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# Exploring synergies between the palm oil industry and bioenergy production in Indonesia

FUMI HARAHA P

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SCHOOL OF INDUSTRIAL ENGINEERING AND MANAGEMENT

# **Exploring synergies between the palm oil industry and bioenergy production in Indonesia**

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Doctoral Thesis

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## Abstract

Climate change along with increasing demand for food and fuel call for sustainable use of natural resources. One way to address these concerns is through efficient use of resources, which is also vital for the achievement of the Sustainable Development Goals and the Paris Agreement. In this context, the sustainable and efficient use of resources in the palm oil industry is an interesting case to scrutinise. This is particularly important for Indonesia, the leading palm oil producer in the world. Large quantities of oils and biomass are generated from oil palm plantations and processing, presenting the potential for the development of bio-based production systems. However, at present, sustainability is a matter of great concern in this industry, including land use issues and the fact that large portions of the residues generated are untreated, releasing greenhouse gas emissions, and imposing environmental threats.

This doctoral thesis aims at exploring how resource efficiency can be enhanced in the palm oil industry. Three research questions are posed to address the objective. The first question examines the sectoral policy goals of biofuel, agriculture, climate, and forestry and their requirements for land. The second question is focused on new industrial configurations for efficient use of palm oil biomass for bioenergy production. The final question summarises the role of enhancing resource efficiency in the palm oil industry with regards to meeting the national bioenergy targets, which include 5.5 GW<sub>e</sub> installed capacity and biofuel blending with fossil fuels (30% biodiesel blending with diesel and 20% ethanol blending with gasoline) in the transport, industry, and power sectors. The research questions are explored using three main methods: policy coherence analysis, techno-economic analysis, and a spatio-temporal optimisation model (BeWhere Indonesia).

The thesis identifies areas in which policy formulation, in terms of sectoral land allocation, can be improved. Adjustments and improvements in policy formulation and implementation are crucial for land allocation. The inconsistencies in the use of recognised land classifications in the policy documents, the unclear definition of specific land categories, and the multiple allocation of areas, should be addressed immediately to ensure coherent sectoral policies on land allocation. This can lead to more effective

policy implementation, reduce pressure on land, enhance synergies, and resolve conflicts between policy goals.

The transition towards a more sustainable palm oil industry requires a shift from current traditional practices. Such transition involves efficient use of palm oil biomass resources through improved biomass conversion technologies and integration of palm oil mills with energy production in biorefinery systems. The upgrading of the conventional production systems can serve multiple purposes including clean energy access and production of clean fuels for the transport, industry, and power sectors, ultimately helping the country meet its renewable energy and sustainable development targets, along with reduced emissions. More specifically, the efficient use of biomass and co-production of bioenergy carriers in biorefineries can enable Indonesia to reach its targets for bioenergy installed capacity and bio-based blending.

At present, many government policies in Indonesia are working in the right direction. Nevertheless, various barriers still need to be overcome so that resource efficiency can be improved. This includes harnessing the full potential of bioenergy in the palm oil industry. There is room for enhancing the sustainability of the palm oil industry in Indonesia with adjustments to existing policies and practices, as shown in this thesis. First, guidance across sectoral policies can help to coordinate the use of basic resources. Second, the shift from traditional practices requires a strategy that includes improvement in agricultural practices (i.e., higher yields), infrastructure for biomass conversion technologies together with improved grid connectivity, and adoption of a biorefinery system. Strengthening policy support is needed to promote such a comprehensive shift. Third, various programmes can forge partnerships between oil palm plantations, the palm oil mills, and energy producers to ensure the development of sustainable industrial practices. A sustainable palm oil industry will improve resource and cost efficiency, and help open international markets for Indonesian products. This could pave the way for an enhanced role for the Indonesian palm oil industry in global sustainability efforts.

**Keywords:** palm oil industry; bioenergy; resource efficiency; sustainability; land allocation; palm oil biomass; biorefinery; policy coherence analysis; techno-economic analysis; spatio-temporal optimisation model; BeWhere Indonesia.

## Sammanfattning

De pågående och väntade klimatförändringarna tillsammans med ökad befolkning och därmed efterfrågan på mat kräver en långsiktigt hållbar användning av naturresurserna. Ett sätt att adressera dessa frågeställningar är genom en effektiv resursanvändning, vilket också är grundläggande för att uppnå de globala målen (Agenda 2030) och Parisavtalet. I detta sammanhang innebär hållbart och effektivt användande av palmolja-branchens resurser ett särskilt intressant fall att studera. Det är av stor betydelse för Indonesien, i kraft av att vara den ledande palmolja-producenten i världen. Stora mängder olja och biomassa genereras från oljepalmsplantager och -förädling, vilket innebär stor potential för utvecklandet av biobaserade produktionssystem. Dock är för närvarande den långsiktiga hållbarheten i produktionen ifrågasatt, vilket inkluderar markanvändning och det faktum att en stor del av biprodukterna från produktionen är obehandlade och därigenom avger växthusgaser och medför andra miljöproblem.

Denna avhandling siktar på att utforska hur resurseffektivitet kan stärkas inom palmolja-sektorn. Tre forskningsfrågor ställs för att adressera denna grundfråga. Den första frågan undersöker policymålen för sektorn - biodrivmedel, jordbruk, klimat och skogsbruk - samt deras behov av mark. Den andra frågan fokuserar på hur en ny industriell konfigurering kan utformas, med hänsyn taget till att möta de nationella målen för biobränsle inom transport-, industri- och elsektorn. Den sista frågan sammanfattar betydelsen av ökad resurseffektivitet inom oljepalmsbranchen, med hänsyn till de nationella målen för bioenergiproduktion. Dessa mål inkluderar 5,5 GWe installerad kapacitet och låginblandning av biodrivmedel (30% biodiesel för diesel, 20% etanol för bensin) såväl inom transportsektorn som energisektorn. Forskningsfrågorna utforskas genom tre huvudsakliga metoder: policy coherence analysis, techno-economic analysis samt en spatio-temporal optimisation model (BeWhere Indonesia).

Avhandlingen identifierar områden inom vilka policyutformning, i termer av sektoriell markallokering, kan förbättras. Justeringar och förbättringar inom policyutformning och implementering är grundläggande för landallokering. Bristen på sammanhängande landklassificering i policydokumenten, den oklara definitionen av specifika landkategorier

samt den multipla allokeringen av områden bör omedelbart adresseras för att nå en sammanhängande sektorspolicy för landallokering. Detta kan leda till mer effektiv policyutformning, dämpad efterfrågan på mark, ökade synergier och att lösa målkonflikter kring policy.

Övergången till en mer hållbar palmoljebransch kräver ett skifte från den nuvarande praktiken. Ett sådant skifte innebär effektivt användande av palmoljebiomassa genom förbättrad teknik för biomassekonvertering samt integrering av palmoljekvarnar med energiproduktion inom bioraffinaderisystemen. Uppgraderingen av konventionell produktion kan tjäna flera syften, inklusive tillgång till ren el och produktionen av rena bränslen för transporter och industri, vilket i slutändan kan hjälpa landet att nå målen för förnyelsebar energi och hållbarhet, tillsammans med minskade utsläpp. Mer specifikt gäller det effektiv samproduktion vid bioraffinaderierna som kan göra att Indonesien når sina mål för bioenergi och biobaserad inblandning.

För närvarande innebär flera regelverk i Indonesien att arbetet går i rätt riktning. Fortfarande finns det dock ett flertal hinder som måste övervinnas för att resurseffektiviteten ska kunna ökas. Detta omfattar också att ta om hand den fulla potentialen för bioenergi inom palmoljebranschen. Det finns utrymme för att förbättra hållbarheten inom branschen i Indonesien genom justeringar i befintlig policy och i tillämpningen av denna, vilket visas i denna avhandling. Först och främst måste vägledning genom sektorspolicy stödja samordningen av hur råvaror används. Därefter måste skiftet från den traditionella produktionen stödjas av en strategi som inkluderar förbättringen i jordbruket, till exempel för att nå ökad avkastning, infrastruktur för att konvertera biomassa samt ökad sammankoppling av elnäten samt att bioraffinaderier introduceras. Stärkt policystöd behövs för att stärka ett så genomgripande skifte. Slutligen måste olika partnerskap slutas mellan palmoljeodlingar, palmoljekvarnar och energiproducenterna för att nå utvecklingen av långsiktigt hållbar industriproduktion. En långsiktigt hållbar palmoljesektor kan öka resurs- och kostnadseffektiviteten samt öppna internationella marknader för indonesiska produkter. Detta kan bana väg för en starkt roll för Indonesiens palmoljesektor inom de globala klimatansträngningarna.

**Nyckelord:** palmoljesektor; bioenergi; resurseffektivitet; sustainability; markallokering; palmoljebiomassa; bioraffinaderier; policy coherence analysis; techno-economic analysis; spatio-temporal optimisation model; BeWhere Indonesia

## **Preface**

This thesis is the outcome of research conducted at the Energy Systems Division at KTH Royal Institute of Technology under the supervision of Professor Semida Silveira. Research at Energy Systems division has an interdisciplinary character with a system perspective, where energy technology, innovation, and policy are linked to sustainable development.

This doctoral thesis focuses on enhancing resource efficiency in the palm oil industry in Indonesia. This country is interesting to investigate as Indonesia is the largest palm oil producer in the world. Currently, sustainability is a great concern in the industry, including land use issue and a large proportion of biomass residues are left untreated. This makes sustainable and efficient use of resources in the palm oil industry, an interesting case to scrutinise. The bioenergy potential of the palm oil industry justifies further analysis to explore sustainable development pathways that can simultaneously address climate change mitigation and renewable energy deployment goals. The results of the analysis lead to recommendations for improving the efficient use of resources in the palm oil industry. The knowledge gained from this analysis may help improve existing practice and inform future decision-making towards efficient policies.

The research for this doctoral thesis has been funded by the Swedish Energy Agency under the Programme INSISTS (Indonesian-Swedish Initiative for Sustainable Energy Solutions). Part of the author's research for this thesis was developed during the Young Scientists Summer Programme of 2018 at the International Institute for Systems Analysis (IIASA) with funding from IIASA.

Stockholm, March 2020

*Fumi Harahap*

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I dedicated this thesis to my parents, thank you for believing in me.

## List of appended papers

This thesis is based on the following scientific papers:

### PAPER I

Harahap, F., Silveira, S., Khatiwada, D., 2017. Land allocation to meet sectoral goals in Indonesia – an analysis of policy coherence. In *Land use policy* 61, 451–465.  
DOI:10.1016/j.landusepol.2016.11.033

### PAPER II

Harahap, F., Leduc, S., Mesfun, S., Khatiwada, D., Kraxner, F., Silveira, S. 2019. Opportunities to Optimize the Palm Oil Supply Chain in Sumatra, Indonesia. In *Energies*, 12,420.  
DOI:10.3390/en12030420.

### PAPER III

Harahap, F., Silveira, S., & Khatiwada, D. 2019. Cost Competitiveness of Palm Oil Biodiesel Production in Indonesia. In *Energy*, 170, 62-72.  
DOI:10.1016/j.energy.2018.12.115

### PAPER IV

Harahap, F., Leduc, S., Mesfun, S., Khatiwada, D., Kraxner, F., Silveira, S. Optimal production of electricity, biodiesel, and ethanol in palm oil-based biorefineries in Indonesia. (submitted manuscript).

A research poster on the topic of Paper I was presented at ICOPE 2016 on Sustainable Palm Oil and Climate Change: The Way Forward through Mitigation and Adaptation, Bali, Indonesia, 16-18 March 2016; and at KTH Energy Dialogue in Stockholm, Sweden, 24 November 2016.

An earlier version of Paper II was presented at the 15<sup>th</sup> World Renewable Energy Congress in Jakarta, Indonesia, 19-23 September 2016. A research poster was also presented at the 25<sup>th</sup> European Biomass Conference in Stockholm, Sweden 12-15 June 2017.

An earlier version of PAPER IV was presented and published in the conference proceedings: Harahap, F., Leduc, S., Mesfun, S., Kraxner, F., Silveira, S., 2019. The role of oil palm biomass to meet liquid biofuels target

in Indonesia, in: Stanek, W., Gładysz, P., Werle, S., Adamczyk, W. (Eds.), Proceedings of the 32nd International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems. Institute of Thermal Technology, Silesian University of Technology 2019, Wrocław, Poland, 23-28 June 2019.

For PAPER I and III, the first author contributed with the conceptual design of the research, performed the literature review, collected and analysed the data, interpreted the results, drew the conclusions, wrote the original draft, reviewed and edited. The second and third authors acted as mentors and reviewers of the papers.

For PAPER II and IV, the first author contributed with the conceptual design of the research, performed the necessary literature review, collected, managed and analysed the data, developed model, interpreted the results and drew the conclusions. The second and third authors assisted in model development and analysis. All co-authors acted as mentors and reviewers of the papers.

## **Other publications by the author not included in the thesis**

Conti, D., Harahap, F., Silveira, S., Santasalo-aarnio, A., 2019. A techno-economic assessment for optimizing methanol production for maritime transport in: Stanek, W., Gładysz, P., Werle, S., Adamczyk, W. (Eds.), Proceedings of the 32nd International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems. Institute of Thermal Technology, Silesian University of Technology 2019.

Silveira, S., Harahap, F., Khatiwada, D., 2018. Sustainable bioenergy development in Indonesia - Summary for policymakers. Project report. Stockholm.

Widayati, A., Oborn, I., Silveira, S., Baral, H., Wargadalam, V., Harahap, E., Pari, G., 2017. Exploring the potential of bioenergy in Indonesia for multiple benefits (Policy Brief no. 82).

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## List of Abbreviations

bL	billion litres
BPH MIGAS	Badan Pengatur Hilir Minyak dan Gas Bumi or the Governing Body of the Downstream Oil and Gas
BPS	Badan Pusat Statistik or the Central Bureau of Statistics
CBA	Cost-Benefit Analysis
CHP	Combined Heat and Power
CPO	Crude Palm Oil
EFB	Empty Fruit Bunch
EU	European Union
FFB	Fresh Fruit Bunch
GFW	Global Forest Watch
GHG	Greenhouse Gas
GIS	Geographic Information System
GoI	Government of Indonesia
GW	GigaWatts
h	hour
ISPO	Indonesia Sustainable Palm Oil
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
MEMR	Ministry of Energy and Mineral Resources
Mha	Million hectares
MoA	Ministry of Agriculture
MoEF	Ministry of Environment and Forestry
Mt	Million Tons
MW	MegaWatts
NPV	Net Present Value
O&M	Operation and maintenance
PFAD	Palm Fatty Acid Distillate
PK	Palm Kernel
PKO	Palm Kernel Oil
PKS	Palm Kernel Shell
PLN	Perusahaan Listrik Negara or the State-Owned Electricity Company
PMF	Palm Mesocarp Fibre
POME	Palm Oil Mill Effluent
PJ	Petajoules
RQ	Research Question
t	tons
y	year



# 1 Introduction

*The global demand for primary materials is increasing at an unsustainable pace. Meanwhile, there are opportunities in the palm oil industry in Indonesia for more efficient use of resources. What development pathways can make the palm oil industry in Indonesia more sustainable?*

## 1.1 Opportunities for resource efficiency improvement in the palm oil industry in Indonesia

Climate change and increasing demand for food and fuel call for sustainable use of natural resources. One way to address these concerns is through the efficient use of resources, which is also vital for the achievement of the Sustainable Development Goals and the Paris agreement (UNEP, 2018). In this context, the sustainable and efficient use of resources in the palm oil industry is important to study. Large quantities of oils and biomass are generated from oil palm plantations and palm oil processing, presenting the potential for the development of bio-based production systems. However, at present, sustainability is a matter of great concern in this industry, including land use issues and the fact that large portions of the residues generated are untreated, releasing greenhouse gas (GHG) emissions and imposing environmental threats.

Indonesia is the top producer of palm oil in the world. Oil palm is an economically vital crop for the country given its use in both food (e.g., cooking oil, chocolate) and non-food products (e.g., biofuel, cosmetics, pharmaceutical products) for domestic and export markets. Out of the 41 million tons (Mt) of crude palm oil (CPO) produced in Indonesia in 2018, 70% went to export markets, 15% was used domestically for food, and 15% was used for industrial and domestic purposes including biodiesel production (USDA, 2019a). The industry also contributed directly and indirectly to the creation of 20 million jobs in the country in 2017, mostly in rural areas where plantations and processing plants are located (Tyson et al., 2018).

For almost five decades, palm oil production has followed the traditional strategy of expanding plantation areas as a way to increase production, which has resulted in land use change and major environmental impacts. Oil palm plantation expansion has occurred in forest area and peatland, leading to environmental degradation, GHG emissions, and biodiversity losses (Gaveau et al., 2016; Pye, 2019). Meanwhile, there are growing concerns regarding land scarcity, not only for agricultural purposes, but also for other economic activities. This calls for more efficient use of land.

While future increases in global demand for vegetable oil will continue to push up demand for palm oil, there is international pressure to improve sustainability principles in the palm oil industry (Sayer et al., 2012). Palm oil is particularly favoured on account of its high yield (80% higher compared to rapeseed oil, sunflower oil, and soy oil) and its low production cost (Corley et al., 2016; Sayer et al., 2012). This gives a valid reason for the palm oil industry in Indonesia to shift from traditional practices along its supply chain, to improve resource efficiency, and to curb negative environmental impacts. Such a shift can help the country to maintain its position as the top palm oil producer in the world while enjoying the full benefits of international trade and contributing to the implementation of the Paris agreement on climate change. Currently, the country is the 10<sup>th</sup> top emitter of GHGs in the world, but the 4<sup>th</sup> when including emissions from land use change and forestry (WRI, 2019).

The commitment to reduce GHG emissions is a national priority in Indonesia, and different policies have been put in place to address this. Climate change mitigation goals include, among others, 23% renewable energy generation by 2025. The bioenergy policy plan aims at 5.5 Giga Watts-electricity (GW<sub>e</sub>) installed capacity and biofuel blending with fossil fuels (30% biodiesel blending with diesel and 20% ethanol blending with gasoline) in the transport, industry, and power sectors. One of the ways to achieve the bioenergy targets is through electricity production from palm oil biomass residues, biodiesel production from CPO, and ethanol production from the lignocellulosic biomass. The bioenergy potential of the palm oil industry justifies further analysis to explore sustainable development pathways that can simultaneously address climate change mitigation and renewable energy deployment goals. In addition, the climate goal includes industrial waste management in the palm oil industry through methane capture from the generated liquid waste.

Thus, given the role that the palm oil industry plays in Indonesia, the need to address environmental degradation, climate and energy security policies, and the existing bioenergy potential at hand, what development pathways (e.g., in terms of policy coherency, technological options, resource efficiency, and production of value-added products) can make the palm oil industry more sustainable?

## **1.2 Scope, objective, and research questions**

This PhD thesis focuses on the role of land and biomass-to-bioenergy in the supply chain of the palm oil industry in Indonesia. According to Atashbar et al. (2016), the biomass-to-bioenergy supply chain analysis is focused on the flow of biomass from land to its use for bioenergy. Concomitantly, in this thesis, the analysis of the palm oil biomass-to-bioenergy supply chain consists of the upstream (planting, harvesting, and transporting fresh fruit bunches (FFB), to the palm oil mill), the midstream (extracting CPO and generating palm oil biomass residues in the palm oil mill), and the downstream activities (producing palm oil-based bioenergy in the energy plant unit and transporting the bioenergy).

There are several types of biomass generated at different stages in the palm oil industry, which can be in liquid, solid, or gaseous forms. There are also different possible conversion pathways from palm oil biomass to bioenergy, as well as diverse carriers of bioenergy (e.g., electricity, heat, liquid fuels). The analysis in this thesis focuses on biomass generated in the palm oil mill (i.e., CPO, palm kernel shells (PKS), palm mesocarp fibres (PMF), empty fruit bunches (EFB), and palm oil mill effluent (POME)) and their conversion into bioelectricity, biodiesel, and ethanol. An integrated system, defined as a biorefinery system, is considered for analysis of efficiency improvements. The biorefinery comprises the palm oil mill and energy plant unit co-producing bioelectricity and liquid biofuels (biodiesel and/or ethanol). The considered pathways are outlined in more detail in Section 2.2.

The geographical focus is Indonesia, exploring policy drivers and opportunities at the national, provincial, and district levels, as well as technological improvements in the existing palm oil industry. The emphasis is on the role that land and bioenergy can play in synergy with the palm oil industry.

The underlying hypothesis is that synergies between the palm oil industry and bioenergy production increase the sustainability of the palm oil industry. Palm oil is foreseen to continue to play a major role in the global market for food and fuel. With extensive plantations, and as the leading palm oil producer in the world, Indonesia is well positioned to develop bioenergy in connection to this industry, and sustainable development of this industry will contribute to addressing several national and international goals.

The overarching objective of this thesis is to explore how resource efficiency can be enhanced in the palm oil industry in Indonesia. Three specific research questions (RQs), are asked:

***RQ 1: How coherent are the policies for allocating land for palm oil biodiesel feedstock production with policy goals in other sectors (i.e., agriculture, climate, and forestry)?***

The first RQ examines the sectoral policy goals of biofuel, agriculture, climate, and forestry and their requirements for land. The case of land is important because of major concerns regarding its scarcity. Securing land for oil palm plantations while avoiding conflict with other sectoral policies is needed to meet the bioenergy target.

***RQ2: How can new industrial configurations provide sustainable solutions for bioenergy production in the palm oil industry?***

The second RQ is focused on new industrial configurations for efficient use of palm oil biomass for bioenergy production. New industrial configurations refer to the improvement of the biomass conversion technologies and integration of palm oil mills with energy plants. The integration is related to the adoption of the biorefinery concept. The current production system has not fully utilised the palm oil biomass residues generated in palm oil mills. In addition, the palm oil mill and the energy plant (e.g., biodiesel refinery) are not located in the same facility.

***RQ3. How can improved resource efficiency in the palm oil industry help to meet the national bioenergy targets?***

The third RQ summarises the overall implications of enhancing resource efficiency in land allocation and palm oil biomass utilisation in relation to the national bioenergy targets. The national bioenergy targets in 2025

include 5.5 GWe of bioelectricity installed capacity, 30% of biodiesel blending with diesel and 20% of ethanol blending with gasoline in the transport, industry, and power sectors. The bioenergy targets will eventually contribute to the goal of decarbonising the transport, industry, and transport sectors and meeting the goal of 23% renewable energy generation in the energy mix by 2025.

The results of this thesis provide insights for policymakers, plantation and plant owners, project developers, and researchers as they seek to enhance resource efficiency in the palm oil industry.

### **1.3 Methods, system boundary, and limitations**

This thesis is based on applied research which uses “scientific methodology to develop information aimed at clarifying or confronting an immediate societal problem” (Hedrick et al., 1993). It is an explorative case study that adopts a mixed-methods approach because it deals with several research questions that cannot be answered by a single method due to the varying scale, size, and dimensions of the individual problems. This approach enhances the validity of the study and provides a deeper understanding of the research problem or phenomenon that one method alone cannot elucidate (Pokorny et al., 2013; Wheeldon et al., 2012).

#### **1.3.1 Analytical frameworks and methodologies**

The analytical frameworks applied in this thesis combine quantitative and qualitative methods. The RQs are explored using three main methods: policy coherence analysis, techno-economic analysis, and an optimisation model. Policy coherence analysis is used to answer the RQ1 related to sectoral land allocation. Whereas techno-economic analysis and the optimisation model are used to answer the RQ2. The answer to the RQ3 builds upon the analysis of the results obtained in answering the first two RQs.

##### **a. Policy coherence analysis**

The bioenergy potential is affected by various sectoral policies, including agriculture, energy, forestry, and climate policy (FAO, 2008; Lucia, 2011). Sectoral policies (directly or indirectly) affecting bioenergy become congested and force policy goals to interact (Kautto, 2011). Thus, coherent

policies are key to enhancing synergies and resolving the potential conflicts of multiple goals. Policy coherence promotes consistency between policy goals and other policy-related signals such as actions, mechanisms for implementation and monitoring, and communication. While searching for coherence, policy amendments may be required (Huttunen et al., 2014).

The framework used for policy coherence analysis in this thesis measures land allocation for achieving multiple sectoral goals (i.e., biofuel, agriculture, climate, and forestry). This includes the identification of the type and quantity of land allocated for palm-biodiesel feedstock production under the recognised land use classifications in Indonesia. The method is applied to explore synergies between and within different sectors and to verify the probability of their reaching the intended policy goals. The concept of measuring the level of coherence on land allocation involving the multi-sector analysis and the various steps taken to determine the coherence characteristics are further explained in Section 3.1 and in PAPER I.

#### b. Techno-economic analysis

Techno-economic analysis provides a framework to estimate the performance, emissions and costs of equipment, technologies, and facilities before they are built (Frey et al., 2012). The tool has been used extensively to assess the technical potential and economic feasibility of improvements of different bio-based technologies (Shah et al., 2016). The economic evaluation in techno-economic analysis deals with monetary value estimation, including capital and operating costs and revenues generated along the biomass-to-bioenergy supply chain.

Cost-benefit analysis (CBA) and life cycle cost (LCC) are the two specific methodologies employed to perform the techno-economic assessment. While both techniques are commonly used in valuation, LCC does not account for the conversion from environmental emissions to monetary measures (Hoogmartens et al., 2014). The CBA is used in PAPER II and integrated into the optimisation model, while the LCC is used in PAPER III to quantify the cost from the construction phase of a facility to the end of its economic life.

In the thesis, indicators are used to compare the techno-economic and environmental impacts of different industrial configurations and

scenarios. In PAPER II, the indicators consist of bioenergy installed capacity, cost, income, profit, GHG emissions, emissions reduction, and technology abatement cost. PAPER III includes the estimation of net income, net present value (NPV), internal rate of return, payback period, and biodiesel breakeven price. PAPER IV uses bioenergy installed capacity as the main indicator.

### c. Spatio-temporal optimisation model

Some tools, such as BeWhere, LocaGISTics, Truck Transport Logistics, and OPTIMASS, have been commonly applied to examine the biomass supply chain (Annevelink et al., 2017; De Meyer et al., 2015). The tools LocaGISTics and Truck Transport Logistics are applied for supply chain simulation, and their main focus is at the regional level (Annevelink et al., 2017). BeWhere is a techno-economic spatial model that enables the optimal design and allocation of biomass supply based on minimisation of supply cost and emissions while considering economies of scale to meet a certain demand (Annevelink et al., 2017). Similar to BeWhere, OPTIMASS is also a deterministic model, but is mainly used to optimise tactical decisions for one representative time period (De Meyer et al., 2015).

The optimisation model in the thesis follows the biomass supply chain assessment tool of the BeWhere model ([www.iiasa.ac.at/bewhere](http://www.iiasa.ac.at/bewhere)). The original model was detailed in two studies (Leduc, 2009; Wetterlund, 2010). It fits the research objective of assessing the supply chain at the national level, and is suitable for the input data that are available from rough-grid biomass availability maps. The model has been applied mostly in the European Union (EU) to develop networks for biomass delivery chains (Leduc et al., 2015). The model helps to determine the optimal selection of technology, location, and capacity, the costs of each segment of the supply chain, the total bioenergy demand, and the avoided emissions.

The original BeWhere model was enhanced to study the specific case of palm oil in Indonesia (BeWhere Indonesia). The model combines a geospatial analysis in the Geographic Information System (GIS) software ArcGIS, with input data managed with the Python programming language and cost optimisation performed in the General Algebraic Modelling System. The optimisation uses a CPLEX solver, and the studied problem is expressed via Mixed Integer Linear Programming. Discrete (binary) variables can be modelled in Mixed Integer Linear Programming, and the

binary variables in this study are associated with the energy plant and aim at selecting the most cost-effective technology and size.

The BeWhere Indonesia model for analysis of the palm oil supply chain in Indonesia was first developed in PAPER II and then extended in PAPER IV. While PAPER II presents the analysis of a single time period, PAPER IV includes the temporal dimension of a multi-period analysis (dynamic model). The structure and the components of BeWhere Indonesia are further detailed in Section 4.1.

d. Scenario development, scenario analysis, and sensitivity analysis

Scenario development and analysis have been increasingly used in research and policymaking processes to better understand potential future challenges and to address associated uncertainties (Fancourt, 2016). In this thesis, scenarios are used to examine how a particular system may plausibly develop in the future and to provide a basis for decision support tools. Scenario development and analysis are used in PAPERS II, III, and IV. The starting point is the reference scenario, commonly referred to as business-as-usual, which is used to provide a reference against the scenarios of change. The scenario analysis aims at measuring the techno-economic and environmental indicators used in the thesis, as listed in this section. A detailed description of the scenarios can be found in Section 4.2.

Table 1: Input parameters tested in the sensitivity analyses

<i>PAPER II</i>	<i>PAPER III</i>	<i>PAPER IV</i>
<ul style="list-style-type: none"> <li>• Average mill operating hours</li> <li>• Palm oil extraction rate</li> <li>• Raw material production cost of large-scale plantations</li> <li>• Transport cost</li> </ul>	<ul style="list-style-type: none"> <li>• Raw material production cost</li> <li>• Price of biofertiliser, biodiesel, electricity</li> <li>• Technology investment cost</li> </ul>	<ul style="list-style-type: none"> <li>• Restriction on the use of CPO for biodiesel</li> <li>• Future energy demand</li> <li>• Bank lending rate, which affects the technology investment cost</li> <li>• Inflation rate, which affects the price of bioenergy</li> <li>• Price of CPO</li> <li>• Transport cost</li> </ul>

Note: Further description of the scenarios for sensitivity analysis of PAPER IV can be found in Table 8 of Section 5.

The effect of various technological/market factors and practices, such as the improvement of milling operations, the agricultural practices (i.e., palm oil yield), and the sale of bioenergy, influence the outputs of the analysis. Sensitivity analyses were carried out to alleviate the uncertainties of the input parameters. Table 1 shows the input parameters tested in the sensitivity analyses of PAPERS II, III, and IV.

### 1.3.2 Methods for data collection

Input data to carry out the analysis were collected by employing techniques for data collection in applied research, which commonly include observations, focus group discussions, interviews, surveys, content analyses, fieldwork, and document reviews, including secondary data analyses (Baimyrzaeva, 2018; Hedrick et al., 1993). Here, a combination of the methods for data collection was applied.

#### a. Qualitative content analysis

Qualitative content analysis is a technique used to analyse text information (Hsieh et al., 2005; Liao, 2016). The research in this thesis involved analysing official/formal policy documents between 2006 (the start of the biodiesel programme in Indonesia) until 2015, as well as other documents published before 2006 but still valid and relevant to support the interpretation of policy documents. Qualitative content analysis involves interpretations of the underlying context that can include false interpretations and personal bias, thus proper research design is required (Bengtsson, 2016). In this thesis, particularly in the research on land allocation, the policy documents were reviewed in relation to the context, which is sectoral land allocation. Scientific work and technical reports are used to elucidate any uncertainty in the interpretation process.

#### b. Secondary data analysis

Secondary data analysis serves to acquire new evidence and is carried out by analysing existing databases/statistics. The use of secondary data analysis is suitable when the available data fit the overarching objective of the research (Majchrzak et al., 2014). This data collection method was used in the analyses carried out in PAPERS I, II, III, IV. The national statistics used in this research are maintained by the Ministry of Agriculture (MoA), the Ministry of Energy and Mineral Resources (MEMR), the Ministry of

Environment and Forestry (MoEF), the Central Bureau of Statistics (Badan Pusat Statistik, or BPS), the state-owned electricity company (Perusahaan Listrik Negara or PLN), and the governing body of the downstream oil and gas industries (Badan Pengatur Hilir Minyak dan Gas Bumi or BPH MIGAS). Data sources from non-governmental institutions were obtained from the USDA Foreign Agricultural Services, Global Forest Watch (GFW), Indonesia Sustainable Palm Oil (ISPO), Roundtable Sustainable Palm Oil, and DIVA-GIS.

### c. Fieldwork and case study

Fieldwork was conducted in 2015 and 2016 to gather the plantation data and the CPO production data from a plantation and a palm oil mill, respectively, located in North Sumatra. These data were used in the techno-economic analysis, particularly in PAPER III. Similar data were also used in the analysis of upscaling the biomass potential to the regional level of Sumatra and Kalimantan (PAPERS II and IV). In reality, each mill has its own technical characteristics, but these data were within the values found in prior research studies and thus can be considered reliable and appropriate as average values for plantations and mills in Indonesia.

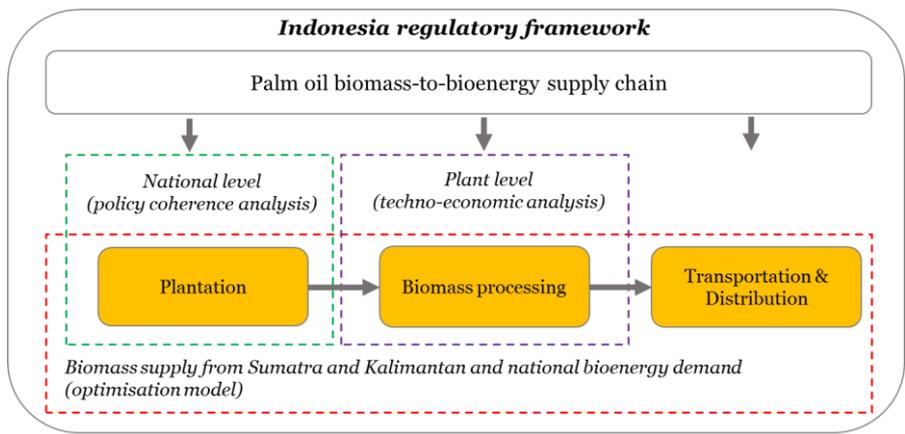
#### 1.3.3 System boundary

Figure 1 illustrates the system boundary of the thesis based on the palm oil biomass-to-bioenergy supply chain and the geographical boundary. As described in Section 1.2, the palm oil biomass-to-bioenergy supply chain includes the upstream (planting, harvesting and transporting FFB to the palm oil mill), the midstream (extracting CPO and generating palm oil biomass residues), and the downstream activities (producing palm oil-based bioenergy in the energy plant unit and transporting the bioenergy).

The specific research boundaries considered in the different papers that compose this thesis are indicated in Figure 1. The research boundary encompasses land use issues at the national policy level, biomass processing at the plant level, and incorporation of the optimisation model to evaluate the biomass-to-bioenergy supply chain in Indonesia. The boundary for the analysis of sectoral land use policies is justified at the national level because the policies for land allocation are formulated by the national government and are applied to all administrative levels. The investigation of biomass processing initially at the plant level is needed as

a basis to assess the potential at the provincial level and the implications at the national level.

This thesis is limited to the supply side of the palm oil industry and accounts only for bioenergy demand in Indonesia. While bioenergy can be used in different forms for various energy services, here the focus is on electricity, biodiesel, and ethanol as carriers. The energy carriers chosen are in line with the Indonesian government’s targets for the provision of modern bioenergy services.



Note: boxes with dotted lines also present the system boundary selected for the paper, as follows:



Figure 1: Schematic representation of the system boundary and methods used (in parentheses).

### 1.3.4 Limitations

The analysis of policy coherence is limited to the evaluation of national policy of Indonesia because the policy elements (e.g. policy goals and policy instruments) are currently set at the national level. The outcome of policy implementation can be steered by informal policy, key actors’ interest and political power. In some cases, the informal mission of actors can have more impact in policy implementation (Bridle et al., 2018). Here, the formal policy documents are reviewed in relation to the context. Institutional capacities, enforcement mechanisms, and public participation are not discussed in the policy analysis, and the influence of policy actors on the policy outcomes is not part of this thesis.

This thesis applies secondary data from various sources, including government databases and the scientific literature. The use of secondary data may require compromises unless the data perfectly fit the concepts that are operationalised in the stated RQs (Majchrzak et al., 2014). In this thesis, especially to complement specific plant data, several validation steps were performed to justify the use of such data to represent a typical operation in the Indonesian palm oil industry.

In the analysis with the optimisation model, data availability posed challenges for the spatial analysis and monitoring of the palm oil industry in Indonesia. Due to the unavailability of public data on the actual planted area categorised into small and large-scale plantations, the estimation of FFB was based on the aggregated regional values from national statistics.

The research also assumed that there was sufficient need for heat generated from the combined heat and power (CHP) plant for internal use in the mill. The production of bioenergy was driven only by demand and by the market prices of the bio-products. The prices of competing products such as fossil fuels or other types of biofuels were not taken into account.

Yield improvement as discussed in PAPERS II and IV was assumed to come from improved agricultural practices using fertilisers and improved harvesting practices. Other factors that may affect yields such as climate impacts were not taken into account.

In PAPER IV, the demand for liquid biofuels only considered domestic demand in Indonesia. Meeting domestic demand is important for energy security and clean energy deployment, and the ambitious governmental targets, together with policy support, are expected to drive the establishment and expansion of the biofuels industry in the country. The research in PAPER IV also did not assign any demand for CPO other than biodiesel production and only included the market price for CPO (the portion that was not used for biodiesel).

#### **1.4 State-of-the-art research on the sustainability of the palm oil industry**

International pressure to improve sustainability in the palm oil industry has led countries producing palm oil to review their practices. The sustainability requirements have motivated a vast body of research on technical aspects of palm oil residue use, land use and land use change,

emissions, and environmental impacts as well as biodiversity and socio-economic aspects (Hansen et al., 2015).

Issues surrounding resource efficiency and sustainability in the palm oil supply chain include the use of biomass for bioenergy, but the complexity of the supply chain leads to variations in the study boundaries chosen to analyse the palm oil industry (Hospes et al., 2017). The majority of previous studies have discussed countries in South East Asia (e.g., Malaysia, Indonesia, and Thailand) and South America (e.g., Colombia and Brazil). This thesis focuses on Indonesia.

### *Land use issues*

Issues surrounding land use are one of the main research topics regarding the sustainability of the palm oil industry. The majority of palm oil research in Indonesia addresses land use issues due to the urgent need to overcome deforestation. Deforestation in Indonesia is largely driven by the expansion of oil palm and timber plantations as well as logging operations (Busch et al., 2014). In the study on mapping the prime drivers of deforestation across Indonesia from 2001 to 2016, Austin et al. (2019) concluded that oil palm plantations were the largest single driver of deforestation over that period. The study also found that there is a substantial difference between the deforestation profile of the two major oil palm producing islands of Indonesia, i.e., Sumatra and Kalimantan. In Kalimantan, the deforestation occurred between 2005 and 2013, whereas oil palm plantation expansion in Sumatra peaked earlier. In addition, Sumatra has a substantially higher rate of deforestation driven by small-scale plantations than Kalimantan.

To curb deforestation, the government of Indonesia introduced several policy interventions. One such intervention is a moratorium prohibiting new concession licenses for planting on primary forest and peat areas (the temporary moratorium was made permanent in the policy revision of 2018). This has inspired many scholars to study the effectiveness of the moratorium policy as a tool to achieve zero deforestation. Austin et al. (2014) assessed the awareness, monitoring, and enforcement among regional and district governments as well as their understanding of the implementation of the moratorium policy. The current implementation of the moratorium policy on land use cover change, deforestation, and GHG emissions was evaluated by Busch et al. (2014), while the future impacts were examined by Austin et al. (2015, 2017) and Mosnier et al. (2017). The

moratorium has slowed down the forest loss rate but has not been effective in stopping deforestation (Chen et al., 2019).

Another issue related to land use falls within the scope of the biodiesel programme in Indonesia. CPO has been chosen as the main feedstock for biodiesel production in the country due to established and affordable sources of supply compared to other vegetable oils. However, Papilo et al. (2018) argue that the implementation of the mandatory bioenergy policy might lead to a significant expansion of oil palm plantations if the implementation of the policy is not accompanied by improvements in land productivity. Khatiwada et al. (2018) estimated the land requirements for satisfying the future domestic and international demand for Indonesian CPO and concluded that 6.3 million hectares (Mha) of new plantation would be required in 2025 if there are no improvements in the yields. However, if yields of 4–6 ton (t) of CPO per ha can be achieved, fewer than 0.5 Mha of additional land will be required to meet domestic and international demands for CPO.

Despite the large amount of existing literature evaluating land use change in the context of climate change, the interlinkages between bioenergy and other sectors in the context of land use in Indonesia have not been widely discussed. In this thesis, the interplay of multi-sector policies and their impact on land allocation is explored in a policy coherence analysis.

### *The potential of palm oil biomass resources*

Hambali et al. (2017) estimated that more than 200 Mt/year (Mt/y) of biomass could be generated by the palm oil industry in Indonesia by 2030. Such significant potential has motivated research on the techno-economic and environmental impacts of biomass conversion into value-added products. Some studies have investigated single alternatives, while others have explored multiple alternative technologies for biomass conversion. Life cycle assessment (LCA) is the most common method used to estimate environmental impacts (Hansen et al., 2015).

The attention to POME is significant in the literature. POME is a toxic compound that causes eutrophication and acidification, pollutes terrestrial and aquatic systems, and releases GHGs (Khatun et al., 2017). The role of POME in the overall sustainability of bioenergy production, especially to reduce GHG emissions, is addressed by Lim et al. (2019). Recent studies have discussed improvements to account for POME at the plant level in

Indonesia, and Nasution et al. (2018) investigated technologies for POME treatment aiming at the lowest global warming potential at a palm oil mill in North Sumatra, Indonesia. Harsono et al. (2013) found that anaerobic treatment of POME in a digestion plant offers significant reduction of GHG emissions from palm biodiesel production in comparison to a system with the aerobic treatment of POME in open ponds. Hasanudin et al. (2015) suggested that POME treatment in an anaerobic digestion plant in a palm oil mill with 45 t<sub>FFB</sub>/h could satisfy the fuel requirements for an installed capacity of 1.5 Mega Watts-electricity (MW<sub>e</sub>). Kamahara et al. (2010) explored not only improvements for POME treatment (i.e., methane capture from POME for biogas), but also the use of solid biomass (i.e., shell and fibre) in a CHP system to satisfy the energy demand of a mill. The study confirmed that improvement in biomass utilisation enhances the net energy balance of palm biodiesel production.

Modelling is appropriate to study a complex biomass supply chain (Mafakheri et al., 2014), and many researchers have used optimisation models, econometric models, and simulation models for studying the palm oil supply chain. Compared to Malaysia (the second-largest palm oil producing country after Indonesia), few studies have applied optimisation and simulation models for the analysis of the palm oil industry in Indonesia. Hadiguna et al. (2017) proposed a framework to manage the palm oil supply chain more effectively using the case of a state-owned palm oil mill. The study focused on operational performance in a single location, including the plantation, processing plant, CPO production, and distribution without discussing the potential from biomass residues. Hidayatno et al. (2011) applied system dynamics to identify the relationship between sustainability aspects and to capture the behavioural dynamics of the biodiesel industry.

There are a large number of studies employing mathematical models to explore the potential of upscaling bioenergy production in an industrial complex or a region in Malaysia and some studies are listed in PAPER II. These studies have taken an integrated spatial modelling approach, and have incorporated spatial and/or temporal decision problems in a single or multi-objective optimisation model. The concept of an integrated palm oil processing complex that comprises interaction of biorefineries with both upstream and downstream processing facilities and the concept of industrial symbiosis were both introduced in the literature on the palm oil industry by D. K. Ng et al. (2013) and R. T. L. Ng et al. (2013). These studies

analysed the economic feasibility of industrial symbiosis in the palm oil industry. Using a similar study boundary, R. T. L. Ng et al. (2014) included the safety aspect of the workplace by using a multi-objective optimisation model. Nevertheless, Memari et al. (2017) pointed out that there are still very few cases where the strategic and operational decisions over a multi-period planning horizon have been assessed or highlighted in the literature.

In other Southeast Asian countries such as Malaysia and Thailand, extensive techno-economic and environmental impact analyses of palm-based products and LCAs have been carried out (Abdul-Manan et al., 2015; Chan et al., 2016; Izzah et al., 2019; Mohd Yusof et al., 2019). Those studies explored various methods for oil palm biomass conversion for heat and power generation, biodiesel, bioethanol, biomethanol, or bio-oil in the case of Malaysia. Ong et al. (2012), Pleanjai et al. (2009) and Silalertruksa et al. (2012) examined the LCA for palm biodiesel production in Thailand, while Castanheira et al. (2017) explored the case of palm oil-based biodiesel in Colombia. Not surprisingly, the LCA results vary widely depending on the chosen dataset, study boundary, and LCA method (Archer et al., 2018).

The concept of biorefineries has been increasingly discussed in the research on palm oil as a way to modernise the industry and integrate the upstream, midstream, and downstream processes (Mohd Yusof et al., 2019). Jong et al. (2015) pointed out that biorefineries can have different degrees of complexity. A simple biorefinery uses one feedstock to produce two or three products (e.g., biodiesel, animal feed, and glycerine) using currently available technologies. The biorefinery offers opportunities to conform with stricter environmental standards and allows the creation of new products, eventually improving the overall economic, environmental, and social performance of the system (Ali et al., 2015; Mohd Yusof et al., 2019).

The work of Kasivisvanathan et al. (2016, 2012) explored the economic performance of retrofitting a palm oil mill into a biorefinery. The study designed the model structure so as to consider all palm biomass generated in the mill and multiple processing pathways, including three stages of upgrading technologies. Delivand et al. (2013) explored simultaneous production of ethanol, biodiesel, and electricity from biomass generated in the milling process in a scaled biorefinery system in Brazil, whereas Beaudry et al. (2018) also considered the biomass generated at the

plantation (i.e., oil palm trunks and fronds). Sadhukhan et al. (2018) reviewed how biorefineries can support a bio-based circular economy and eventually contribute to the Sustainable Development Goals.

Many studies have discussed pathways to improve the sustainability of the palm oil industry at various stages of the palm oil supply chain, but few studies have discussed the implications of promoting bioenergy as part of the palm oil industry as a whole. Still, most of the studies explore the potential at the plant level, in a single location, or at the district level. No study has modelled the palm oil supply chain in Indonesia in a geographically explicit way using a spatio-temporal analysis as proposed in this thesis. The case of Indonesia provides a valuable contribution to the body of literature on oil palm research globally.

## **1.5 Thesis contribution**

The review of the state-of-the-art on sustainability research in major palm oil producing countries highlights concerns regarding the expansion of bioenergy in the palm oil industry. However, the impact of bioenergy systems is site and case specific (Creutzig et al., 2015). The main contribution of this thesis is to improve the understanding of sustainability in the palm oil industry in Indonesia, particularly in terms of increased efficiency in the use of land and biomass resources for bioenergy.

First, the research develops a framework to evaluate the utilisation of land and palm oil biomass resources, which are crucial elements for the sustainability of the palm oil industry. It is the first known effort to scrutinise the land allocation involving several sectoral policy goals (i.e., biofuel, agriculture, forestry, and climate) using a policy coherence framework in Indonesia. Another novelty of the research is the development of a spatio-temporal optimisation model to examine the case of the palm oil supply chain in Indonesia (BeWhere Indonesia). The model is applied based on newly developed spatial datasets, which have not previously been used in other studies, and improves the database structure of the agriculture and palm oil sectors of Indonesia. The policy coherence framework and the spatio-temporal optimisation model can be extended to evaluate other resources. The frameworks developed in the thesis can support the policy monitoring process, which can ultimately improve the national bioenergy policy formulation.

The thesis provides solutions to known problems of land scarcity and large untapped palm oil biomass resources, demonstrating the solutions' efficacy for enhancing the sustainability of the palm oil industry. It identifies the type of land and the amount of land allocated for palm biodiesel feedstock production, considering other prevailing policies (i.e., agriculture, forestry, and climate) that require land for meeting the policy goals. This is a first and critical step to reducing land competition in Indonesia. The analysis provides support for revising land-dependent policies to eliminate uncertainties and inconsistencies in land allocation.

Second, the analysis of palm oil biomass resources has provided novel results for the optimal utilisation of the resources in Indonesia. It pinpoints the optimal location for palm oil mills upgrading into biorefineries, the alternative combination of biomass conversion technologies, and the capacity to enhance both the short term and long term utilisation of palm oil biomass. This information is significant for designing an integrated system comprising the palm oil industry and the bioenergy sectors. The findings are also beneficial for encouraging palm oil mill owners and power producer to invest in bioenergy technology.

The research on pathways for harnessing the palm oil biomass potential, enhancing resource efficiency and meeting national energy and climate goals illustrates the multiple benefits of a sustainable palm oil-based industry. The results can be used to identify optimal options (technology and location), thus providing alternatives for policies and incentives to promote investments in biorefineries. The synergies between the palm oil industry and bioenergy production in Indonesia are key to the development of bioenergy deployment in the country and are highly important for meeting energy and climate goals.

## **1.6 Thesis structure**

This thesis is based on four journal articles and elaborates on the context under which each study has been carried out. Following this introductory chapter, the next chapter presents the general characteristics of palm oil and palm oil biomass production and use, as well as the regulatory framework of bioenergy in Indonesia. Chapter 3 presents the analysis of sectoral policy coherence on land allocation. Chapter 4 is focused on palm oil biomass utilisation in new industrial configurations. Chapter 5 discusses the role of improving resource efficiency in the palm oil industry

to meet the national bioenergy targets. This thesis closes with Chapter 6, which provides the main conclusions, recommendations, and suggestions for future research on the topic. The schematic of the thesis structure is shown in Figure 2.

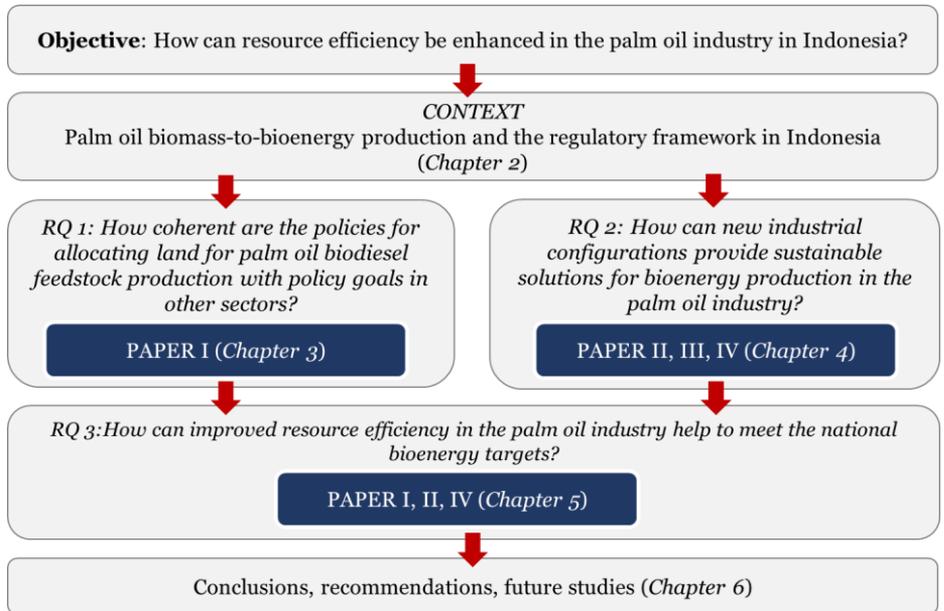


Figure 2: Thesis structure

## 2 Palm oil biomass-to-bioenergy production and the regulatory framework in Indonesia

*This chapter provides an overview of the palm oil industry in Indonesia. It describes the current practices for plantation establishment and palm oil production, biomass availability and its utilisation in the country, and technological options for the biomass-to-bioenergy conversion. Prevailing conditions and regulatory frameworks are also discussed.*

### 2.1 Oil palm plantation development – ecological and legal suitability

The oil palm, *Elaeis guineensis* Jacq., is a monocotyledon that belongs to the Arecaceae family (also known as Palmaceae) (Souza et al., 2017). It has a hard-shelled nut, which contains the palm oil, surrounded by pulp. The physical evidence strongly suggests that the tree originated from the African region and has been used by humans for several thousand years (Corley et al., 2016). It is a perennial crop with an economic lifetime of 25–30 years, producing fruits throughout the year.

Warm and wet conditions (in the range of 24–28°C), as well as optimal rainfall (2,000–2,500 mm per year), are favourable for the oil palm to grow (Corley et al., 2016). The palm's growth is constrained by chemical (e.g., nutrient) and physical (e.g., water, soil) conditions, which can be improved by irrigation and fertiliser application. If the guidelines for best management practices are followed carefully, the oil palm can give a high yield at an acceptable cost (Woittiez, 2019).

Land suitability for oil palm cultivation is determined by the climatic conditions, which can be found in the Amazon region, Central Africa, Western Africa, and Southeast Asia (Indonesia, Malaysia, Thailand) (Pirker et al., 2016). In Indonesia, oil palm plantations are mostly found in the islands of Sumatra and Kalimantan, as shown in Figure 3. The total cultivated area (11.3 Mha in 2019) is equivalent to about 11% of the combined land area of Sumatra and Kalimantan (USDA, 2019a).

In 2005, oil palm plantations occupied 5.9 Mha. Over the next 14 years, the cultivated area grew to 11.3 Mha with an average annual area expansion of 6% (MoA, 2017; USDA, 2019a). This growth is even more remarkable in terms of the production of CPO. Within the same period, production tripled, from 14.6 Mt of CPO in 2005 to 41.5 Mt in 2018 (MoA, 2017; USDA, 2019a). A higher growth rate in CPO production compared to area expansion can be explained by productivity improvements in both crops and palm oil processing. The trend of productivity improvement in crops is taken into consideration in the analysis in Chapter 4 (further details are explained in Section 4.1) and in PAPERS II and IV.

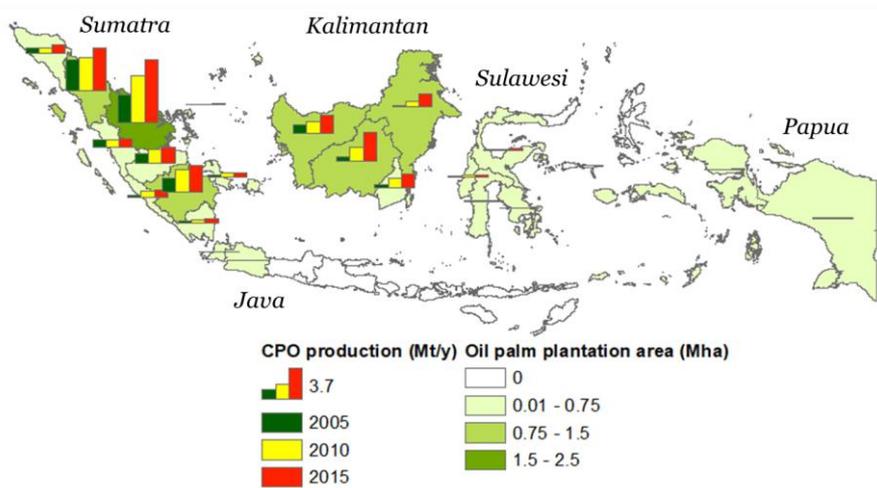


Figure 3: CPO production (Mt) in 2005, 2010, 2015 and oil palm plantation area (Mha) in 2015 in Indonesia per province. Data were obtained from MoA (2017)

Oil palm plantations in Indonesia have been claimed to be the prime cause of land use change, resulting from the conversion of natural forest and peatland (Austin et al., 2019). The practice of planting on forest and peatland was common in the past. Current regulations claim that environmental impact on peatland can be avoided by not planting in areas with peat depth of more than 3 m, planting only in non-forest areas, and avoiding areas where the mineral substratum below the peat layer is quartz sand or acid sulphate soils (Harahap et al., 2017). Forest and peatland

conversion into plantation agriculture is a substantial source of GHG emissions (Carlson et al., 2012), and this explains the high annual GHG emissions in Indonesia.

In Indonesia, peat is largely found in swamp areas (Osaki et al., 2015; Sorensen, 1993). Peat is generally defined as soil with a high organic matter content and is formed in areas that are saturated with water (high water table). Peatland can store carbonaceous materials and is hence vital for the atmospheric carbon cycle (Lee et al., 2013). Peat soils in Malaysia and Indonesia absorb carbon at the rate of 100 kg/ha-y, which accounts for 20–33% of the Earth’s terrestrial carbon (Mukherjee et al., 2014). Even though the cost of establishing plantations on peatland can be two or three times that of establishing them on mineral soils, planting on peat has increased due to a shortage of good mineral soils. The estimated amount of peat ecosystem in Indonesia is 24.14 Mha, which covers 12% of the forest area (MOEF, 2018). Concessions for oil palm plantations in peatland amount to approximately 3 Mha (Hooijer et al., 2006; Page et al., 2007).

Thus, understanding the legal land classification in Indonesia is key to identifying the areas available for future plantation expansion, and also to verify potential overlaps that may occur in land allocation when considering other sectors. The areas allocated for oil palm plantations under Indonesian regulations are discussed in PAPER I and Chapter 3 and Chapter 5 of this thesis.

## **2.2 Palm oil biomass-based bioenergy**

The International Energy Agency (IEA, 2012) defines bioenergy as “energy derived from the conversion of biomass, where biomass may be used directly as fuel or processed into liquids and gases”. Various biomass feedstock can be used as sources of bioenergy, including wet organic wastes, sewage sludge, animal wastes, organic liquid effluents, the organic fraction of municipal solid waste, residues from agriculture and forestry, energy crops, and vegetable oils (IEA, 2017). Modern bioenergy can be used for electricity, heat, and as liquid fuels. Biofuels usually represent liquid biofuels (e.g., biodiesel and ethanol) and gaseous fuels (e.g., biogas and syngas).

Depending on the source of feedstock production, liquid biofuels can be grouped into first, second, and third-generation biofuels. The first-

generation or conventional biofuels are generally extracted from food crops such as rapeseed, soybean, sugarcane, or palm oil. More advanced biofuels, or second-generation, can be derived from a variety of biomass sources such as wood, residues, and waste using more sophisticated technologies, while the third-generation can be produced from algae (Mukherjee et al., 2014). Advanced biofuels have the advantage of not directly competing with food crops (Lee et al., 2013).

Oil palm is the main source of agriculture biomass in Indonesia. The biomass is mainly generated from the plantation after the harvesting and milling processes. Only 10% of the whole palm tree produces oil (i.e., CPO and palm kernel oil (PKO)), and the remaining comprises solid biomass (e.g., fronds, leaves, trunks, and roots) (Lee et al., 2013). The CPO and PKO are the main products of palm oil industry. They have different fatty acid profiles, which increases the crop's versatility in several food and non-food applications (Barcelos et al., 2015). The production of CPO involves sterilising, stripping, digesting, and pressing the fruits for oil extraction (Harsono et al., 2013). The CPO extraction process generates PKS, PMF, EFB, and POME. These residues contain energy, organic matter, and mineral elements, and they have a substantial economic value such as through energy generation (e.g., electricity, steam, and liquid fuels). Furthermore, the decomposition of untreated residues produces significant GHG emissions (Kurnia et al., 2016). The average amount of biomass generated in palm oil mills from 1 ha of oil palm plantation per year is shown in Figure 4.

A typical residues treatment system in Indonesia palm oil mills is shown in Figure 5. A small portion of PKS and PMF are used in the CHP plant for internal energy use. The mill effluent is treated in aerobic and facultative open lagoons. Some mills have a co-composting system of EFB and POME for producing biofertilisers, while others return the EFB directly to the plantation without prior treatment (Hasanudin et al., 2015).

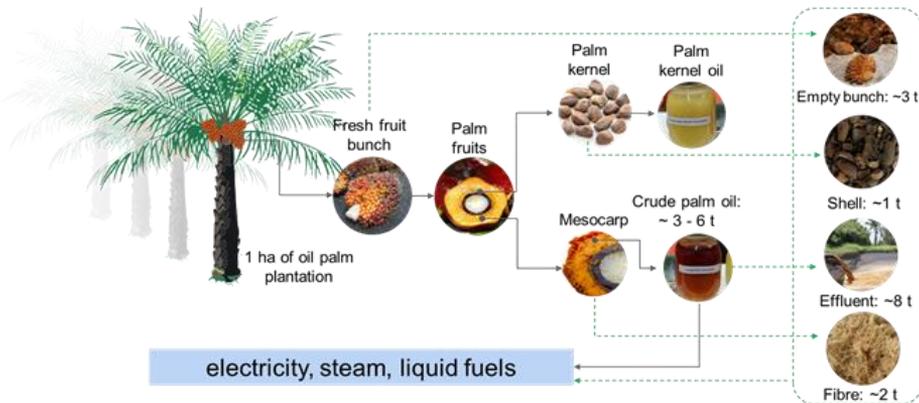


Figure 4: Sources of palm oil biomass in palm oil mills and pathways for bioenergy production in biorefineries. Biomass conversion values are expressed in  $t_{\text{biomass}}/y$ .  
Compiled by Harahap et al. (2019).

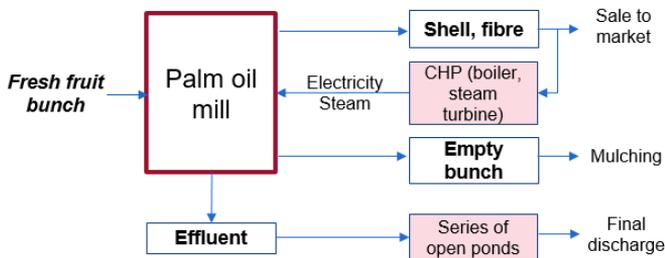


Figure 5: Common residues treatment system in Indonesia palm oil mill.  
Abbreviation: combined heat and power (CHP)

Evaluating opportunities to improve the utilisation of biomass residues in the palm oil mill is crucial to achieving more efficient use of resources, reducing GHG emissions (from the untreated residues/wastes) and generating income. Improvements to enhance the use of biomass resources in the palm oil mills are discussed in PAPERS II, III, and IV and in Chapter 4, and their role in meeting the national bioenergy targets are presented in Chapter 5.

Technological options to produce bioelectricity, biodiesel, and ethanol from palm oil biomass which are considered in this thesis are presented in this section.

a. Palm oil biomass-based electricity

*Combined heat and power units*

Some mills in Indonesia meet their energy demand using on-site energy generation. Such mills install a cogeneration plant, or CHP plant, and use PKS and PMF as the feedstock. Still, many mills use a diesel generator to meet the internal energy demand (Nasution et al., 2014).

A palm oil mill can be self-sufficient in energy by utilising PKS and PMF in a CHP system. The system consists of steam boilers, back pressure turbine, and electrical networks which are integrated into one system. A typical plant has 20 bar (2.0 MPa) and 350°C of steam, a boiler with 70% boiler efficiency, and a steam turbine with 16% electrical efficiency for producing steam (500 kg/t<sub>FFB</sub>) and electricity (22 kWh/t<sub>FFB</sub>) for the palm oil milling operation. In a typical palm oil mill that has a low-efficiency CHP plant, the system only combusts a small portion of the PKS (2%) and PMF for energy generation. Most palm oil mills in Indonesia are not connected to the external electricity grid. Hence, the CHP plant is installed mainly to meet the energy demand at the mill and surrounding facilities. For a typical palm oil mill processing 30 t<sub>FFB</sub>/h, a CHP plant producing 0.6 MW<sub>e</sub> is sufficient to meet the electricity demand (detailed calculations are presented in PAPER III).

Besides PKS and PMF, EFB can also be utilised in a high-efficiency CHP plant (4.0 MPa and 360°C of steam with a 90% boiler efficiency) coupled with a steam turbine (30% electrical efficiency) to generate more energy. Such plants have a pre-treatment system for pressing, cutting, and drying the EFB in order to convert the EFB into a better feedstock for the boiler (Chiew et al., 2013). Based on calculations carried out in PAPER III, a 4 MW<sub>e</sub> CHP unit can be installed in a typical palm oil mill processing 30 t<sub>FFB</sub>/h. Where more feedstock is available (a mill size of 60 t<sub>FFB</sub>/h), it is possible to install a 9 MW<sub>e</sub> CHP unit (UNFCCC, 2008). PAPERS II and IV analyse the capacities of these CHP units.

*Biogas plant with anaerobic digestion*

Another alternative feedstock for electricity production is the mill effluent, or POME. The POME has high methane content and is thus a potent gas with high global warming potential. In most of the palm oil mills in Indonesia, POME is treated in a series of open ponds to reduce the organic

content. Such treatment can reduce water pollutants but does not reduce the methane content. The methane can be captured in an anaerobic process and converted into biogas, which can then be used to generate electricity. To meet the sustainability requirement as defined by the national policy, the palm oil mill has to manage the effluent in a biogas plant by capturing the methane for producing biogas for electricity. The biogas plant comprises a biodigester, scrubber, gas engine, boiler, and flare (Rahayu et al., 2015). Some applications of anaerobic digestion technologies (biodigester) for biogas recovery are the covered lagoons (covered ponds with mixing mechanisms) and continuously stirred tank reactors. This thesis considers covered lagoon technology due to lower installation costs, although the gas production efficiency is lower (Rahayu et al., 2015). The installed capacity of the biogas plant in a typical palm oil mill of 30 t<sub>FFB</sub>/h is about 0.5 MW<sub>e</sub> (detailed calculations are presented in PAPER III). In PAPERS II and IV, 1 MW<sub>e</sub> and 2 MW<sub>e</sub> biogas plant units are considered.

#### b. Palm oil biomass-based biodiesel

In Indonesia, 100% of the feedstock used for biodiesel production comes from palm oil (Lee et al., 2013) and is produced from CPO and Palm Fatty Acid Distillate (PFAD). The PFAD is a residue from refining CPO. The ratio of feedstock to biodiesel is 1.042 kg<sub>CPO</sub>/kg<sub>biodiesel</sub> (Papong et al., 2009; Queiroz et al., 2012; Rincón et al., 2014) and 1.096 kg<sub>PFAD</sub>/kg<sub>biodiesel</sub> (Cho et al., 2013).

Biodiesel from CPO and PFAD, also called fatty acid methyl ester or palm methyl ester, is produced through the transesterification process using short chain alcohols, e.g., ethanol or methanol (Rincón et al., 2014). An alkaline catalyst such as potassium hydroxide can accelerate the reaction rate. It converts the ester that separates the triglycerides, removes the glycerol from the triglyceride, and replaces it with an alkyl radical of the alcohol (Canakci et al., 2008). Biodiesel can be used in diesel engines in its pure form or blended with petroleum diesel.

The biodiesel blends currently used worldwide range from B<sub>5</sub><sup>1</sup> to B<sub>95</sub>, but

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<sup>1</sup> B<sub>5</sub> refers to 5% biodiesel and 95% petroleum diesel

most commonly from B<sub>5</sub> to B<sub>20</sub>. A high blending rate requires special engine modifications (Lee et al., 2013). Compared to CPO, PFAD has a higher free fatty acid component (70-90%), thus for PFAD-based biodiesel acid catalysts are preferred. The input material needed to produce 1 kg of biodiesel from CPO can be found in PAPER III.

### c. Palm oil biomass-based ethanol

Bio-ethanol or ethanol has been used extensively as a gasoline substitute in many parts of the world. Globally, commonly used ethanol blends are E<sub>10</sub><sup>2</sup>, E<sub>15</sub>, and E<sub>20</sub> (Lee et al., 2013). The EFB produced from the milling process of FFB is an ideal feedstock for ethanol production due to its high carbon content and abundant supply (Mohd Yusof et al., 2019). However, the process of converting EFB to ethanol is more complex than ethanol produced from corn or sugarcane (Chiew et al., 2013).

Ethanol production through biochemical processing consists of EFB pre-treatment, enzymatic hydrolysis of the pretreated EFB, simultaneous saccharification and fermentation using enzymes, and product purification (Delivand et al., 2013; Xuan Do et al., 2014). Chiew et al. (2013) indicate a wide range of EFB to ethanol conversion yields (84–494 kg/t<sub>EFB(dry)</sub>) depending on the production techniques.

Ethanol can also be produced via thermo-chemical conversion processes (e.g., gasification) to produce syngas with subsequent catalytic conversion of the syngas to ethanol (Deurwaarder et al., 2006). The process consists of biomass gasification, gas cleaning, and catalytic higher alcohol synthesis (Chew et al., 2008). While several studies have analysed ethanol production from agricultural residues (e.g., wood chips, sugarcane bagasse, and straw) via gasification, none specifically presented the techno-economic feasibility of EFB-based ethanol. The production yield via the thermo-chemical route significantly depends on the type of reactor and catalyst. Taylor-de-Lima et al. (2018) argued that the indirect gasification process has more techno-economic advantages compared to the direct gasification process and the entrained flow gasification process.

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<sup>2</sup> E<sub>10</sub> refers to 10% bio-ethanol and 90% gasoline

In terms of the synthesis catalyst, Reyes Valle et al., (2013) found MoS<sub>2</sub> to be more economical than Rh/SiO<sub>2</sub>. Further review of the different type of reactors and catalysts and their efficiency can be found in Sikarwar et al. (2017).

Compared to the biochemical process, the gasification process also converts the lignin fraction into alcohols, thus resulting in higher conversion yields. Ethanol yields of up to 50% have been obtained using gas-to-ethanol synthesis processes (Demirbaş, 2005). Geng (2013) indicated that among the studies on EFB thermo-chemical conversion, gasification is the most suitable approach to obtain bioenergy from EFB and has the potential to become commercially viable in the near future.

The production of second-generation ethanol from EFB is not yet at the commercial stage in Indonesia. However, the country is continuing to explore this option through research and development (USDA, 2018). In this thesis, the potential of ethanol from EFB is considered in PAPER IV together with the investigation of the role that the palm oil industry can play in achieving the national bioenergy targets.

### **2.3 Recent progress and development in bioenergy**

Bioenergy is an important part of the Indonesian energy agenda, and the national energy policy (Regulation 22/2017) places bioenergy as a top priority for the country to achieve 23% and 31% of renewable energy supply in the total energy mix in 2025 and 2050, respectively. Three main driving forces place bioenergy on the national agenda: (1) bioenergy for energy security by reducing fossil fuel dependency, (2) bioenergy for sustainability by producing clean energy and reducing GHG emissions and mitigating the impacts of climate change, and (3) bioenergy for economic development, particularly for rural and agricultural development.

In terms of the actual renewable energy share in the country's energy mix, a study by Maulidia et al. (2019) showed that from 2010 to 2017 the achievements were behind the set target. In 2017, the actual renewable share was 8.7%, while the initial target was 10.9%. As shown in Figure 6, bioenergy is expected to contribute 8% and 12% to the country's total primary energy in 2025 and 2050, respectively. However, it should be noted that the bioenergy mix is not expected to come entirely from modern bioenergy application. As illustrated in Figure 7, the national energy policy includes the use of biomass for primary energy use, such as cooking.

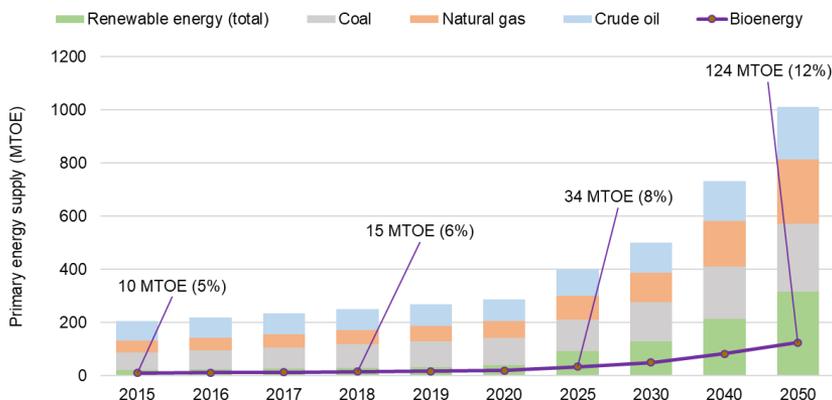


Figure 6: The role of bioenergy in Indonesia's primary energy mix. Source: (GoI, 2017a)

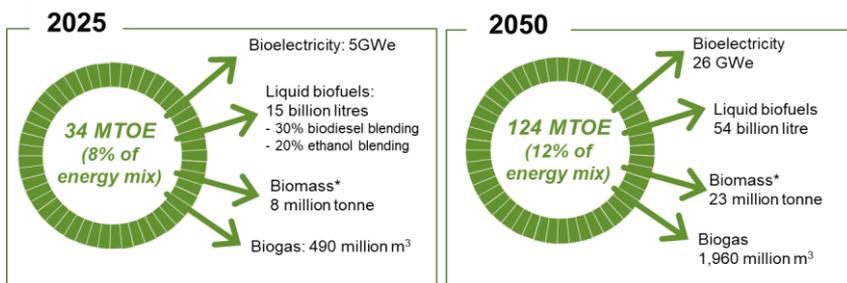


Figure 7: Bioenergy targets for 2025 (left) and 2050 (right) per type of bioenergy in the national energy policy. Source: (GoI, 2017a)

MEMR monitors bioenergy development. As of 2018, the installed capacity of bioelectricity was 1.8 GW<sub>e</sub> (or 5.3% of the total potential), fulfilling 33% of the target for 2025 (Maulidia et al., 2019; MEMR, 2019; Yudha et al., 2019). The palm oil industry produces 0.5 GW<sub>e</sub> from biomass combustion and biogas from methane capture for electricity production. The current palm oil biomass utilisation is far below. Until 2015, only 3.6% and 1.06% of the total electricity potential from biomass and biogas sources, respectively, were found in palm oil mills in Indonesia (MEMR, 2016).

A remarkable development is seen in the biodiesel programme. Biodiesel in Indonesia is mainly produced from palm oil, and the biodiesel blending rate has reached 11.3% within a decade, although it is mostly implemented

in the transport sector (Yudha et al., 2019), shown in Figure 8. The biodiesel programme in Indonesia started in 2006, and its main objective was to reduce dependency on fossil fuel. Financial support from the government has helped to sustain the biodiesel market in Indonesia in the last years, as shown in Figure 9. In 2015, biodiesel producers in Indonesia had to considerably reduce their biodiesel production due to low fossil diesel prices and high feedstock prices (Putrasari et al., 2016; USDA, 2016). Meanwhile, due to the lack of production infrastructure and feedstock—as well as for economic and political reasons—the ethanol blending program ended in 2010 (Silveira et al., 2019). The overall role of the palm oil industry in meeting the national bioenergy targets is discussed in Chapter 5.

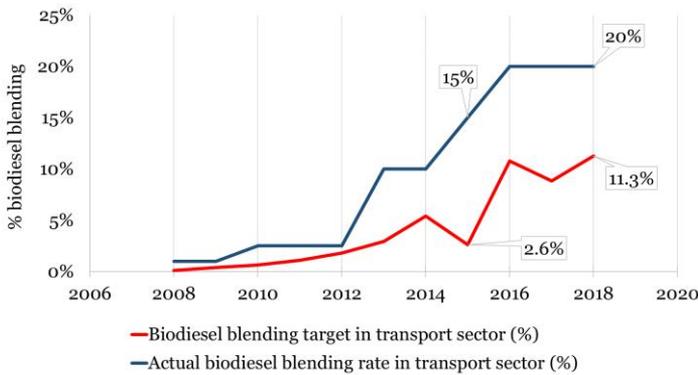


Figure 8: Biodiesel policy target (blue line) and achievement (red line) in the domestic road transport sector in Indonesia. Source: (USDA, 2018)

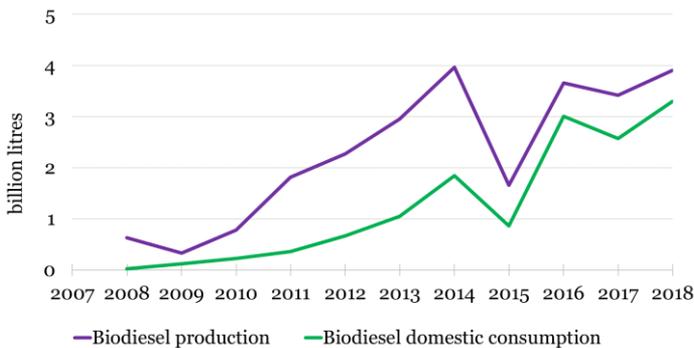


Figure 9: Biodiesel production (purple line) and domestic consumption (green line) in Indonesia 2008-2018, in billions of litres. Source: (USDA, 2018)

## 2.4 Policy framework for bioenergy development in the palm oil industry

A variety of support schemes for bioenergy production have been applied in many countries. Some of the most common instruments to enhance renewable energy deployment, including bioenergy systems, are either price-based or quantity-based policy instruments (Ragwitz et al., 2014). This section discusses specific policies in force affecting bioenergy deployment in the palm oil industry in Indonesia, and the current bioenergy policies, as listed in Table 2 are focused on biodiesel and bioelectricity production.

Table 2: Enabling policies for enhancing bioenergy deployment in the palm oil industry in Indonesia.

<b><i>Policy specification</i></b>	<b><i>Policy area</i></b>	<b><i>Policy description (reference to policy document)</i></b>
Policy for biodiesel production and use	Energy	Provision, utilisation, and administration of biodiesel, biodiesel blending rate and target sectors (i.e., transport, power, and industry). (Regulation 12/2015)
	Energy	Provision and utilisation of biodiesel as an alternative fuel. A target to produce 11.6 billion litres of biodiesel until 2025. CPO is the main feedstock. (Regulation 22/2017)
	Climate	Contribution of biodiesel use in the transport sector for emissions savings. (GoI, 2017b)
	Trade	Provision of biodiesel export tax of 20 USD/t. (Regulation 30/2016)
	Economy	Formulation of the biodiesel domestic market price is based on CPO price. (Regulation 6034/2016)
	Economy	Financial support to cover the market price gap between fossil diesel and biodiesel through palm oil export tax. (Regulation 45/2018)
Policy to allocate land for biofuels (biodiesel and bioethanol) feedstock production	Agriculture	Land for biofuel feedstock plantation. (Regulation 1/2006)  Moratorium to suspend new licenses for oil palm plantation expansion (Regulation 8/2018)

<b><i>Policy specification</i></b>	<b><i>Policy area</i></b>	<b><i>Policy description (reference to policy document)</i></b>
Policy for bioelectricity production	Agriculture, Energy	Utilisation of palm biomass residues (i.e., PMF, PKS, EFB and POME) for bioelectricity. (Regulation 11/2015)
	Energy	Purchase obligation for bioelectricity from palm biomass. (Regulation 22/2007)
	Economy	Special electricity tariffs are provided for electricity generated from biomass and biogas sources, and the state-owned electricity company as the grid operator is obligated to purchase the electricity from renewable energy sources. (Regulation 21/2016)
	Climate	Emission savings from POME treatment and, methane capture and utilisation. (Intended Nationally Determined Contribution or INDC document: GoI, 2016)
	Climate	Contribution of renewable energy in electricity production. This includes energy from palm biomass. (INDC: GoI, 2016)
Policy for bioenergy industry and new infrastructure	Economy	Income tax reduction, tax incentives for imports of machinery required for production. (Regulation 1/2007, Regulation 21/2010, Regulation 144/2012)
	Economy	Government fund for biofuel infrastructure. (Regulation 8/2007)

The provision and utilisation of biofuels as alternative fuels and the acknowledgement of the contribution of biofuels to the energy mix gained political momentum in 2006 (Regulation 5/2006). According to (Regulation 22/2017), one way to achieve the biodiesel blending target is by utilising CPO for biodiesel production.

Various regulatory instruments (e.g., standards and procedures for the cultivation, supply and distribution of biofuels, the provision of land and the development of research and technology) and economic instruments (e.g., financial incentives, market prices and trading systems) were established to develop the biodiesel industry, see Table 2. Regional governments (including governors, district heads and mayors) also take part in the development of the domestic biodiesel industry by facilitating the provision of land for feedstock plantation (Regulation 1/2006).

The core policy governing land use for biofuel production (Presidential Instruction 1/2006) indicates non-productive areas in forest and non-forest as suitable for the production of all types of biofuel feedstock. Chapter 3 and PAPER I discuss the policies governing land allocation for palm oil biodiesel feedstock and the connection with other sectoral policies. It is important to note that the recent moratorium policy (Regulation 8/2018) has temporarily held back the establishment of new oil palm plantations, at least until 2021 (the end of the validity of the policy).

As described in Section 2.3, notable progress has been observed towards achieving the biodiesel blending target. Up to 2015, financial support from the government helped to establish the biodiesel industry in the country. In 2015, the support cost became too high when the diesel price became too low in relation to the high feedstock prices. In response, the government introduced a scheme to channel the export tax on CPO and derivative products to fund the price discrepancy between biodiesel and diesel. The use of the tax revenues, also called the CPO fund, for subsidising biodiesel has driven the production growth and deployment in recent years. The CPO fund can also be used for oil palm replanting programmes. The initial programme aimed at replanting 2.4 Mha of smallholder plantations over six years until 2022 (USDA, 2019a).

Biodiesel support has attracted a lot of attention from the private sector. The biodiesel industry has reached a total capacity of 12 billion litres (bL) from 31 plants in Indonesia (USDA, 2018). That capacity is sufficient to meet the domestic production target by 2025 equivalent to 10.11 bL as estimated in PAPER IV. The ambitious governmental targets are expected to further drive the expansion of the biofuels industry.

Nevertheless, the trend shows that biodiesel is currently feasible only when the price of oil is at its lowest, meaning that biodiesel production is still dependent on financial support (USDA, 2018). In fact, the production cost of biodiesel in Indonesia is considerably higher than that of conventional fuels, which is why it requires support subsidies. In this context, a biorefinery could play a role in making biodiesel production more competitive. Chapter 4 and PAPER III compare the profitability of producing biodiesel in the present system and in a conceptual biorefinery plant (integration between palm oil mill and energy plant unit in the same facility).

There is currently no specific sustainability requirement for bioenergy in Indonesia. However, the ISPO certification has been used since 2011 as a guideline for sustainability compliance in oil palm plantations and palm oil processing in Indonesia. Following the guidelines in ISPO is mandatory for large-scale oil palm plantations with or without an integrated processing plant, but only voluntary for smallholder plantations as well as for integrated plantation and processing plants producing palm oil biodiesel. The voluntary scheme can potentially jeopardise efforts to ensure the sustainable production of palm oil-based biodiesel.

### 3 Sectoral policy coherence on land allocation

*This chapter describes the methods used to analyse the coherence of land allocation for multiple sectoral goals. The areas allocated for meeting sectoral goals under the recognised national land use classifications are pinpointed.*

#### 3.1 Framework to assess policy coherence

The concept for measuring the degree of coherence on sectoral land allocation is explained in PAPER I, and the framework used in this thesis is inspired by Huttunen et al. (2014), Lindstad et al. (2015), and Nilsson et al. (2012). The policy coherence analysis explores sectoral policy interactions in relation to land allocation via internal dimensions (in the single policy area of biofuel) and external dimensions (in the multiple policy areas of agriculture, climate, and forestry). In addition, the analysis also considers three policy layers, namely goals, instruments, and planned implementation. The policy elements used in the framework for policy coherence analysis are illustrated in Figure 10.

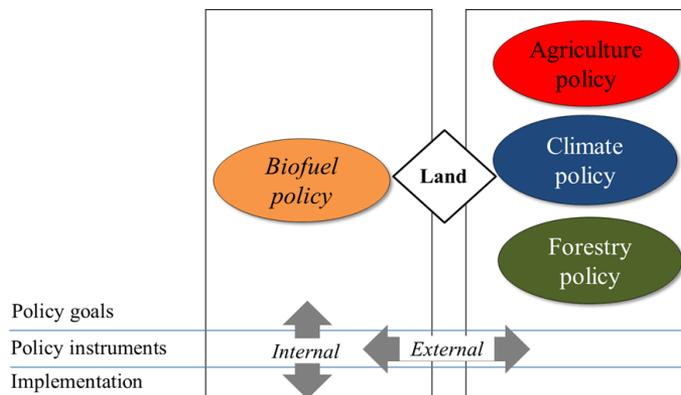


Figure 10: Schematic representation of the framework for policy coherence analysis with interacting layers of sectoral national policies. Source: (Harahap et al., 2017) and PAPER I

Initially, one main sectoral goal based on the importance of land for meeting that goal is chosen. The key instruments for the following goals are outlined in PAPER I. For biofuel, the goal is to meet the target for blending biodiesel into fossil diesel in various sectors for energy security. The key goal selected for the agriculture sector is in relation to securing food supply. Climate change mitigation efforts are set to reduce the GHG emissions from land use change. Finally, the key goal for forestry policy considers the improvement in forest management.

The investigation of land allocation uses the recognised land use classifications in Indonesia. It is important to note that Indonesia uses dual land classifications encompassing the legal status of the land (forest and non-forest area) and land cover (area with forest cover and area without forest cover) as shown in Figure 11. The dual land classifications suggest that discrepancies can be found on the actual land allocation, i.e., between the legal status of the land and the physical land cover. In this thesis, the dual land use categories are used as the basis to confirm how land issues are addressed in the policy documents. The analysis involves investigating 23 legal documents governing land use within the thematic areas of biofuel, agriculture, climate, and forestry.

The qualitative method of content analysis interprets how land allocation is defined in the formal policy documents (the technique for content analysis is described in Section 1.3). The analysis is also supported by scientific literature and reports from a number of institutions to clarify uncertainties in the policy documents. Figure 11 illustrates the approach for the content analysis of the policy documents. Subsequently, the official data on the area that fulfil dual land classifications (based on legal land status and land cover) are used to quantify the land actually allocated to meeting the stated policy goals considering sectoral policy interactions. Discussions on what type of land associated with each sector are discussed in more detail in PAPER I.

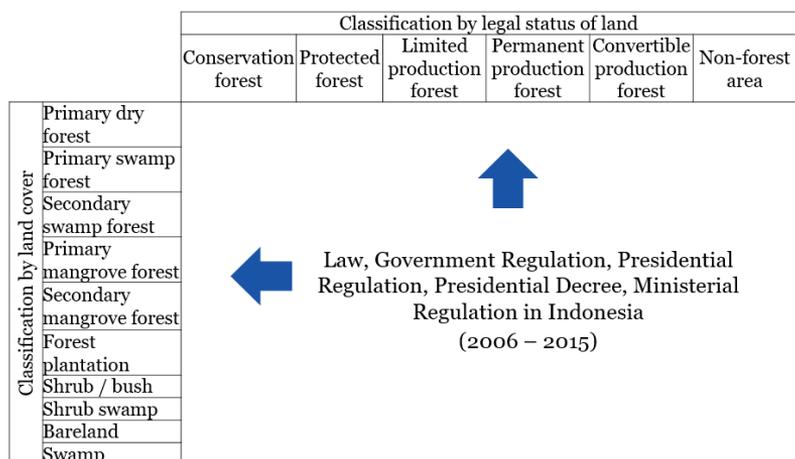


Figure 11: Framework for content analysis to scrutinise policy documents within the thematic areas of biofuel, agriculture, climate, and forestry on the issue of land use allocation. Source: (Harahap, 2018)

### 3.2 Coherency of the biofuel policy with other sectoral policies on land allocation

***RQ 1. How coherent are the policies for allocating land for palm oil biodiesel feedstock production with policy goals in other sectors (i.e., agriculture, climate, and forestry)?***

The cross-sectoral policy analysis using the framework explained in Section 3.1 and detailed in PAPER I indicates areas of uncertainties and inconsistencies when it comes to the allocation of land to meet multi-sectoral policy goals. The uncertainties and inconsistencies show incoherency in the policies that can lead to ineffective policy implementation (Howlett et al., 2007). The policy incoherencies appear due to the factors described in this section.

It is observed that the recognised land use classifications are not consistently used in the policy documents. This raises difficulties in understanding the type of land allocated to which sector, and also allows room for multiple interpretations. For example, various terms in the local language are observed when referring to “degraded land”, which is in the local language referred to as *lahan kritis*, *lahan yang tidak produktif*, *lahan terdegradasi*, *lahan yang penutupan vegetasinya sangat*

*jarang/kosong* (or area with sparse vegetation cover). For the purpose of the analysis, degraded land within the recognised land use classifications is interpreted as areas covered with shrub, shrub swamp, and bare land in forest and non-forest areas. It is also observed that the term of abandoned areas for food crop expansion is used in agriculture policy documents. Such areas according to the agriculture policy documents can refer to areas that were abandoned after the issuance of land rights utilisation, or were located in protected forest, production forest, and non-forest area. Nevertheless, such a definition does not help to clarify the land category under the recognised land classifications.

Multiple land allocations are found in some areas. For instance, land allocated for the expansion of both biofuel feedstock plantation (biofuel policy) and food production (agriculture policy), as well as for climate mitigation purpose (climate policy), can include swamps located in production forest and non-forest areas (see Table 3). The main concern is that these policies sometimes have contradicting objectives, one for exploiting the land (agriculture and biofuel policies), and the other for preserving the land (climate policy). It is evident that adjustments are required when only looking at a single policy area to allocate land.

The priorities of land use that have been defined by the government can help to resolve the multiple land allocation problems. The priority shows that agriculture policy should be put first, before climate policy, forestry policy, and biofuel policy. Thus, food security comes before climate change mitigation and energy security. This hierarchy in the priority of policy goal aims to avoid conflict in land allocation. The hierarchy of sectoral policy goals in Table 3 is arranged from left to right implying that priority is given to the sectoral goal indicated first in each box, resulting in Table 4.

Nevertheless, policy implementation does not always comply with the hierarchy of policy goals. For example, although the agriculture policy should be prioritised, the conversion of rice fields into oil palm plantations still occurs. This is predominantly driven by better income generation from selling palm oil products compared with other agricultural commodities (Feintrenie et al., 2008).

		Classification by legal status of land					
		Conservation forest	Protected forest	Limited production forest	Permanent production forest	Convertible production forest	Non-forest area
Classification by land cover	Primary dry forest	C, F	C, F	C, F	C, F	C, F	C
	Primary swamp forest	C, F, B	A, C, F, B	A, C, F, B	A, C, F, B	A, C, F, B	A, C, B
	Secondary swamp forest	C, F, B	A, C, F, B	A, C, B	A, C, B	A, C, B	A, C, B
	Primary mangrove forest	C, F	C, F	C, F	C, F	F	
	Secondary mangrove forest	C, F	C, F	C	C	F	
	Shrub / bush	F, B	F, B	B	B	B	B
	Shrub swamp	F, B	F, B	B	B	B	B
	Bareland	F, B	F, B	B	B	B	B
	Swamp	C, F, B	A, C, F, B	A, C, B	A, C, B	A, C, B	A, C, B

Table 3: Areas where multiple allocations are identified for sectoral policies (A: Agriculture policy, C: Climate policy, F: Forestry policy, B: Biofuel policy). Source: (Harahap, 2018)

		Classification by legal status of land					
		Conservation forest	Protected forest	Limited production forest	Permanent production forest	Convertible production forest	Non-forest area
Classification by land cover	Primary dry forest	C	C	C	C	C	C
	Primary swamp forest	C	A	A	A	A	A
	Secondary swamp forest	C	A	A	A	A	A
	Primary mangrove forest	C	C	C	C	F	
	Secondary mangrove forest	C	C	C	C	F	
	Shrub / bush	F	F	B	B	B	B
	Shrub swamp	F	F	B	B	B	B
	Bareland	F	F	B	B	B	B
	Swamp	C	A	A	A	A	A

Table 4: Areas allocated after adjustments are made using the hierarchy of sectoral policy goals (A: Agriculture policy, C: Climate policy, F: Forestry policy, B: Biofuel policy).

## 4 Industrial configurations for sustainable bioenergy production in the palm oil industry

*Realising the potential of palm oil biomass residues can bring new income streams while reducing emissions. If biorefinery systems are developed, the cost competitiveness of CPO-based biodiesel would increase. To obtain maximum benefits from biorefineries, the location of the production facility and planning time frames need to be considered.*

### 4.1 The BeWhere Indonesia model for analysing the palm oil supply chain

As explained in Section 1.3, the palm oil biomass-to-bioenergy supply chain is evaluated using BeWhere Indonesia. The model allows the modelling of discrete (binary) variables. In this thesis, the binary variables relate to the energy plant, helping to select the most cost-effective technology and plant size for bioenergy production. The model chooses the optimal pathways from one set of biomass supply points to a set of processing plants and further to a set of demand points (Leduc, 2009).

The schematic representation of the model structure and the linkages between model components (model parameters) are shown in Figure 3. The model has three main components:

- i) the data processing component where information (spatial and techno-economic data) on biomass, mills, technologies, and transports is collected and managed;
- ii) the optimisation component where the objective function of total profit is maximised by minimising the total cost; and
- iii) the scenario analysis component, where various scenarios are analysed and a sensitivity analysis on various parameters is performed.

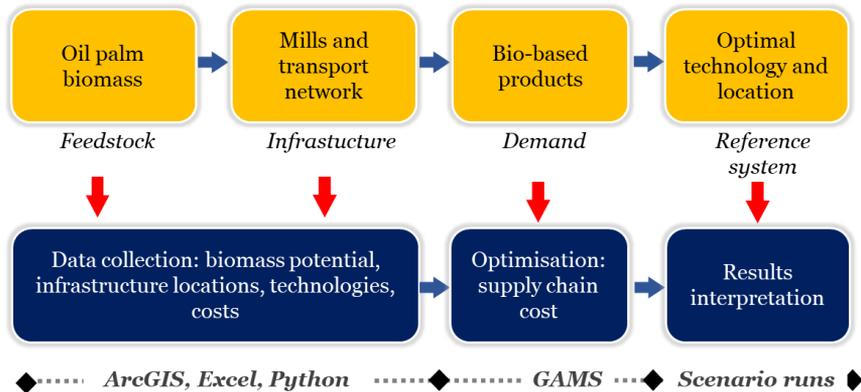


Figure 12: Schematic representation of BeWhere Indonesia for analysing palm oil supply chain.

The model consists of elements along the chain, i.e. raw materials, processing plants, intermediate products, conversion facilities, bio-products, and the demand for the final products. The model superstructure (see Table 5) shows the relationships and possible combinations between the model elements.

The model was first developed in PAPER II and subsequently extended in PAPER IV by incorporating the temporal dimension and the components of the liquid biofuels (i.e., cost, conversion technology, and transport), as well as expanding the geographical scope for the assessment to the whole of Indonesia. The graphical representation of the palm oil biomass-to-bioenergy supply chain considered in PAPERS II and IV is shown in Figure 13.

The requirements for residue treatment (i.e., methane capture from POME, power generation from solid biomass, and biofertiliser production from EFB and POME) set by the Indonesian government are considered in the analysis. In PAPER II, the evaluation takes into account the geographical coordinates of individual mills in Sumatra. In PAPER IV, the palm oil mills in Sumatra and Kalimantan are grouped at the grid level and represent the potential sites for the location of biorefineries. While the model applied in PAPER II considers the single year of 2015, PAPER IV includes a dynamic model that incorporates a multi-period analysis from 2015 to 2030, with five-year time intervals.

Source of raw material (i.e. FFB) (M)	Processing plant (P)	Intermediate product (IP) (IP)	Technology (Tech)	Bio-product (BP)	Demand (D)
1 Small-scale plantation	1 Palm oil mill	1 CPO	1 CPO - CPO (efficiency = 1) (IP 1)	1 CPO (Tech 1)	1 Sumatra island power demand
2 Large-scale plantation		2 PK	2 PK - PK (efficiency = 1) (IP 2)	2 PK (Tech 2)	2 Country biodiesel demand
		3 PKS	3 PKS - PKS (efficiency = 1) (IP 3)	3 PKS (Tech 3)	3 Country ethanol demand
		4 PMF	4 PMF - PMF (efficiency = 1) (IP 4)	4 PMF (Tech 4)	
		5 EFB	5 EFB - EFB (efficiency = 1) (IP 5)	5 EFB (Tech 5)	
		6 POME	6 POME - POME (efficiency = 1) (IP 6)	6 POME (Tech 6)	
			7 Composting (IP 5,6)	7 Biofertiliser (Tech 7)	
			8 Anaerobic digestion, 1 & 2 MW (IP 5)	8 Bioelectricity (Tech 8 - 10)	
			9 Low efficient CHP, 1 MW (IP 2,3)	9 Biodiesel (Tech 11)	
			10 High efficient CHP, 4 & 9 MW (IP 2,3,4)	10 Ethanol (Tech 12)	
			11 Biodiesel transesterification, 100, 150 & 200 kt (IP 1)		
			12 Ethanol fermentation & gasification, 10, 30 & 50 kt (IP 4)		

Table 5: The BeWhere Indonesia model superstructure for the palm oil supply chain. Abbreviations: bio-product (BP), crude palm oil (CPO), demand (D), empty fruit bunch (EFB), fresh fruit bunch (FFB), intermediate product (IP), processing plant (P), palm kernel (PK), palm kernel shell (PKS), palm mesocarp fibre (PMF), palm oil mill effluent (POME), raw material (M), technology (Tech). Note: Blue boxes are only included in PAPER II, and red boxes are only included in PAPER IV.

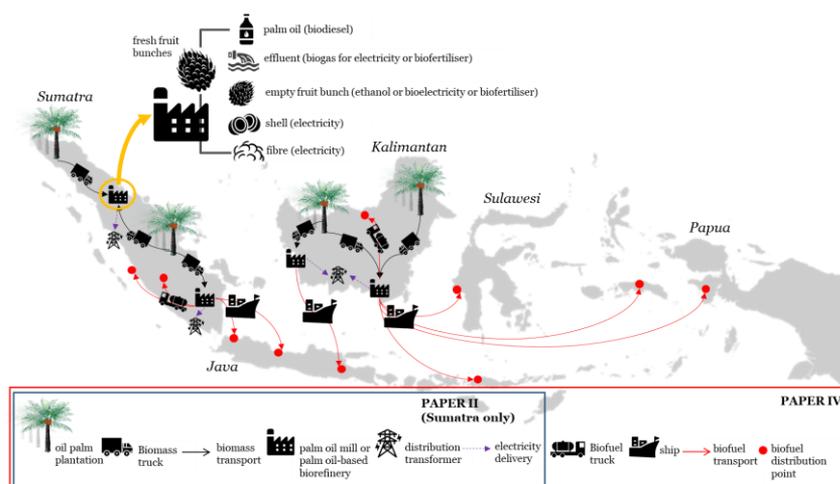


Figure 13: Graphical representation of the palm oil biomass-to-bioenergy supply chain in BeWhere Indonesia.

Note: Elements in blue box are only included in PAPER II, and elements in red box are included in PAPER IV.

The estimation of raw material (i.e., FFB) availability is based on the existing plantation area at the district level in 2015, published by MoA (2017). Only the mature plantation area, which is when yield and leaf are stable, thus between 8 and 14 years after planting, is considered (Woittiez, 2019). The immature and damaged areas are excluded from the analysis. The total mature plantation areas amount to 5.35 Mha on Sumatra and 2.59 Mha on Kalimantan in 2015 in Sumatra (MoA, 2017).

The yield difference between large-scale (private and state-owned) and small-scale plantations is taken into account. In PAPER IV, the increase in biomass supply is assumed to come from improved plantation yields (i.e.,  $t_{CPO}/ha$ ) and is limited to the existing mature plantation area (not generated by plantation expansion). This is in line with i) government replanting programmes intended to increase the plantation yield especially from the small-scale plantations (USDA, 2018) and ii) suspension of the granting of new concession licenses for oil palm plantations, which puts a temporarily hold on plantation expansion at least until 2021 (Regulation 8/2018). The yield of large-scale plantations in all districts is assumed to increase to 4  $t_{CPO}/ha$  in 2020 and 6  $t_{CPO}/ha$  starting from 2025 (Khatiwada et al., 2018). The improvement in small-scale plantation in all districts is assumed to follow the trend of the large-scale plantations, thus 3.6  $t_{CPO}/ha$  in 2020 and 4  $t_{CPO}/ha$  after 2025. This gives a total 40.5  $Mt_{CPO}$  produced in Sumatra and Kalimantan in 2025.

The model defines demand at the delivery point, including the distribution transformer for electricity (PLN, 2018) and the biofuels distribution point to retailers for biodiesel and ethanol (BPH MIGAS, 2018). Demand for electricity is based on the average per capita electricity consumption, the annual electricity demand growth, and the population. This gives a total electricity demand of 153 petajoules (PJ) and 54 PJ, respectively, in Sumatra and Kalimantan in 2025. Demand for liquid biofuels is in line with the government targets of 30% biodiesel for blending with diesel and 20% ethanol for blending with gasoline. This gives a domestic demand of 10.11  $bL_{biodiesel}$  and 13.1  $bL_{ethanol}$  in 2025. A detailed projection of biomass supply and bioenergy demand is further discussed in PAPER IV.

The model's objective function is to maximise system profit by minimising the supply chain cost, which is expressed as:

$$TotProfit = TotIncome - TotCost - TotEnvCost$$

The total system profit (*TotProfit*) consists of total revenues generated from selling bio-products (*TotIncome*) minus the supply chain cost (*TotCost*) (i.e., feedstock production, palm oil mill, biomass and biofuels transportation, production of bio-products, and electricity transmission line costs), and the cost of environmental impacts (*TotEnvCost*) (i.e., total GHG emissions) in the studied system.

The environmental impacts in PAPER II include the supply chain emissions, economic losses due to peat fires, water, and biodiversity losses from the plantation development. PAPERS II and IV account for supply chain emissions from process inputs, feedstock production, transport, plant operations, and biomass processing. The emission from the direct land use change is only considered in PAPER IV, and the effects of the indirect land use change are not in the scope of the thesis. This thesis considers gases that contribute to the greenhouse effect, namely carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), and nitrous oxide (N<sub>2</sub>O), which are added together and converted into carbon dioxide equivalents (CO<sub>2</sub>eq). The cost of GHG emissions is internalized in the model in the form of a CO<sub>2</sub>eq tax.

A description of the mathematical model of BeWhere Indonesia is provided in the Appendix of this thesis. Model input data (i.e., technical, economic, and spatial) are presented in PAPERS II and IV.

## **4.2 Towards sustainable bioenergy production in the palm oil industry**

### ***RQ2. How can new industrial configurations provide sustainable solutions for bioenergy production in the palm oil industry?***

#### *Harnessing the full potential of palm biomass residues in palm oil mills in Sumatra*

Efficient utilisation of palm biomass residues not only provides opportunities for energy recovery, but also avoids significant amounts of GHG emissions from the decomposition of untreated residues. Four scenarios are developed in PAPER II to assess the potential of upscaling the utilisation of biomass residues in Sumatra, as summarised in Table 6. Sumatra accounts for more than 70% of the total palm oil production in Indonesia (MoA, 2017).

Table 6: Scenarios to assess the potential of utilising palm oil biomass residues in Sumatra. Source: (Harahap et al., 2019a) and PAPER II

<b><i>Scenario</i></b>	<b><i>Description of the scenario</i></b>
Reference ( <i>Sc-ref</i> )	Incorporating the policy for utilising palm oil biomass residues, including biogas for electricity from POME, electricity generation from solid biomass (PKS, PMF, and EFB), and biofertiliser production from POME and EFB
Scenario with higher yields in small-scale plantations ( <i>Sc-yield</i> )	Yield improvement in small-scale plantations, which affects fertiliser use and associated emissions
Scenario with enhanced grid connectivity ( <i>Sc-grid</i> )	Grid connectivity is enhanced, connecting all mills to the distribution transformers
Scenario with higher yields in small-scale plantations and enhanced grid connectivity ( <i>Sc-yield-grid</i> )	Scenario with combined aspects in <i>Sc-yield</i> and <i>Sc-grid</i>

Note: Utilisation of the biomass residues are incorporated in all scenarios. Abbreviations: empty fruit bunch (EFB), fresh fruit bunch (FFB), palm kernel shell (PKS), palm mesocarp fibre (PMF), and palm oil mill effluent (POME).

The findings show that the scenario with higher yields in small-scale plantations and enhanced grid connectivity (*Sc-yield-grid*) has the highest cost of 12.3 billion USD/y. However, the related improvements also result in the highest profits for the palm oil industry (4 billion USD/y), yielding 1.5 times greater profit levels than what can be obtained in the reference scenario (2.5 billion USD/y). A substantial investment in the range of 760 million USD/y is required in scenario *Sc-yield-grid*, including 56 million USD/y to improve grid connectivity.

Interestingly, the scenario with higher yields in small-scale plantations (*Sc-yield*) could provide higher profits than the reference scenario (*Sc-ref*) with three times lower investment than what is necessary for scenario *Sc-grid* or *Sc-yield-grid* (see Figure 14). Although *Sc-yield* could provide a more significant profit compared to *Sc-grid* or *Sc-yield-grid*, this does not necessarily lead to a lower environmental impact. Better grid connectivity in *Sc-grid* and *Sc-yield-grid* makes electricity production from biogas attractive. In this case, more emissions are reduced due to methane capture. At the same time, renewable electricity is provided to the grid to substitute for fossil-based electricity or to expand the system with renewables.

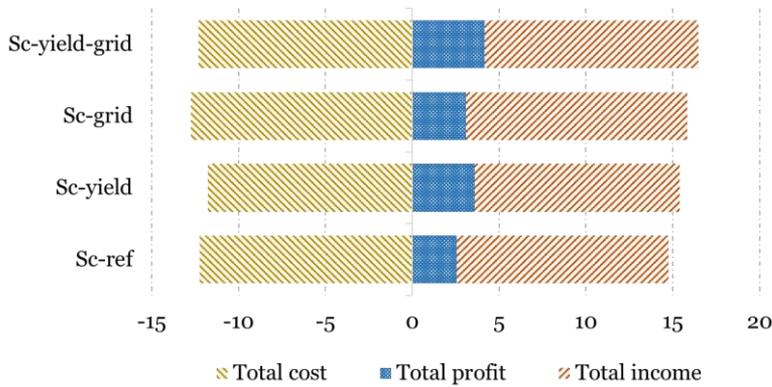


Figure 14: Total costs, income, and profits (in billion USD/y) of a more efficient use of palm oil biomass residues. Source: (Harahap et al., 2019a) and PAPER II

Note: Sc-ref: Incorporating the government policy to foster the utilisation of palm biomass residue; Sc-yield: Improving the yield of small-scale plantations; Sc-grid: improving bioelectricity delivery; Sc-yield-grid: Improving the yield of small-scale plantations and improving bioelectricity delivery.

### *Integrating palm oil mill and biodiesel plant*

Profitability is one of the challenges in biodiesel production, which is heavily reliant on subsidies. The positive economic impact from utilising the palm biomass residues, as outlined in this section, indicates opportunities for improving the overall profitability of CPO-based biodiesel production in Indonesia.

An industrial configuration around the creation of biorefineries combining the production of CPO and biodiesel in a single location is investigated in PAPER III. In current practice, the palm oil mill and biodiesel plant are usually not located in the same facility. A typical palm oil mill is located close to the plantation, and the biodiesel plant is often located near a seaport.

In order to examine the most cost-effective biorefinery configuration for CPO-based biodiesel production, three biorefinery cases (Case 1 to Case 3) are studied in PAPER III. The biorefinery system is compared with a conventional system depicting the typical production of CPO-based biodiesel in Indonesia. The schematic representations of the conventional

system and the biorefinery concept are shown in Figure 15. The comparisons of the systems in relation to the biomass conversion technologies, the feedstock use, and type of bio-products generated are presented in Table 7. The energy input of the system depends on whether the system is energy self-sufficient from the on-site generation or requires additional fossil fuels.

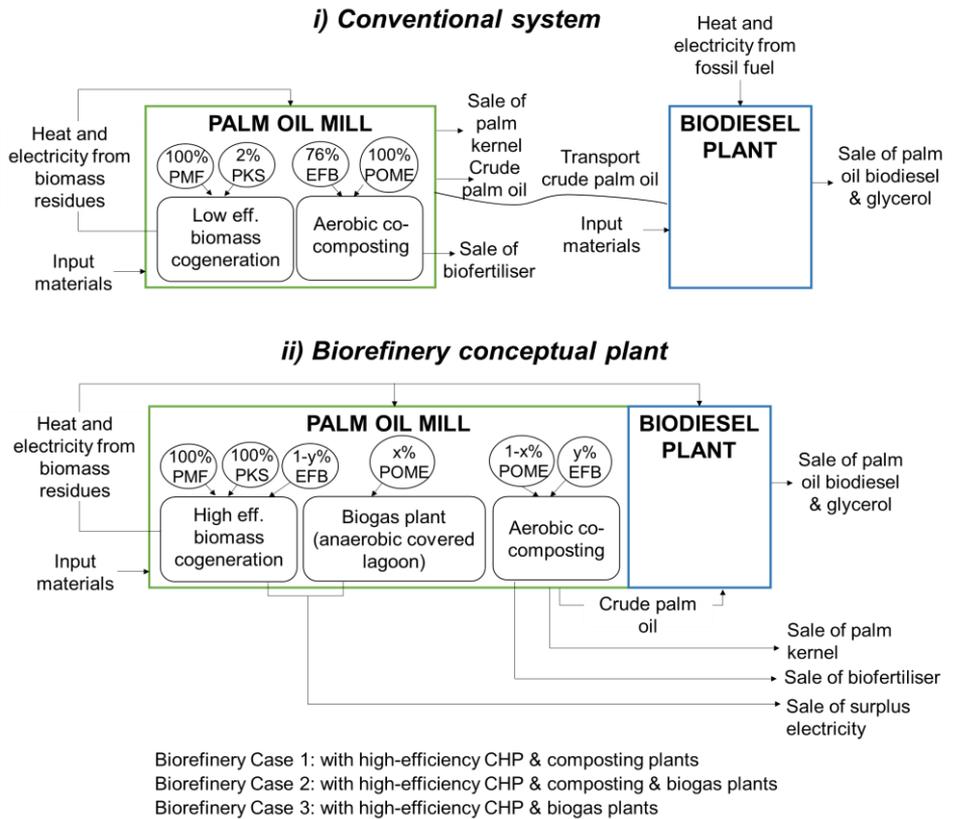


Figure 15: Schematic representation of the *Conventional System* – top (a 30  $t_{FFB}/h$  palm oil mill with a low-efficiency CHP and a co-composting plant) and the *Biorefinery* – bottom (a 30  $t_{FFB}/h$  palm oil mill with a high-efficiency biomass cogeneration plant, a biogas plant, or with a co-composting plant and a biodiesel plant). Source: (Harahap et al., 2019b) and PAPER III

Abbreviations: combined heat and power (CHP), empty fruit bunch (EFB), fresh fruit bunch (FFB), palm kernel shell (PKS), palm mesocarp fibre (PMF), palm oil mill effluent (POME).

Table 7: Biomass conversion technologies and the quantity of biomass residues in a Conventional System and in Biorefinery Case 1 to Case 3.

Biomass conversion technology	Type of biomass residues	Type of bio-product	Percentage of total biomass residues used			
			Conventional System	Case 1	Case 2	Case 3
Low-efficiency CHP plant	PKS	Electricity	2%	-		
	PMF		100%	-		
Aerobic co-composting plant	POME	Biofertiliser	100%	100%	50%	-
	EFB		76%	82%	41%	-
Biogas plant	POME	Electricity	-	-	50%	100%
High-efficiency CHP plant	EFB	Electricity	-	18%	59%	100%
	PKS		-	100%		
	PMF		-	100%		

Note: The quantity of EFB treated in a co-composting plant is calculated based on recommended substrate ratio of  $3.2 \text{ m}^3 \text{ POME} / \text{t}_{\text{EFB}}$  for producing mature compost (Mohammad et al., 2015; Schuchardt et al., 2002).

Abbreviations: combined heat and power (CHP), empty fruit bunch (EFB), fresh fruit bunch (FFB), palm kernel shell (PKS), palm mesocarp fibre (PMF), palm oil mill effluent (POME).

Figure 16 summarises the net income and NPV of the conventional system and the three biorefinery cases for an average-size palm oil mill (i.e.,  $150 \text{ kt}_{\text{FFB}}/\text{y}$ ) that supplies all of its produced CPO (i.e.,  $30 \text{ kt}_{\text{CPO}}/\text{y}$ ) to a medium-size biodiesel plant for producing biodiesel only. Using the LCC method, the result shows that *Biorefinery Case 1* provides the highest net income (i.e. 25 Million USD/y) and NPV (i.e. 31 Million USD/y), the lowest biodiesel breakeven price ( $0.57 \text{ USD}/\text{l}_{\text{biodiesel}}$ ), and a 17% internal rate of return.

The plant configuration with high-efficiency CHP and composting plants (*Biorefinery Case 1*) is identified as the most cost-effective configuration among the considered alternatives. It can improve the economic competitiveness of palm oil biodiesel production in Indonesia the most and can reduce the subsidy level for biodiesel by 0.07 USD/l. This in total can generate savings of 0.7 billion USD/y for meeting the consumption target of 30% biodiesel blending rate with fossil diesel by 2020.

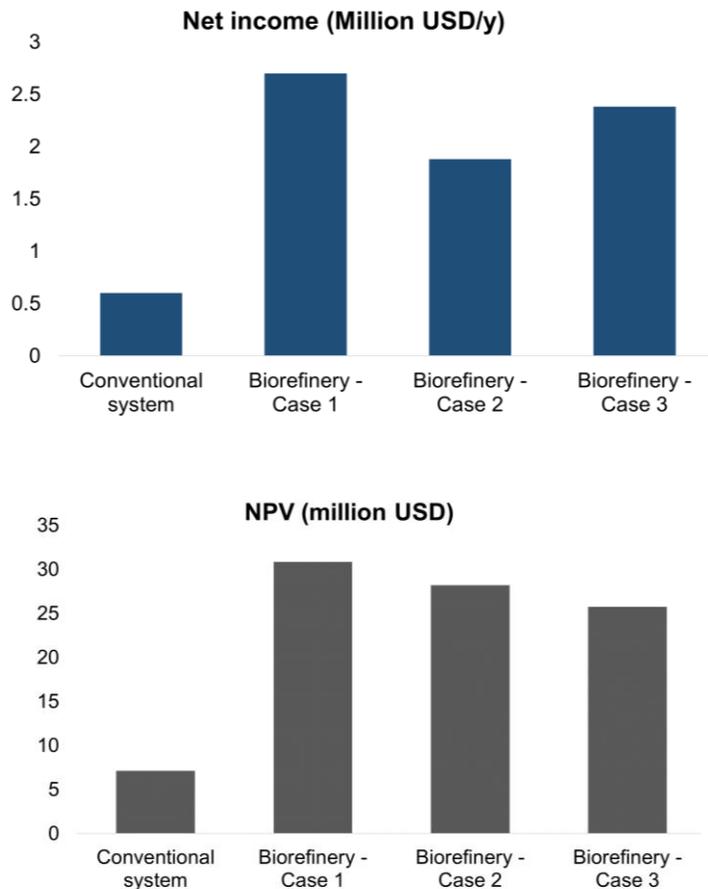


Figure 16: Net income (top) and NPV (bottom) of the Conventional System and the Biorefinery Case 1 to Case 3.

### *Optimal technology, plant size, and location of biorefineries*

The new industrial biorefineries are instrumental for resource efficiency in the palm oil industry. The optimal technology and plant size are discussed in PAPERS II and IV. In addition, PAPER IV also investigated the optimal location of biorefineries.

The biorefinery system discussed in PAPER IV also considers ethanol from the conversion of lignocellulosic residues, such as EFB. EFB is an ideal feedstock for ethanol production due to its high carbon content (Mohd Yusof et al., 2019). Ethanol is an important fuel to improve energy supply security and mitigate climate change, mainly by substitute for gasoline fuel, which accounted for 60% of the total energy consumption in the transport sector in 2015 in Indonesia (MEMR, 2017).

In terms of technology selection for electricity production, most mills install a 1 MW<sub>e</sub> CHP plant, generating just enough electricity to run the mill operations (PAPER II). When there is additional onsite electricity demand (for biodiesel and ethanol production), the systems choose higher CHP capacity, i.e., 4 MW<sub>e</sub> or 9 MW<sub>e</sub> CHP plants. The biorefinery system that meets onsite electricity demand and generates excess electricity will likely choose a 2 MW<sub>e</sub> biogas plant and a 9 MW<sub>e</sub> CHP plant.

As discussed in PAPER IV, economies of scale affect the choice of all technologies, implying that medium- and large-capacity plants are preferred over small-capacity plants. In a system with the simultaneous production of biodiesel and ethanol, using the smallest capacity biodiesel plants (100 kt), co-location of a 10 kt or a 30 kt ethanol plant is justified. Larger biodiesel plants (150 kt or 200 kt) will tend to co-exist with larger ethanol plants (30 kt or 50 kt). Medium-to-large biorefineries with co-production of biodiesel and ethanol are expected to dominate.

The research in PAPER IV shows that in terms of technology selection for ethanol production, gasification is chosen over fermentation for two reasons. First, the investment requirements are lower for fermentation, but the yield of EFB to ethanol in the gasification process is about twice as high as in the fermentation process. Second, the operation and maintenance cost of the gasification process is significantly lower than that of the fermentation process due to the high cost of the enzymes needed for fermentation.

PAPER II discusses the importance of the co-composting technology for utilising EFB and POME when there is low electricity demand and limited investment funding available. In addition to significantly reducing the amount of methane that would have been released from untreated POME, the organic fertiliser produced can partly substitute for chemical fertilisers in the plantation, thus reducing the environmental impact.

The product mix or co-production of bioelectricity, biodiesel, and/or ethanol within a biorefinery set-up is feasible. As can be seen in Figure 17, in 2020 the plant configuration of biorefineries is likely to include co-production of bioelectricity, biodiesel, and ethanol in the same facility (22 potential sites). However, to meet the national ethanol demand (the ethanol blending target doubles from 10% in 2020 to 20% in 2025), a substantial increase in ethanol production is required. Consequently, from 2025 onwards, the dominant biorefinery configuration comprises the co-production of bioelectricity and ethanol only, which is justified in 74 locations in 2025 and in 100 locations in 2030. Details of the technology and plant size choices in palm oil-based biorefineries are presented in PAPER IV.

In terms of the distribution of biodiesel, Sumatra is strategic to the supply of biodiesel mainly to the western part of Java, whereas Kalimantan appears to be strategic for biodiesel distribution to the eastern part of Java and Sulawesi. The ethanol produced in Sumatra is important to supply demand in Sulawesi.

This thesis identifies key parameters for market stability in the transition towards a biorefinery system, namely technology investments and pricing of bioenergy products. The analysis in PAPER IV shows that by providing support for investments at the beginning of such a strategic programme, annual technology costs can be reduced over time. Combined with the optimal location of biorefineries, increased production of bioenergy can be established in the country to meet national renewable targets and improve resource efficiency in the palm-oil industry. In addition, pricing of bioenergy products is critical for market stability, thus justifying careful attention from policymakers.

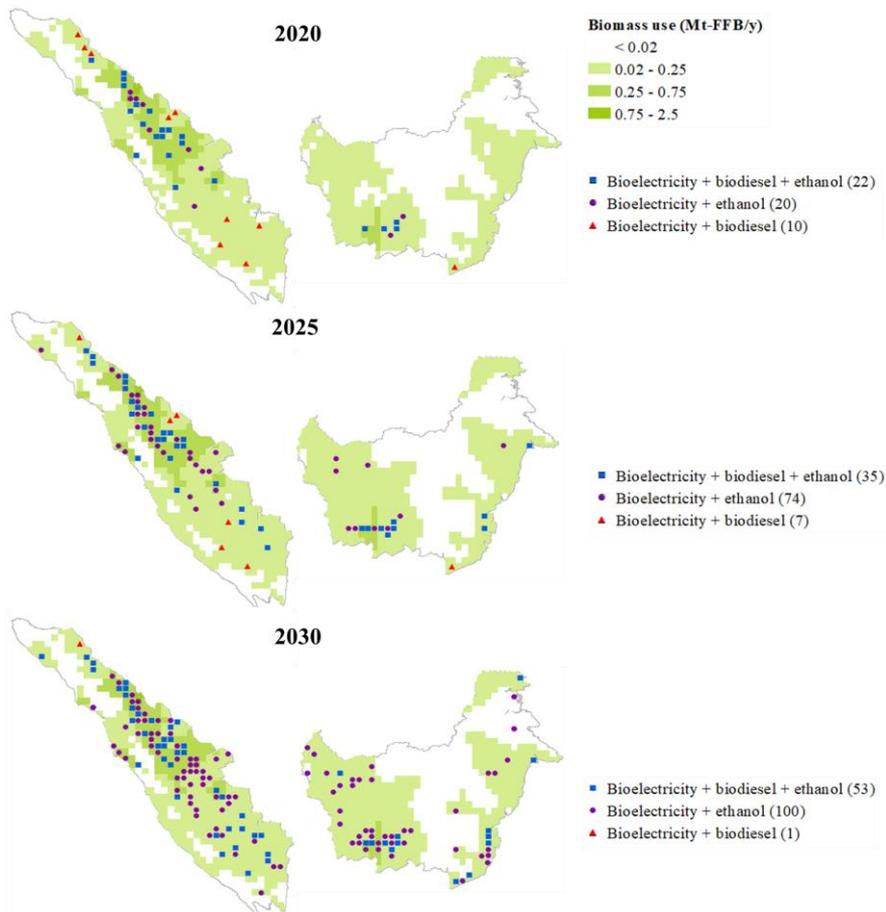


Figure 17: Optimal location for palm oil-based biorefineries in 2020, 2025, and 2030.  
Source: PAPER IV

## 5 The role of the palm oil industry in meeting Indonesia's bioenergy targets

*This chapter discusses how enhancing efficiency on land allocation and palm oil biomass utilisation in the palm oil industry can help Indonesia to meet its national bioenergy targets. The land needed for meeting sectoral policy goals is identified. The co-production of energy carriers in biorefineries indicates pathways to enable Indonesia to reach its bio-based blending targets.*

### ***RQ3. How can improved resource efficiency in the palm oil industry help to meet the national bioenergy targets?***

The overall implications of improved resource efficiency in the palm oil industry are assessed in relation to the national bioenergy targets in 2025. The targets comprise 5.5 GWe of bioelectricity installed capacity, 30% biodiesel blending with diesel, and 20% ethanol blending with gasoline in the transport, industry, and power sectors.

#### *The role of efficient allocation of land*

Land is an important resource to meet multiple policy goals. The policy analysis to assess policy coherence as outlined in Section 3.1 and PAPER I verifies the actual area allocated for each sectoral policy (i.e., biofuel, agriculture, forestry, and climate). For food crop expansion, 10.19 Mha are allocated (4 Mha of abandoned area is excluded due to unknown land cover classification). For climate change mitigation from land use change, 43.07 Mha are allocated to reduce emissions (instead of 53.57 Mha when agriculture policy is not considered). Furthermore, 9.23 Mha are allocated for productive forest units (instead of 67.08 Mha when agriculture and climate policies are not considered). Finally, 20.86 Mha are allocated for palm biodiesel feedstock production (instead of 29.33 Mha when considering biofuel policy only). The latter can be found in the categories of shrub/bush, shrub swamp, and grassland (in PAPER I referred to as degraded land) located in production forest and non-forest area.

However, there are uncertainties and inconsistencies, as outlined in Section 3.2, in the policy designed for biofuel, agriculture, forestry, and climate, all of which involve land allocation. These can jeopardise the efforts to use land more efficiently and to prioritise its use, which eventually can endanger the achievement of policy goals (including bioenergy). These uncertainties need to be urgently addressed to improve the way land is allocated across sectors (PAPER I).

First, inconsistency in land use classification needs to be clarified so that land allocation can be made clear in various policies. Presently, the recognised land use classifications are ambiguous and are not consistently used in the policy documents. The issue can be addressed by providing uniformity in the land use classification (e.g., degraded land and abandoned land). In particular, there is urgency in defining what characterises degraded land and abandoned land and which category they belong to in the official land classifications.

Second, the dual land classification creates uncertainties related to land allocated in the various policies, and this consequently hampers the monitoring of land use change. It would be advisable to adopt a single, coherent, and unified land classification, thus harmonising the real landscape coverage with the legal status of the land in order to achieve a more stringent allocation of different types of land for food and fuel production, preservation, and restoration. This would be beneficial for monitoring purposes. Overall, clear monitoring of land use change is necessary, not least for Indonesia to reduce GHG emissions.

Indeed, degraded land is essential for the achievement of the biofuel policy target. Planting on degraded land may result in lower productivity, and this could be discouraging to industries and farmers. Provision of appropriate fiscal incentives and introduction of best practice concepts for planting on degraded land are missing in the present policy, and addressing this will be crucial for promoting the efficient use of degraded land and sustainable palm oil plantations.

Furthermore, the legal definition of peatland in present regulations also needs to be further clarified. Peatland eligibility for oil palm plantation regardless of its physical characteristics should be omitted at least until more is known about how to reduce the environmental impacts from the use of peatland.

*The role of efficient use of biomass in the palm oil industry*

Improving the current practices on palm oil biomass utilisation is significant for meeting the national bioenergy targets. In this thesis, the optimal production of bioenergy is studied using the spatio-temporal optimisation model (BeWhere Indonesia) as previously outlined in Section 4.1. Various scenarios (see Table 8) are developed in PAPER IV to examine the optimal range of bioenergy production in the palm oil industry.

Table 8: List of scenarios to estimate the optimal bioenergy production in the palm oil industry in Sumatra and Kalimantan. Source: PAPER IV

Scenario	Scenario description	Source
Restriction on the use of CPO for biodiesel ( <i>LimitCPOforBiodiesel</i> )	To avoid increased competition for the use of CPO for non-fuel purposes, the amount of CPO that can be used for biodiesel is capped at 10% of the annual CPO production (similar to the share in 2018).	(USDA, 2019a, 2019b)
Energy efficiency program lowering energy demand ( <i>EnergyEfficiency</i> )	The energy efficiency target (Regulation 22/2017), which includes the reduction of fuel consumption by 17% in 2025 and 22% in 2030 from the level of 2015, is factored into the bioenergy demand.	(MEMR, 2018)
High technology investment cost ( <i>High-InvestCost</i> )	The high technology investment cost applies a bank lending rate of 13.11%, which is the highest lending rate in the past five years. The reference value is 12.01%.	(Bank Indonesia, 2019a)
Low technology investment cost ( <i>Low-InvestCost</i> )	The low technology investment cost applies a bank lending rate of 7.56%, which is the lowest lending rate in the past five years. The reference value is 12.01%.	
High bioenergy prices ( <i>High-BioProductPrice</i> )	The future price of bioenergy is based on the highest inflation rate in the past five years at 8.8%.	(Bank Indonesia, 2019b)
Low bioenergy prices ( <i>Low-BioProductPrice</i> )	The future price of bioenergy is based on the lowest inflation rate in the past five years at 2.8%.	

Scenario	Scenario description	Source
High CPO price ( <i>High-CPOprice</i> )	The estimation of future price of CPO is based on World Bank projections.	(World Bank, 2019)
High biomass transport cost ( <i>High-BiomassTransportCost</i> )	The biomass variable transport cost is 50% more than the reference scenario.	PAPER IV
Low biomass transport cost ( <i>Low-BiomassTransportCost</i> )	The biomass variable transport cost is 50% less than the reference scenario.	
High biofuel transport cost ( <i>High-BiofuelTransportCost</i> )	The biofuel variable transport cost is 50% more than the reference scenario.	PAPER IV
Low biofuel transport cost ( <i>Low-BiofuelTransportCost</i> )	The biofuel variable transport cost is 50% less than the reference scenario.	

For bioelectricity, 0.84–1 GW<sub>e</sub> can be produced in palm oil-based biorefineries in Sumatra and Kalimantan (PAPER IV). This implies that the industry can meet 15%–19% of the target for bioelectricity installed capacity in 2025. Not surprisingly, there is a higher potential to generate excess electricity when all mills are connected to the power grid (PAPER II). Improvement in grid connections in Sumatra can provide the basis for an installed capacity of bioelectricity plants equivalent to 2.8 GW<sub>e</sub>, meeting 50% of the national bioenergy target by 2025 (see Figure 18). This also means covering 50% of the electricity demand of Sumatra, helping the island to reduce its dependence on highly fossil fuel-based electricity. The biomass-to-electricity potential is significant and could play a major role in the development of electrification in Sumatra and Kalimantan (the current electrification rate is below 90% on these islands) (PLN, 2018).

The utilisation of palm oil biomass residues is also included in the government’s commitment to reducing GHG emissions. When it comes to the climate mitigation target, up to 5% of the national GHG emissions reduction target for 2030 can be met with more efficient utilisation of palm oil biomass residues in Sumatra. This is not very substantial because the largest share of emissions in Indonesia comes from forest and peatland conversion. However, from the point of view of emissions reduction in the waste sector, the contribution is tremendous. Emissions avoided through efforts to manage POME in Sumatra only can be up to 22 MtCO<sub>2</sub>eq/y

(PAPER II). This demonstrates that efforts to improve POME treatment and management in Sumatra can help to achieve the emissions reduction target set for the waste sector in the unconditional mitigation scenario (i.e., 11 MtCO<sub>2</sub>eq/y) and nearly all of the emissions reduction in the conditional mitigation scenario (i.e., 26 MtCO<sub>2</sub>eq/y) by 2030 (GoI, 2016). This might be an indication that there are opportunities to set a higher targets for reducing emissions from the waste sector.



Figure 18: Total installed capacity of biomass plants per district in Sumatra, *Sc-ref* (left) and *Sc-yield-grid* (right). Source: (Harahap et al., 2019a) and PAPER II

Note: *Sc-ref*: Incorporating the government policy to foster the utilisation of palm biomass residue; *Sc-yield-grid*: Improving the yield of small-scale plantations and improving bioelectricity delivery.

The technology abatement cost (the cost to reduce one tonne of CO<sub>2</sub>eq) for mills in Sumatra, as discussed in PAPER II, can be used to facilitate the upgrading of mills to achieve the greatest emissions reduction (see Figure 19). The average abatement cost of all mills in the scenario with improved grid connectivity (i.e., 18.5 USD/tCO<sub>2</sub>eq) is twice that obtained in the reference scenario (i.e., 8.5 USD/tCO<sub>2</sub>eq).

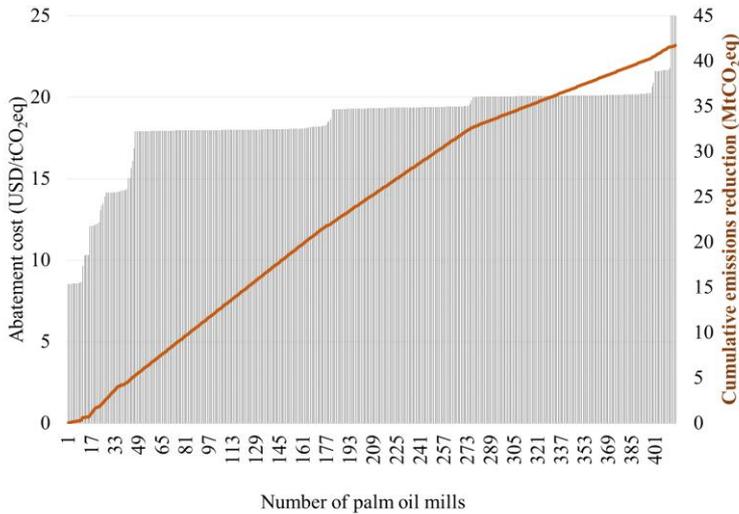
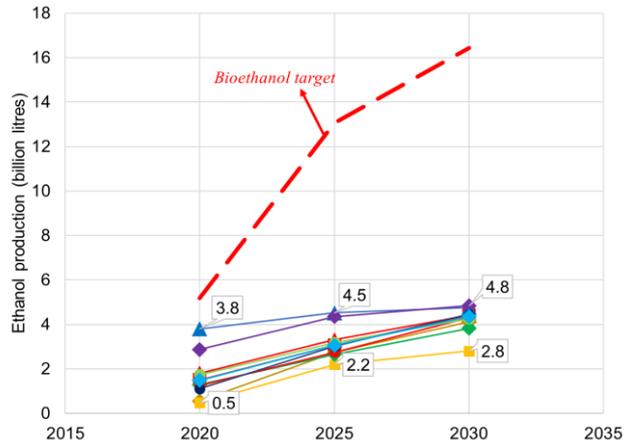
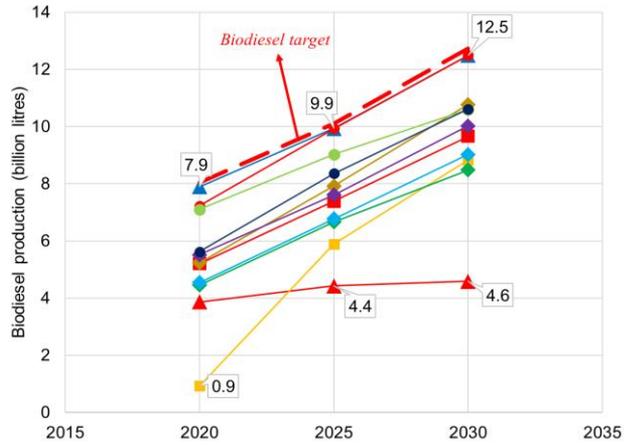


Figure 19: The technology abatement cost of each palm oil mill in Sumatra (bar chart, primary Y-axis) and cumulative emissions reduction (line, secondary Y-axis) of scenario *Sc-yield-grid* (improving the yield of small-scale plantations and improving bioelectricity delivery). Source: (Harahap et al., 2019a) and PAPER II

When it comes to the biodiesel target (30% biodiesel blending with diesel in transport, industry, and power sectors in 2025), between 4.4 and 10 bL of biodiesel can be produced, reaching 44%–98% of the target (PAPER IV). The lowest biodiesel production is found when limited amounts of CPO can be used for biodiesel production. The highest biodiesel production (10 bL<sub>biodiesel</sub>/y using 9 Mt<sub>CPO</sub>/y) is obtained when the technology investment cost is reduced. Finally, 2.2–4.5 bL of ethanol can be produced in 2025. This means that the industry can meet 17%–35% of the ethanol target in 2025 (20% ethanol blending with gasoline in the transport sector). For ethanol, the highest production in 2025 is obtained when the technology cost is lowest, whereas the production will be the least when the market price for ethanol is lowest. Figure 20 presents the total biodiesel and ethanol production for each scenario listed in Table 8, respectively.



Legend:

- Reference
- LimitCPOforBiodiesel
- High-TechInvestCost
- Low-TechInvestCost
- High-ProductPrice
- Low-ProductPrice
- High-CPOPrice
- High-BiomassTransportCost
- Low-BiomassTransportCost
- High-BiofuelTransportCost
- Low-BiofuelTransportCost

Figure 20: Biodiesel (top) and bioethanol (bottom) production of each scenario and the target in billion litres, 2020 – 2030. Source: PAPER IV  
 Note: the target for biodiesel blending with fossil diesel is 30% from 2020 to 2030, and the target for ethanol blending with gasoline is 10% in 2020 and 20% from 2020 to 2030.

## 6 Conclusions, recommendations, and future studies

*This chapter reflects on how resource efficiency can be enhanced in the palm oil industry in Indonesia. The study concludes that the efficient allocation of land through improved sectoral policy coherency and utilisation of palm oil bio-resources in biorefineries can improve the sustainability of the palm oil industry in Indonesia. Policy recommendations are provided together with scope for future research.*

The research in this thesis explores synergies between the palm oil industry and bioenergy production, and it confirms the hypothesis that such synergies can lead to a more sustainable palm oil industry through efficient use of resources (i.e., land and palm oil biomass). The improved sustainability performance in the palm oil industry is instrumental and urgently needed to address multiple sustainability challenges currently faced by the industry.

This thesis identifies areas in which policy formulation, in terms of sectoral land allocation, can be improved. The inconsistencies in the use of recognised land classifications in the policy documents, the unclear definition of specific land categories, and the multiple allocations of areas indicate incoherent sectoral policies on land allocation. These need to be addressed for efficient policy implementation. The improvement of coherence across sectoral policies might not only reduce pressure on land, but also clarify what land is actually allocated for biofuel, agriculture, climate, and forestry policies. Such improvement can guide better regulation, enhance synergies, and resolve the dilemma of conflicting goals.

The main takeaway of the thesis is that transition towards a more sustainable palm oil industry requires changes along the palm oil supply chain and, in particular, a shift from current traditional industrial practices. This requires moving from plantation expansion to improved

land management along with diversification towards a bio-based industry. The latter includes electricity generation and the production of liquid biofuels in a modern facility with value chain integration through a biorefinery system.

Harnessing the full potential of palm oil biomass and reorganising the industry in a biorefinery set-up can deliver multiple benefits. The production of bioenergy from palm oil biomass diversifies the energy sources in the country, improves energy security, and reduces the country's dependence on fossil fuels. Biorefineries can improve the overall profitability of CPO-based biodiesel production, hence reducing its reliance on government subsidies for competing with fossil diesel. This brings opportunities for securing feedstock supply, reducing feedstock transport, and making the whole integrated system more energy and carbon efficient. Upgrading the conventional system for better utilisation of palm biomass residues can be used to expand energy access, provide clean fuel for transport, industry, and power sectors, enhance renewable energy deployment, and, ultimately, contribute to sustainable development along with reduced GHG emissions.

Furthermore, the efficient use of biomass and the co-production of bioenergy carriers in biorefineries can enable Indonesia to reach its targets for bioenergy installed capacity and bio-based blending. The analysis shows opportunities to set a higher target to reduce emissions from the waste sector by capturing methane from the generated effluent or POME. Through optimal biomass conversion technologies, plant sizes, and strategic locations of biorefineries, the palm oil industry in Sumatra and Kalimantan can help to meet the national demand for biodiesel and bioethanol.

Finally, this thesis demonstrates that the inclusion of multi-sector analysis and biomass-to-bioenergy supply chain integration are key considerations not only for the development of the palm oil industry, but also for policy cycles from design and implementation to evaluation and adjustment. Inclusion of these aspects is crucial for better policy coordination and integration and can help to avoid resource competition. To meet the set targets, it is essential to integrate bioenergy policies with other sectors and explore complementarity. A wide range of sectoral policy instruments affect the palm oil biomass-to-bioenergy supply chain, hence interventions

in other sectors may either support or jeopardise the fulfilment of bioenergy policy goals.

### **What more can be done to enhance resource efficiency in the palm oil industry in Indonesia?**

There is room for enhancing the sustainability of the palm oil industry in Indonesia with adjustments to existing policies and practices. Presently, government policies are working in the right direction. Still, various barriers identified in this thesis need to be overcome so that the bioenergy potential in the palm oil industry can be fully harnessed.

Sectoral coordination is important, especially when dealing with basic resources or materials such as land and water. In this thesis, the issue of land allocation has been particularly analysed, showing that a lack of policy coordination leads to overlapping land allocation (PAPER I). This creates confusion on what areas are actually allocated and where. Guidelines are needed to clarify the qualification of land types and the allocation and the priority of land for different purposes. Policy information and guidance across sectoral policies should be compiled in a single database. A publicly available database would enhance the efficiency of land allocation and pave the way for the effective implementation of multiple policies, and such a tool should also be made available to the monitoring institutions.

Combining improvements in the utilisation of palm oil biomass residues and increased yields in small-scale plantations has positive economic impact and is key to meeting the climate goals of the waste sector (PAPER II). Such a combination should be the focus in short to medium-term planning. It is optimal to maximise the economic gains from the palm oil industry through increased biomass supply and efficient utilisation of biomass for value-added bio-products.

A necessary condition to maximise the environmental benefits from utilising palm oil biomass residues is the establishment of grid connectivity to palm oil mills (PAPER II). The establishment of infrastructure to connect more palm oil mills to the grid can stimulate investment in electricity capacity at mills and promote more efficient use of biomass in highly efficient biorefineries. This would have a decarbonising effect on the power sector.

The government has made considerable efforts to establish the biodiesel industry in Indonesia. The question remains whether the current mechanism is effective for long-term biodiesel market expansion and development of a bio-based economy. High reliance of the biodiesel programme on financial support can jeopardise the achievement of policy targets for the future of the palm oil industry. The national biodiesel fund is dependent on the amount of primary products exported, and in the event of small export volumes the fund is reduced. The reduction of exports has already occurred due to EU environment-related restrictions and reluctance of European consumers to use of palm oil products. Therefore, shifting towards the biorefinery model should be promoted as a way to modernise the industry and make it more sustainable.

The establishment of biorefineries in the palm oil industry can provide sustainable solutions for bioenergy production but only if accompanied by improved agricultural practices (i.e., for higher yields) to enhance land use efficiency and prevent further land degradation (PAPERS II and IV). Significant government support will be needed to trigger development in this direction. Support can come in the form of technology demonstrations and installation investments, price monitoring for bioenergy products, and fiscal policies (PAPER IV). Carbon taxes can make bioenergy technologies, such as biogas, more attractive. The government should phase out the subsidies still provided to fossil diesel, and possibly direct those to promoting a clean fuel program. The capital required for upgrading biomass conversion technologies and enhancing power grid connections to palm oil mills could be partly offset by emissions reductions if a carbon market is established.

The current regulatory framework for utilising the palm oil biomass residues for bioenergy generation has made it mandatory for the palm oil mills to use bio-resources more efficiently. Multiple benefits, including avoiding emissions, are discussed in this thesis. Despite the provision of financial incentives for electricity generated from biomass and biogas sources, policy implementation has evolved slowly. Thus, it is crucial to make the palm oil mill owners aware of the opportunities at hand to incorporate energy production in their business models. New skills and collaboration with independent power producers can pave the way to harness the full potential of bioenergy and promote investments. Various programmes for forging partnerships between oil palm plantations, palm oil mills, and energy producers are necessary to ensure the development of

sustainable industrial practices. The upstream (oil palm plantations) and the midstream (palm oil mills) industries have been able to operate at a profit. In contrast, the downstream industry (bioenergy producer) needs to work further on its industrial and financial model to become an attractive proposition for investors.

Last but not least, more attention is needed to the policy monitoring process. The use of land, for example, requires close monitoring to avoid further environmental degradation. Enforcement measures to motivate the use of biomass residues in palm oil mills need to be discussed. Penalties for non-compliance can help make sure that the policies reach the desired outcomes.

Improving the sustainability of the palm oil industry will not only open international markets for Indonesian products but also guarantee the cost-efficiency of the palm oil industry. This could pave the way for an enhanced role for the Indonesian palm oil industry in global sustainability efforts.

### **Scope of future studies**

The role of land remains important for future CPO production, but land is a scarce resource. In this context, mapping of actual degraded land and identification of areas suitable for bioenergy production is much needed. Future research can explore the optimisation of land allocation and land use to reduce pressure on land and avoid biodiversity losses. The research should take into account biomass availability and technical infrastructure, ways to enhance plantation yields, and ownership arrangements along the biomass supply chain (e.g., land owners) in order to guarantee sustainable long-term land management.

It is important to continue exploring the synergies and trade-offs between palm oil biomass use for the food, energy, and transport sectors as a way to resolve resource conflicts. In addition, a multi-objective optimisation study can incorporate social aspects related to palm oil production, which are not discussed in this thesis. Indonesia plays a vital role in the international CPO trade and other commodities, and thus this type of research is of interest not only for Indonesia, but also for global sustainability goals.

The biomass-to-bioenergy supply chain analysis in this thesis included a large amount of techno-economic data on different bioenergy technologies – both current and projections. The model structure is expected to represent the Indonesian palm oil bioenergy system for the foreseeable future. However, the data included will need to be updated in future modelling studies in order to accommodate the latest techno-economic development and policy directions.

Finally, future work can incorporate the sustainable use of other abundant biomass sources in Indonesia, such as biomass from sugar and rice production. This thesis has shown that the palm oil industry can pave the way, but other segments may also become part of a major bioenergy program in the country, and this is worth further investigation.

## Appendix

### Description of BeWhere Indonesia model for the palm oil supply chain

<u>Sets</u>	
BP	set of bio-products {bp: CPO, PK, biofertiliser, bioelectricity, biodiesel, ethanol}
D	set of bioenergy demand
IP	set of intermediate products
M	set of raw materials (i.e., FFB from small-scale and large-scale plantations)
P	set of processing plants (palm oil mills)
S	set of supply locations of biomass feedstock
Tech	set of biomass conversion technologies
Y	set of year
<u>Indices</u>	
bp	bio-products belongs to set BP
d	bioenergy demand belongs to set D
ip	intermediate products belongs to set IP
m	raw materials (i.e., FFB from small-scale and large-scale plantations) belongs to set M
p	processing plants (palm oil mills) belongs to set P
s	supply locations of biomass feedstock belongs to set S
tech	biomass conversion technologies belongs to set Tech
y	year belongs to set Y
<u>Binary variable</u>	
$UP_{y,p,ip,tech}$	Binary variable indicating technology of type <i>tech</i> to process

	intermediate product of type $ip$ in plant $p$ in year $y$ (0 or 1)
<u>Variables</u>	
$MILLCOST_y$	Total cost of capital and operation and maintenance (O&M) of processing plants in year $y$
$MILLEMISSIONS_y$	Total emissions of operating plants in year $y$
$RM COST_y$	Total cost of raw material production in year $y$
$RMEMISSIONS_y$	Total emissions from production of raw material in year $y$
$TECHCOST_y$	Total cost of capital and O&M for installing and operating technologies in year $y$
$TECHEMISSIONS_y$	Total emissions of operating technologies in year $y$
$TOTCOST_y$	Total cost of the studied system in year $y$
$TOTEMISSIONS_y$	Total emissions of the studied system in year $y$
$TOTINCOME_y$	Total income of the studied system from bio-products sale in year $y$
$TOTPROFIT_y$	Total profit of the studied system from bio-products sale in year $y$
$TRANSMISSIONCOST_y$	Total cost of capital and O&M of power transmission line in year $y$
$TRANSPORTCOST_y$	Total cost of biomass/biofuel transport in year $y$
$TRANSPORTEMISSIONS_y$	Total emissions of biomass/biofuel transport in year $y$
$XBP_{y,p,ip,tech,bp}$	The amount of bio-product of type $bp$ produced using technology of type $tech$ by utilising intermediate product of type $ip$ generated in plant $p$ in year $y$
$XBP_{y,p,d}^{excess}$	The amount of excess electricity delivered to the grid after meeting

	plant electricity consumption in year $y$
$XBP_{y,p,ip,tech,bp}^{onsiteconsumption}$	The amount of onsite consumption of electricity produced using technology of type $tech$ by utilising intermediate product of type $ip$ in plant $p$ in year $y$
$XBioenergy_{y,d}$	The amount of bioenergy delivered to the demand point of type $d$ in year $y$
$XDemand_{y,d}$	Total energy demand of type $d$ in year $y$
$XFossil_{y,d}$	The amount of energy from fossil fuels to meet the remaining energy demand in year $y$
$XIP_{y,p,ip}$	The amount of intermediate product of type $ip$ generated in plant $p$ in year $y$
$XSP_{y,s,p,m}$	The amount of FFB of type $m$ delivered to plant $p$ from supply site $s$ in year $y$
<u>Parameters</u>	
$AvailableSupply_{y,s,m}$	The amount of raw material of type $m$ available at the supply site $s$ in year $y$
$CarbonPrice_y$	Carbon price in year $y$
$CostCapitalTransmission$	Annualised cost of building new transmission lines
$CostFixBiofuelTransport$	Fix cost for transporting liquid biofuel
$CostFixBiomassTransport$	Fix cost for transporting biomass
$CostGridConnection$	Annualised cost of grid connection
$CostTech_{ip,tech,bp}$	Annualised capital cost and O&M cost of technology of type $tech$ to produce bio-product of type $bp$ from intermediate product of type $ip$
$CostVariableBiofuelTransport$	Variable cost for transporting liquid biofuel

<b><i>CostVariableBiomassTransport</i></b>	Variable cost for transporting biomass
<b><i>DistDistribution<sub>p,d</sub></i></b>	Distance between plant <i>p</i> to nearest biofuel demand point <i>d</i>
<b><i>DistPlantGrid<sub>p,d</sub></i></b>	Distance between plant <i>p</i> to nearest power grid <i>d</i>
<b><i>DistSupplyPlant<sub>s,p</sub></i></b>	Distance between supply <i>s</i> and plant <i>p</i>
<b><i>EmissionFactorBiofuelTransport</i></b>	Emissions of truck/ship for biofuel transport
<b><i>EmissionFactorBiomassTransport</i></b>	Emissions of truck for biomass transport
<b><i>EmissionFactorTech<sub>tech,bp</sub></i></b>	Emission factor from operating technology of type <i>tech</i> to produce bio-product of type <i>bp</i>
<b><i>PlantCapacity<sub>p</sub></i></b>	Installed capacity of plant <i>p</i>
<b><i>PlantCost<sub>p</sub></i></b>	Annualised capital cost and O&M cost of plant <i>p</i>
<b><i>PlantEmissions<sub>p</sub></i></b>	Emissions from processing raw material of plant <i>p</i>
<b><i>PlantOperatingHours<sub>y,p</sub></i></b>	Maximum plant operating hours of plant <i>p</i> in year <i>y</i>
<b><i>PriceBioProduct<sub>bp</sub></i></b>	Market price of bio-product of type <i>bp</i>
<b><i>RMProdCost<sub>y,m</sub></i></b>	Raw material production cost of type <i>m</i> in year <i>y</i>
<b><i>RMProdEmissions<sub>y,m</sub></i></b>	Emissions from raw material <i>m</i> production in year <i>y</i>
<b><i>TechCapacity<sub>p,ip,tech,bp</sub></i></b>	Installed capacity of technology of type <i>tech</i> to produce bio-product of type <i>bp</i> from intermediate product of type <i>ip</i> in plant <i>p</i>
<b><math>\eta_{\text{mill}_{ip}}</math></b>	Conversion rate of intermediate product of type <i>ip</i>
<b><math>\eta_{\text{tech}_{ip,tech,bp}}</math></b>	Technological efficiency of type <i>tech</i> to produce bio-product of type <i>bp</i> from intermediate product of type <i>ip</i>

The objective function of the optimisation model is to maximise system profit (Eq. (4)) by minimising the supply chain cost (Eq. (1)). It comprises the total annual cost (Eq. (2)) and the total emissions Eq. ((3)) multiplied by the carbon price.

$$\min \left( \sum_y +TOTCOST_y + TOTEMISSIONS_y * CarbonPrice_y \right), \forall y \in Y \quad (1)$$

$$TOTCOST_y = RM COST_y + TRANSPORTCOST_y + MILLCOST_y + TECHCOST_y + TRANSMISSIONCOST_y, \forall y \in Y \quad (2)$$

$$TOTEMISSIONS_y = RMEMISISONs_y + TRANSPORTEMISSIONS_y + MILLEMISSIONS_y + TECHEMISSIONS_y, \forall y \in Y \quad (3)$$

The total profit (Eq. (4)) is quantified based on the total income (Eq. (5)) of the studied system. The total income is the multiplication of the quantity of the bio-product and the market price.

$$TOTPROFIT_y = TOTINCOME_y - TOTCOST_y + TOTEMISSIONS_y * CarbonPrice_y, \forall y \in Y \quad (4)$$

$$TOTINCOME_y = \sum_{p,ip,tech,bp} XBP_{y,p,ip,tech,bp} * PriceBioProduct_{bp}, \forall y \in Y \quad (5)$$

The total annual cost as shown in Eq. (2) comprises feedstock production (Eq. (6)), biomass and biofuels transportation (Eq. (7)), palm oil mill (Eq. (8)), production of bio-products (Eq. (9)), and electricity transmission line costs (Eq. (10)). The transport cost (Eq. (7)) accounts for variable and fixed costs and transport distance.

$$RM COST_y = \sum_{s,p,m} XSP_{y,s,p,m} * RMProdCost_{y,m}, \forall y \in Y \quad (6)$$

$$\begin{aligned}
TRANSPORTCOST_y &= \sum_{s,p,m} XSP_{y,s,p,m} \\
&\quad * (CostVariableBiomassTransport * DistSupplyPlant_{s,p} \\
&\quad + CostFixBiomassTransport) \\
&\quad + \sum_{p,d} XBioenergy_{y,d} * CostVariableBiofuelTransport \\
&\quad * (DistDistance_{p,d} + CostFixBiofuelTransport), \\
\forall y \in Y & \tag{7}
\end{aligned}$$

The annualised capital cost, O&M, cost and plant design capacity are considered for the mill cost (Eq. (8)). The biomass technology cost (Eq. (9)) accounts for the amount of bio-products generated and the annualised capital cost and O&M cost of the specific technology and capacity.

$$MILLCOST_y = \sum_p PlantCapacity_p * PlantCost_y, \forall y \in Y \tag{8}$$

$$\begin{aligned}
TECHCOST_y &= \sum_{p,ip,tech,bp} TechCapacity_{p,ip,tech,bp} * CostTech_{ip,tech,bp} \\
&\quad * UP_{y,p,ip,tech}, \quad \forall y \in Y \tag{9}
\end{aligned}$$

The cost of transmission lines (Eq. (10)) are calculated for connecting the mill to the nearest power grid for supplying excess electricity.

$$\begin{aligned}
TRANSMISSIONCOST_y &= \sum_{p,d} XBP_{y,p,d}^{excess} \\
&\quad * (DistPlantGrid_{p,d} + CostCapitalTransmission + CostGridConnection), \\
\forall y \in Y & \tag{10}
\end{aligned}$$

The emissions from each activity within the study boundary are described as follows. The total emissions include emissions from feedstock production (Eq. (11)), transport (Eq. (12)), plant operations (Eq. 13)), and biomass processing (Eq. (14)). In PAPER II, the environmental cost also

includes the external cost of biodiversity losses, water supply disruption and peat fires. The emissions from raw material production and the amount of FFB produced by the small- and large-scale plantations are taken into account in the total raw material emissions (Eq. (11)). The transport emissions (Eq. (12)) considers the emissions factor and transport distance. Eq. (13) presents emissions of the mill from processing the FFB. The technology emissions (Eq. (14)) are resulted from the biomass processing.

$$RMEMISSIONS_y = \sum_{s,p,m} XSP_{y,s,p,m} * RMProdEmissions_{y,m}, \quad \forall y \in Y \quad (11)$$

$$\begin{aligned} TRANSPORTEMISSIONS_y &= \sum_{s,p,m} XSP_{y,s,p,m} * EmissionFactorBiomassTransport \\ &* DistSupplyPlant_{s,p} \\ &+ \sum_{p,d} XBioenergy_{y,d} * EmissionFactorBiofuelTransport \\ &* DistDistribution_{p,d}, \quad \forall y \in Y \end{aligned} \quad (12)$$

$$MILLEMISSIONS_y = \sum_{s,p,m} XSP_{y,s,p,m} * PlantEmissions_p, \quad \forall y \in Y \quad (13)$$

$$\begin{aligned} TECHEMISSIONS_y &= \sum_{p,ip,tech,bp} XBP_{y,p,ip,tech,bp} \\ &* EmissionFactorTech_{tech,bp}, \quad \forall y \in Y \end{aligned} \quad (14)$$

The material balance of input and output in this study is subject to a number of constraints, described as follows.

The amount of FFB that can be harvested at supply site  $s$  to be processed in palm oil mill  $p$  cannot exceed the availability of FFB (Eq. (15)).

$$\sum_p XSP_{y,s,p,m} \leq AvailableSupply_{y,s,m}, \quad \forall y \in Y, \forall s \in S, \forall m \in M \quad (15)$$

The travel time for transporting FFB to the mill is restricted to 4 hours (Harahap et al., 2019a). The material balance from FFB to intermediate products is applied based on the plant capacity (Eq. (16)) and conversion rate of the intermediate product (Eq. (17)).

$$XIP_{y,p,ip} \leq PlantCapacity_p * \eta_{mill_{ip}} * PlantOperatingHours_y, \quad \forall y \in Y, \forall p \in P, \forall ip \in IP \quad (16)$$

$$XIP_{y,p,ip} \leq \sum_{s,m} XSP_{y,s,p,m} * \eta_{mill_{ip}}, \quad \forall y \in Y, \forall p \in P, \forall ip \in IP \quad (17)$$

The binary variable is used to restrict the selection of biomass conversion technology (whether to build or not) and the capacity in a mill that is suitable to convert the intermediate product to bio-product (Eq. (18)). In the inclusion of the temporal dimension (PAPER IV), a technology with a specific size and location that is selected in year  $y$  remain until the end of the assessment period.

$$\sum_{y,p,ip,tech} UP_{y,p,ip,tech} \leq 1, \quad (18)$$

The final material balance restricts the amount of bio-products generated in a mill to be equal to the amount of intermediate products multiplied by the technological efficiency (Eq. (19)).

$$XBP_{y,p,ip,tech,bp} \leq XIP_{y,p,ip} * \eta_{tech_{ip,tech,bp}}, \quad \forall y \in Y, \forall p \in P, \forall ip \in IP, \forall tech \in Tech, \quad \forall bp \in BP \quad (19)$$

The excess electricity is based on total electricity production minus the internal electricity demand for processing the FFB (Eq. (20)).

$$\sum_{ip,tech,bp} XBP_{y,p,ip,tech,bp} = \sum_{ip,tech,bp} XBP_{y,p,ip,tech,bp}^{onsiteconsumption} + \sum_d XBP_{y,p,d}^{excess}, \quad \forall y \in Y, \forall p \in Y, bp = bioelectricity \quad (20)$$

The final constraint is that the final energy demand is supplied by bioenergy and other types of fuel (e.g., fossil fuel) (Eq. (21)).

$$XFossil_{y,d} + XBioenergy_{y,d} = XDemand_{y,d}, \forall y \in Y, \forall d \in D \quad (21)$$

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