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TECHNO-ECONOMIC ANALYSIS OF CELLULOSIC ETHANOL IN INDONESIA USING PALM RESIDUES

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EXECUTIVE SUMMARY

Indonesia has ambitious goals for replacing petroleum with biofuels and has the highest biodiesel blending target in the world. Despite successfully growing its biodiesel industry, however, Indonesia has made virtually no progress on bioethanol, which is commonly blended with gasoline. This study is a techno-economic analysis of cellulosic ethanol, a second-generation biofuel, in Indonesia.

Unlike many other countries, the availability of low-cost feedstock is not a factor limiting the development of a cellulosic ethanol industry in Indonesia. Indonesia's palm industry produces enormous volumes of palm biomass residues, more than enough to support dozens of commercial-scale cellulosic ethanol plants. At present, these residues, which include palm trunks, palm empty fruit bunches (PEFB), and press fiber, are typically not utilized and instead are left on the field to rot. The cellulosic ethanol industry could take advantage of this abundant resource.

We estimate the levelized production cost of cellulosic ethanol in Indonesia using a discounted cash flow (DCF) model. This model accounts for the various costs of building and operating a new cellulosic ethanol plant, including equipment, construction, land, feedstock, and labor. We then explore a roadmap in which a new cellulosic ethanol industry could be developed and ramped up over the next two decades. To our knowledge, this is the first study to assess the costs and potential ramp up of cellulosic ethanol production specifically in Indonesia.

We find that Indonesia has great potential to produce cellulosic ethanol cost efficiently as a result of its competitive feedstock, land, and construction costs compared to other countries. Nonetheless, government support is needed for the initial establishment of this new industry. We estimate that an annual government subsidy of IDR 4.7–6 trillion (US$335–430 million) would be needed to support the ramp up of 10 moderately large facilities (each with a production capacity of 70 million liters), depending on the availability of different types of feedstock. Figure ES1 shows the timing of when those subsidy amounts would need to be paid based on the ramp-up rate of the industry (left axis). We assume that over the coming years, as the first wave of cellulosic ethanol facilities ramps up, learning could reduce costs for future facilities, and a second wave of facilities would be cost-competitive without government incentives.

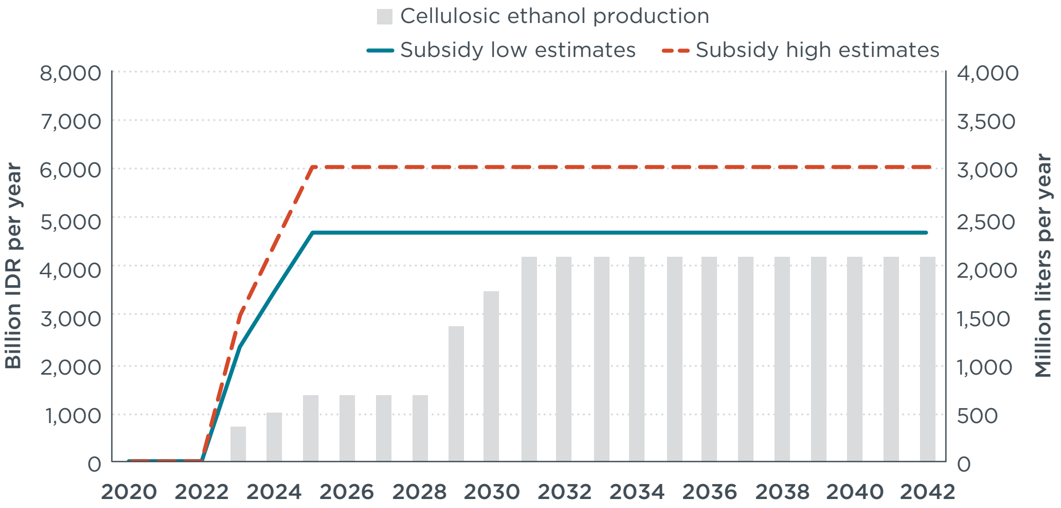

Figure ES1. Annual subsidy needed to support the establishment of a cellulosic industry (left axis) and the total quantity of cellulosic ethanol that could be produced each year (right axis)

The amount of cellulosic ethanol that could potentially be produced from the first wave of 10 subsidized facilities and from a larger, second wave of 20 unsubsidized facilities is illustrated on the right axis of Figure ES1. Alternatively, the Indonesian government could support the development of the industry by providing incentives in the form of an upfront, one-time grant. We estimate that this would be a one-time payment of IDR 90–116 trillion (US$6.4–8.3 billion).

Developing a domestic cellulosic ethanol industry can bring multiple benefits to Indonesia:

- It would reduce gasoline imports and improve Indonesia's trade balance, which is one of the government's goals.
- It would also foster a new industry and create jobs, utilize otherwise wasted palm residues, and bring additional revenue to the palm industry.
- It would offer greater greenhouse gas (GHG) savings than conventional, first-generation biofuels.

To achieve these benefits, Indonesia could consider the following policy recommendations, which stem from our analysis:

- Introduce regulation clarifying that palm residues are an eligible biofuel feedstock.
- Create government incentives, such as a production subsidy or investment grants, to support the initial establishment of a domestic cellulosic ethanol industry.
- Expand road infrastructure in palm planation areas and build awareness about the value of palm residues among smallholder farmers. Both would help to foster the establishment of a stable and sustainable feedstock supply chain.
- Designate Special Economic Zones (KEKs) around cellulosic ethanol facilities and supply chains to boost regional economic development.
- Integrate cellulosic ethanol into government initiatives to improve gasoline octane and reduce air pollution from vehicles.

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INTRODUCTION

Biofuel is a key component of Indonesia's national energy plan. The country has made significant efforts to advance biodiesel, including increasing blending mandates and providing financial incentives, and the biodiesel industry has grown rapidly as a result. B20, which is 20% biodiesel blended with fossil diesel, has been implemented in the transportation sector since 2016, and the current blending mandate for the year 2020 is 30% biodiesel (Ministry of Energy and Mineral Resources [MEMR], 2015). Further, in late 2019, the Indonesian government announced a plan to expand biodiesel blending to above 50% within the next few years (Gorbiano, 2019).

Indonesia's biodiesel is primarily made from palm oil. To support the biodiesel mandate, the government previously provided a subsidy to the biodiesel industry using the state budget, but this was replaced by a new financial support scheme in 2015. Since then, the proceeds from a palm oil export levy are used to offset the price difference between biodiesel and fossil diesel. Most recently, though, in response to the reduction in demand and lower price of fossil diesel caused by the COVID-19 pandemic, the Indonesian government has again allocated additional funds from the state budget to subsidize the palm biodiesel industry.

In contrast, there has been zero fuel-grade ethanol production or consumption in Indonesia since 2016 (U.S. Department of Agriculture [USDA], 2019a). This is despite efforts by the government to implement an ethanol blending target of 2% in some Indonesian cities (Aprobi, 2016). As shown in Figure 1, Indonesia's gasoline consumption increased by 48% from 2010 to 2019 and surpassed diesel consumption in 2015. In order to meet the rising gasoline demand, Indonesia has been increasing imports, and studies project that Indonesia's gasoline demand and imports are likely to continue increasing in the near future (Akhmad & Amir, 2018; Mayasari & Dalimi, 2019; Shao, Miller, & Jin, 2020; Xie & Harjono, 2020).

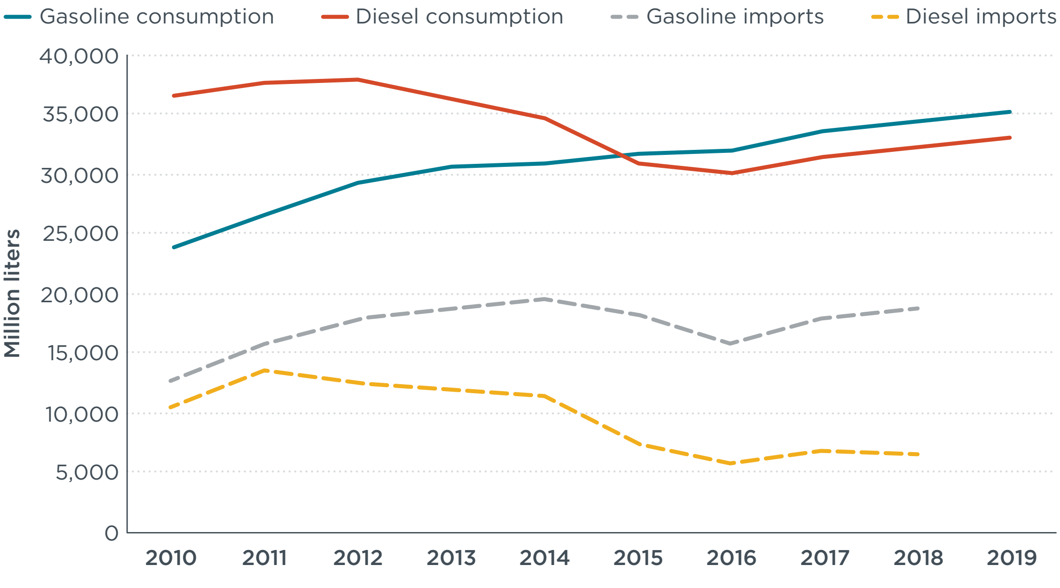

Figure 1. Gasoline and diesel consumption and imports in Indonesia.
Sources: MEMR, 2018; USDA, 2019a

One potential way to meet the rising demand for gasoline while limiting the need for imports is to domestically produce cellulosic ethanol and blend it with gasoline. Cellulosic ethanol is a second-generation biofuel, and unlike conventional, first-generation starch- and sugar-based ethanol, cellulosic ethanol is made from cellulose, which is one of the main structural materials of plants. Examples of cellulosic ethanol feedstocks include wood, agricultural residues like palm biomass and sugarcane bagasse, and municipal solid waste. To make cellulosic ethanol, these feedstocks are first pretreated to separate lignin, a non-carbohydrate compound in plant cell walls, from cellulose and hemicellulose; the cellulose and hemicellulose undergo cellulose hydrolysis using enzymes to turn cellulose into sugar, and the derived sugar undergoes fermentation with yeast to produce ethanol. (This final step is identical to the production process for conventional starch- and sugar-based ethanol.) Lignin, on the other hand, can be combusted onsite to generate electricity as a byproduct. Baldino, Berg, Pavlenko, and Searle (2019) provided details of the fuel conversion process.

In addition to supporting energy independence, given the reduced need for gasoline imports, cellulosic ethanol could have several other benefits for Indonesia. First, it could help stimulate a new market for fuel-grade bioethanol in Indonesia and thus bring socioeconomic benefits, such as job opportunities. Second, as the feedstocks of cellulosic ethanol are typically residues or wastes, their use in fuel production is unlikely to disrupt other industries. Moreover, cellulosic ethanol offers greater greenhouse gas (GHG) savings than conventional biofuels (Padella, O'Connell, & Prussi, 2019).

Given all of these benefits, this study aims to assess the feasibility of producing cellulosic ethanol in Indonesia. We evaluate the production cost of cellulosic ethanol and estimate the government incentives that would be necessary to support the deployment of this new technology. Based on the cost estimates, we then explore a roadmap for how Indonesia could scale up the industry. Last, we provide several policy recommendations for promoting cellulosic ethanol in Indonesia.

METHODOLOGY

FEEDSTOCKS AND AVAILABILITY

We expect that the cellulosic ethanol industry could take advantage of excess palm residues from Indonesia's palm oil industry. A previous ICCT study of the use of palm oil processing residues and palm field residues in Indonesia found that although a small portion of palm residues is utilized, such as for soil amendment and power generation, a great amount is wasted and could be used for advanced biofuel production (Paltseva, Searle, & Malins, 2016). This finding was based in part on a soil science study finding that it is not necessary to apply palm residues, such as empty fruit bunches, as mulch; rather, it would be more effective to retain pruned palm fronds as soil cover and fertilizer (Teh, 2016). Therefore, using palm residues other than palm fronds for cellulosic ethanol production would not disrupt palm oil production or other industries.

In this study, we consider three types of palm residues as cellulosic ethanol feedstocks:

1. Palm empty fruit bunch (PEFB): This is the casing around the palm oil fruit that remains after the fruit is extracted at palm oil mills.
2. Palm press fiber: This is the fiber residue left after palm oil is pressed from the fruit.
3. Palm trunk: This is the stem of a palm tree that remains after felling oil palm trees at the end of their productive lifespan.

We estimate the availability of each of the three types of palm residues by calculating the annual amount of each feedstock from the annual per-hectare production of each (Paltseva et al., 2016) and the mature oil palm plantation area from Statistics Indonesia (2019) using 2018 data. Because oil palm plantation area is increasing, we likely underestimate potential biomass availability in future years. It is also possible that with government programs and other efforts, smallholder farmers may opt to replant before the typical end of life of their palm trees in order to introduce higher yielding varieties; this would also result in higher availability of palm trunk biomass than we estimate here. Table A1 in the Appendix provides the per-hectare production and the chemical composition of the three types of palm residues. We do not consider palm kernel shell because it is not commonly considered as a potential feedstock for making cellulosic ethanol and it also has a higher cost than the other palm residues studied here.

DISCOUNTED CASH FLOW MODEL

We use a discounted cash flow (DCF) model to estimate the production cost of cellulosic ethanol and the financial incentives needed to support this industry. A DCF model evaluates the cost of making a product by looking at the value of the money at different points in time, and it incorporates three main components: capital cost, operational cost, and revenue from product sales. Capital cost is the upfront investment necessary to build a cellulosic ethanol plant and get it ready for operation; this investment typically includes costs for design, construction, and purchasing and installing equipment. Operational cost is the expense of running the ethanol plant after it is constructed; this is the annual maintenance and operating cost resulting from annual ethanol production.

We collected data specific to cellulosic ethanol plants from both techno-economic studies (Eisentraut, 2010; Humbird et al., 2011; Kugemann, 2015; Zhao et al., 2015; Cheng et al., 2019; Parbowo, Ardy, & Susanto, 2019) and project developers (Peters, Alberici, & Passmore, 2015; Brown et al., 2020). Particularly, Humbird et al. (2011) presented a comprehensive techno-economic analysis on cellulosic ethanol in the United States based on the process design by the National Renewable Energy Laboratory (NREL). This study is useful because it provides a detailed breakdown of different cost components and served as the basis for later techno-economic studies on cellulosic ethanol. Additionally, Zhao et al. (2015) updated the DCF model from Humbird et al. (2011) with parameters applicable to Chinese contexts; we refer to this study for necessary adjustments for developing economies. Further, Peters et al. (2015) collected detailed cost data and estimates from interviews with the cellulosic ethanol industry in the United States and the European Union and literature reviews. In combination, these studies helped shape our cost analysis. Since most of the cost data is based on U.S. projects, we made several data adjustments to better reflect the Indonesian context, where there are typically lower costs for construction, land, and labor. For all collected cost data from previous studies and projects, we converted them into present monetary value to account for inflation.

Table 1 details our assumptions about the ethanol plants and the key parameters in our DCF model. Based on reviews of other cellulosic ethanol projects, we assumed plant design and construction would take 3 years, and another 2 years would be needed for the facility to ramp up to its full production capacity. We assumed full production capacity to be 55,000 tonnes or 70 million liters of ethanol annually. There is a wide range in assumptions of ramp-up time from previous studies and projects, ranging from several months to several years. This is due to the different pre-treatment techniques applied for different feedstocks and unexpected pre-treatment issues that caused very long ramp-up times for some projects (Pavlenko, 2018; Baldino et al., 2019). The plant lifetime, including ramp-up phase, is 20 years in our analysis.

Table 1. Assumptions of each of our cellulosic ethanol plants and key parameters in the DCF model

Parameter	Value		Sources
Design and construction time	3 years		Peters et al., 2015; Pavlenko, 2018; Pavlenko, Searle, and Baldino, 2019; Pavlenko and Searle, 2019
Plant ramp-up time	5 years		
Percentage of plant capacity during ramp-up phase	Year 1	Year 2	
	50%	75%	
Plant lifetime	20 years		
Plant capacity	55 thousand tonnes (= 70 million liters) ethanol production per year		
Discount rate	10%		Humbird et al., 2011; Peters et al., 2015
Depreciation	5% (straight-line method)		PriceWaterhouseCoopers (PWC), 2019
Inflation rate	3%		Trading Economics, 2020
Corporate income tax	25%		PWC, 2019

There are several key parameters used when calculating cash flow. A DCF analysis estimates the cost of production at present value; therefore, a discount rate is used to convert future cash flows into present value and account for the time value of money. We assume a 10% discount rate, the same as many other DCF studies for biofuels.

Depreciation takes into account the decrease in asset value over time. An ethanol plant with a 20-year lifetime in Indonesia is expected to have a 5% depreciation using the straight-line method (PWC, 2019). We also factor in Indonesia's inflation rate to account for the price increase in the future. Last, the corporate income tax is considered as 25%, as in Indonesia (PWC, 2019).

Capital cost

There are many components of capital cost (CAPEX), or upfront investment, including land, site development, construction, equipment purchases and installation, working capital, and some other costs. Table A2 in the Appendix provides details of the CAPEX components in our analysis. Following the methodology by Humbird et al. (2011), the total equipment purchase cost is the starting point of the CAPEX estimation, as the rest of the CAPEX components are proportional to the total equipment purchase cost. A dataset by Peters et al. (2015) provided per unit equipment purchase costs for two U.S. and EU projects of similar plant capacity as assumed in this study, and the costs were approximately US$1.08 (2020) per annual liter ethanol capacity. We assume that Indonesia would import equipment from the European Union and thus do not make any adjustment to the unit equipment purchase cost. We multiply the unit equipment purchase cost by the plant capacity of 70 million liters of ethanol to estimate the total equipment purchase cost.

Because the equipment would need to be imported, trade tariffs and shipping costs were also included in the CAPEX. For equipment from the European Union, the export duties for machinery are 1.7% of the value of the exported product (European Commission, 2020). Indonesia's import duties for machinery are 5% of the value of imported product (International Trade Center, 2020). Thus, we assumed a total tariff of 6.7% for equipment imports. Further, we assumed shipping freight and insurance cost to be 10% of equipment purchase cost (Organisation for Economic Co-operation and Development [OECD] & World Trade Organization [WTO], 2017). For the rest of the CAPEX components, we used the same ratio of the cost of each component to the equipment purchase cost as given in Humbird et al. (2011), except for the equipment installation cost; for this component, we downscaled the installation cost from a ratio of 50% of the equipment purchase cost to 39%. This follows Zhao et al. (2015) and accounts for regional differences between developed and developing economies, including differences in labor costs. Similarly, we also made adjustments to other CAPEX components by taking the ratio of high-tech factory construction cost between the United States and Indonesia from Turner and Townsend (2019) as the downscaling factor. We used the land cost of building a similar advanced biofuel plant in Indonesia from Parbowo et al. (2019). We assumed the same CAPEX across the three types of feedstocks in this study.

Operational cost

Operational cost consists of the fixed operational costs of labor and maintenance and the variable operational costs of feedstock and material inputs. Fixed operational costs are incurred regardless of whether the plant is running at full capacity and we assumed that this cost, like CAPEX, does not vary when using different types of palm residues as the feedstock. Similar to CAPEX, we used a mixed methodology from Humbird et al. (2011) and Zhao et al. (2015) to reflect costs in a developing country. In particular, we downscaled the employee salaries from Humbird et al. (2011) using the labor cost difference between the United States and Indonesia from Turner and Townsend (2019). We assumed the labor burden, including payroll overheads, general utilities, and security and cleaning services, to be 40% of employee salaries as in Zhao et al. (2015), instead of the 90% in Humbird et al. (2011). We followed the methodology from Humbird et al. (2011) to estimate maintenance and other miscellaneous costs such as property insurance.

Unlike fixed operational cost, variable operational cost is dependent on the annual amount of cellulosic ethanol production. It includes feedstock cost (which varies by type of feedstock), as well as other input materials, such as enzymes, energy, and water. Table 2 shows the specific data used to calculate the consumption and cost of each of the three feedstocks. We used the cost of feedstock delivered to the cellulosic ethanol facility, which has three components—farmgate price, feedstock loading cost, and feedstock transportation cost. Multiple studies provided farmgate prices of PEFB and palm press fiber in Indonesia and we took the average for each feedstock. No farmgate price for palm trunks was located, and based on earlier research (Paltseva et al., 2016), we understand that palm trunks are generally not utilized nor considered as a commodity in Indonesia and therefore assume a zero farmgate price. Reeb, Hays, Venditti, Gonzalez, and Kelley (2014) developed a model to evaluate the loading and transportation cost of palm residues; we used their results to estimate these costs and added them to the feedstock farmgate price to calculate the final feedstock delivered cost.

The consumption of each feedstock is estimated based on the feedstock's specific ethanol yield. While studies generally provide ethanol yield per unit dry biomass, our feedstock price estimates are usually in wet biomass. Therefore, to get the actual amount of feedstock consumed per liter ethanol produced, and apply our feedstock price estimates, we accounted for the typical moisture content for each feedstock.

Table 2. Cost, ethanol yield, and moisture content of feedstocks in this study

	Palm trunk	Palm empty fruit bunch	Palm press fiber	Sources
Feedstock farmgate price	0	IDR 146/kg (US$0.01/kg)	IDR 280/kg (US$0.02/kg)	Reeb et al., 2014; Kresnowati, Mardawati, and Setiadi, 2015; Afifah, Sriyoto, and Sumantri, 2016; Alamsyah and Supriatna, 2018; Erivianto, 2018; Parbowo et al., 2019
Feedstock loading cost	IDR 77/kg (US$0.005/kg)			
Feedstock transportation cost	IDR 327/kg (US$0.02/kg)			
Feedstock delivered cost	IDR 404/kg (US$0.03/kg)	IDR 550 IDR/kg (US$0.04/kg)	IDR 684/kg (US$0.05/kg)	
Ethanol yield (g ethanol per g dry biomass)	0.25	0.14	0.08	Joseph, 2010; Prawitwong et al., 2012; Geng, 2013; Emo et al., 2015; Elgharbawy et al., 2018; Pangsang et al., 2019
Moisture content	71%	65%	40%	Sudiyani et al., 2013; Paltseva et al., 2016

In addition to feedstock expense, variable operational cost also includes the cost of material inputs—including chemicals, energy, and water—that are needed to convert cellulosic biomass into ethanol. We took consumption estimates of other material inputs for cellulosic ethanol production from the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model. Cellulosic feedstocks modeled in GREET include agricultural residues like corn stover, energy crops like Miscanthus, forest residues, and woody biomass like poplar. GREET does not provide data specific to palm residues, but we found that the defaults of material inputs do not vary much among these different feedstocks, as GREET uses similar assumptions for pre-treatment and ethanol production. Therefore, we used GREET's default data for poplar to estimate the consumption amount of each material input in this study. We collected the price of each chemical material from previous studies (The Glosten Associates, 2010; Tao et al., 2017). We suspect that Indonesia would import enzymes from other countries and thus included the trade tariffs—6.3% export duties from the European Union (European Commission, 2020) and zero import duties by Indonesia (International Trade Center, 2020)—and a shipping cost equal to 10% of the enzyme purchase cost (OECD & WTO, 2017). For energy and water, we took the industrial sector specific price in Indonesia. We provide details regarding material input quantity and unit price in Table A4 in the Appendix.

Revenue

Although the main revenue stream of a cellulosic ethanol plant is selling ethanol to gas stations, these facilities can also make money by selling excess electricity. The cellulosic feedstocks in this study contain lignin as well as cellulose. Lignin is the non-carbohydrate structural material in plants, especially in wood; it cannot be converted into sugars and thus cannot be made into cellulosic ethanol. Lignin is an extremely low-value product and generally the only use of it is to combust it for energy. We assumed that lignin is used to generate heat and electricity to run the cellulosic ethanol facility and that the excess is sold. The GREET model also provides the output of electricity as a by-product of cellulosic ethanol, and together with Indonesia's wholesale electricity price, we were able to estimate the revenue from electricity sales.

Levelized cost of production and government incentives

Using the results from the DCF, we calculated the levelized production cost, which is the minimum selling price for an investment to break even. Specifically, here the levelized production cost is the overall net present value of producing one liter of cellulosic ethanol after taking into account the investment in building the facility (capital costs), running it (operational costs), and the revenue from selling ethanol and its by-product of electricity. From there, we estimate the amount of government incentives that would be necessary (as a subsidy, for example) for the cellulosic ethanol facility to break even. The necessary incentive value is calculated as the difference between the levelized cost of production and the wholesale ethanol price that is comparative to gasoline on an energy-equivalent basis. Ethanol is less dense than gasoline, and a car would consume around 1.5 liters of ethanol to travel the same distance as it would on 1 liter of gasoline. Therefore, we recognize that ethanol will have to be sold at a lower price than gasoline's wholesale price due to its lower energy density, and we account for that in our analysis.

As Indonesia imports a large amount of gasoline from Singapore, we used the Singapore Free on Board (FOB) gasoline price to represent the wholesale gasoline price in Indonesia. Among different gasoline grades, we expect gasoline with research octane number (RON) at or above 90 will be used most widely in Indonesia, as a result of the government's intention to promote high-octane gasoline. We thus retrieved the RON 92 FOB Singapore price between 2017 and 2019 from OPEC (2020) and took the average.

CELLULOSIC ETHANOL DEPLOYMENT MODEL

To simulate the potential development of a new cellulosic ethanol industry in Indonesia, we used a deployment model and assumed two waves of cellulosic ethanol facilities are built in the next 20 years, and that Indonesia aggressively starts with investment in a first wave of 10 cellulosic ethanol plants. For context, there are fewer than 10 currently operational standalone cellulosic ethanol plants in the world (Padella et al., 2019). Thus, this scenario represents an ambitious program. After these plants ramp up to their full capacities, the technology and the industry can be considered to have been proven as economically viable and we assumed a drop in production cost thereafter. As such, more plants could be built in the second wave at lower risk, and we thus assumed an additional 20 plants could be constructed at that point. We used the same assumptions as are shown in Table 1 for all 30 plants in the first and second waves.

RESULTS

We summarize the cost results from our DCF model and a range of results from previous studies in Table 3. We estimate the total capital cost for building a 55,000 tonne cellulosic ethanol plant in Indonesia to be IDR 2,860 billion (US$204 million). The per annual liter ethanol capital cost from our analysis is IDR 41,022 (US$2.93), which is within the range from other studies but toward the lower end. This is because most of the other studies estimate costs for plants built in the United States or Europe, and we expect some capital cost elements, such as construction and land cost, to be relatively cheaper in Indonesia. (Recall that Table A2 in the Appendix provides a detailed breakdown of CAPEX components.)

We estimate the total fixed operational cost (labor and maintenance) of running the cellulosic ethanol plant to be IDR 57.7 billion IDR (US$4 million) each year, or 828 IDR (US$0.06) per annual liter ethanol production. This result is also close to the lower end of the range in previous estimates due to cheaper labor in Indonesia. (Table A3 in the Appendix gives the breakdown of fixed operational cost.) We find that the variable operational cost of feedstock and material input is IDR 7,000 – 13,860 (US$0.5 – 0.99) per annual liter ethanol production, depending on the feedstock. Palm trunk has the lowest operational cost because it has a lower feedstock cost and a higher ethanol yield, which means comparatively lower feedstock consumption than the other two feedstocks. The range of variable operational cost in previous estimates is pretty wide, IDR 317 – 12,908 (US$0.02 – 0.95) per annual liter. This is because of the wide variety in feedstocks analyzed. For instance, some studies considered wastes as the feedstock and assumed no feedstock cost at all. Meanwhile, most of the studies included substantial feedstock cost that comes from the high cost of labor and the machinery used to collect the feedstocks.

Our analysis shows that feedstock cost makes up 55% (if using palm trunk) to 75%(if using palm press fiber) of total annual operational cost, including both fixed and variable costs. This is consistent with the findings of most of the studies we reviewed, which also showed that that feedstock is usually the largest cost component (Humbird et al., 2011; Cheng et al., 2019; Padella et al., 2019; Brown et al., 2020). It also indicates that the total cellulosic ethanol production cost results are highly sensitive to feedstock cost.

Table 3. Per liter ethanol capital, operational, and total levelized production costs for feedstocks estimated in this study, compared to range of estimates for cellulosic ethanol from other studies.

Cost in IDR per liter (USD per liter)	Palm trunk	Palm empty fruit bunch	Palm press fiber	Range from other studies
Capital cost		IDR 41,022 (US$2.93)		IDR 23,784 – 78,013 (US$1.75 – 5.75)
Annual fixed operational cost		IDR 828 (US$0.06)		IDR 645 – 5,034 (US$0.03 – 0.37)
Annual variable operational cost	IDR 7,000 (US$0.5)	IDR 11,480 (US$0.82)	IDR 13,860 (US$0.99)	IDR 317 – 12,908 (US$0.02 – 0.95)
Levelized production cost	IDR 10,970 (US$0.78)	IDR 14,798 (US$1.06 USD)	IDR 18,077 (US$1.29)	IDR 7,054 – 21,163 (US$0.52 – 1.56)

Sources: Eisentraut, 2010; Humbird et al., 2011; Diep et al., 2012; Kugemann, 2015; Peters, Alberici, and Passmore, 2015; Zhao et al., 2015; Cheng et al., 2019; Parbowo et al., 2019; Brown et al., 2020

Figure 2 shows the levelized production costs and the amount of government incentives that would be needed to enable new cellulosic ethanol plants using different feedstocks to break even. Palm trunk offers the lowest levelized production cost among the three feedstocks, and as a result, the necessary government incentive is smallest, at IDR 6,720 (US$0.48) per liter ethanol. However, using palm empty fruit bunch and palm press fiber would require much higher incentives, at IDR 10,548

(US$0.75) and IDR 13,827 (US$0.99) per liter ethanol, respectively, to enable cellulosic ethanol to be cost competitive with gasoline in Indonesia.

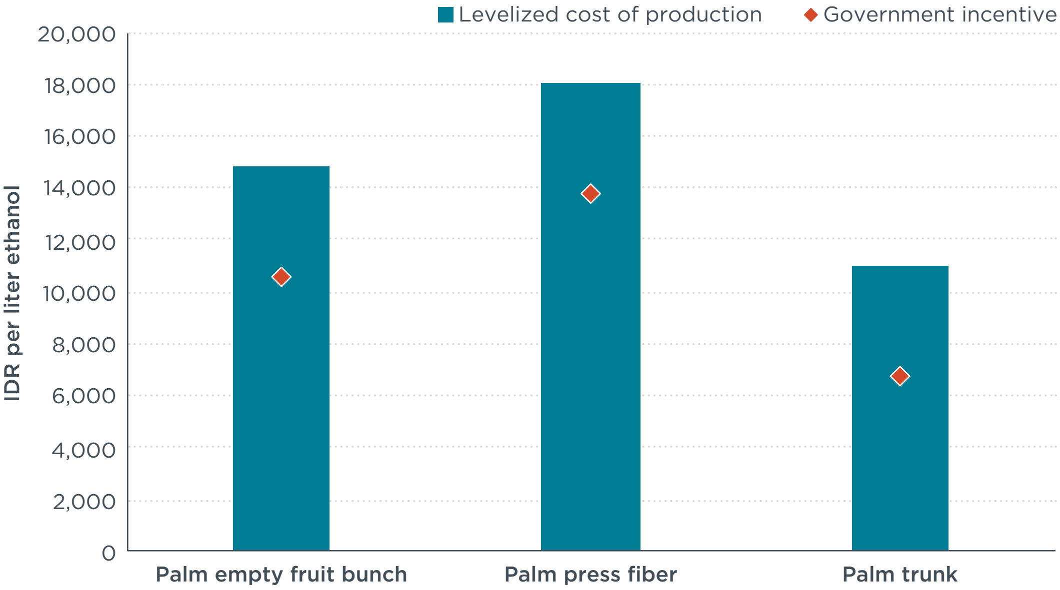

Figure 2. Levelized cost of production and required government incentive to be break even on investment

Table 4 shows the amount of feedstock needed to support a 55,000 tonne cellulosic ethanol plant if using one single feedstock, the palm plantation area needed to produce that specific feedstock, and that area as a fraction of Indonesia's total palm plantation area. Since using palm trunk would result in a very low production cost, we suspect that Indonesia would prioritize this feedstock and then turn to the second cheapest feedstock, PEFB. In Figure 3, we compare the estimated availability of these two feedstocks from Paltseva et al. (2016) with the amount necessary to support full capacity of the cellulosic ethanol industry, as shown by our deployment model. We estimate a sustainable availability of about 13 million wet tonnes of palm trunks in Indonesia each year, which could supply 17 plants at the capacity of 55,000 tonnes. This would be insufficient to supply all 30 plants in 2031 when they are all running at the full capacity. In this case, full deployment would require the use of PEFB in addition to palm trunks. However, if the oil palm industry continues to expand, palm trunk availability would increase and could potentially be sufficient to supply 30 plants in the future.

Table 4. The amount of feedstock and corresponding palm plantation area needed to support a 55,000 tonne cellulosic ethanol plant using each feedstock

Quantity needed for a 55,000 tonne plant	Palm trunk	Palm empty fruit bunch	Palm press fiber
Feedstock (million dry tonnes)	0.22	0.39	0.69
Palm area (million ha)	0.24	0.25	0.86
Proportion of Indonesia's total palm plantation	2.35%	2.36%	8.26%

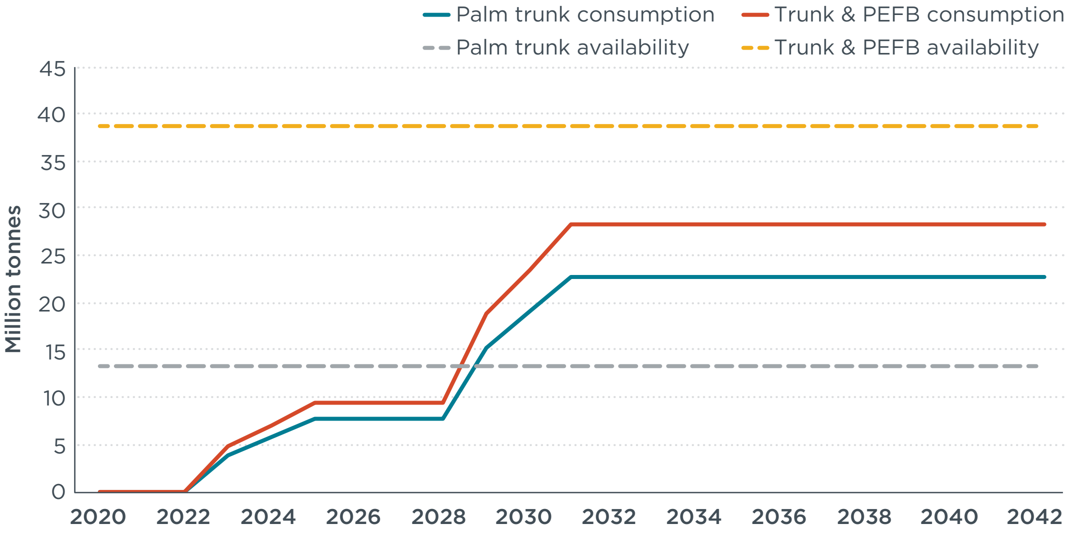

Figure 3. Current annual sustainable availability of palm trunk and palm empty fruit bunches compared to the amount of feedstock needed to supply the cellulosic ethanol industry according to our deployment model

As both palm trunks and palm empty fruit bunches may be needed, we developed two feedstock-utilization scenarios. In the first scenario, palm trunk is used to its full availability, for 17 plants, and after that PEFB is used. This means that the 10 plants in the first wave are all using palm trunk, and for the second-wave facilities, 7 use palm trunks and the remainder use the more expensive PEFB. In the second scenario, half of the feedstocks are palm trunk and half are PEFB for all 30 plants. This second scenario is represented by "Trunk & PEFB consumption" in Figure 3. This scenario considers the possibility of not being able to exhaust the theoretical supply of palm trunks before sourcing PEFB. The 13 million wet tonnes of palm trunks from our analysis is the amount that is physically produced (i.e., chopped down) each year in Indonesia, but this entire amount might not be readily available for cellulosic ethanol production. For instance, some of this amount is likely to be in remote areas or would otherwise be difficult to collect and transport to cellulosic ethanol facilities.

We then evaluated how the different feedstock utilization scenarios affect the amount of government incentives needed by assessing two primary types of incentives: (1) an annual subsidy or (2) an upfront grant to partially cover the capital costs of construction. Figure 4 shows the amount needed in an annual subsidy to support the first wave of cellulosic ethanol plants for both deployment scenarios. The amount increases as cellulosic ethanol production ramps up. When the 10 first-wave facilities reach their full capacities in 2025, the annual subsidy required is IDR 4.7 trillion (US$335 million) if using palm trunk only, or IDR 6 trillion (US$430 million) if using half trunk and half PEFB. As a comparison, the annual subsidy distributed to the biodiesel industry between 2015 and 2019 was about IDR 7.6 trillion (US$543 million) on average (Hariandja, 2020), and the 2020 subsidy is likely to be higher due to government support related to the COVID-19 crisis (Ministry of Finance, 2020).

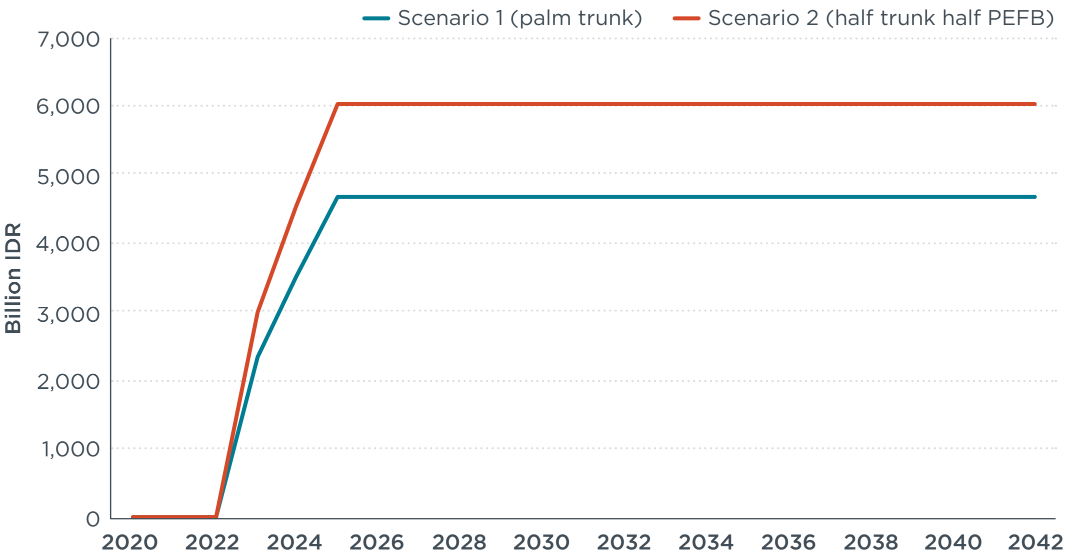

Figure 4. Annual subsidy to support cellulosic ethanol industry

Table 5 shows the upfront one-time grant amount for the two feedstock utilization scenarios. To support a first wave of 10 plants, the total amount of upfront grants needed is almost IDR 90 trillion (US$6.4 billion) if using palm trunk only, or IDR 116 trillion (US$8.3 billion) if using half trunk and half PEFB. For both policy options, we assume government support is only needed at the beginning of a new technology, for the first wave of facilities, and that by the second wave 10 years later, the industry is economically viable on its own, without incentives.

Table 5. Upfront grant needed to support cellulosic ethanol industry

Scenario	Grant Needed
Scenario 1 (Palm trunk only)	IDR 90 trillion (US$6.4 billion)
Scenario 2 (50% palm trunk + 50% PEFB)	IDR 116 trillion (US$8.3 billion)

Figure 5 illustrates the annual amount of cellulosic ethanol produced using our assumptions and the percentage of gasoline demand that can be met on an energy basis. By 2031, all the 30 facilities from first and second waves will be running at their full capacities and approximately 2,100 million liters ethanol (1,400 million liters of gasoline equivalent) will be produced annually; this is about 4% of 2019 on-road gasoline demand in Indonesia (USDA, 2019a). However, as the gasoline demand in Indonesia is likely to increase, the percentage that can be met by the cellulosic ethanol may be lower than shown in Figure 5.

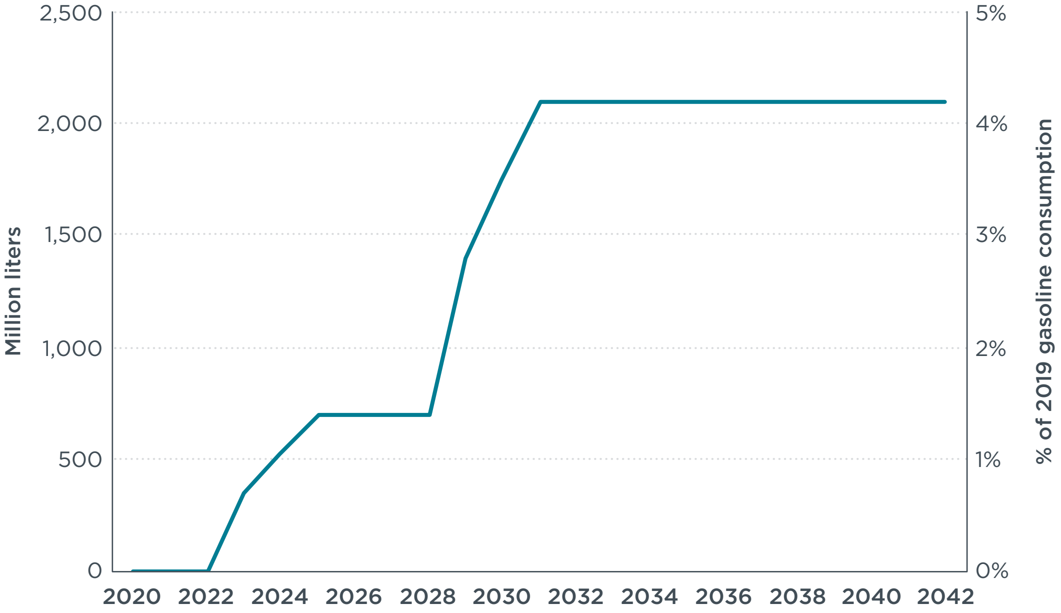

Figure 5. Annual cellulosic ethanol production amount and its percentage of 2019 gasoline demand

DISCUSSION

Indonesia has a unique opportunity to leverage domestic resources for cellulosic ethanol production. Cellulosic ethanol could contribute to several of the country's priorities: renewable energy, energy independence, jobs and economic benefits, waste management, and climate change mitigation. Unlike many other countries, Indonesia has an abundance of low cost, easily collectable feedstock in palm biomass. We find that Indonesia could replace 4% of 2019's gasoline consumption with cellulosic ethanol at relatively low cost compared to other countries.

Other countries have struggled with deploying cellulosic ethanol. There are few successful projects in the world; fewer than 10 cellulosic ethanol plants are running at commercial scale, and the world's annual cellulosic ethanol production in recent years was approximately 125 million liters, even though the built capacity is higher than this amount (USDA, 2019b; USDA, 2019c; USDA, 2019d; U.S. Environmental Protection Agency, 2020). The main barrier to new cellulosic ethanol projects is the relatively high production cost. In particular, many project developers consider capital availability as the biggest barrier. Cellulosic ethanol has high upfront costs, which may deter investment, especially for emerging technologies that have not yet been proven at commercial scale (Peters, Alberici, & Passmore, 2015).

These financial challenges are common to many kinds of new and advanced technologies, not just cellulosic ethanol. One strategy that can help effectively overcome the barriers is policy support. In particular, financial incentives help relieve the financial burden of building high-capital expense projects and serve as a strong signal of the government's intention to promote the industry; this could, in turn, attract financiers (Zhou et al., 2020).

In this study, we looked at two government incentive options: an annual subsidy and an upfront grant. These are two common types of policy support and both should work well in theory. Promising an annual per liter unit subsidy should help cellulosic ethanol producers attract investment as investors see that the subsidy will help their investment pay off in years to come. On the other hand, providing an upfront grant defrays the immediate cost of constructing the facility and makes the project more financially viable. Generally, upfront grants are thought to be more effective at attracting non-governmental investment because it is safer for the investors, given that the money is already in place, whereas there is always a risk that the annual subsidy could be revoked in a later year.

The Indonesian government could design a subsidy program for cellulosic ethanol that is similar to the palm biodiesel subsidy currently in place. With this subsidy, the government sets the biofuel price and pays a subsidy equivalent to the price difference between the biofuel production cost and the wholesale price of fossil fuel. This type of scheme is particularly efficient because it never overpays biofuel producers (i.e., when the gasoline or diesel price increases, a lower subsidy amount is needed to support biofuel producers). In this analysis, since we do not project future volatility in diesel and gasoline prices, we are essentially assuming the Indonesian government would structure a subsidy in this way, and only pay the necessary amount at any point in time.

We found that either incentive option for cellulosic ethanol would be an efficient way to support renewable fuel production. We estimated that supporting the commercialization of a cellulosic ethanol industry in Indonesia would cost IDR 4.7–6 trillion (US$335 – 430 million) each year, compared to an average of IDR 7.6 trillion (US$543 million) spent annually in subsidy to the biodiesel industry in recent years. In terms of cost, Indonesia has strong advantages over other countries. Our analysis showed that the Indonesian government would only need to contribute as little as IDR 6,720 (US$0.48) per liter to support cellulosic ethanol, compared to around IDR 16,000 (US$1.1) per liter for the European Union (Pavlenko et al., 2019).

Another advantage that Indonesia possesses in cellulosic ethanol production is the abundance of cheap feedstocks. Indonesia has a vast and growing amount of available palm residues, but palm residues are not the only feedstocks that Indonesia could use. As a significant producer of rice, corn, and sugarcane, Indonesia could also utilize the agricultural residues from these crops (namely rice straw, corn stover, and sugarcane bagasse) for cellulosic ethanol production. We estimate Indonesia's production of agricultural residues from its top three produced crops (apart from palm oil) in 2018 using crop production data from the United Nations Food and Agriculture Organization (FAO, 2020), as shown in Table 6. Following the methodology of Searle and Malins (2016) and Pavlenko and Searle (2019), we estimate the amount of agricultural residue produced from each of these crops and the amount of cellulosic ethanol from those residues. We find that using all these agricultural residues could result in more than 50 billion liters of cellulosic ethanol production each year.

Table 6. Agricultural residue production from other major crops in Indonesia and potential cellulosic ethanol production from those residues.

	Crop production in 2018 (million tonnes)	Agricultural residue	Residue amount (million tonnes)	Cellulosic ethanol (billion liters)
Rice, paddy	83	Rice straw	151	40
Corn	30	Corn stover	31	10
Sugarcane	21.2	Sugarcane bagasse	8	2

Sources: Searle and Malins, 2016; Pavlenko and Searle, 2019; FAO, 2020

Overall, Indonesia has the potential to leverage abundant and cheap feedstocks, as well as less expensive labor, land, and other resources compared to other countries, to produce cellulosic ethanol more cost efficiently. These advantages could enable Indonesia to become a global leader in this area of advanced technology. This would lead to environmental and economic benefits not just in Indonesia but elsewhere in the world.

POLICY RECOMMENDATIONS

Cellulosic ethanol is a complex technology and building new facilities will require significant capital investment. Based on our findings, government support will be necessary to promote an emerging cellulosic ethanol industry. We have the following recommendations for government policy to support cellulosic ethanol:

Introduce a regulation on eligibility of cellulosic feedstock
It is necessary to introduce a regulation by the central government which states that palm biomass is eligible as cellulosic ethanol feedstock. This does not mean that the use of palm residues is illegal currently. However, the production of all fuels, including cellulosic ethanol, at the commercial scale must be approved and regulated by the government.

Support the initial establishment of the cellulosic ethanol industry through government incentives
In Indonesia, almost all fuels intended for the public, or the so-called “non-premium class” fuels, are sold at subsidized and/or fixed prices. The Indonesian government could develop a policy on spending part of the fossil fuel subsidies to support the use of palm residues for cellulosic ethanol.

Two effective forms of incentive for the development of the cellulosic industry in Indonesia are the provision of advance grant assistance or annual production subsidies. Providing upfront grants would reduce the initial investment burden, while providing incentives for annual production cost would enable the products to be available at competitive prices. Both kinds of incentive can help make the establishment of a cellulosic ethanol factory financially feasible.

Build road infrastructure and awareness to establish a stable and sustainable feedstock supply chain
The development of a cellulosic ethanol industry in Indonesia depends partly on maintaining a stable, sustainable feedstock supply. For this reason, the Indonesian government could develop two types of supportive policies to establish a mature feedstock supply chain. First, establish farm roads in palm plantation areas—but not through surrounding forests—and connect them to district arterial roads, so that palm residues from all locations can be transported to cellulosic biorefineries. Farm roads are currently rare in rural areas. Combined efforts from the national and local governments are needed to expand road infrastructure. The construction of farm roads is usually the responsibility of local governments, but since local governments often lack sufficient funding to build them, intervention from the national government is needed. This will especially help independent smallholders gain access to the market for their palm residues and avoid on-site burning.

Second, build awareness among independent smallholders so that they understand the economic value of their palm residues. For example, local governments can develop training programs to educate farmers and independent smallholders on how to manage palm residues. There are positive impacts from involving independent smallholders as feedstock suppliers of an emerging cellulosic ethanol industry. Specifically, independent smallholders are typically not well educated on proper residue treatment or maintenance from plantation and replanting activities. Collecting palm residues and selling them as feedstocks for cellulosic ethanol producers will bring additional income and may reduce the financial incentive for independent smallholders to expand their plantation area.

Create Special Economic Zones (KEKs) around cellulosic ethanol facilities and supplying palm plantations to boost regional economic development
Results from this study show that the cost of transporting feedstock is a significant

fraction of the total cost of producing cellulosic ethanol. Siting cellulosic ethanol plants near the sources of their feedstocks could thus make it possible for the cellulosic ethanol industry to operate more cost efficiently. This will drive regional agglomeration, a process by which a group of companies in one area form an industrial center and concentrate the workforce. The positive impacts of agglomeration include reduced transportation costs and better spatial planning.

The Indonesian government could declare a Special Economic Zone (KEK) around an emerging cellulosic ethanol industry and its supplying palm oil plantations. KEKs are areas in which the national government offers preferential taxation and addresses development-related issues, such as labor and infrastructure, to encourage investment in these specific locations (Rothenberg and Temenggung, 2019). KEKs are generally designed to maximize industrial activities, trade, and other high economic value aciticities. KEKs are intended to fulfill the achievement of the National Priority Development Agenda (National Council for Special Economic Zone, 2020) by (1) improving productivity and competitiveness in international markets; (2) accelerating regional development and alleviating uneven development among regions; (3) increasing Indonesia's production of high-value products rather than raw materials; and (4) increasing the economic competitiveness of Indonesia's lesser developed outer islands through regional infrastructure development. Designating a KEK around cellulosic ethanol facilities and their feedstock suppliers could help fulfill these aims.

Integrate cellulosic ethanol into a comprehensive strategy for increasing gasoline octane and reducing air pollution

The Indonesian government is aiming to improve fuel quality and reduce vehicle air pollution through a set of actions, including adopting cleaner vehicle emission standards and phasing out low-octane gasoline. High-octane gasoline can support more efficient vehicles, and that will lead to a reduction of exhaust emissions, including pollutants and GHGs, that corresponds to the reduction in fuel consumption. Ethanol has high octane, and blending it into gasoline can thus help achieve high-octane fuel. The government can help support fuel quality improvement and emissions reduction by integrating cellulosic ethanol into its plans for increasing gasoline octane.

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APPENDIX

Table A1. Feedstock production rates and chemical composition of palm trunks, palm empty fruit bunches, and palm press fiber

		Palm trunk	Palm empty fruit bunch	Palm press fiber	Assumption in this study (default value for poplar in the GREET model)
Residue production per palm plantation area (average dry tonne per hectare per year)		0.9	1.6	0.8	—
Chemical composition (%, dry weight)	Lignin	16–23	18–32	11–37	26
	Hemicellulose	26–29	24–34	20–35	17
	Cellulose	42–46	37–50	38–63	46

Sources: Bahari, 2010; Ahmad et al., 2011; Anis et al., 2011; Sudiyani et al., 2013; MdYunos et al., 2015; Paltseva et al., 2016

Table A2. Breakdown of capital cost (CAPEX)

CAPEX components	Calculation description	Billion IDR (Million US$)	Proportion of total CAPEX
Equipment purchase	1.08 USD per liter ethanol capacity	1,052 (75)	37%
Equipment installation	39% of equipment purchase	410 (29)	14%
Total Equipment Purchase + Installation (TEPI)		**1,462** **(104)**	**51%**
Equipment trade tariffs	6.7% of equipment purchase	70.5 (5)	2%
Equipment shipping freight and insurance	10% of equipment purchase	105 (7.5)	4%
Warehouse	4% of TEPI, multiplied by 0.23 to downscale to Indonesia situation	13.5 (0.96)	0.5%
Site development	9% of TEPI, multiplied by 0.23 to downscale to Indonesia situation	30 (2.2)	1%
Additional piping	4.5% of TEPI, multiplied by 0.23 to downscale to Indonesia situation	15 (1.1)	1%
Total Direct Cost (TDC)		**1,697** **(121)**	**59%**
Prorateable expense	10% of TDC	170 (12)	6%
Field expenses	10% of TDC	170 (12)	6%
Construction fee	20% of TDC	339 (24)	12%
Project contingency	10% of TDC	170 (12)	6%
Other start-up and commissioning costs	10% of TDC	170 (12)	6%
Fixed Capital Investment (FCI)		2,714.5 (194)	95%
Land cost	From Parbowo et al. (2019)	9 (0.6)	0.3%
Working capital	5% of FCI	136 (9)	5%
Total CAPEX		**2,859** **(204)**	**100%**

Sources: Peters, Alberici, and Passmore, 2015; Parbowo et al., 2019

Table A3. Breakdown of annual fixed operational cost (OPEX)

OPEX components	Calculation description	Billion IDR (Million US$) per year	Proportion of total annual fixed OPEX
Labor salary	4.76 U.S. cents per gallon ethanol production from a U.S. study, multiplied by 0.02 to downscale to Indonesia situation	0.19 (0.014)	0.3%
Overhead	40% of labor salary	0.077 (0.006)	0.1%
Maintenance	3% of TEPI from Table A2	44 (3)	76%
Insurance	0.5% of FCI from Table A2	14 (1)	24%
Total Annual OPEX		**58** **(4)**	**100%**

Sources: Humbird et al., 2011; Turner and Townsend, 2019

Table A4. Material input unit quantity and unit price for variable operational cost (OPEX) other than feedstock purchase

Material	Unit	Quantity (unit per liter ethanol production)	Price_IDR per unit (US$ per kg)	Cost _IDR per liter ethanol production (U.S. cent per liter)	Proportion of non-feedstock annual variable OPEX
Diesel fuel	Btu	89	0.15	13.5 (0.1)	0.5%
Sulfuric acid	g	91.5	1.82 (0.13)	166.5 (1.2)	6.3%
Ammonia	g	11	9.24 (0.66)	101.4 (0.7)	3.8%
Corn steep liquor	g	34.8	1.12 (0.08)	38.9 (0.3)	1.5%
Diammonium phosphate (DAP)	g	3.7	20.02 (1.43)	73.2 (0.5)	2.8%
Sodium hydroxide (NaOH)	g	31.1	2.08 (0.15)	64.8 (0.5)	2.5%
Calcium oxide (CaO)	g	20.1	3.29 (0.24)	66.2 (0.5)	2.5%
Urea	g	5.5	5.04 (0.36)	27.7 (0.2)	1%
Cellulase	g	28.2	61.71 (4.41)	1,739.8 (12.4)	65.8%
Yeast	g	7	38.22 (2.73)	268.3 (1.9)	10.2%
Water	gallon	1.4	58.06	82.1 (0.6)	3.1%

Sources: The Glosten Associates, 2010; Tao et al., 2017