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Evaluation of Decarbonisation Pathways for Palm Oil Mills Integrated with Carbon Capture and Storage

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Malaysia is the second largest producer and exporter of palm oil products. The palm oil industry generates significant amounts of by-products during the extraction of crude oil from oil palm fruits. This presents opportunities for energy generation and production of green products, thus contributing to emissions reduction efforts. Especially, the palm by-products have potential to align with the country's focus on green hydrogen, bioenergy, carbon capture and storage (CCS). Therefore, this study presents a systematic approach to evaluate the decarbonisation potential of palm oil industry by integrating hydrogen production and CCS pathways. A case study involving 24 palm oil mills in Sarawak state in Malaysia is used to demonstrate the proposed analysis. The results show that pathway involving biomass power generation, steam methane reforming, and CCS results in the highest emissions reduction potential between 3.7 – 4 $MtCO_2$-eq/y.

1. Introduction

Malaysia has announced its aim to achieve net-zero emissions by 2050. To achieve this target, the government has published the National Energy Transition Roadmap (NETR) in 2023. NETR has identified six energy transition levers pivotal to achieve the country's climate targets. These include energy efficiency, renewable energy, hydrogen, bioenergy, green mobility, and carbon capture utilisation and storage (CCUS). Notably, the roadmap proposes to achieve 2.5 Mt/y (MTPA) of green hydrogen production, 1.4 GW of bioenergy power generation, and develop 40 – 80 MTPA of carbon dioxide (CO_2) storage capacity as part of the energy transition strategy (MoE, 2023). The palm oil industry, which generates substantial amounts of biomass, has the largest potential to align with these targets.

Malaysia is the second largest producer and exporter of palm oil in the world (MPOB, 2024). Palm oil mills process the fresh fruit bunches (FFBs) to produce crude palm oil (CPO) as the primary product. Besides CPO, the mills also generate by-products such as palm mesocarp fiber (PMF), palm kernel shell (PKS), empty fruit bunch (EFB), and palm oil mill effluent (POME). If such by-products are left untreated, emit substantial greenhouse gas (GHG) emissions. However, with proper processing, they present opportunities for energy generation and the production of green products, thus contributing to emissions reduction efforts. Over the years, the Malaysian government has undertaken various initiatives to harness palm-based biomass. For example, the palm oil mills in Malaysia utilise PMF and PKS as boiler fuels to meet the power and steam requirements of the milling process. With the introduction of the Feed-in Tariff scheme in 2011, it enabled palm oil mills to export surplus power to the national grid, incentivising the industry to increase the utilisation of PMF and PKS. Similarly, in 2014, the government mandated that all new palm oil mills and expansions of existing ones must install biogas facilities to avoid methane emissions from POME degradation. As of 2021, about 35 % of palm oil mills have installed biogas facilities (Bernama, 2022).

Despite these progresses, significant amounts of biomass remain unutilised. Though PMF has very high utilisation, EFB utilisation remains minimal while PKS provides opportunities for increased domestic utilisation (currently most of the excess PKS and some of the EFB at palm oil mills is exported to Asian markets as boiler

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fuel). One of the major reasons that hinders the use of these biomass materials is the lack of economics of scale in developing a profitable venture. An independent palm oil mill may find it economically infeasible to utilise all the biomass. Moreover, since most of the palm oil mills are located in the hinterlands, transportation of biomass remains a major challenge. With respect to POME, though biogas facilities have seen increased adoption, there is no ready market for the produced biogas. This results in some of the palm oil mills to flare the biogas, missing out on revenue generation and emission reduction. Recently, the National Biomass Action Plan (NBAP) released by the Ministry of Plantation and Commodities, has proposed clustering of palm oil mills to address the above-stated issues.

Besides, Malaysia has identified 16 offshore depleted oil and gas fields for CO_2 storage with a total capacity of more than 46 trillion cu ft. Notably, 40 % of this capacity is designated for non-oil and gas industries (MPM, 2021). This presents an opportunity for palm oil mills to capture the biogenic carbon emissions from the combustion of biomass, resulting in negative emissions (i.e., emissions removal).

In this study, a systematic approach is presented to evaluate decarbonisation of palm oil industry integrated with hydrogen production and CCS pathways. This work proposes clustering of palm oil mills with each cluster consisting of a biorefinery. The palm-based biomass PMF, PKS, and EFB are transported to the biorefinery while POME is anaerobically treated at the mill and the generated biogas is transported to the biorefinery for further processing. The biorefinery consists of biomass conversion technologies such as biomass power plants, gasifiers, steam methane reformers, etc offering multiple pathways for producing renewable electricity and green hydrogen. Furthermore, the CO_2 produced at the palm oil mills and biorefineries can be captured and transported to the offshore storage field. A mathematical model is developed in this work to estimate the decarbonisation potential of each pathway, facilitating a high-level analysis to identify the feasibility of hydrogen (H_2) production, CO_2 collection and storage network.

2. Methodology

This section presents methodology employed to evaluate the decarbonisation potential for different utilisation pathways of palm by-products. The study involves two stages. First, the palm oil mills in the considered region are grouped into clusters to achieve economies of scale and logistical efficiency. Later, a mathematical model is developed to evaluate the decarbonisation potential of the different palm byproducts utilisation pathways.

2.1. Cluster analysis

This work used Python programming to perform the clustering. To begin, the geographical coordinates of palm oil mills within the considered region were collected alongside vector data delineating the region's boundaries. The SHAPEFILE and MATPLOT packages were utilised to plot the boundary of the region. Subsequently, the PANDAS package was utilised to plot the coordinates of the palm oil mills. Finally, KMeans algorithm from the SKLEARN package was utilised to perform the clustering of the palm oil mills. The generated results are provided as input to the mathematical model.

2.2. Mathematical model

This section presents the mathematical formulation developed to analyse the decarbonisation potential of different pathways. This work considers a set of palm oil mills $m \in M$ which produce a set of palm byproducts $b \in B$, which includes palm-based biomass like PMF, PKS, and EFB. The palm byproducts $b \in B$ are transported to biorefineries $f \in F$. This work considers one biorefinery facility at each cluster. Hence, the biorefinery receives the palm byproducts only from those palm oil mills as determined previously by the cluster analysis. At the biorefinery, the by-products are processed via biomass conversion technologies $k \in K$ to produce intermediate products $i \in I$. The intermediate products are then transported via transport modes $t \in T$, from biorefinery to the utilisation technologies $u \in U$, where the final products $p \in P$ are produced. Besides, the intermediate product can also be directly transported to the storage fields. The material and energy flows are modelled based on the superstructure in Figure 1. The italic font indicates variables while the non-italic font represents parameters. Some of the key mathematical formulations are discussed as follows - the total byproduct b received by the biorefinery f from the palm oil mills $m \in M$, $F_{b,f}^{\mathrm{BP}}$ (t/y) can be determined as shown in Eq(1).

$$F_{b,f}^{\mathrm{BP}} = \sum_{m}^{M} F_{m,b,f}^{\mathrm{BP}} \, \mathrm{I}_{m,f} \qquad \forall b \, \forall f \tag{1}$$

where, $\mathrm{I}_{m,f}$ is the binary parameter used to constrain the material flow between the palm oil mills and biorefineries based on the cluster analysis. At the biorefinery, the by-products are treated via biomass conversion technologies to produce intermediate products. The amount of intermediate products $i \in I$ produced at biorefinery f, $F_{f,i}^{\mathrm{IP}}$ (t/y) can be determined as shown in Eq(2).

$$F^{IP}_{f,i} = \sum_{b}^{B}\sum_{k}^{K} F^{BP}_{b,f.k}\, X_{b,k,i} \qquad \forall i\, \forall f \qquad (2)$$

where, $X_{b,k,i}$ is the conversion factor of byproduct *b* to intermediate product *i* at biomass conversion technology *k*. The intermediate product *i* is then transported to utilisation technologies or storage fields $u \in U$. The total amount of intermediate product *i* received by utilisation technology or storage field *u*, $F^{IP}_{u,i}$ (t/y) can be determined as shown in Eq(3).

$$F^{IP}_{u,i} = \sum_{f}^{F} F^{IP}_{f,i,u} \qquad \forall i\, \forall u \qquad (3)$$

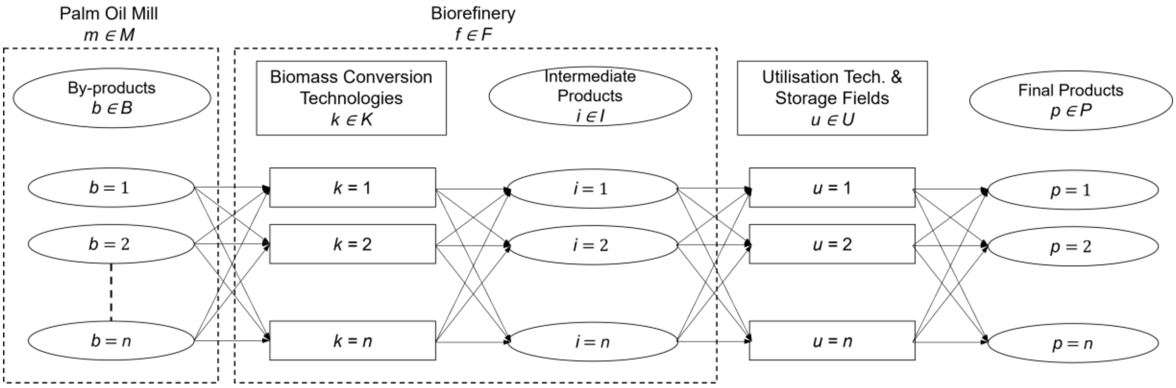

Figure 1: Generic superstructure – palm by-products utilisation pathways

At the utilisation technologies, the intermediate products are processed to final products. The amount of final products $p \in P$ produced via utilisation technology *u*, F^{FP}_{p} (t/y) can be determined as shown in Eq(4).

$$F^{FP}_{p} = \sum_{u}^{U}\sum_{i}^{I} F^{IP}_{u,i} X_{i,u,p} \qquad \forall p \qquad (4)$$

where, $X_{i,u,p}$ is the conversion factor of intermediate product *i* to final product *p*_f$X_{i,u,p}$ value is taken as 1. In this work, the major sources of emissions of the palm oil industry are the emissions from transport and process energy consumption. The amount of emissions from transport, E^{TR} (tCO_2/y) and process energy consumptions, E^{PR} (tCO_2/y) can be determined as shown in Eq(5) and Eq(6).

$$E^{TR} = \sum_{t}^{T}\sum_{f}^{F}\sum_{m}^{M}\sum_{b}^{B} F^{BP}_{m,b,f,t} Z_t + \sum_{t}^{T}\sum_{u}^{U}\sum_{f}^{F}\sum_{i}^{I} F^{IP}_{f,i,u,t} Z_t \qquad (5)$$

$$E^{PR} = \sum_{f}^{F}\sum_{b}^{B}\sum_{k}^{K} F^{BP}_{b,f.k} Z_{b,k} \qquad (6)$$

where, Z_t is the emission factor of transport mode *t* and $Z_{b,k}$ is the emission factor of processing byproduct *b* in biomass conversion technology *k*. Likewise, the amount of carbon emissions removed and avoided can be determined as shown in Eq(7).

$$E^{DC} = \sum_{a}^{A}\sum_{p}^{P} F^{FP}_{p} Z_a \qquad (7)$$

where, Z_a is the emission reduction factor of the final product *p*.

3. Case study

The case study involves 23 palm oil mills in the Miri region of Sarawak state in Malaysia. The geographic coordinates of the palm oil mill, along with their annual FFB throughput, were collected from industrial partners.

In this work, a maximum distance of 40 km is considered in the clustering of the palm oil mills. The amount of palm byproducts generated at the mill are estimated using standard conversion factors of 60 kgs PKS, 140 kgs of PMF, 230 kgs of EFB, and 600 kgs of POME for every 1 ton of FFB processed. Figure 2 shows the schematic of the case study. This case study considers biomass-based power plant (Biomass PP), gasification, and steam methane reforming (SMR) as biomass conversion technologies at the biorefinery. Likewise, cofiring of green H_2 in natural gas power plants (NGPP) and CO_2 offshore storage as utilisation and storage options. The final products produced are electricity, steam, and captured CO_2. The decarbonisation potential is evaluated for four pathways, as described in Table 1. The conversion factors and process energy requirements related to biomass conversion technologies at the palm oil mill and biorefinery are shown in Table 2. Note that emissions reduction due to substitution with palm-based biomass or green hydrogen derived from palm by-products is termed as emissions avoided, while the emissions reduction from CO2 captured and storage is named emissions removal.

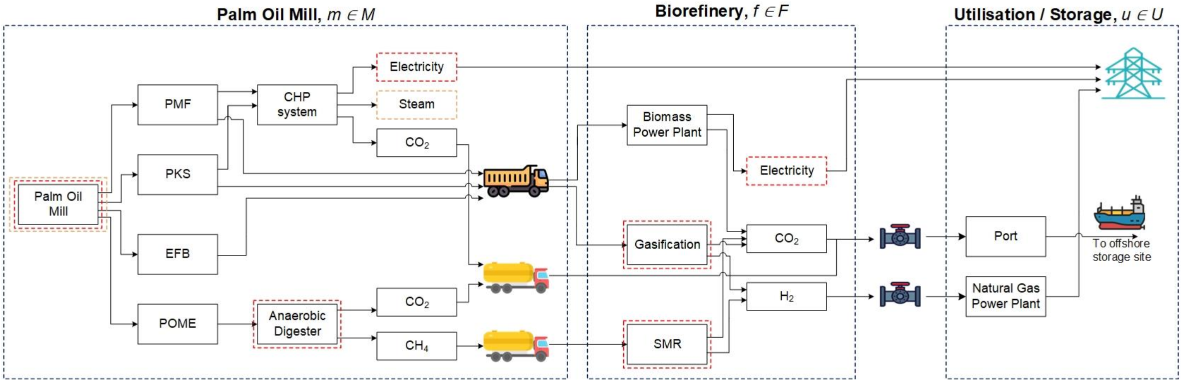

Figure 2: Schematic of the case study superstructure

Table 1: Configuration of biomass conversion pathways

Pathway	Palm Oil Mill	Biorefinery	Utilisation / Storage
P1	CHP system + Anaerobic Digester	Biomass PP + SMR	H_2 cofiring in NGPP
P2	CHP system + Anaerobic Digester	Biomass PP + SMR	H_2 cofiring in NGPP + CO_2 storage in offshore field
P3	CHP system + Anaerobic Digester	Gasification + SMR	H_2 cofiring in NGPP
P4	CHP system + Anaerobic Digester	Gasification + SMR	H_2 cofiring in NGPP + CO_2 storage in offshore field

3.1. Assumptions

The case study considers the following assumptions in performing the analysis,

- CHP system is operational in palm oil mills with a fuel mixing ratio of 80:20 (PMF: PKS). The palm oil mills' power and steam requirements are 20 kWh and 450 kg per t FFB. It is estimated that about 42 % of PMF and 25 % of PKS is consumed by the CHP. Therefore, 58 % of PMF and 75 % of PKS is available for transport to the biorefinery from the palm oil mills.
- The palm oil mills are installed with an anaerobic digester system, which includes a biogas purification and compression system.
- The palm byproducts (PMF, PKS, EFB) and gaseous products (CO_2, CH_4) are transported from the mill to the biorefinery via heavy-duty trucks (10 t) and trailer trucks (40 t). The gaseous products, CO_2, and H_2 from the biorefinery are transported to the port and NGPP via pipeline. Subsequently, the CO_2 from the port is transported to the offshore storage field via tanker ships.
- For illustration purpose, the distance between each palm oil mill to the biorefinery is assumed to be 30 km. Likewise, the distance between the port to offshore storage fields is taken as 500 km.
- The emissions factors of heavy-duty trucks, trailer trucks, and tanker ships are estimated as 0.0315, 0.0158, and 0.0005 $kgCO_2/t{\cdot}km$ based on their fuel economy. The emissions for pipeline transport of H_2 and CO_2 are estimated as 0.32 $kgCO_2/t$ and 0.03 $kgCO_2/t$ based on compressor power requirement.
- The emissions factor of Sarawak power grid is taken 0.222 $kgCO_2/kWh$ as reported by Energy Commission.

Table 2: Palm oil mill and biorefinery process data

Technology / Process	Conversion Factors Electricity (kWh/input)	CH_4 (kg/input)	H_2 (kg/input)	CO_2 (kg/input)	Process Energy Requirement (kWh/output)	Unit input	Ref
CHP system							
Fuel mix (80:20)	1.33	-	-	1.42	-	kg fuel mix	-
Anaerobic digester	-	9.09	-	13.31	4.83*	t POME	Zamri et al. (2022)
Biomass PP							
PMF	1.23	-	-	1.41	-	kg PMF	Zamri et al. (2022)
PKS	1.74	-	-	1.47	-	kg PKS	
EFB	1.65	-	-	1.32	-	kg EFB	
Gasification	-	-	0.04	0.13	0.45**	kg biomass	Loh (2017)
SMR	-	-	0.34	0.25	0.45**	kg CH_4	Loh (2017)
Carbon capture	-`	-	-	0.90	0.30	kg CO_2	-

*Output is CH_4; **output is H_2

4. Results

This section presents the results generated for the above-discussed case study. Figure 3 shows palm oil clustering generated using the methodology discussed in Section 2.1. The decarbonisation potential of the pathways is estimated as discussed in Section 2.2 and is presented in Table 3. The analysis includes two cases – inclusion (Case 1) and exclusion (Case 2) of the biogenic CO_2 emissions from the combustion of biomass. The results show that P2, which involves biomass power plant, SMR, hydrogen cofiring in NGPP, and CO_2 storage yields the highest emissions reduction of about 3.7 $MtCO_2$-eq/y in Case 1 and 4 $MtCO_2$-eq/y in Case 2. It is worth noting that P1, which excludes CCS from P2, results in net emissions when biogenic emissions are accounted for. Apart from this, P4 involving SMR and gasification also results in substantial removal of 1.9 - 2 $MtCO_2$-eq. Table 4 shows the contribution of emissions sources and the emissions reductions achieved through different options for Case 1. It can be noted that CCS accounts for 72.4 % and 45.6 % of CO_2 removal in P2 and P4. Besides, emissions reductions due to the cofiring of H_2 are higher in pathways with gasification and SMR, P3 and P4.

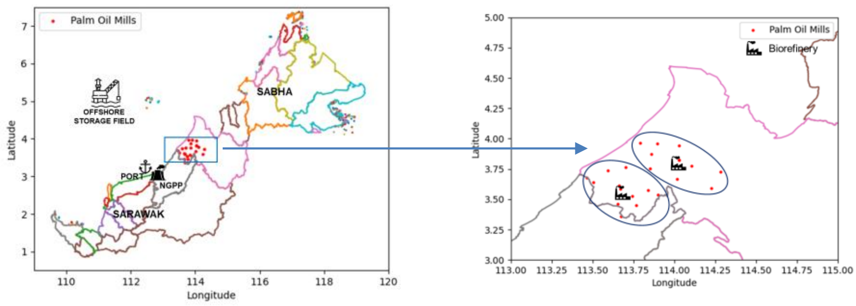

Figure 3: Palm oil mill clusterting – Miri region, Sarawak state, Malaysia

Table 3: Decarbonisation potential of pathways

Pathway	Emissions, (tCO_2-eq/y) POM*	BR**	Transport	Emissions avoidance & removal, (tCO_2-eq/y) POM*	BR**	NGPP***	Storage	Net emission (tCO_2-eq/y)
Case 1 – Inclusion of biogenic emissions								
P1	801,175	2,516,786	6,346	524,143	537,046	74,810	0	2,189,140
P2	75,692	251,679	108,174	524,143	537,046	74,810	2,986,913	-3,687,264
P3	801,175	261,851	29,535	524,143	0	606,743	0	-39,343
P4	75,692	33,624	56,054	524,143	0	606,743	949,285	-1,915,820
Case 2 – Exclusion of biogenic emissions								
P1	44,256	7,481	6,346	524,143	537,046	74,810	0	-1,077,916
P2	0	748	108,174	524,143	537,046	74,810	2,986,913	-4,013,990
P3	44,256	261,851	29,535	524,143	0	606,743	0	-795,244
P4	0	33,624	56,054	524,143	0	606,743	949,285	-1,990,493

*POM – Palm oil mill; ** BR – Biorefinery; *** NGPP – Natural gas power plant

Table 4: Contribution of emission sources and reduction options

Pathway	P1	P2	P3	P4
Total CO_2 emissions (tCO_2-eq/y)	*3,324,307*	*435,545*	*1,092,561*	*165,370*
Biomass combustion in CHP	22.8 %	17.4 %	69.3 %	45.8 %
Process emissions from anaerobic digestor	1.3 %	0.0 %	4.1 %	0.0 %
Combustion in Biomass PP	75.5 %	57.6 %	0.0 %	0.0 %
Energy for SMR process	0.0 %	0.0 %	0.1 %	0.6 %
Process emissions from SMR	0.2 %	0.2 %	0.7 %	0.5 %
Process emissions from Gasification	0.0 %	0.0 %	22.5 %	14.9 %
Energy for gasification process	0.0 %	0.0 %	0.7 %	4.4 %
Transport emissions	0.2 %	24.8 %	2.7 %	33.9 %
Total CO_2 avoidance & removal (tCO_2-eq/y)	*1,135,999*	*4,122,164*	*1,130,886*	*2,080,171*
Replacement of grid power with CHP system	5.6 %	1.6 %	5.7 %	3.1 %
Replacement of diesel boiler with CHP system	40.5 %	11.2 %	40.7 %	22.1 %
Biomass power generation	47.3 %	13.0 %	0.0 %	0.0 %
Hydrogen co-firing in NGPP	6.6 %	1.8 %	53.7 %	29.2 %
CO_2 offshore storage	0.0 %	72.4 %	0.0 %	45.6 %

5. Conclusion

This work evaluates the decarbonisation potential of the palm oil industry by integrating hydrogen production and CCS pathways. The results show that biomass power generation and SMR with CCS yield the highest emissions reduction compared to gasification, SMR and CCS configuration. The other pathways without CCS also yield significant emissions reduction. Though this study has analysed the decarbonisation potential of pathways, the economic feasibility of these pathways needs further investigation. Additionally, it is noted that the developed model included several simplifications of the pathway conversions, which is a limitation of this study.

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