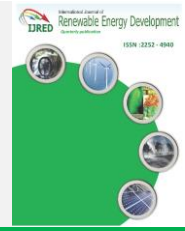




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Research Article

Supply and Demand Characteristics of Palm Kernel Shell as a Renewable Energy Source for Industries

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Abstract. Depleting stockpile of fossil fuels and rising global temperature due to the greenhouse effect are probably the two most threatening factors to civilization sustainability. Converting biomass into a readily available energy source will help reduce dependency on fossil fuels, whilst at the same time moderating greenhouse gas emissions due to its carbon neutrality. Palm oil industry is the largest source of biomass in Indonesia and the available quantity to be utilized is growing inline with the steady growth of the generating industry. Among various wastes from palm oil processing, palm kernel shell is an oil palm biomass with high potential to be applied as a source of energy, given its high caloric value and distinctive physical properties. This source of renewable energy can be utilized by industries with thermal conversion processes. As a prerequisite, a feasibility study on technical, environmental, and economic aspects needs to be carried out. From long term perspective, supply, demand, and regulatory situational analysis will also be required. Lastly, a review on the existing palm kernel shell supply chain will help to understand its current situation. Based on literature studies and field observations, we have identified supply and demand characteristics that will be valuable in constructing an effective, efficient, and sustainable supply chain model of palm kernel shell. Understanding these characteristics is a precursor in realizing this massive potential of renewable energy source in the industrial context.

Keywords: biomass supply chain, industrial energy, palm kernel shell, palm oil industry, renewable energy

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1. Introduction

In the global context, depleting stockpile of fossil fuels and rising global temperature due to the greenhouse effect are probably the two most threatening factors to civilization sustainability. The detrimental effects of burning fossil fuels to the environment from carbon dioxide emission have been recognised, particularly by damaging the biosphere through environmental degradation and increasing overall pollution (Lim & Lam 2015; Anwar & Elgaki 2021). Even with the most recent pandemic of Covid-19 that causes considerable global economic downturn, it is predicted that CO₂ emissions remain at a high level despite a decreasing trend (Le Quéré *et al.* 2020). Therefore, it is inevitable that the energy-mix to support civilization must be shifted away from unsustainable fossil fuels to renewable sources, such as biomass (Lim & Lam 2015). Converting biomass into readily available energy source helps to reduce dependency on oil (Martins *et al.* 2019), whilst at the same time moderating greenhouse gas (GHG) emission due to its carbon neutrality (McDermott *et al.* 2015).

Indonesia, with its massive availability of plant-based resources, has a strategic advantage to foster its biomass potential with an estimate of more than 30,000 MWe in 2020 (DitjenEBTKE 2020). Palm oil industry is the largest source of biomass in Indonesia and the available quantity to be utilized is growing along with the steady growth of the generating industry (Hambali & Rivai 2017). The biomass come from various stages of processing in crude palm oil (CPO) and palm kernel oil (PKO) mills. Oil palm plantation generates biomass in the form of trunks and fronds, by which 50% of biomass are retained in the plantation for soil management and the rest are removed (Loh 2017). Processing of the main products, CPO and PKO, generate solid and liquid wastes, all with rich carbon content of around 50% (w/w) or more, which make them good sources of renewable energy (Loh 2017; Susanto *et al.* 2017).

Palm kernel shell (PKS) is the result of mechanical separation process of palm nut at a palm oil mill (POM), with a quantity of around 26.7 tonnes of PKS for every 100 tonnes of CPO produced (Hambali & Rivai 2017). PKS is a good source of energy for industries with thermal conversion processes (Poh *et al.* 2020). This is the reason

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why PKS is chosen as a potential renewable energy source for industries in this study.

Industries will commercially use PKS as biomass fuel, if PKS supports industries' processing requirements. Additionally, as an input, PKS supply chain must be integrated with industries' operation management system. Therefore, it is important to design an effective, efficient, and sustainable supply chain model from the source of generation up to the point of consumption. Prior to designing such a model, we intend to answer a question on what the key aspects of PKS are, as an oil palm biomass, and its relevant supply and demand characteristics that need to be considered in order to ensure the robustness of the built model. Having good understanding on those aspects and characteristics will help in realizing the massive potential of PKS as a source of renewable energy for industries.

During the course of this research, we have identified those key aspects and the interrelations among them, as pre-requisites in constructing an improved supply chain model for PKS to be used in industrial applications. Based on our study, some technical, environmental, and economic aspects have been identified, which will enable further researches on PKS feasibility of those aspects. From a long-term perspective, an analysis on supply-demand characteristics and regulatory aspects has also been conducted to pinpoint internal and external variables that may influence the dynamics of PKS supply chain system. Lastly, an overview on the existing PKS supply chain will enable a better understanding on its current situation and hence helping in building an improved supply chain model.

2. Methodology

In this study, we used descriptive research method through a combination of literature study and field observations with some secondary data from various published sources and relevant firsthand information to analyze the current situation of PKS in respect to product, supply-demand, and supply chain aspects.

The bibliography search on PKS feasibility aspects was conducted using open literature which were published predominantly in the past 10 years, resulting in the selection of articles in various scientific journals and conference proceedings written in English and Bahasa Indonesia. The study was supplemented by relevant dissertation and recognized textbook analyses on the subject area.

In relation to supply-demand characteristics, and regulatory situational analysis, we deployed system dynamics methodology to identify the interrelationships among relevant aspects, which in combination will delimit the availability of PKS for industrial applications. We summarized the findings in the form of a causal loop diagram. Whilst analyzing the situation of current PKS supply chain, a conceptual framework from Vorst (2006) is used to identify some key aspects that will determine the chain performance. The framework will help further works in building an improved supply chain model for PKS, which is more effective, cost efficient, and sustainable.

3. PKS Feasibility as Industrial Fuel

There is an eminent potential of renewable energy source from palm oil industry coming in the form of solid biomass. Solid biomass generated from oil palm plantation and production activities is estimated at around 18.2 tonnes per hectare (Paltseva 2016), which is much higher proportionally compared to only around 3.3 tonnes of usable oils per hectare (Hambali & Rivai 2017). With 42 million tonnes annual CPO production (Ditjenbun 2020), there is an estimated quantity of more than 320 million tonnes solid biomass that can be utilized out of oil palm plantations and palm oil mills by 2020. Such massive opportunities from the excess oil palm biomass can be utilized as energy sources, only if they are technically, environmentally, and economically feasible (Mahlia *et al.* 2019), for which Figure 1 is showing the inter-relation of these aspects.

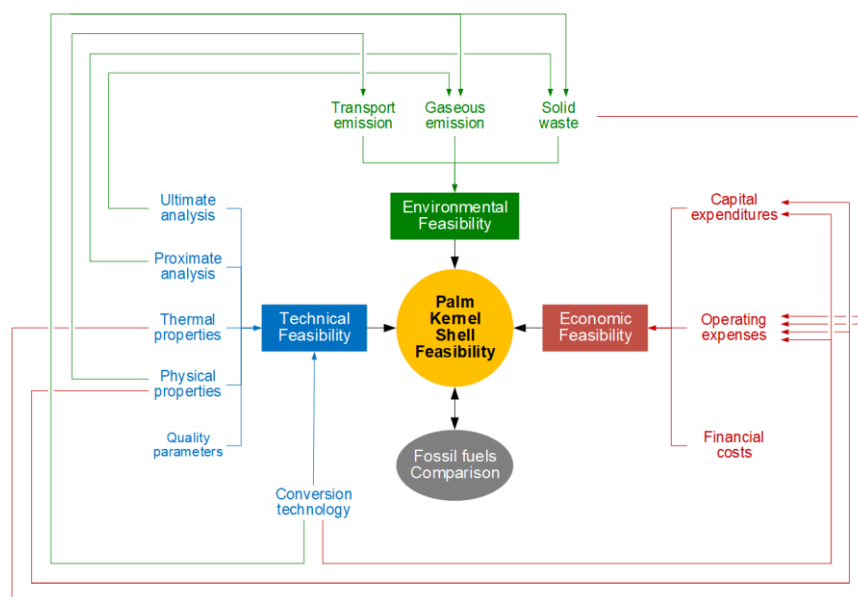


Fig. 1 Key Aspects of PKS Feasibility

3.1 Technical Aspects

According to biofuels classification (Lee & Lavoie 2013), oil palm biomass can be categorized as a second-generation biofuel, which are originated from agricultural industrial waste and are comprised of lignocellulosic as main constituent. Besides lignocellulosic, oil palm biomass also contains other components that affect calorific value, storage and process conditions, and environmental impacts during and post firing (Loh 2017; Ping *et al.* 2016). Each type of oil palm biomass can be characterized by its unique composition, yet predominantly containing the same components, which need to be verified through proximate and ultimate analyses (Patel & Gami 2012). In term of gross calorific value (GCV), Loh (2017) reported that PKS is at a range of 4,700-4,900 kcal/kg, which is the highest compared to other oil palm biomass. Despite this, PKS calorific value is still much lower compared to most fossil fuels, such as coal with a GCV of 4,400-8,300 kcal/kg (Speight 2013) and natural gas with a GCV of 10,200-13,100 kcal/kg (Mokhatab *et al.* 2019). Therefore, it is crucial to also look at other aspects prior to determining the overall feasibility of using PKS as an alternative fuel.

Since thermophysical properties of a biomass material and its usage determine how the material should be stored, transported, and used, it is important to understand these properties before deploying it in industrial applications (Veal 2018). These thermophysical properties along with selected chemical compositions can be used to define biomass material quality specifications. Given the natural variability of biomass in general (Kenney *et al.* 2013) and oil palm biomass in particular, such standardization will provide some benefits in designing, planning, and executing the supply chain (Gaber *et al.* 2014). Subsequent to defining quality specifications, quality assurance systems and quality control measures can then be set up to support as the foundation of an efficient and sustainable biomass supply chain operation.

The last aspect of technical feasibility is the selection of available conversion technology, in particular combustion where biomass is combined with oxygen in temperature ranging from 800 to 1000 °C to form CO₂, water vapour and heat, which is a particular interest of technology in this research for heat generation from PKS due to its wide applicability and robustness in industrial applications (Yue *et al.* 2014). There are three options of combustion technology that can be fueled by solid oil palm biomass, namely fixed bed combustion, fluidized bed combustion, and pulverized fuel combustion (Loo & Koppejan 2008). The choice of conversion technology will affect the design of supply chain model, which is supplemented by considerations on processing and capacity requirements, capital and operating costs, and environmental impacts (Mahlia *et al.* 2019).

3.2 Environmental Aspects

From an environmental viewpoint, utilizing oil palm biomass such as PKS by itself can already be considered as an effort to improve sustainability of palm oil value chain as a whole, since if left unattended, then it will lead to environmental problems (Embrandiri *et al.* 2012). Replacing fossil fuels with biomass for combustion does not directly reduce GHG emissions, yet the carbon neutrality comes from the assumption that burning biomass only returns CO₂ absorbed by growing plants, although in

practice the net impact may not be truly zero due to processes within the supply chain, i.e. storage and transportation (Mafakheri & Nasiri 2014). Nonetheless, substituting a fossil fuel with a biomass may result in highly variable GHG mitigation depending upon how the biomass is generated (Serra *et al.* 2019). Because of this, a thorough study on the impact of utilizing biomass is required to confirm its environmental advantages over fossil fuels.

To ensure the environmental feasibility of biomass utilization as an energy source, a system analysis needs to be carried out throughout the whole supply chain by deploying Life-cycle Assessment (LCA) methodology (Harsono *et al.* 2012). Since PKS is categorized as a waste from agricultural based industry, the system boundary for LCA is started at the point where it is generated and CO₂ counting can then be conducted throughout the supply chain and consumption stages up to the end of lifecycle (Rabl *et al.* 2007).

With respect to fossil fuel utilization in the combustion process, there are various degree of emissions depending on the fuel types, e.g. coal, oil, and gas (Loo & Koppejan 2008). A similar analysis can be done through a comparative LCA study for energy generation to demonstrate advantages of biomass over fossil fuels from environmental impacts viewpoint (Cheng *et al.* 2020).

3.3 Economic Aspects

An economic assessment of biomass usage is critical for further development and commercialization, as economic benefits will encourage firms to invest in this renewable energy (Shin *et al.* 2018). From an industrial user viewpoint, there are capital investment required to shift from current fossil fuel infrastructure into a new solid fuel system (Jeswani *et al.* 2020), as in the case of switching from natural gas into PKS. Therefore, a careful feasibility study is needed based on the calculation of operating expenses and capital expenditures and by considering the cost of capital (Michaelides 2012; Syromyatnikov *et al.* 2021).

In this study, PKS is considered as a waste of palm oil industry, which implies the material cost will be calculated as bought in price from palm oil mills and added by logistic costs up to the user's site (Mafakheri & Nasiri 2014). Other remaining operating expenses that will be needed at the user's site are manpower, handling equipment, utility, maintenance, and waste disposal costs (Mahlia *et al.* 2019; Yazan *et al.* 2016). Based on our calculation, the total cost of energy from PKS at present is around \$21 per MWh-heat, which is 33% lower than natural gas and 22% lower compared to coal. This appears as an attractive opportunity of cost saving by switching from fossil fuels to PKS, yet to ensure sufficient level of return on investment, a careful identification on capital expenditures needs to be carried out before the decision to invest is made.

The capital expenditures will mainly consist of combustion unit along with costs of auxiliary equipment, infrastructure, installation, and commissioning (Kumar 2018). These costs can then be compared with fossil fuel costs to identify relative advantages, which determine the economic feasibility of using PKS (Michaelides 2012; Yazan *et al.* 2016).

Only when a biomass like PKS is proven feasible in technical, environmental, and economic aspects can it be considered as a potential substitute of fossil fuel for

industrial purposes. As part of the decision-making process to switch from any fossil fuel to a biomass, the next evaluation that needs to be carried out is on its supply and demand characteristics along with regulatory aspects that govern the biomass value chain. This will give some ideas on long term supply security of the biomass and how these characteristics will influence its supply chain dynamics.

4. Supply and Demand Characteristics

Before designing a supply chain system of biomass, supply and demand characteristics have to be understood to foresee potential risks of supply chain disruption, for instance an imbalance between supply and demand sides that may lead to price volatility (Bravo *et al.* 2012). According to Hemstock (2007), to achieve a sustainable supply chain, an analysis of biomass availability and consumption is crucial, of which there are two ways to assess biomass resources, namely resource-focused approach and demand-driven approach (Vis & van den Berg 2010).

The causal loop diagram in Figure 2 summarizes the key aspects of PKS supply and demand with their interrelationships. This characterizes the current supply-demand situation along with the relevant regulatory aspects that may influence PKS supply chain dynamics.

4.1 Supply Characteristics

By using the resource-focused approach, the investigation of a potential biomass source is primarily commenced with the estimation of biomass generation rate and its competing uses (Vis & van den Berg 2010). With the annual CPO production of 42 million tonnes, it is estimated at around 11.2 million tonnes of PKS generated in Indonesia by 2020 (Hambali & Rivai 2017; Ditjenbun 2020), which is equivalent with 5.4 MTOE per annum.

The determination of PKS availability for longer term purposes, such as in industrial applications, can be done through the assessment of natural and technical variability factors in PKS generations and sustainability constraints (Wicke *et al.* 2015), which are:

- Natural seasonality due to rainfall variations, of which FFB yield typically rises 14% above average in the period of July to November and drops 16% below average in January to April during the heavy rainfall period that also disrupts transportation system leading to palm oils production decline (Abdullah & Wahid 2010; Abdullah 2012).
- The growth cycle of oil palm tree may cause supply gaps if replanting efforts do not catch up with the natural ageing process as palm trees' productivity drops after 23-25 years since they were planted (Simadiputra *et al.* 2018).

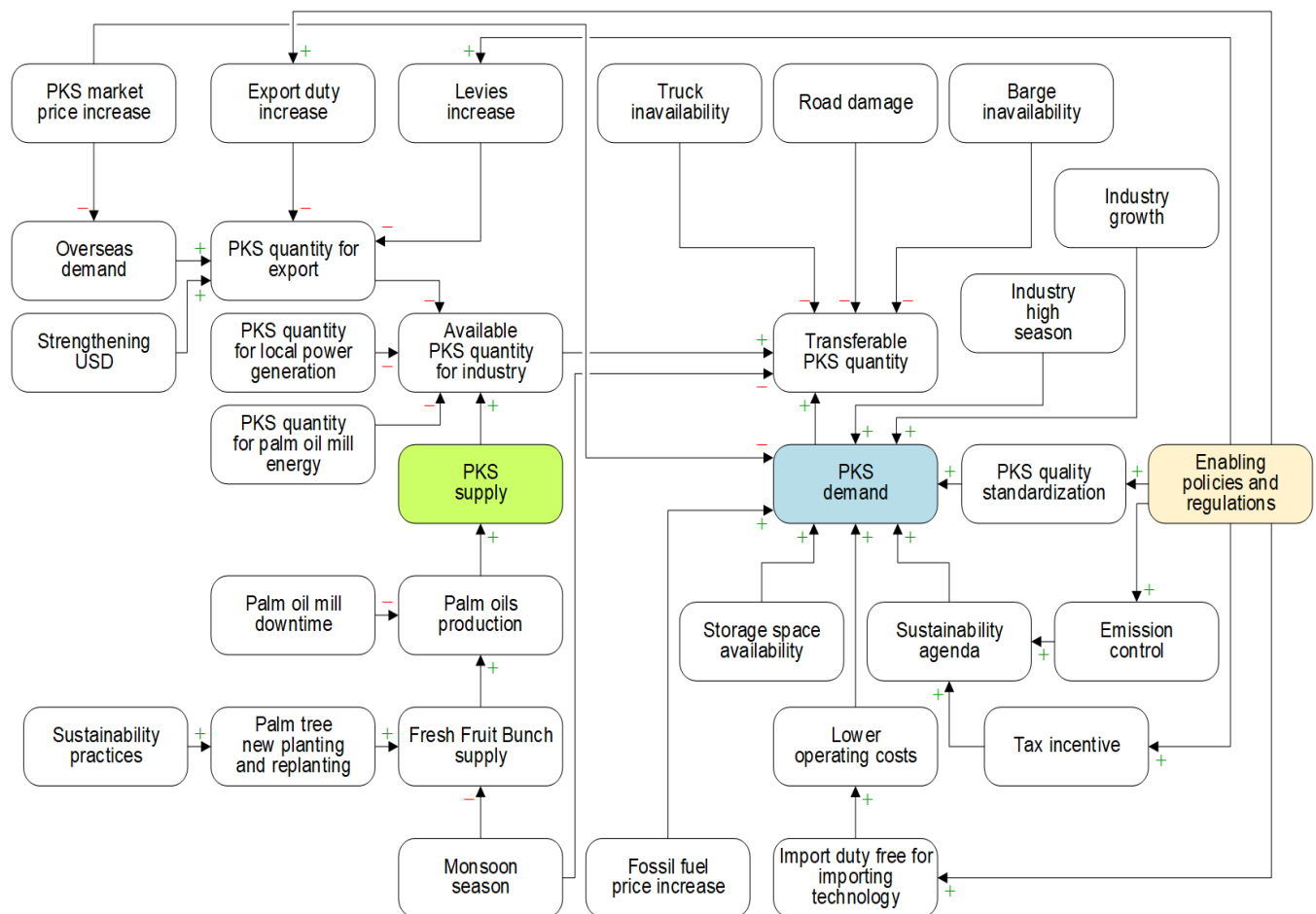


Fig. 2 Key Aspects of PKS Supply and Demand

Table 1
Criteria to Evaluate PKS Demand for Industries

Criteria	Sub Criteria	Factors to be considered
Operational continuity	Supply reliability	Availability, supply timeliness, delivery frequency
	Technology reliability	Technology readiness, operability, ease of maintenance
Financial performance	Capital expenditure	Capital requirement, return on investment
	Operating cost	Bought-in price, storage, handling, maintenance, manpower
Technical performance	Energy efficiency	Ratio between value output to value input
	Quality consistency	Process capability index
Environmental impact	GHG emission	Measured post firing emissions: CO ₂ , CO, NO _x , SO _x
	Waste processing	Solid waste handling, storage, and disposal

• Sustainability issues surrounding palm oil industry, such as GHG emissions from land use change, biodiversity loss, and land conflicts (Wicke *et al.* 2015; Simadiputra *et al.* 2018), may also hamper the growth of palm oil production, which consequently affect sustainability of PKS supply.

In setting up PKS as an alternative renewable energy source for a large-scale biomass energy plant, all these factors need to be considered during the strategic and operational planning phases. Any of these factors can lead to supply uncertainty, and therefore mitigating actions need to be put in place, such as careful inventory planning (Mafakheri & Nasiri 2014) and conceivably adoption of internet-based technological solutions (Lim *et al.* 2021).

As with any other biomass, PKS requires a series of transportation and storage arrangements, which is composed of a logistics system with its cost, as a major part of biomass cost-to-source (Malladi & Sowlati 2018). The logistics system may cover multi-modal transportations, e.g. land and sea freights, and a storage network, from the point of generation up to the point of consumption (Lautala *et al.* 2015). The choices will depend on distance, geographic, infrastructure conditions, and cost consideration (WBA 2018).

The storage network functions as buffer points to accommodate the operating windows of generation, inter-location shipment, and consumption process by industrial end-users. Constructing such network also aims to minimize material loss and quality deterioration as well as to serve as a backup in case of supply disruptions, such as palm oil mill production slow down or transportation delay (Malladi & Sowlati 2018; WBA 2018).

The supply of PKS is also exposed to various risks, that may result on sporadic operational disruptions at the end-user's site and/or threaten its sustainability for long term usage. Those that need to be taken into account are climate, operational, quality, and market risks (Panoutsou *et al.* 2020).

4.2 Demand Characteristics

Related to growing demand of energy for the industrial sector, Suharyati *et al.* (2019) identified six subsectors with the highest energy usages that consume around 82% of the total industrial energy consumption, which are cement, metal, food and beverage, paper, ceramics, and fertilizer. These industries deploy thermal processes in the production process, such as heating, drying, evaporating, sintering, and steam generation, most of which can be fueled with biomass like PKS, either through direct

combustion, pyrolysis, or gasification, depending upon technical process specifications (Yue *et al.* 2014). Besides direct usage, biomass can also be converted into electricity via steam power plants as the most common technique (Mahlia *et al.* 2019). It should also be noted that seasonality on production demand of industrial users, which are typically driven by weather or holidays (Hemstock 2007; Heizer & Render 2014), will cause fluctuation on energy consumption and leading to PKS demand variability.

As processing industries use a large amount of energy, it is crucial for such industries to constantly pursue energy efficiency improvements that typically start with the selection of alternative energy source followed by the effectiveness evaluation (Önüt *et al.* 2008). This situation is multi-criteria by nature, therefore it requires a multi-criteria decision making (MCDM) methodology.

In preceding studies, there are a number of scholars who attempted to define various criteria of selecting renewable energy source and to apply MCDM methods in getting the most optimal option, as done by Yazdani-Chamzini *et al.* (2013) for the selection of best renewable energy project in general, Vasković *et al.* (2018) for the selection of optimal solid wood fuel supply, Saba (2019) for a power plant in the city of Rotterdam, and Karaşan & Kahraman (2020) for municipalities. Although the scope of studies are related to energy supply for public services in most cases, several criteria are also valid in an industrial context. Based on those studies, the chosen criteria for evaluating demand of PKS, as an industrial energy source, are listed in Table 1.

For the purpose of industrial energy application, a distinctive characteristic of solid biomass that also need to be considered by a prospective user is the onsite storage space requirement along with material handling equipment (Veal 2018). In comparison with fossil fuels, this characteristic is closely similar to coal yet very different with fuel oils and gas, which may deter the intention to use biomass, especially for factories that have limited available space.

Besides potential demand for local industries, there is also a growing opportunity in exporting PKS, yet posing threats on longer term supply continuity for fulfilling local demand, as well as indirectly causing price volatility. In-line with this development, the Indonesian government has put efforts to curb the growth of PKS export by introducing export duty at the progressive rates between US\$ 7 to US\$ 30 per MT, depending on CPO market price, as stated in the Regulations of the Ministry of Finance of the Republic of Indonesia Number 13/2017 and Number

166/2020, and in addition charging plantation fund levies at the rate of US\$ 7 per MT, as stipulated in the Regulation of the Ministry of Finance of the Republic of Indonesia Number 191/2020.

4.3 Regulatory Aspects

Some studies have shown evidences that a well-implemented policy supported by adequate institutional supports, will foster applications of renewable energy sources in industrial sectors (Horschig & Thrän 2017). The existing policies and regulations on biomass energy have not been yet fully implemented, even though Indonesia has great potential in utilizing abundant biomass resources (Dani & Wibawa 2018). It requires a strong alignment between renewable energy initiatives with government programs and support to better utilize biomass for energy source (Tasri & Susilawati 2014).

As with other products, regulations on PKS trading and supply chain are necessary to prevent and rectify market failures as well as to promote an efficient market, since a lack of regulation may encourage chain actors falling into exploitative behaviors (Molinuevo & Sáez 2014). Despite market mechanism, government interventions will still be required when a market is unable to compromise externalities and due to the lack of available information (Pindyck & Rubinfeld 2015). The impacts from these occurrences within the context of renewable energy industry can be alleviated through regulations and

standards, such as in the area of quality standardization, duties and levies exemption and protection, tax incentive on biomass technology, permits and licensing, emission control, etc (Shayegh 2015).

After having some understandings on PKS supply and demand characteristics, a situational analysis on its supply chain can be performed to comprehend how the current system works and to identify opportunities for improving the overall value chain. Such analysis will enable further modelling works to enhance PKS supply chain performance in fulfilling industry needs.

5. Situational Analysis on PKS Supply Chain

A system design is required in order to accomplish a set of desirable supply chain performance that will lead to economic profit maximization and investment sustainability through minimizing costs and environmental impacts, maintaining quality, and supplying sufficient PKS quantity all year round (Lautala *et al.* 2015). The situational analysis of the current PKS supply chain as a framework in Figure 3, which was developed by Vorst (2006), consists of four elements, namely the network structure, chain business processes, network and chain management, and chain resources, coupled with the modeling approaches in biomass supply chain.

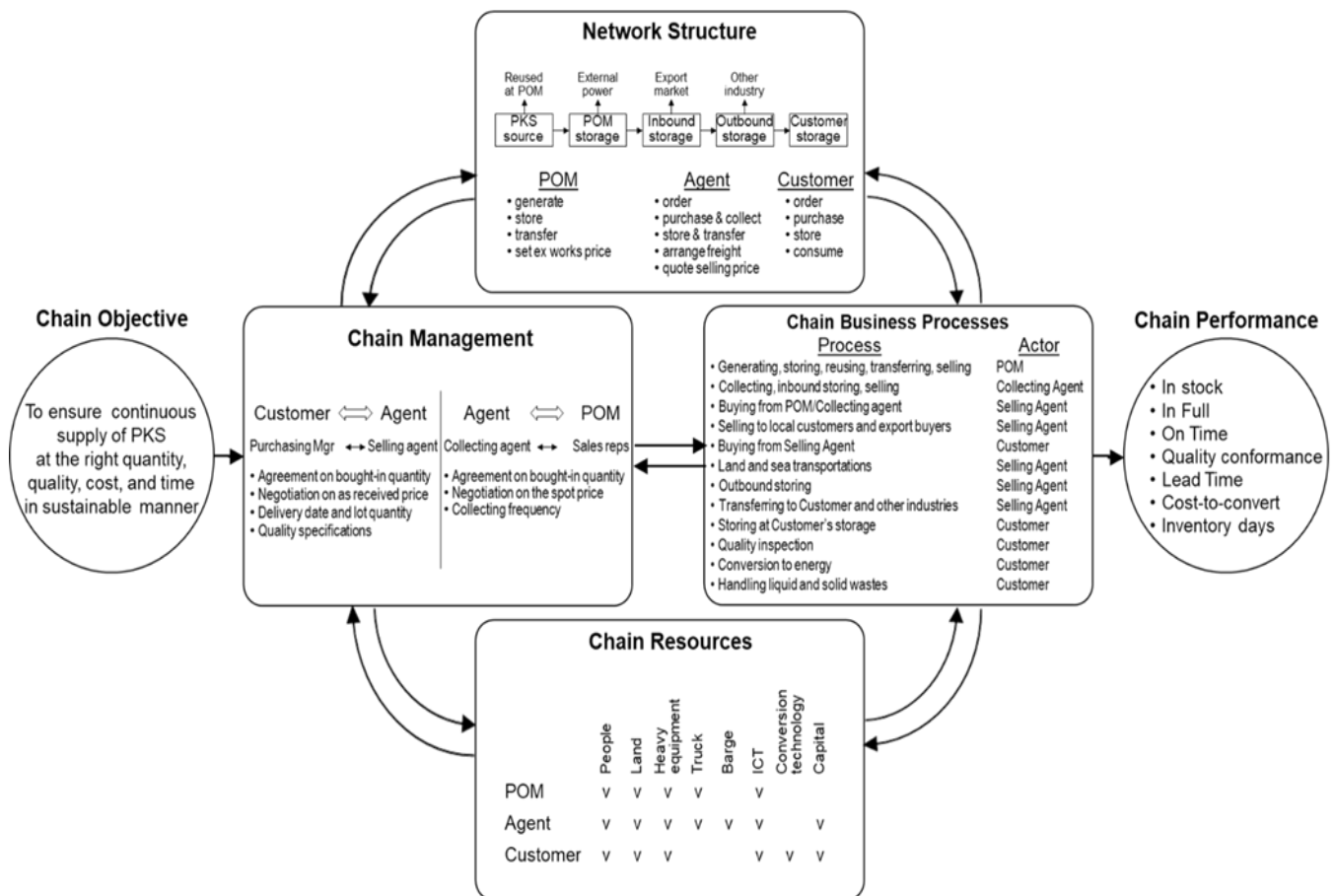


Fig. 3 Situational Analysis on Current PKS Supply Chain

5.1 Setting Chain Objectives

For the purpose of defining the objectives of a supply chain, Vorst (2006) proposed three generic value propositions that can be attained individually or in combination, namely (1) network differentiation and market segmentation, (2) integrated quality, and (3) network optimization. Related to the supply chain of PKS, as an industrial renewable energy source, a combination of propositions 2 and 3 are found to be applicable. Therefore, the proposed objective is to ensure continuous supply of PKS at the right quantity, quality, cost, and time in a sustainable manner.

This comprehensive objective covers all of the key aspects in biomass supply chain, as suggested in prior studies (Lautala *et al.* 2015), which are:

- Supply continuity; ensuring no disruption on heat generation process with sufficient PKS supplied quantity in timely manner.
- Quality requirements; meeting the predefined quality specifications to obtain efficient energy conversion with minimum waste.
- Economic viability; providing the lowest supply cost to achieve the profit target and investment return.

Sustainability; minimizing environmental impacts throughout the supply chain.

5.2 Network Structure

A PKS supply chain network consists of main actors, who perform certain roles and form the network configuration, which determines successful executions of the chain objective (Vorst 2006). For supplying a single industrial customer, the network may be constructed by several sources of PKS, number of intermediary agents, acting as collectors and/or sellers, as illustrated in Figure 4.

These three actors in the network have certain key roles in delivering performance of the supply chain. The palm oil mill as the producer will continuously generate PKS, as long as the operation of palm oil production is running. Whilst the intermediary agent acts as a middleman that connects the palm oil mill and the industrial end

user, of which the latter provides PKS demand quantity and quality standards.

5.3 Chain Business Processes

A typical PKS supply chain is composed by a set of business processes, as depicted in Figure 4, that result in supplied material for energy conversion at the end customer. Each process owner performs certain business activities to produce a specified output of the entire supply chain (Vorst 2006).

Whilst processes related to the palm oil mill and the customer are usually carried out by individual business entities, agent's activities may be done by two or more entities with particular roles, such as the collecting agent and the selling agent. The red lines in Figure 4 represent the main flow that will be the object of modeling works.

5.4 Chain Management

The chain management is the coordination and structures within the chain network that enable the instantiation and execution of processes by chain actors (Vorst 2006). In current PKS supply chain network, such contract is either non-existent or violated due to improper supply planning, particularly during the off-season period when there is limited PKS availability at POM.

Nonetheless, some short-term agreements do exist at present, which mostly occur between two parties involved in the chain based on transactional modus. Such agreements are not sustainable as cater only short-term requirements, thus need to be transformed into more long-term coordination, which will facilitate more sustainable supply chain.

5.5 Chain Resources

A supply chain needs transforming resources to perform its function in producing and delivering the product to customer (Vorst 2006). In PKS supply chain, each actor must have such resources to conduct the range of activities within the chain, as listed in Table 2.

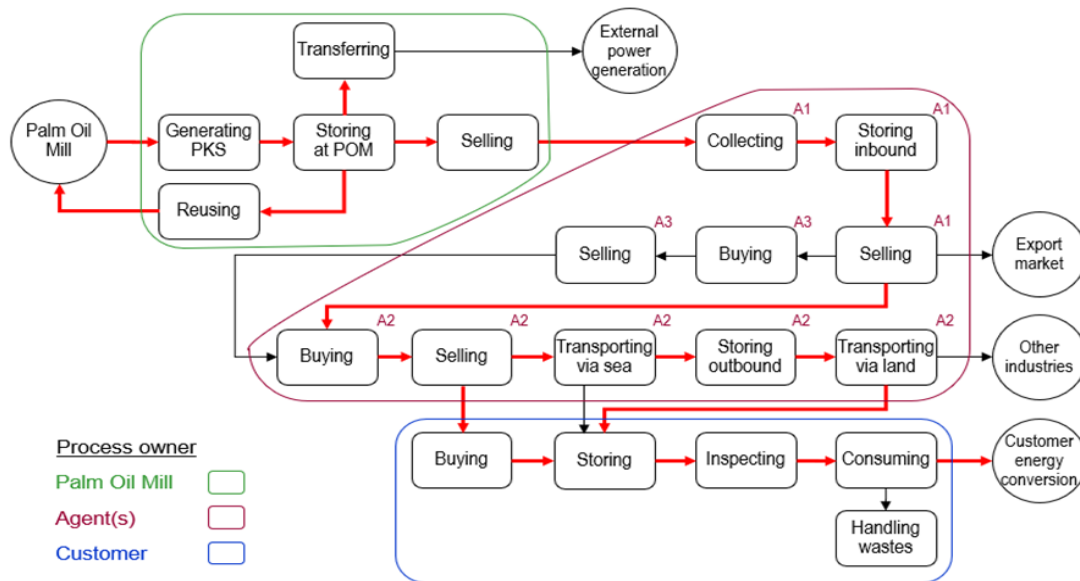


Fig. 4 PKS Supply Chain Network and Business Process

Table 2
 Resources in PKS Supply Chain

Resources	Activity	Custodian
People	Physical and administration works	All actor
Land	Storing at source, in-transit, and usage points	All actor
Heavy equipment	Moving material in each storing point, including loading and unloading	All actor
Truck	Transferring material between storing points	POM, Agent
Barge	Inter-island material transfer	Agent
Information and communications technology (ICT)	Communication, calculation, and document processing	All actor
Conversion technology	Converting PKS into energy for thermal processes	Customer
Capital	Acquiring fixed assets and inventories	Agent, Customer

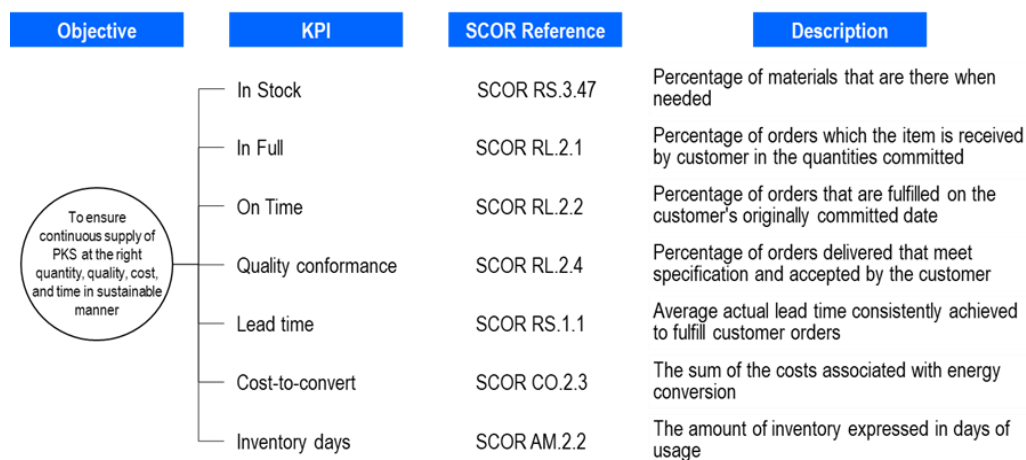


Fig. 5 PKS Supply Chain Key Performance Indicators

5.6 Chain Performance

Vorst (2006) defined supply chain performance measurement, which supports the chain objective realization, as the outcome of supply chain execution, performance evaluation, and identification of improvement actions. Figure 5 shows the selected key performance indicators (KPIs) that can be used in measuring PKS supply chain performance in reference to Supply Chain Operations Reference (SCOR) definitions (APICS 2017).

Further analysis on gaps between the desired performance and the actual performance will be needed as part of the overall supply chain improvements. Only by meeting those gaps can the chain objective be attained and thereafter the continuous usage of PKS as a renewable energy source for industries can be ascertained in long run.

6. Conclusion

PKS, an agriculture industrial waste with energy potential of 5.4 MTOE per annum, is expected to offer environmental and economic benefits to become a renewable energy source for continuous usage in-line with the growth of palm oil industry. Despite its relatively lower calorific value in comparison with fossil fuels, utilizing PKS for heat generation at present gives 22%-33% energy cost reduction

depending on the comparative fuel and will even yield larger saving with the rising trend of coal and natural gas prices. Understanding its supply and demand characteristics is a precursor in realizing this massive potential of renewable energy source for industries.

As shown in this study, there are various interrelated aspects that need to be taken into account in designing an effective, efficient, and sustainable supply chain model of PKS, which will determine the viability of application and the continuity of supply for industrial purposes. Having a proper framework that enable identification of elements within the system will facilitate PKS supply chain development from its current state more comprehensively. Such a framework will be also useful in initiating further modeling works for designing an improved supply chain system.

The methodology used in this study largely can be applied to other biomass, particularly those originated from agriculture industrial waste. Further studies are desirable in some areas, such as how to enhance biomass usage feasibilities, identification of regulatory measures to smoothen supply and demand dynamics, and construction of new supply chain models. Future researches in these areas will open more opportunities to foster greater use of renewable energy for industrial purposes.

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