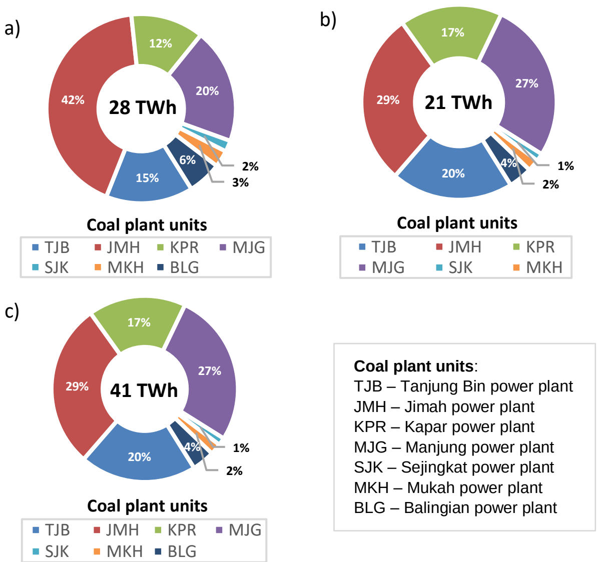

Figure 2: Co-fired electricity generation in the existing coal plants at 2030: a) EMT, b) EMT_CUM, c) EMT_MIN

The CO_2 emission reduction potentials follow closely to the rate of co-fired electricity generated in each scenario as shown in Figure 3a. Up to 29 Mt CO_2/y of emission reduction can be achieved by 2030 as shown in EMT_MIN, followed by 20 Mt CO_2/y and 15 Mt CO_2/y in EMT and EMT_CUM. The minimization of system cost due to the optimized annual capacity in EMT_CUM compared to EMT is shown in Figure 3b where EMT_CUM illustrates lesser annual cost approaching to 2030. This can be translated to 51 % and 26 % of annual cost savings in 2028 and 2030. The minimum avoidance cost is observed at 39 USD/t CO_2 in EMT_CUM while the maximum avoidance cost is observed at 78 USD/t CO_2 in EMT_MIN when the CO_2 emission is minimized at its full potential.

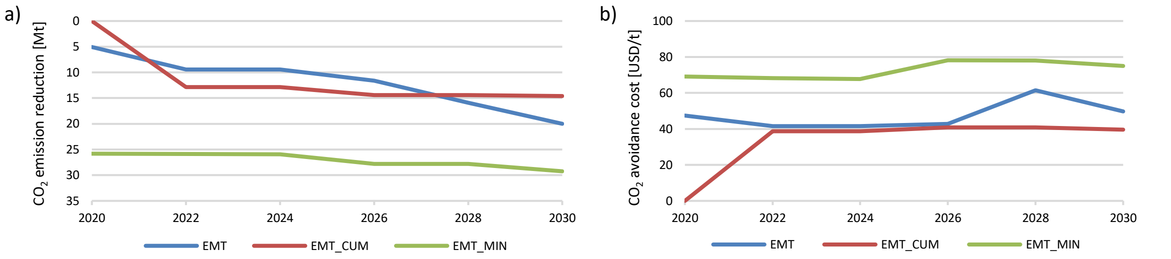

Figure 3: Emission and cost associated with each scenario: a) CO_2 emission reduction, b) CO_2 avoidance cost

Distributions of the supply chain cost of solid biofuel in each scenario at 2030 are shown in Figure 4 where the reference coal price at 11 USD/MWh is compared with the solid biofuel production costs. All scenarios illustrate higher unit price of solid biofuel production compared with the coal price. To substitute portion of coal in the existing boilers, more than double of price increase of the input boiler fuel (solid biofuel) compared to coal price can be observed in the EMT scenario while approximately thrice price increase can be seen in the EMT_MIN scenario. The solid biofuel production cost in the EMT scenario can be minimized by 16 % when EMT_CUM strategy is implemented. The highest cost share is contributed by the feedstock cost at range of 37 % to 42 %, followed by the overall transport cost (including shipping) at range of 21 % to 37 % and the operating expenditures (OPEX) of pre-treatment technology at approximately 11 % of cost share.

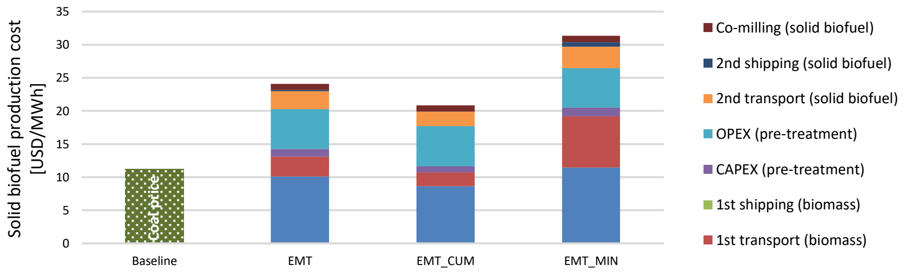

Figure 4: Comparison of the solid biofuel production cost with the reference coal price at 2030

The multi-scale production capacities of solid biofuel for each scenario are illustrated in Figure 5. It can be observed that higher commitment of emission reduction will impact the choices of the pre-treatment technologies and the scales needed. For instance, torrefaction are needed to meet the ambitious emission reduction in EMT_MIN as it posseses the highest allowable co-firing share while only pelletization is needed when less stringent annual emission reduction is optimized in EMT_CUM compared to EMT. Drying facilities would only be needed when lower emission target than the NDC's target is applied.

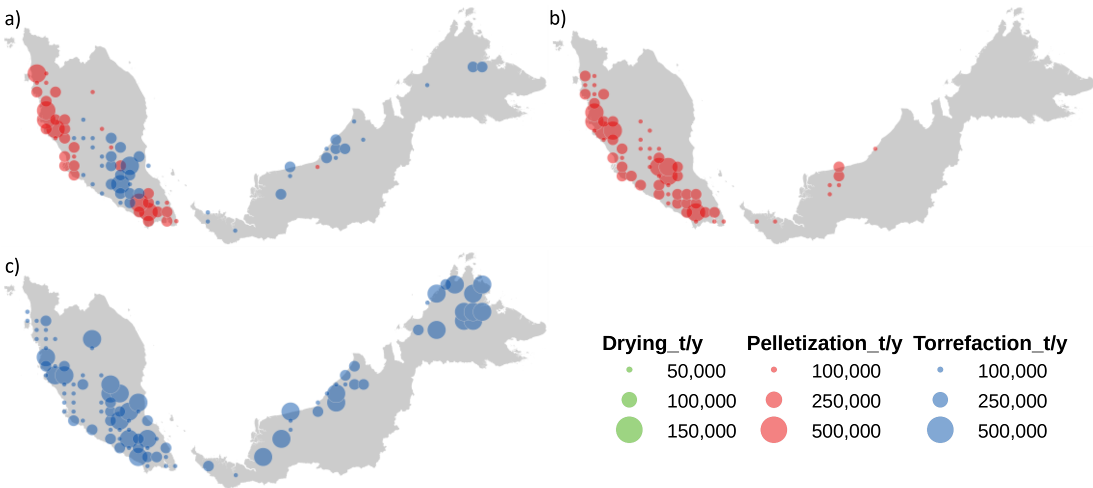

Figure 5: Spatial distributions of solid biofuel production facilities at 2030: a) EMT, b) EMT_CUM, c) EMT_MIN

4. Conclusions

The application of a spatio-temporal techno-economic supply chain model was successfully demonstrated to examine the policy scenarios related to the scaling up of co-firing capacity in Malaysia's coal plants through the proposed multi-level production of solid biofuel from oil palm biomass to enhance the maximum co-firing share. The findings have been showing that co-firing is capable to mitigate up to 20 Mt/y of CO_2 emission by 2030 to meet the unconditional NDC's target but requiring high level of emission avoidance cost at up to 62 USD/t CO_2. This cost can be potentially minimized through the re-structuring of annual CO_2 emission targets as shown in the alternative scenario where the cost can be reduced by up to 51 %. To further explore the strategy to minimize the cost of deploying oil palm-based bioenergy at the national scale, more comprehensive bioenergy chains should be considered in the future assessment which include other technological pathway on top of co-firing.

Acknowledgements

The authors would like to acknowledge the research funds provided to support this work under Vote No. R.J130000.7309.4B397 and Q.J130000.2409.08G96.

References

Adams P.W.R., Shirley, J.E.J., McManus M.C., 2015, Comparative cradle-to-gate life cycle assessment of wood pellet production with torrefaction, Applied Energy, 138, 367–380.

Agar D.A., 2017, A comparative economic analysis of torrefied pellet production based on state-of-the-art pellets, Biomass and Bioenergy, 97, 155–161.

Batidzirai B., Mignot A.P.R., Schakel W.B., Junginger H.M., Faaij A.P.C., 2013, Biomass torrefaction technology: Techno-economic status and future prospects, Energy, 62, 196–214.

Chai L., Saffron C.M., 2016, Comparing pelletization and torrefaction depots: Optimization of depot capacity and biomass moisture to determine the minimum production cost, Applied Energy, 163, 387–395.

Chin K.L., H'ng P.S., Go W.Z., Wong W.Z., Lim T.W., Maminski M., Paridah M.T., Luqman A.C., 2013, Optimization of torrefaction conditions for high energy density solid biofuel from oil palm biomass and fast growing species available in Malaysia, Industrial Crops and Products, 49, 768–774.

Cutz L., Berndes G., Johnsson F., 2019, A techno-economic assessment of biomass co-firing in Czech Republic, France, Germany and Poland, Biofuels, Bioproducts and Biorefining, 13 (5), 1289–1305.

Furubayashi T., Nakata T., 2018, Cost and CO_2 reduction of biomass co-firing using waste wood biomass in Tohoku region, Japan, Journal of Cleaner Production, 174, 1044–1053.

How B.S., Tan K.Y., Lam H.L., 2016, Transportation decision tool for optimisation of integrated biomass flow with vehicle capacity constraints, Journal of Cleaner Production, 136, 197–223.

IEA, 2016, Southeast Asia energy outlook – World energy outlook special report, International Energy Agency, <www.iea.org>, accessed 20.01.2019.

IIASA, 2020, the BeWhere Malaysia model, International Institute for Applied Systems Analysis, <www.iiasa.ac.at/bewhere>, accessed 05.04.2020.

Khorshidi Z., Ho M.T., Wiley D.E., 2014, The impact of biomass quality and quantity on the performance and economics of co-firing plants with and without CO_2 capture, International Journal of Greenhouse Gas Control, 21, 191–202.

Matali S., Rahman N.A., Idris S.S., Yaacob N., 2017, Combustion properties, water absorption and grindability of raw/torrefied biomass pellets and Silantek coal, AIP Conference Proceedings, 1901 (1), p100005.

MESTECC, 2018, Third national communication and second biennial update report to the UNFCCC, Ministry of Energy, Science, Technology, Environment and Climate Change, <www.mestecc.gov.my/web/wp-content/uploads/2019/04/10.Malaysia-3rd-National-Communication-and-2nd-Biennial-Update-Report-to-UNFCCC-NC-3-BUR-21.pdf>, accessed 03.11.2019.

Nurariffudin M., Hashim H., Lee C.T., 2018, Spatial biomass resource planning framework for co-firing under carbon policy scheme, Chemical Engineering Transactions, 63, 445–450.

Rentizelas A.A., Li J., 2016, Techno-economic and carbon emissions analysis of biomass torrefaction downstream in international bioenergy supply chains for co-firing, Energy, 114, 129–142.

Truong A.H., Patrizio P., Leduc S., Kraxner F., Ha-Duong M., 2019, Reducing emissions of the fast growing Vietnamese coal sector: the chances offered by biomass co-firing, Journal of Cleaner Production, 215, 1301–1311.

Uemura Y., Omar W.N., Tsutsui T., Yusup S.B., 2011, Torrefaction of oil palm wastes, Fuel, 90 (8), 2585–2591.