Environmental and socioeconomic assessment of rice straw conversion to ethanol in Indonesia: the case of Bali

Victor Samuel
ABSTRACT
The vast rice production in some developing Asian countries like Indonesia raises expectation on poverty alleviation and energy diversification through second generation biofuel production from rice residues, specifically rice straw. This work attempts to estimate the potential environmental and socioeconomic benefits of rice straw-to-ethanol project in Indonesia. Literature research and interviews are performed to quantify several environmental and socioeconomic indicators that are considered as the major concerns in implementing an energy project. Assuming all the technically available rice straw in Bali is used (~244-415 kilotonne/year), ethanol production may yield gasoline replacement, lifecycle GHG savings, GDP contribution, foreign exchange savings, and employment beneficiaries of 55-93 ML/year, 140-240 million USD/year, 19-32 kilotonne of CO₂-equivalent/year, 100-180 million USD/year, and 2,200-3,700 persons, respectively. Sensitivity analyses are done for some parameters, showing that ethanol yield, total capital cost, feed-in-tariff for electricity, and imported crude oil price are the major factors affecting the viability of rice straw-to-ethanol project in Indonesia.

Keywords: rice straw-to-ethanol conversion, second-generation biofuel, employment creation, lifecycle GHG reductions
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<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>BPS</td>
<td>Badan Pusat Statistik (Central Bureau of Statistics)</td>
</tr>
<tr>
<td>CBP</td>
<td>consolidated bioprocessing</td>
</tr>
<tr>
<td>EtOH</td>
<td>ethanol</td>
</tr>
<tr>
<td>FAO</td>
<td>Food and Agriculture Organization</td>
</tr>
<tr>
<td>FIT</td>
<td>feed-in-tariff</td>
</tr>
<tr>
<td>F-T</td>
<td>Fischer-Tropsch</td>
</tr>
<tr>
<td>FX</td>
<td>foreign exchange</td>
</tr>
<tr>
<td>GDG</td>
<td>ground dry grain</td>
</tr>
<tr>
<td>GDP</td>
<td>gross domestic produce</td>
</tr>
<tr>
<td>GHG</td>
<td>greenhouse gases</td>
</tr>
<tr>
<td>GOI</td>
<td>Government of Indonesia</td>
</tr>
<tr>
<td>GREET</td>
<td>Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation</td>
</tr>
<tr>
<td>ha</td>
<td>hectare</td>
</tr>
<tr>
<td>HDG</td>
<td>harvested dry grain</td>
</tr>
<tr>
<td>IDR</td>
<td>Indonesian rupiah</td>
</tr>
<tr>
<td>kt</td>
<td>kilotonne (that is, thousand tonnes)</td>
</tr>
<tr>
<td>MEMR</td>
<td>Ministry of Energy and Mineral Resources</td>
</tr>
<tr>
<td>ML</td>
<td>megalitre (that is, million litres)</td>
</tr>
<tr>
<td>MMUSD</td>
<td>million US dollar</td>
</tr>
<tr>
<td>Mt</td>
<td>megatonne (that is, million tonnes)</td>
</tr>
<tr>
<td>MW</td>
<td>megawatt</td>
</tr>
<tr>
<td>NPV</td>
<td>net present value</td>
</tr>
<tr>
<td>NREL</td>
<td>National Renewable Energy Laboratory</td>
</tr>
<tr>
<td>OPEC</td>
<td>Organization of the Petroleum Exporting Countries</td>
</tr>
<tr>
<td>RB</td>
<td>rice bran</td>
</tr>
<tr>
<td>RH</td>
<td>rice straw</td>
</tr>
<tr>
<td>RS</td>
<td>rice husk</td>
</tr>
<tr>
<td>SHF</td>
<td>separate enzymatic hydrolysis and fermentation</td>
</tr>
<tr>
<td>SSCF</td>
<td>simultaneous saccharification and co-fermentation</td>
</tr>
<tr>
<td>SSF</td>
<td>simultaneous saccharification and fermentation</td>
</tr>
<tr>
<td>TCI</td>
<td>total capital cost</td>
</tr>
<tr>
<td>t&lt;sub&gt;straw-db&lt;/sub&gt;</td>
<td>tonne of straw in dry basis</td>
</tr>
<tr>
<td>USD</td>
<td>US dollar</td>
</tr>
</tbody>
</table>
I. INTRODUCTION

Despite the global financial crisis, Indonesia has been achieving high yearly economic growth of more than six per cent and is expected to continue growing at such rates in upcoming years. The outstanding economic growth is also reflected in the total primary energy consumption, which grew by around 50 per cent between 1999 and 2008 (EIA 2011). According to the Government of Indonesia (GOI), the growth of Indonesian energy consumption has reached 7 per cent in 2012, far surpassing the world’s 2.6 per cent (Ministry of Energy and Mineral Resources 2012). In spite of being the world’s largest palm oil exporter and the second largest exporter of coal (Coordinating Ministry for Economic Affairs 2011), the country has withdrawn from OPEC and been a net-oil importer since 2005. If the current trend of high consumption continues without finding alternative sources of energy, Indonesia is projected to become a net-energy importer by 2030 (Ministry of Energy and Mineral Resources 2012).

Actually, Indonesia has abundant energy resources. In 2011, it ranked as the ninth biggest natural gas producer and the fifth coal producer worldwide (IEA 2012). In terms of trade, it is the sixth biggest exporter of natural gas and the first largest of coal (IEA 2012). To electrify the nation, the State Electricity Company (PLN) is completing two 10,000 MW programs, mostly coal- and gas-fired (State Electricity Company 2011). The GOI expects that 33 per cent of total primary energy production in 2025 will come from coal-based power plants, diminishing the role of oil.

On one side, oil is still expected to prevail as the third biggest contributor with 20 per cent share of total primary energy production. This is understandable as the transportation sector, which accounted for 36 per cent of final energy consumption in 2010 (Ministry of Energy and Mineral Resources 2011), is highly dependent on liquid fuels. Liquid fuels, however, can only be produced by biomass-based energy sources, consequently limiting possibilities of replacing oil with decarbonised, renewable sources.

On the other side, the increasingly dominant use of coal in the future will bring environmental problems as carbon emission will certainly proliferate. To reduce and prevent further harm on the earth due to climate change, there have been efforts in mitigating the carbon emissions. Carbon capture and sequestration is one of the major technological options. However, it is relatively costly due to the high cost of CO₂ capture and is not commercially demonstrated in the power plants yet (Rubin, et al. 2012). At the same time, nuclear power plant has been under criticism concerning its cost and safety, especially after the Fukushima disaster. At any rate, the nuclear power plant is only appropriate for electricity generation, not transportation fuel production.

Therefore, there have been global interests in developing the use of the first- and the second-generation biofuel, alongside hydro, geothermal, solar, and wind power. Nonetheless, solar and wind power are still relatively expensive. Consequently, the abundance of well-established agricultural feedstock, which can be converted to biofuel, is perceived as the low-hanging fruit to achieve energy diversification, on top of job creation and poverty alleviation (Peskett, et al. 2007, Dawe 2007).

To that end, the GOI has issued Presidential Regulation no. 5/2006, which provides guidelines for the management of national energy. It sets the diversification targets for 2025, including that 5 per cent is the minimum share of biofuel to the national energy consumption. To achieve this, the GOI issued Presidential Regulation no. 10/2006 on forming the National Team for Biofuel Development. The team has important tasks for drawing the roadmap, recommendation, and evaluation of the national biofuel strategy. This roadmap then serve as guideline for further implementation planning by the Ministry of Energy and Mineral Resources (MEMR), as regulated by the MEMR Ministerial Regulation no. 32/2006 on preparing, using, and managing the market of biofuel as an alternative fuel.

Indonesian biodiesel production has shown sizable growth, from 65 million litres in 2006 to 1.8 billion litres in 2012, thanks to the growing palm oil industry (see Table 1). Indonesia now is the world’s largest producer of palm oil, replacing Malaysia since 2007 (Slette and Wiyono 2012). On the contrary, Indonesian fuel ethanol production was stopped in 2010 by the GOI due to disagreements of the market price index formulation between producers and the GOI. The reduction of sugarcane production and increasing sugar consumption in the national scale demotivate the fuel ethanol production, as the price of molasses—the primary Indonesian ethanol feedstock—rises (Slette and Wiyono 2012). However, the MEMR and the parliament has agreed to increase the subsidy for both biodiesel and ethanol in 2013 (Ministry of Energy and Mineral Resources 2011), fostering the profitability of the ethanol producers who

---

collectively already have 273 million litres installed capacity but no actual production in the recent years (see Table 1).

Table 1. Installed capacity and production of biofuels in Indonesia.
Source: Slette and Wiyono (2012)

<table>
<thead>
<tr>
<th></th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Biodiesel</td>
<td>215</td>
<td>1,709</td>
<td>3,138</td>
<td>3,528</td>
<td>3,936</td>
<td>3,936</td>
<td>4,280</td>
</tr>
<tr>
<td>Ethanol</td>
<td>215</td>
<td>13</td>
<td>243</td>
<td>273</td>
<td>273</td>
<td>273</td>
<td>273</td>
</tr>
<tr>
<td>Production</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Biodiesel</td>
<td>65</td>
<td>270</td>
<td>630</td>
<td>330</td>
<td>740</td>
<td>1,520</td>
<td>1,800</td>
</tr>
<tr>
<td>Ethanol</td>
<td>0.3</td>
<td>1</td>
<td>1.2</td>
<td>1.72</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Biofuel development, however, is not without harmful toll. Despite the improved livelihoods obtained by people involved in the palm oil industry, the development of palm oil-based biofuel has led to environmental impacts (i.e. deforestation, water pollution and flooding) and even social impacts (i.e. conflicts over land between indigenous communities and oil palm companies) (Andriani, et al. 2011).

For that reason, there is an increase in global attention to second-generation biofuel, that is, biofuel that is converted from inedible biomass, such as lignocellulosic biomass. One of the major sources of lignocellulosic biomass is agricultural residues, such as sugarcane bagasse, oil palm empty fruit bunch, rice husk, and rice straw (RS).

During the last decade, the agriculture sector in Indonesia contributed around 15 per cent to the national gross domestic product (GDP). At the same time, agriculture provides jobs for 38 per cent of the total Indonesian labour force. Furthermore, the agricultural GDP has shown positive growth.

Within the agricultural scope, paddy rice has a major position in Indonesia. In terms of national production, rice is the second largest crop after the roaring oil palm fruit; rice brings in 21 per cent of total national agricultural production. Globally, Indonesia is noted as the third biggest rice producer, with annual rice production of 65.7 Mt. The yield—the mass of rice produced per hectare area—of Indonesian rice farms is 5.0 tonne per hectare, which is greater than India's, most of neighbouring countries' and the world's average (see Table 2).

Table 2. Rice production statistics 2011.
Source: FAO 2013.

<table>
<thead>
<tr>
<th>Nr.</th>
<th>Countries</th>
<th>Production in 2011 (Mt)</th>
<th>Ratio of national to world's production (per cent)</th>
<th>Yield (tonnes/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-</td>
<td>World</td>
<td>722</td>
<td>100</td>
<td>4.4</td>
</tr>
<tr>
<td>1</td>
<td>China</td>
<td>203</td>
<td>28</td>
<td>6.7</td>
</tr>
<tr>
<td>2</td>
<td>India</td>
<td>156</td>
<td>22</td>
<td>3.5</td>
</tr>
<tr>
<td>3</td>
<td>Indonesia</td>
<td>66</td>
<td>9</td>
<td>5.0</td>
</tr>
<tr>
<td>4</td>
<td>Bangladesh</td>
<td>51</td>
<td>7</td>
<td>4.2</td>
</tr>
<tr>
<td>5</td>
<td>Vietnam</td>
<td>42</td>
<td>6</td>
<td>5.5</td>
</tr>
<tr>
<td>6</td>
<td>Thailand</td>
<td>35</td>
<td>5</td>
<td>3.0</td>
</tr>
<tr>
<td>7</td>
<td>Myanmar</td>
<td>33</td>
<td>5</td>
<td>4.1</td>
</tr>
<tr>
<td>8</td>
<td>Philippines</td>
<td>17</td>
<td>2</td>
<td>3.7</td>
</tr>
<tr>
<td>9</td>
<td>Brazil</td>
<td>14</td>
<td>2</td>
<td>4.9</td>
</tr>
<tr>
<td>10</td>
<td>Cambodia</td>
<td>9</td>
<td>1</td>
<td>3.0</td>
</tr>
</tbody>
</table>

In economic terms, rice production brings the largest amount of gross production value, underlining the significance of rice in the national economy. According to Simatupang and Rusastra (2004), the important role of rice in the Indonesian economies has three founding arguments. Firstly, rice is the staple food for Indonesia so that rice agribusiness is linked to the food security. Secondly, rice agribusiness system can create jobs and benefits for different stakeholders. Lastly, rice agribusiness is instrumental in poverty alleviation efforts as most of the poor are farmers.

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3 Ibid. See Appx. Figure 2 in Appendix C.
4 Ibid. See Appx. Figure 3 in Appendix C.
6 Mt is the acronym of megatonne, meaning million tonnes.
7 FAO, loc. cit. See Appx. Figure 5 in Appendix D.
Indonesian vast rice production raises expectations on the second-generation biofuel produced from the residue of this crop. This work seeks to quantify the potential that can be realised, based on existing residue flows from rice production in Indonesia, given the availability of cost-efficient technology and enabling policy frameworks.

Besides, there is also straw-to-electricity application, which might compete straw-to-biofuel application concerning the feedstock. Straw-to-electricity has been commercially available in several developing countries like China and India. In this matter, Delivand, Barz, et al. (2012) found that the straw-to-ethanol project yields higher socioeconomic and environmental benefits and the possibility for long-distance trade with advanced biofuels, which are becoming increasingly sought-after in international markets. However, as straw-to-electricity technology starts to be commercially deployed and disseminated, there will be economies of scale and economies of learning, which may bring the technology outperform that of straw-to-ethanol. Nevertheless, in Indonesia neither application exists yet, so there is still a need to look into the benefits of both before deciding which is more appropriate to be applied.

II. OBJECTIVES AND BOUNDARIES

This work attempts to estimate 1) how much second-generation biofuel, namely ethanol, is potentially produced from RS; 2) how much lifecycle GHG can be reduced; 3) how much GDP contribution can be generated; 4) how much foreign exchange can be saved by gasoline replacement; 5) and, how many jobs can be created in the production.

The long-term impact of the climate change on the rice production is not considered. The ethanol production analysis will be limited only on RS, since it is the rice residues that now have the lowest economic value and few competing usages. The analysis will be based on the chemical composition of the residues. In addition, the technological possible routes for the RS conversion will be reviewed.

This paper limits the scope of research only on the rice production in the province of Bali. It is also assumed that the ethanol is sold and distributed in Bali only, although interprovincial and even international trade will surely occur in real life circumstances.

III. INTRODUCTION TO BALINESE RICE PRODUCTION

In the province of Bali, rice production reached 860 kt (harvested dry grain; see Figure 1) in 2011. The harvested area of the island amounted at 153,000 ha, yielding rice grain at the annual rate of 5.6 t/ha. Normally, the harvest time is twice a year; three times is possible but rare (Wiguna 2013). There are 1,545 processing milling site in Bali in various size (The Ministry of Agriculture 2008).

Rice post-production basically consists of three steps: harvesting, drying, and milling (see Figure 1). Harvesting separates the grain and aboveground rice straw (RS). The process yields harvested dry grain (HDG) that contains water moisture above sixteen per cent. The grain is then dried, with solar power or mechanical dryer, yielding ground dry grain (GDG) that has moisture content varying from 12 per cent to 14 per cent. Then, the milling process takes place, consisting of three sub-steps: 1) skin separation, which yields rice husks (RH) as by-product; 2) polishing, separating rice bran (RB) from the rice; and 3) separation of good-shaped and bad-shaped rice.

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8 kt is the acronym of kilotonne, meaning thousand tonnes.
9 BPS Provinsi Bali, loc. cit.
10 Ibid.
Figure 1. Steps in rice post-production in Bali.

According to Yasa (2011), the RS production rate in Indonesia is 2.0 to 3.9 t\(\text{straw-db}/\text{ha/harvest}\), or around 4.0 to 6.8 t\(\text{straw-db}/\text{ha/year}\), which is comparable with the older studies. Djajegara and Rangkuti (1983) reported that it was 2.3 t\(\text{straw-db}/\text{ha/harvest}\) and Marsetyo (2008) stated 3.86 t\(\text{straw-db}/\text{ha/year}\).

As RS is left on the paddy field, they are diversely located. Without incentive, the farmers, which are the owners of RS, tend to burn them or let them decompose on the ground as mulch. From the whole RS produced, 21 per cent has been used for cattle feed, 18 per cent is used for mulch, and the rest (61 per cent) is open-burnt. However, out of the 21 per cent used for cattle feed, 82 per cent is not fermented beforehand, resulting in low quality cattle feed (Wiguna, Inggriati, et al. 2007).

The RH production consists of 35 per cent to 40 per cent of HDG (Wiguna, Inggriati, et al. 2007). Therefore, the RH produced in Bali during the year 2011 would be around 300 kt, or around 2.0 t/ha\text{harvested}. As of now, almost all of RH is used, mostly for poultry litter, but also for red brick manufacturing, fertiliser, and burning fuel for grain dryer machine. Similar to RB, RH is centrally produced in the rice mills and belongs to the rice millers. The bigger the capacity of the rice mill, the more concentrated the RH and the RB productions are.

Among the by-products, RB is the least in quantity, numbered 6 to 10 per cent of HDG (Wiguna, Ingeriati, et al. 2007). Albeit the little amount, it is the most valuable among other residues as it can be used directly as animal feed. RB is produced in the mills but usually belongs to the farmer, as commonly agreed. The summary of the residues and their economic properties are shown in Table 3.

Table 3. Rice production residues and their economic properties in Bali.

<table>
<thead>
<tr>
<th>Yield (t/ha)</th>
<th>Annual production in Bali (kt)</th>
<th>Approx. selling price per kg(^a)</th>
<th>First-hand owner</th>
<th>Location</th>
<th>Actual uses</th>
<th>Perceived market value(^b)</th>
<th>Not open-burnt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rice straw</td>
<td>4.0-6.8</td>
<td>600-1200</td>
<td>IDR 100</td>
<td>Farmer</td>
<td>Dispersed on the field</td>
<td>Cattle feed (fermented)</td>
<td>Medium</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>USD 0.01</td>
<td></td>
<td></td>
<td>Cattle feed (unfermented)</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Mulch</td>
<td>Low</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Burnt</td>
<td>Low</td>
</tr>
<tr>
<td>Rice husk</td>
<td>2.0-2.2</td>
<td>300-340</td>
<td>IDR 500</td>
<td>Rice mill</td>
<td>In the mill</td>
<td>Poultry litter</td>
<td>Medium</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>USD 0.05</td>
<td></td>
<td></td>
<td>Red brick</td>
<td>Medium</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Fertiliser</td>
<td>Medium</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Burning fuel for dryer</td>
<td>Medium</td>
</tr>
<tr>
<td>Rice bran</td>
<td>0.3-0.6</td>
<td>51-86</td>
<td>IDR 3,000</td>
<td>Farmer</td>
<td>In the mill</td>
<td>Animal feed</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>USD 0.31</td>
<td></td>
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</tr>
</tbody>
</table>

\(^a\) The prices depend on the season. During the dry season, for example, the price of RS can increase dramatically due to the scarcity of cattle feed.

\(^b\) Obtained from interviews with experts and farmers in Bali.
In Tabanan, the largest rice producer district in Bali, there is 45 ha of rice plantation area for around 90 farmers (Wiguna, Inggriati, et al. 2007). That means the average land ownership is 0.5 ha per farmer. The average rice yield of Bali is 5.6 tonnes per ha\(^1\) and the price of GDG ranges from IDR 3,500 to 4,000 (USD 0.36 to 0.41). Therefore, the gross income per year, which consists of two times of harvest, varies from IDR 19.6 million to 22.4 million (USD 2,000 to 2,300). However, the operational cost of the farmer ranges from 43 per cent to 56 per cent of the gross income (Wiguna 2008). This leaves the farmers annual net income ranging from IDR 8.4 million to 12.8 million (USD 860 to 1,310). To a smaller extent, the farmers may also gain some revenue by selling the rice bran.

The rice mills buy the GDG for IDR 3,500 up to 4,000 (USD 0.36 to 0.41), according to the season, and sell the good-shaped rice at the price level varying from IDR 7,300 to 7,800 (USD 0.75 to 0.80) per kg. The difference is the gross income, which is around IDR 3,800 (USD 0.39) per kg rice. The mill may also gain some revenues by selling RH for around IDR 500 (USD 0.05) per kg. However, there are also worker costs, which is around IDR 50,000 (USD 5) per person per day.\(^2\) The amount of workers depends on the size of the mill. For instance, for 6-t/day capacity, a mill requires around two dryers and five millers.

IV. INTRODUCTION TO STRAW CONVERSION TO ETHANOL

As shown in Figure 2, the technologies developed to convert RS to ethanol can be divided into two major categories: the sugar (biochemical) platform and syngas (thermochemical) platform (Binod, Sindhu, et al. 2010).

Like other biomass, RS consists of three different components: cellulose, hemicellulose, and lignin. In the sugar platform, the biomass is first pretreated to make cellulose and hemicellulose accessible for enzymatic reaction. Then, the enzymatic hydrolysis converts the cellulose and hemicellulose into fermentable sugars, such as glucose, xylose, arabinose, galactose, and mannose. The fermentable sugars are then fermented by industrial yeasts to produce ethanol.

In the syngas platform, the biomass is first gasified in a high temperature process, producing synthetic gas (or syngas). Syngas essentially consists of carbon monoxide and hydrogen. It can be then either fermented or catalytically converted to produce ethanol.

![Diagram of ethanol production from rice straw and rice husks](image)

Figure 2. General concept of ethanol production from rice straw and rice husks. Adapted from Binod, Sindhu, et al. (2010).

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11 BPS Provinsi Bali, loc. cit.
12 The numbers are based on the interviews with the local farmer and miller in the district of Tabanan.
A. Sugar Platform

1. Pretreatment

Pretreatment is needed to disrupt the structure of biomass so that the cellulose is more accessible to the enzymes that convert the cellulose into fermentable sugars. This is done by decreasing the crystallinity of cellulose, increasing biomass surface area, removing hemicellulose, and breaking lignin seal (Mosier, Wyman, et al. 2005). The expected results are faster cellulose-to-fermentable sugars conversion, and with higher yields.

Pretreatment is one of the most expensive steps in cellulosic biomass-to-fermentable sugars conversion, accounting for 33 per cent of the total cost (Mosier, Wyman, et al. 2005, Tomas-Pejo, Oliva and Ballesteros 2008). Efforts in making this step cheaper and more efficient are the key to economic viability of second-generation biofuel production plants (Zhang 2011).

Talebnia, Karakashev and Angelidaki (2010) have classified the pretreatment options into four types: physical, physicochemical, chemical, and biological pretreatment. Physical processes usually involve milling, grinding, or chipping. It has been more than a decade when Cadoche and López (1989) found out that mechanical size reduction is required as preliminary step to obtain higher yields of ethanol. It increases the accessible surface area of pores, and decreases the crystallinity and the polymerization degrees of cellulose (Sudhagar, Tabil and Sokhansanj 2004, Koullas, et al. 1992). The physical processes, however, have disadvantages. Milling is highly energy intensive and generally not economically viable (Hideno, Inoue and Tsukahara, et al. 2009). That said, Hideno, Inoue and Tsukahara, et al. (2009) showed that wet disk milling is an economical and reasonable pretreatment of RS. Albeit having lower xylose yield than dry ball milling and hot-compressed water treatment, the wet disk milling technique had a high efficacy for enzymatic hydrolysis and low-energy consumption, without generating fermentation inhibitors.

Among physicochemical pretreatments, the commonly used methods are liquid hot water, steam explosion, and ammonia fiber explosion (Talebnia, Karakashev and Angelidaki 2010). Liquid hot water is a hydrothermal pretreatment by applying pressure to maintain water in liquid state at elevated temperature. The aim is to solubilise especially the hemicellulose to make the cellulose better accessible and to avoid the formation of fermentation inhibitors (Hendriks and Zeeman 2008, Mosier, Hendrickson, et al. 2005).

Steam explosion, or autohydrolysis, is one of the most cost-effective and widely used pretreatment methods (McMillan 1994). The biomass is first exposed to high pressure steam (0.69-4.83 MPa, with corresponding temperature of 160-260°C) for several seconds to a few minutes. Then, the pressure is suddenly reduced so that the materials suffer an explosive decompression. The results are the disrupted material’s structure, the degradation of hemicellulose, and lignin transformation due to the high temperature, thus facilitating the subsequent hydrolysis of cellulose (Ballesteros, et al. 2006, Ohgren, et al. 2007).

Ammonia fiber explosion resembles the mechanism of steam explosion, but uses liquid ammonia as the working gas. It has drawbacks of the solubilisation of a very small fraction of solid material especially hemicellulose. Mes-Hartree, Dale and Craig (1988) made a comparison between steam and ammonia pretreatment of wheat straw. They found that the enzymatic hydrolysis was improved by several folds and in the similar order of magnitude for both pretreatments. However, the highest glucose yield concentration was achieved with ammonia pretreatment.

In chemical pretreatment, acids, alkalis, oxidising agents, or organic solvents (organosolv) are used. The most widely used method is dilute acid pretreatment using H2SO4 (Talebnia, Karakashev and Angelidaki 2010). However, the use of these chemicals have some drawbacks such as the formation of inhibiting substances for the hydrolysis and fermentation, and the pH requirements for downstream processes (Hideno, Inoue and Tsukahara, et al. 2009, Sun and Cheng 2002, Hendriks and Zeeman 2008, E. M. Rubin 2008). On top of that, the use of strong acids raises environmental risks (Hideno, Inoue and Tsukahara, et al. 2009).

It is reported that alkali is more promising than acid pretreatment (Binod, Sindhu, et al. 2010). Alkali pretreatment can result in a sharp increase in saccharification yields. It is the most effective method in breaking the ester bonds between lignin, hemicellulose, and avoiding fragmentation of the hemicellulose polymers (Gaspar, Kalman and Reczey 2007).

In oxidative pretreatment, oxidising agents, like hydrogen peroxide or peracetic acid, are added to the biomass that is suspended in water. In the process, several reactions may occur, such as electrophilic...
substitution, displacement of side chains, cleavage of alkyl aryl ether linkages or the oxidative cleavage of aromatic nuclei (Hon and Shiraishi 2001). The drawback of the process is the high chance on the formation of inhibitors and the loss of hemicellulose and cellulose (Hendriks and Zeeman 2008).

Organosolv pretreatment enhances the enzymatic digestibility by lignin extraction and hemicellulose removal leaving a cellulose-rich (or, carbohydrate-poor) residue, which can be hydrolysed with enzymes at high rates and to almost theoretical glucose yield. However, the pretreatment is still expensive compared to the other alternatives. However, the separation and recycling of the applied solvent can reduce the operational costs of the process (Bin et al. 2010, Huijgen, et al. 2012, Wildschut, et al. 2012).

Biological pretreatment consists of using microorganisms such as fungi for selective degradation of lignin and hemicellulose. It offers a cheap, low chemical and low-energy process as the core advantages. However, the rate of hydrolysis reaction is very low and still needs major development to reach commercial application (Talebnia, Karakashev and Angelidaki 2010). The most efficient lignin degraders in nature are white-rot fungi that belong to the class Basidiomycetes (Eriksson, Blanchette and Ander 1990). Tamiguchi, et al. (2005) studied the effects of using four white-rot fungi on the structural changes of RS and susceptibility to enzymatic hydrolysis. Of these white-rot fungi, P. ostreatus selectively degraded lignin rather than the holocellulose part (that is, the total polysaccharide part, comprising cellulose and all of the hemicelluloses, excluding lignin). The sugar yields based on the amounts of holocellulose and cellulose of RS were 33% for total soluble sugar from holocellulose and 32% for glucose from cellulose.

Out of five different fungi, Patel, Onkarappa and Shobba (2007) reported that Aspergillus niger and Aspergillus awamori gave the best ethanol yield.

That said, the most efficient methods are usually a combination of different pretreatment types. Inoue and Yanagina, et al. (2012), for instance, found out that the combination of hot-compressed water treatment and wet disk milling could improve xylose yield as compared with only wet disk milling and thus reduce 19–67 per cent of the enzymes cost for ethanol production. Niu, et al. (2009) reported that alkali pretreatment assisted by photocatalysis could increase the rate of RS enzymatic hydrolysis by 2.56 times than what is obtained with only alkali pretreatment. Jin and Chen (2006) studied the combination of low severity steam explosion and superfine grinding pretreatment with respect to side products generation and enzymatic hydrolysis efficiency. The enzymatic hydrolysis of the superfine ground product gained the highest hydrolytic rate and yielded more sugar.

As pretreatment is one of the most expensive processes in biomass-to-ethanol production, deciding which pretreatment to undertake is crucial. The objectives of pretreatment are to increase accessible surface area of the biomass, decrystallise cellulose, remove hemicellulose, and break lignin seal. So far, no single pretreatment method was found fulfilling all of these objectives; a combined method might be needed (Talebnia, Karakashev and Angelidaki 2010, Mosier, Wyman, et al. 2005). Each pretreatment has its own advantages and disadvantages. The desired shorter reaction time generally corresponds to undesired higher temperature. The parameters that need to be considered are energy balance, higher solids loading, minimum use of chemicals, and other environmental factors such as wastewater treatment, catalyst recovery, and solvent recycling. However, due to the strikingly large impact of the pretreatment on the efficiency and economy of the succeeding stages, the final decision must be made within the picture of overall process (Talebnia, Karakashev and Angelidaki 2010).

2. Hydrolysis

The second step in biomass-ethanol conversion is hydrolysis or saccharification. It converts the cellulose and hemicellulose into simpler monomers that are fermentable. It can be chemical hydrolysis (using acids or alkalis) or enzymatic hydrolysis (using enzymes) (Soccol, et al. 2011). The latter needs less energy and mild environment conditions thus requires lower operational costs than chemical hydrolysis (Sun and Cheng 2002). The catalyst is a class of enzymes called cellulase. These enzymes can be produced by fungi such as Trichoderma reesei and Aspergillus niger or bacteria such as Clostridium cellulovorans (Arai, et al. 2006). However, fungi has been a focus of most research because the bacteria have very low growth rates. At least, there are three major groups of fungal enzymes, namely endo-glucanase, exo-glucanase, and β-glucosidase, synergetically involved in hydrolysis of cellulose to glucose. Endo-glucanase attacks regions of low crystallinity in the cellulose fiber and creates free chain ends. Exo-glucanase breaks the molecule further by removing cellobiose units from the free chain-ends which is then cleaved to glucose by β-

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13 “Solids loading” is defined by Modenbach and Nokes (2012) as the amount of biomass that enters the process divided by the total mass of the biomass and water added to the biomass. The use of high-solids loading offers many advantages over low-solids loading, including increased sugar and ethanol concentration, and decreased production and capital costs.
glucosidase. In turn, β-glucosidase is inhibited by glucose (Talebnia, Karakashev and Angelidaki 2010, Rabinovich, Melnik and Bolobob 2002).

Cellulose usually contains glucans while the hemicellulose contains polymers of several sugars e.g. mannan, xylan, glucan, galactan, and arabinan. Therefore, the main hydrolysis product of cellulose is glucose, whereas the hemicellulose converts into pentoses and hexoses (Taherzadeh and Niklasson 2004). However, high lignin content hampers enzyme accessibility, causes inhibition of the product, and reduces the rate and yield of the hydrolysis. Besides lignin, cellobiose and glucose also inhibit cellulases.

Valkanas, et al. (1998) reported that, in the hydrolysis of RS with different acids with varying concentrations (0.5–1% H2SO4, 2–3% HCl and 0.5–1% H3PO4), hemicellulosic pentosans converted to a fermentable monosaccharides after three hours retention time. Roberto, Mussatto and Rodrigues (2003) pointed out that the optimum H2SO4 concentration and retention time are respectively 1 per cent and 27 minutes, yielding a high yield of xylose (77 per cent). Abedinifar, et al. (2009) carried out an experiment of ethanol producing by separate enzymatic hydrolysis and fermentation by Mucor indicus, Rhizopus oryzae, and Saccharomyces cerevisiae. The optimum temperature and pH of commercial cellulase and β-glucosidase enzymes were obtained at 45°C and pH 5.0. Furthermore, the concentration increase of the dilute-acid pretreated straw from 20 to 50 and 100 g L−1 resulted in the lowering of sugar yield by respectively 3 per cent and 16 per cent. At higher substrate concentrations, there could be enzyme activation and inhibition by hydrolysis products. Additionally, it was shown that dilute-acid pretreatment is more efficient in improving enzymatic hydrolysis than steaming.

3. Fermentation

The sugars produced in the hydrolysis step can be fermented into ethanol in several strategies:
- simultaneous saccharification and fermentation (SSF),
- separate enzymatic hydrolysis and fermentation (SHF),
- simultaneous saccharification and co-fermentation (SSCF), and
- consolidated bioprocessing (CBP).

In SSF, the enzymatic hydrolysis and fermentation take place in the same reaction vessel while, in SHF, the processes are carried out in separate steps. Using SSF is generally more favorable due to the increase of hydrolysis rate by reducing end product inhibition of cellulase, lower enzyme requirement, higher ethanol yield, lower requirement for sterile conditions, shorter process time, and cost reduction by eliminating expensive reaction and separation equipment (Binod, Janu, et al. 2011).

However, the main disadvantage of SSF is the inhibition of cellulase enzyme by ethanol produced after fermentation. Ethanol inhibition may limit ethanol yield (Wyman 1996). The other drawback is the incomplete hydrolysis of the substrates at the end of the reaction. This causes the close association of the yeast and adsorbed cellulases with the recalcitrant residue (Binod, Janu, et al. 2011). Another drawback of SSF, which does not occur in SHF, is the difference of optimum temperature of the hydrolysing enzymes (40-50°C) and of the fermenting microorganism (30-35°C), which do not tolerate the high temperature. The separate steps in SHF, in the other hand, allows optimum conditions for both processes, however, creates end-product inhibition (Galbe and Zacchi 2002). However, SSF is still preferred in many studies (Kádár, Szengyel and Réczey 2004, Tomas-Pejo, Oliva and Ballesteros 2008, Olsson, et al. 2006).

Karimi, Emtiaz and Taherzadeh (2006) studied the ethanol production from dilute-acid hydrolysis pretreated RS using SSF with Mucor indicus, Rhizopus oryzae, and Saccharomyces cerevisiae. Overall yield of 40-74 per cent of the maximum theoretical SSF, based on the glucan available in the solid substrate. R. oryzae allows the best ethanol yield of 74 per cent. It means 208 ml ethanol can be produced from 1 kg of RS. More recently, Watanabe, et al. (2012) achieved stable ethanol production of 38 g/L, or 85 per cent of ethanol yield, from alkali-treated RS by using repeated-batch SSF14 with immobilised S. cerevisiae cells.

SSCF is the improvement to SSF. In SSF, only hexoses (from cellulose) are converted to ethanol whereas pentoses (from hemicellulose) are fermented in another bioreactor with different microorganism. Therefore, SSF would require two bioreactors and two biomass production setups. In SSCF, both

14 Repeated-batch SSF process is a concept of reusing fermentation yeast cells for the next batch of fermentation. It can reduce the processing costs of ethanol production associated with inoculum preparation, such as immobilised yeast cells or flocculating yeast cells. The process has been successfully applied in several studies (Choi, Kang and Moon 2009, Morimura, Ling and Kida 1997).
hexoses and pentoses are fermented in a single bioreactor with a single microorganism (Teixeira, Linden and Schroeder 2000).

Oberoi, et al. (2010) used SSCF to convert neutralised hydrolysate and sulfuric-acid pretreated RS. They used cellulase, β-glucosidase, and Candida tropicalis ATCC 13803 microbial cells. C. tropicalis cells that were adapted to fermentation medium produced nearly 1.6 times more ethanol than non-adapted cells. A 36-hour SSCF with adapted cells resulted in ethanol yield and production efficiency of, respectively, 0.20 g/g (ethanol to sugar) and 77 per cent. This showed a scale-up potential for the process.

Takano, Yokozawa and Hoshino (2009) found a novel fungus for efficient fermentation from high-yielding rice and its RS. The fungus, Mucor javanicus NBRC 4572, was able to ferment both glucose and xylose in high ethanol yield that is 0.505 and 0.226 g/g, respectively. SSCF was used to achieve efficient ethanol production.

All of the three previous processes require separate enzyme production. In CBP, ethanol and all enzymes are produced by a single microorganism community in a single reactor. CBP is seen as the logical endpoint in the evolution of biomass conversion technology. The process implies no capital or operating costs for enzyme production or purchase, reduced diversion of substrate for enzyme production, and compatible enzyme and fermentation systems (Taherzadeh and Karimi 2007, Lynd, et al. 2005). However, the process is still in research scale and there is no rice straw-to-ethanol research using CBP yet. The main challenge is finding a highly engineered microorganism suitable for several different process-specific characteristics. The dominant strategy for engineering a CBP biocatalyst is to express multiple components of a cellulolytic system from either fungi or bacteria in the yeast S. cerevisiae (Hasunuma and Kondo 2012).

The comparison of the technological options in the sugar platform is summarised in Table 4.
Table 4. Comparison of routes in sugar platform.

<table>
<thead>
<tr>
<th>Steps</th>
<th>Routes</th>
<th>Advantages</th>
<th>Disadvantages</th>
<th>Maturity</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pretreatment</td>
<td>Physical</td>
<td>• No chemicals are used</td>
<td>• High energy requirement&lt;br&gt;• Inability of removing lignin&lt;br&gt;• Not suitable for commercial application</td>
<td>Commercial</td>
<td>Taherzadeh and Karimi (2008)</td>
</tr>
<tr>
<td></td>
<td>Chemical and physicochemical</td>
<td>• Most effective and most promising for industrial application</td>
<td>• Need of harsh conditions&lt;br&gt;• Chemical requirements</td>
<td>Commercial /Pilot</td>
<td>Kazi, et al. (2010)</td>
</tr>
<tr>
<td></td>
<td>Biological</td>
<td>• Low energy requirement&lt;br&gt;• No chemical requirement&lt;br&gt;• Mild environmental conditions</td>
<td>• Very low treatment rate&lt;br&gt;• Not suitable for commercial application</td>
<td>Laboratory</td>
<td>Menon and Rao (2012)</td>
</tr>
<tr>
<td>Hydrolysis</td>
<td>Chemical</td>
<td>• Low cost of catalyst&lt;br&gt;• Short time of hydrolysis</td>
<td>• Formation of inhibitory by-products&lt;br&gt;• High temperature and low pH&lt;br&gt;• Corrosive condition</td>
<td>Commercial</td>
<td>Taherzadeh and Karimi (2007)</td>
</tr>
<tr>
<td></td>
<td>Enzymatic</td>
<td>• Less energy requirement&lt;br&gt;• Mild environment&lt;br&gt;• High yields of hydrolysis</td>
<td>• Product inhibition during hydrolysis</td>
<td>Commercial</td>
<td>Menon and Rao (2012)</td>
</tr>
<tr>
<td>Fermentation</td>
<td>SHF</td>
<td>• Allowing optimum conditions for both saccharification and fermentation&lt;br&gt;• Faster</td>
<td>• Inhibition of cellulase enzyme by sugars&lt;br&gt;• Lower hydrolysis rate&lt;br&gt;• More costly equipments</td>
<td>Commercial</td>
<td>Binod, Janu, et al. (2011)</td>
</tr>
<tr>
<td></td>
<td>SSF</td>
<td>• Low cellulose inhibition by sugars&lt;br&gt;• Higher hydrolysis rate than SHF&lt;br&gt;• Cheaper equipments</td>
<td>• Inhibition of cellulase enzyme by ethanol produced&lt;br&gt;• Incomplete hydrolysis when fermentation is initiated</td>
<td>Commercial</td>
<td>Kazi, et al. (2010)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Different optimum temperatures between saccharification and fermentation</td>
<td></td>
<td>Ojeda, et al. (2011)</td>
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<td></td>
<td></td>
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<td>Menon and Rao (2012)</td>
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<td>Lynd, et al. (2005)</td>
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<td></td>
<td></td>
<td></td>
<td>Hasunuma and Kondo (2012)</td>
</tr>
<tr>
<td></td>
<td>SSCF</td>
<td>• Higher exergy efficiency than SHF and SSF&lt;br&gt;• No inhibition of cellulase enzyme by ethanol&lt;br&gt;• Lower undesirable products&lt;br&gt;• Higher rate than SSF and SHF</td>
<td>• Different optimum temperatures between saccharification and fermentation</td>
<td>Pilot</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CBP</td>
<td>• Lowest capital and operational cost: no need for separated enzyme production&lt;br&gt;• Highest efficiency by alleviating product inhibition of cellulase&lt;br&gt;• Simplification of total operation&lt;br&gt;• Reduction of contamination risk by reducing glucose and producing ethanol&lt;br&gt;• Higher hydrolysis rates&lt;br&gt;• Reduced reactor volume</td>
<td>• Different optimum temperatures between saccharification and fermentation&lt;br&gt;• Need for highly engineered microorganism (e.g. thermotolerant yeast strains)</td>
<td>Laboratory</td>
<td></td>
</tr>
</tbody>
</table>

Note: the comparison is general and does not refer to rice straw application in particular.
B. SYNGAS PLATFORM

1. Gasification

Gasification is a complete depolymerisation process of biomass with limited oxygen at high temperature (more than 850°C). The product is synthetic gas (or syngas) that mainly consists of hydrogen and carbon monoxide.

Whereas the types of biomass gasification vary, the most popular gasifier for thermochemical ethanol is a steam-blown indirectly heated gasifier, such as the one proposed by Phillips, et al. (2007) and He and Zhang (2011). The advantages of this type of gasifier are the absence of syngas dilution with nitrogen and low-pressure operation. However, the syngas from the indirect gasifiers contain higher concentration of tars that must be removed before the next step, which is catalytic ethanol synthesis (Heijden and Prasinski 2012).

2. Catalytic conversion

The catalytic ethanol synthesis reactor is the core of the entire plant, where ethanol and other products are catalytically produced from the cleaned syngas. At least, there are three different methods for catalytic conversion of syngas to ethanol and higher alcohol (Spath and Dayton 2003, Subramani and Gangwal 2008).

- Direct conversion of syngas to ethanol, in which selective hydrogenation of carbon monoxide occurs on a catalyst surface to directly produce ethanol.
- Methanol homologation, which involves reduction carbonylation of methanol over a redox catalyst surface to make a C-C bond and produce ethanol.
- Multistep ENSOL process, in which syngas is first converted to methanol over a commercial methanol synthesis catalyst followed by methanol carbonylation to acetic acid in the second step, and finally, subsequent hydrogenation of acetic acid to ethanol in the third step.

Among these routes, both methanol homologation and the ENSOL process have been developed to pilot scale but none of them has been commercially developed. Homologation via reductive carbonylation has lower ethanol yield and selectivity than commercially accepted levels. The direct synthesis of ethanol is the most extensively studied pathway.

Having reviewed different types of catalysts, Subramani and Gangwal (2008) concluded that higher selectivity to ethanol could be achieved with homogeneous catalysts, but a commercial process based on these catalysts requires extremely high operating pressures, complex catalyst recovery, and expensive catalysts. Therefore, the commercialisation of homogeneous catalysts-based ethanol plant is almost impractical.

Among the heterogeneous catalysts, the most studied for the ethanol synthesis are the rhodium-based and MoS$_2$-based Dow Chemical catalysts (Heijden and Prasinski 2012, Hu, et al. 2007, Phillips, et al. 2007). The carbon monoxide conversion performance is comparable in both catalysts; however, ethanol selectivity is much higher for the Rh-based catalysts. Furthermore, an Rh-based catalyst produces mainly methane and water as by-products while MoS$_2$-based one co-produces carbondioxide and methanol. Nevertheless, the limited availability and high-cost of Rh, and the insufficient ethanol yield, can make the catalysts unattractive for commercial application (Subramani and Gangwal 2008).

3. Fermentation

Apart from the catalytic conversion route, fermentation can also be done to convert the syngas to ethanol (Figure 2). The syngas fermentation is more attractive due to several advantages over the biochemical approach and the catalytic conversion (Bredwell, Srivastava and Worden 1999, Heiskanen, Virkajarvi and Viikari 2007, Munasinghe and Khanai 2010), namely (a) use of the whole biomass including lignin irrespective of the biomass quality; (b) elimination of complex pre-treatment steps and costly enzymes; (c) higher specificity of the biocatalysts; (d) independence of the H$_2$/CO ratio for bioconversion; (e) aseptic operation of syngas fermentation due to generation of syngas at higher temperature; (f) bioreactor operation at ambient conditions; and (g) no issue of noble metal poisoning.

---

15 That is, the catalysts that works in the same phase as the reactants. In contrast, heterogeneous catalysts are those that have different phase with the reactants.
Anaerobic bacteria, such as, Clostridium ljungdahlii and Clostridium autoethanogenum, can convert carbon monoxide, carbon dioxide, and molecular hydrogen to ethanol and acetic acid, of which reduction produces ethanol (Abrini, Naveau and Nyns 1994, Vega, Clausen and Gaddy 1990). These syngas-fermenting microorganisms use acetyl-CoA pathway to produce ethanol, acetic acid, and other by-products from syngas. The electron required for the conversion is supplied by hydrogen and carbon monoxide through the hydrogenase16 and carbon monoxide dehydrogenase enzymes, respectively (Ahmed and Lewis 2007).

The syngas fermentation route is still at infant stage of development. It has several limitations such as low productivity and poor solubility of gaseous substrates in the liquid phase. These drawbacks prevent the commercialisation of the syngas fermentation technology. Moreover, the published research data on the techno-economic analysis of microbial syngas fermentation is very limited; it is difficult to draw a firm conclusion on the economic viability (Munasinghe and Khanai 2010).

The comparison of the technological options in the sugar platform is summarised in Table 5.

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16 A hydrogenase is an enzyme that catalyses the reversible oxidation of molecular hydrogen.
Table 5. Comparison of technological options in syngas platform.

<table>
<thead>
<tr>
<th>Steps</th>
<th>Route</th>
<th>Advantages</th>
<th>Disadvantages</th>
<th>Maturity</th>
<th>Reference</th>
</tr>
</thead>
</table>
| Gasification  | Indirectly heated circulating fluidised bed | • No syngas dilution with nitrogen  
• Low pressure operation  
• Syngas produced at high heating value  
• No need of oxygen or air as a reactant | • Higher concentration of tars  
• High capital costs  
• Separate combustion chamber | Pilot      | • Heijden and Ptasinski (2012)  
• Phillips, et al. (2007)  
• Ciferno and Marano (2002) |
|               | Directly heated circulating fluidised bed | • Low CO₂ content in syngas | • Need for particle size reduction  
• Need for biomass drying  
• Low H₂/CO ratio | Commercial |                                |
|               | Directly heated bubbling fluidised bed | • Low capital cost  
• No methane, hydrocarbons, or tar forming at high temperature  
• No need for gas compression at high pressure | • Need for complicated solid feedstock handling equipment  
• Need for particle size reduction  
• Need for biomass drying | Commercial |                                |
|               | Fixed bed | Ability to handle extremely inhomogeneous feedstocks | High amount of tar production | Commercial |                                |
| Catalytic conversion | Direct conversion | Thermodynamically favorable | • Kinetically controlled  
• Many side reactions | Laboratory | Subramani and Gangwal (2008) |
| Methanol homologation | Multistep ENSOL process | High ethanol yield and selectivity on certain catalysts | Many side reactions | Pilot |                                |
| Fermentation  |                                | • Whole conversion of biomass  
• Elimination of complex pretreatment steps and costly enzymes  
• Higher specificity of biocatalysts  
• Independence of the H₂/CO ratio  
• Bioreactor operation at ambient conditions  
• No issue of noble metal poisoning | • Poor mass transfer properties of the gaseous substrates  
• Low ethanol yield | Laboratory | Munasinghe and Khanai (2010) |

Note: the comparison is general and does not refer to rice straw application in particular.
C. Choosing among options

Determining which biomass-to-ethanol conversion route to take is a challenging task. Several aspects are to be considered, namely ethanol yields, efficiencies, technology robustness, and environmental impacts. A number of comparative studies have been done to compare different routes.

Piccolo and Bezzo (2009) analysed both enzymatic hydrolysis-fermentation and gasification-fermentation routes for fuel ethanol production from lignocellulosic feedstock (see Figure 2). Both processes were assessed in terms of ethanol yield, power generation, and financial viability. In the enzymatic hydrolysis-fermentation route, the ethanol selling price was quite beyond the market value of fuel-grade ethanol. Substantial technological improvements were still needed to lower selling price significantly and make the technology attractive on a large-scale business.

Similarly, for the gasification-fermentation route, the state of the art was not mature enough for an attractive business. The burdens of large capital cost, energy expensive recovery, and a moderate final yield required a very high production cost. The route, therefore, required higher price of ethanol than that of hydrolysis-fermentation route. Only substantial technological improvements can decrease the ethanol selling price and make the technology a sensible alternative to the enzymatic hydrolysis-fermentation process. However, gasification-fermentation process allows significant electric power generation. That could be an important economic advantage in countries where electricity is expensive or renewables-based power generation is subsidised.

Foust, et al. (2009) looked at sugar and syngas platforms for second-generation ethanol production. They found that although both routes have their individual strength and weaknesses, the two processes have very comparable yields, economics, and environmental impacts. However, they pointed out gasification (that is, the thermochemical route) converts the organic portion of biomass into syngas, hydrocarbon, and tar while the inorganics becomes ash, which increased costs. Since RS and RH have high ash content, respectively 19 per cent and 20 per cent (Jenkins, et al. 1998), they are well suited for biochemical routes. Moreover, sulfur content in feedstock is detrimental to catalyst for tar reforming and alcohol synthesis. Due to high sulfur content in RS (van Paasen, Cieplik and Phokawat 2006), chances are that they are not suitable for the thermochemical route.

The general comparison between sugar and syngas platform is shown in Table 6.

Table 6. Comparison of sugar and syngas platform.

<table>
<thead>
<tr>
<th>Route</th>
<th>Advantage</th>
<th>Disadvantage</th>
<th>Maturity (in RS application)</th>
<th>References</th>
</tr>
</thead>
</table>
| Sugar platform: enzymatic hydrolysis | • No problem with ash  
• Suitable for feedstock with high sulphur content  
• Higher overall energy efficiency | • High energy needed for pretreatment  
• High energy needed to separate ethanol with water  
• Only the cellulose and hemicellulose are converted  
• Enzymes must be tailored to the feedstock | Demonstration | Piccolo and Bezzo (2009)  
Foust, et al. (2009)  
Waltz (2008) |
| Syngas platform: catalytic conversion | • Converting all the carbon compounds  
• More mature technology  
• Wider range of feedstock  
• Higher profit from electricity production | • High capital investment  
• Unsuitable for feedstock with high ash or sulphur content | Demonstration | Piccolo and Bezzo (2009)  
Foust, et al. (2009)  
Waltz (2008) |
| Syngas platform: Fermentation | • Whole conversion of biomass  
• Elimination of complex pretreatment steps and costly enzymes  
• Higher specificity of biocatalysts  
• Independence of the H2/CO ratio  
• Bioreactor operation at ambient conditions  
• No issue of noble metal poisoning | • Poor mass transfer properties of the gaseous substrates  
• Low ethanol yield | Laboratory | Munasinghe and Khanai (2010) |


**D. Commercial status**

Despite the research undertaken, there has been no commercial RS-to-ethanol project yet (Villanueva Perales, et al. 2011, Heijden and Ptasinski 2012, Rivera, et al. 2010). Some pilot projects, nonetheless, have been carried out.

BC International Corporation and National Renewable Energy Laboratory of the U. S. Department of Energy ran an ethanol demonstration project using biomass gasifier in California from 2002 to 2004. The technology used was developed by Pearson Technologies, Inc., which had the theoretical potential to annually produce 20 millions gallons of ethanol from 102,500 tonnes of dried RS, co-host process heat and/or electricity (TSS Consultants 2005). The Pearson process, named after the founder of Pearson Technologies, Inc., was developed for the production of syngas, electrical power, and ethanol using combination of gasification and steam reforming processes. The process is a versatile process for converting biomass material to syngas and/or liquid fuel products by a combination of steam reforming (gasification) of solid feed and a Fischer-Tropsch (F-T) series of gas reforming steps. In addition, Pearson developed proprietary F-T catalysts to convert syngas to ethanol.

Within the sugar platform, Chemical Engineering and Pilot Plant Department of Egyptian National Research Center undertook a pilot project of ethanol production from RS using both SHF and SSF (Tewfik 2011). The latter gives higher yield at the concentration level varying from 26 to 28 g/L, corresponding to the fermentation efficiency of 65 per cent.

Furthermore, Iogen, a Canadian company has been running a demonstration plant since 2005, using enzymatic hydrolysis and fermentation route. It reached annual lignocellulosic ethanol production of 220 kL in 2012. The claimed yield is more than 340 L/t feedstock, however, rice straw is not the only feedstock being used.

While pursuing the commercialisation, companies now try to look beyond biofuels to by-products, such as electricity and food ingredients, which boost the plant’s profitability. In 2008, the US Department of Energy awarded up to 200 MMUSD for pilot plants proposals that can convert lignocellulosic feedstock into combination of transportation fuel, chemicals, and substitutes for petroleum-based products (Waltz 2008).

**V. Methodology**

In this paper, there are five indicators quantified: 1) the amount of gasoline can be substituted by RS-based ethanol, 2) the reduction of lifecycle GHG emissions, 3) the GDP contribution can be generated, 4) the foreign exchange savings due to the substitution; 5) and, jobs can be created in the ethanol production.

For all the calculation, the basis used is 24-ML ethanol production plant using biochemical route, equipped with cogeneration system that produces electricity and heat (see Figure 3). The process strategy follows the recommendation used in NREL report (Humbird, et al. 2011), which has been the most comprehensive analysis on lignocellulosic ethanol plant. The annual demand of RS for this plant, with the corresponding ethanol yield, is ~72 kt.

Primary and secondary sources are used, complementing each other. The secondary data of Balinese rice production is gained from literatures, Central Bureau of Statistics (BPS) for Bali province, and other internet sources. Some primary agricultural data are gathered in Tabanan, Bali’s largest producer district, through some interviews with experts and farmers.

To see the provincial impact, the specific value of the results (the output per tonne RS) is multiplied by the technically available RS in Bali.

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18 MMUSD refers to million US Dollar.
19 ML is the acronym of megalitre, meaning million litres.
A. **Gasoline Replacement**

To determine the amount of potential gasoline replacement by ethanol, there are three factors that matter, namely RS availability, collection efficiency (CE), ethanol yield, and ethanol-gasoline equivalency (see Figure 4).
RS availability itself depends on the paddy harvested area available and the RS yield (tonne of RS per hectare of harvested area). In the province of Bali, rice production reached 860 kt (HDG) in 2011.20 The harvested paddy area of the island amounted at 153,000 ha.21 And as discussed earlier, the RS yield varies from 4.0 to 6.8 t

The available RS, however, is scattered on the field. From the collection to the processing plant, there are shredding, baling, transporting, and storing. Each of these steps has losses (Sokhansanj and Turhollow 2002). Therefore, researchers use CE to determine the amount of actually usable RS for either ethanol or power plant. CE is defined as the ratio of ready-to-process-RS to that is available on the field.

In the case of corn stover, Sokhansanj and Turhollow (2002) pointed out that the material is shredded, raked into a windrow, baled, transported, and finally stored (see Table 7). The overall CE is 42 per cent. Gadde, Menke and Wassmann (2009) used the pragmatic assumption of 50 per cent for CE of RS in India, Thailand, and the Philippines. In the analysis of logistics cost of Thai RS for biomass power generation, Delivand, Barz and Gheewala (2011) assumed CE value of 40 per cent. It included the accessibility of paddy fields for mechanised collection system and the use of rice straw residues for other purposes. Multiplying the yield with the rice production and the CE, the technically available RS in Bali ranges from 244 to 415 kt/year, corresponding to the RS yield range of 4.0 to 6.8 t/ha/year.

### Table 7. Efficiencies of RS collection steps.

Source: Sokhansanj and Turhollow (2002)

<table>
<thead>
<tr>
<th>Collection steps</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shredding</td>
<td>70</td>
</tr>
<tr>
<td>Raking into a windrow</td>
<td>95</td>
</tr>
<tr>
<td>Baling</td>
<td>70</td>
</tr>
<tr>
<td>Transporting</td>
<td>95</td>
</tr>
<tr>
<td>Storing</td>
<td>95</td>
</tr>
</tbody>
</table>

To determine how much ethanol can be produced from the collected RS, the parameter used is ethanol yield (litres of ethanol per tonne of dry RS), for which different technologies have different values. Delivand, Barz, et al. (2012) used the value of 260 L/\text{EtOH}/t\text{straw-db} in the environmental and socio-economic feasibility assessment of RS conversion to power and ethanol in Thailand.22 For the technology, they adopted the US NREL’s dilute-acid pretreatment-SSCF design for corn-stover-to-ethanol conversion (Aden, et al. 2002). However, the conversion efficiency used in the NREL report is much higher, that is, 374 L/\text{EtOH}/t\text{straw-db}

Recently, NREL has updated their report and used SHF instead of the more advanced SSCF (Humbird, et al. 2011). Based on their experience, the 5-day SHF process with batch fermentation was more realistic than the 3-days SSCF continuous process. However, the design, which was estimated to be 2012 technology, resulted in the ethanol yield of 330 L/\text{EtOH}/t\text{straw-db}, which is lower than that of 2002 report. These values of yield are summarised in Table 8.

For this work, the ethanol yield is determined by involving the conversion factors for processing glucan (cellulose), xylan, and arabinan, which are the components of RS content (see Table 9). The yield of each component, as shown in Table 10, is based upon the NREL assumptions (Humbird, et al. 2011). Basically the yields are categorised into three steps of reaction: pretreatment, enzymatic hydrolysis, and fermentation. The yields represent the percentage of the theoretical, stoichiometric conversion.23

Ethanol, however, is not gasoline. Although both can fuel vehicles, they have different energy contents. Each litre of gasoline has energy content of 1.5 litre of ethanol.24 The factor of 1.5, called as the gasoline-ethanol equivalency ratio, is then needed to determine the gasoline potential replacement. The aforementioned major assumptions for the gasoline replacements are summarised in Table 11.

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21 Ibid.

22 EtOH is a shorthand form of ethanol.

23 The more detailed reactions and individual products from each process steps are shown in Appx. Table 2 (see Appendix B).

Table 8. RS-to-ethanol conversion efficiencies as per different studies.

<table>
<thead>
<tr>
<th>Route</th>
<th>Efficiency</th>
<th>Remarks</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Aden, et al. (2002)</td>
</tr>
<tr>
<td>Dilute-acid pretreatment, SHF process, electricity co-product</td>
<td>228</td>
<td>Estimated 2012 technology</td>
<td>Humbird, et al. (2011)</td>
</tr>
<tr>
<td>Syngas catalytic conversion</td>
<td>225</td>
<td>Demonstration project in Gridley, California</td>
<td>TSS Consultants (2005)</td>
</tr>
<tr>
<td>This work: Dilute-acid pretreatment, SHF process, electricity co-product</td>
<td>335</td>
<td>Calculated with conversion factors assumed for estimated SHF 2012 technology</td>
<td>Humbird, et al. (2011)</td>
</tr>
</tbody>
</table>

*The value of original documents are modified into SI units and the figures are rounded.

Table 9. RS constituting components.

<table>
<thead>
<tr>
<th>Component</th>
<th>Dry wt (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glucan</td>
<td>37.1</td>
</tr>
<tr>
<td>Xylan</td>
<td>21.8</td>
</tr>
<tr>
<td>Arabinan</td>
<td>3.7</td>
</tr>
<tr>
<td>Galactan</td>
<td>1.3</td>
</tr>
<tr>
<td>Lignin</td>
<td>15.1</td>
</tr>
<tr>
<td>Ash</td>
<td>14.1</td>
</tr>
</tbody>
</table>

Table 10. Conversion factors for straw-to-ethanol processes.
Source: Humbird, et al. (2011)

- **Dilute-acid pretreatment yield**
  - Glucan to glucose (%) 9.8
  - Glucan to non-fermentables (%) 0.6
  - Xylan to xylose (%) 90.0
  - Arabinan to arabinose (%) 90.0
- **Enzymatic hydrolysis yield**
  - Glucan to glucose (%) 91.2
- **Fermentation yield**
  - Glucose to ethanol (%) 95.0
  - Xylose to ethanol (%) 85.0
  - Arabinose to ethanol (%) 85.0
- **Contamination loss in fermentation (%)** 3
- **Saccharified slurry diversion for inoculation (%)** 10

*The term “yield” is a percentage of the theoretical, stoichiometric yield.

Table 11. Assumptions for gasoline replacement calculation.

<table>
<thead>
<tr>
<th>Assumption</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Harvested area (ha/year)</td>
<td>153,000</td>
</tr>
<tr>
<td>Straw yield (t\text{straw-RS}/ha/year)</td>
<td>4.0-6.8</td>
</tr>
<tr>
<td>Collection efficiency (%)</td>
<td>40</td>
</tr>
<tr>
<td>Ethanol yield (L/t\text{straw-RS})</td>
<td>335</td>
</tr>
<tr>
<td>Gasoline-ethanol equivalency ratio (-)</td>
<td>1.5</td>
</tr>
</tbody>
</table>

B. Lifecycle GHG savings

To see the comprehensive environmental impacts of ethanol production project, lifecycle GHG saving analysis is required (Wang, Wu and Huo 2007). For the ethanol side, the emissions or savings from the straw logistics until the combustion in vehicles are taken into account (see Figure 5). Additionally, the avoided emissions due to RS open-burning are added, assuming that the converted RS would have been open-burnt by default. The result is then added with the avoided emissions of the fossil-fuel based gasoline, from the extraction into the combustion phase (see Figure 6).
Figure 5. Boundary of the lifecycle analysis.

It is noteworthy that the lifecycle boundary for the ethanol side is only from the straw logistics and not from the emissions generated during paddy cultivation. The reason is that the paddy plantation (thus the emissions associated with it) has already existed for the purpose of food, not fuel, production. Due to the enormity of Indonesian rice production, the urgency of planting rice in the purpose of ethanol production will not occur, at least in the foreseeable future. Hence, using residual RS to produce ethanol can be seen as a way to enhance the rice sector in Bali, by using its waste better.

Both GHG savings and emission causes in the whole process of conversion are described below. The major causes of the emissions are straw logistics, the use of chemical and enzymes, by-product combustion, and ethanol fuel combustion. The savings are caused by electricity displacement, avoidance of open-burning of RS, and the avoidance of fossil fuel combustion (see Figure 6).

Figure 6. Approach to determine the lifecycle GHG savings.
1. Straw logistics

It is assumed that the total distance travelled by the truck is ~186 km, including the collection and delivery to gas station. The value is obtained by calculating the collection and the delivery distance.

For the collection, it is common to assume a circular area with the power plant as the centre (Delivand, Barz and Gheewala 2011, Kadam, Loyd and Jacobson 2000). This collection area is estimated with eq. 1, which includes the factor of collection efficiency and availability factor (Delivand, Barz and Gheewala 2011).\(^{25}\) Collection efficiency, as mentioned above, is defined as the ratio of ready-to-process-RS to that is available on the field. Availability factor indicates the portion of the soil that is not occupied by the infrastructures (road, building, etc.). The radius of the circular collection area is estimated to be the maximum trip distance to deliver the straw to the plant. The actual distance of course will not be a simple straight line; there is the winding nature of the road. Therefore, the factor of square root of two is taken into account.\(^{25}\)

\[
\text{Collection area (km}^2\text{)} = \frac{\text{Annual demand for RS} \left( \frac{\text{t/year}}{} \right)}{\text{Average RS yield} \left( \frac{\text{t/km}^2\cdot\text{year}}{} \right) \times \text{collection efficiency} \times \text{availability factor}}
\]

The second term added into the total distance is the delivery distance to the gas station.\(^{26}\) It is assumed that the gas stations will be only in the island. Therefore, 153 km, which is the east to west span of the island, is taken as the value for the round trip for the delivery.

To determine the fuel cycle, or well-to-wheel, GHG specific emissions of the diesel truck used for the straw logistics, GREET 1.6 is used.\(^{27}\) In addition, the fuel efficiency of the diesel truck is obtained from BioGrace 4b-public.\(^{28}\)

These input parameters for the logistics are summarised in Table 12.

<table>
<thead>
<tr>
<th>Collection</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual demand for RS (kt/year)</td>
<td>72</td>
</tr>
<tr>
<td>Average RS yield (t/ha)</td>
<td>5.45</td>
</tr>
<tr>
<td>Collection efficiency (-)</td>
<td>0.4</td>
</tr>
<tr>
<td>Availability factor (-) (^{a})</td>
<td>0.75</td>
</tr>
<tr>
<td>Distance travelled (km) (^{b})</td>
<td>33</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Delivery to gas stations</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Round trip distance (km) (^{c})</td>
<td>153</td>
</tr>
<tr>
<td>Truck payload (t) (^{d})</td>
<td>11</td>
</tr>
<tr>
<td>Driving speed (km/h) (^{e})</td>
<td>40</td>
</tr>
<tr>
<td>Fuel efficiency (MJ/t.km) (^{f})</td>
<td>0.94</td>
</tr>
<tr>
<td>GHG specific emissions (kgCO$_2$-eq/t) (^{g})</td>
<td>15.94</td>
</tr>
</tbody>
</table>

\(^{a,b,e}\) Taken from Delivand, Barz and Gheewala (2011).
\(^{b}\) Calculated as the radius of the circular area multiplied by two and square root of two for the round trip factor and the winding factor, respectively (Delivand, Barz and Gheewala 2011).
\(^{c}\) Estimated from west-to-east span of Bali.
\(^{d}\) Estimated from Pertamina’s (Indonesian state oil company) blending site. From there, Pertamina will transport the blended ethanol fuel to the gas station.
\(^{e}\) Estimated from west-to-east span of Bali.
\(^{f}\) Estimated from Pertamina’s (Indonesian state oil company) blending site. From there, Pertamina will transport the blended ethanol fuel to the gas station.
\(^{g}\) Obtained from BioGrace 4b-public.

\(^{25}\) Delivand, Barz and Gheewala (2011) also include farmland factor as one of the factors. It is defined as the fraction of the field in the available area that can be exploited for energy purposes. In this paper, however, farmland factor is perceived to be already incorporated in the collection efficiency (CE). For example, Sokhansanj and Turhollow (2002), with the overall CE value of 42 per cent, assumed that 70 per cent of the available corn stover in the field is effectively shredded.

\(^{26}\) Actually, the delivery is not immediately to the gas station. Instead, the anhydrous ethanol is transported to Pertamina’s (Indonesian state oil company) blending site. From there, Pertamina will transport the blended ethanol fuel to the gas station. However, there are virtually no emissions or energy required for blending therefore the step is omitted in the lifecycle analysis.

\(^{27}\) GREET, the acronym for Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation, is a model for evaluating the emissions and usage of primary resources associated with transportation fuels production and use, developed by Argonne National Laboratory (M. Wang 2001). \hspace{1cm} http://greet.es.anl.gov/

2. Chemical and enzymes

In the study of contribution of enzymes and chemicals to the lifecycle of ethanol, MacLean and Spatari (2009) wrote that many lifecycle studies of biofuels did not examine the impact of process chemicals and enzymes. They found out that chemical and enzyme inputs account for 30 per cent to 35 per cent of the lifecycle GHG emissions. For dilute acid saccharification technologies, their calculation resulted in 0.192 kgCO₂-eq of emissions for every litre of ethanol produced. This value is adopted for this work, which also uses similar technological route.

3. By-products combustion

As previously shown in Figure 3, the combustible by-products are burnt to produce steam and electricity. These by-products include all of the lignin and unconverted cellulose and hemicellulose from the feedstock, biogas from anaerobic digestion, and biomass sludge from the wastewater treatment. As the rice plantations absorb carbon dioxide during the cultivation, the net carbon dioxide emission associated with the combustion is assumed to be zero. However, there are some methane and nitrous oxide emissions generated during the combustion. For this work, the related emission is 0.67 kgCO₂-eq/t straw-db, adapted from a study of energy balance and GHG reduction cost of cassava-based ethanol production in Thailand (Nguyen, Gheewala and Garivait 2007).

4. Ethanol fuel combustion

Since the ethanol fuel is also a bioenergy product, the net carbon dioxide emission of its combustion is also considered to be zero. The methane and nitrous oxide emissions of ethanol fuel combustion are estimated to be the same as their emissions from gasoline combustion in the vehicle (Delivand, Barz and Pipatmanomai 2011). The values are taken from GREET 1.6.

5. Electricity displacement

The electricity produced by burning the by-products is assumed to be sold to the grid. The specific electricity generation is taken from the NREL report by Humbird, et al. (2011), which is 0.48 kWh/LeOH. This generation replaces a portion of Indonesian current electricity generation, which is mostly powered by fossil fuel. The specific emission Indonesia is 0.715 kgCO₂-eq/kWh, as per data published by ABB (2011).

6. Straw open-burning avoidance

The amount of emissions per tonne of open-burnt RS is compiled by Gadde, Bonnet, et al. (2009). For carbon dioxide, methane, and nitrous oxide emissions, the respective values are 1460, 1.2, and 0.07 g/kgstraw-db. The combustion factor of 0.8 is used as the fraction of the mass combusted during the coarse burning. However, carbon dioxide emitted from biomass burning is considered neutralised by the plant’s photosynthesis process. Yet, avoiding open-burning can improve local air quality and thus the health of the population (Gadde, Bonnet, et al. 2009).

7. Fossil fuel displacement

Substituting gasoline with ethanol will displace the emissions of gasoline combustion. The specific carbon dioxide emission of gasoline engine is 2.32 kg per litre of gasoline (FIEL; ITBA; 2009).

C. Contribution to GDP

To determine how much the energy project can contribute in increasing the country’s GDP, the calculation of present value added is used as basis (see Figure 7).
Figure 7. Approach to determine GDP contribution.

A simplified cost benefit analysis is done based on the specific costs reported by Humbird, et al. (2011). The net present value (NPV) of the project is calculated with eq. 2.

\[
NPV = \sum_{t=0}^{n} \frac{(I - C)_t}{(1 + r)^t}
\]  

(2)

where \(I\) is the income gained by selling ethanol and electricity; \(C\) is the total cost, including capital costs, recurring costs, and tax; \(r\) is the real discount rate;\(^2\) \(n\) is the lifetime of the project (year); and \(t\) is the operating year.

For the total capital investment (TCI), the exponential scaling exponent is used because the plant size used for this work is different from that of Humbird, et al. (2011). The adapted cost is calculated with eq. 3 (Humbird, et al. 2011).

\[
\text{New cost} = \text{Base cost} \times \left( \frac{\text{New size}}{\text{Base size}} \right)^n
\]  

(3)

where \(n\) is a characteristic scaling exponent. The set value for \(n\) is 0.67, as generally regarded as conservative in this type of chemical industry (Kaylen, et al. 2000). Using the formula for 24-ML capacity, the estimated TCI is 55.5 MMUSD. This is comparable with the lignocellulosic ethanol plant TCI model.

\(^2\)Real discount rate is the discount rate after the effect of inflation is removed. It is calculated by \(r = \frac{(1+i)}{(1+p)} - 1\), where \(i\) is the market discount rate while \(p\) is the inflation rate.
constructed by Kaylen, et al. (2000), which is USD $34,066.47X^{0.67}$, where $X$ is the annual mass of feedstock converted (US ton/year). This alternative approach yields 57.1 MMUSD, which only has slight difference with this work’s.

For the operation and maintenance cost, linear downscaling from that of NREL document is done with some modifications on fixed cost, which represents the salary of the workers in the plant, and feedstock and handling cost. The feedstock cost is taken from the estimated RS selling price, which is around IDR 100/kg$_{straw-db}$ (USD ~10.3/t$_{straw-db}$), lower than that of NREL’s report, which is USD 25.9/t$_{straw-db}$. Besides, the salary is assumed to be a third that of the US.

The income from selling surplus electricity depends on the feed-in-tariff set by the GOI. For less-than-10-MW-biomass system connected to medium voltage, the tariff is IDR 975/kWh (or, USD 0.10/kWh). The amount of specific surplus of electricity, as reported by Humbird, et al. (2011), is 0.48 kWh/L$_{EtOH}$, or 159.5 kWh/t$_{straw-db}$.

The discount rate is set to be 10 per cent, following Humbird, et al. (2011) and the recommendation given by Short, Packey and Holt (1995) on performing economic evaluations of renewable energy technologies. They wrote, “in the absence of statistical data on discount rates used by industrial, transportation, and commercial investors for investments with risks similar to those of conservation and renewable energy investments, it is recommended that an after tax discount rate of 10 per cent … be used.”

After calculating the net present value of the project, GDP contribution is calculated by removing the tax for GDP is measured at the market price, that is, without subsidies or taxes (M. K. Delivand, M. Barz, et al. 2012, Faaij, et al. 1998).

Unlike straw-to-electricity application, ethanol production is not yet considered eligible for any carbon credit (e.g. CDM) (Seabra and Macedo 2011). There can be no extra income from carbon credit mechanism for the ethanol production.

The economic assumptions are summarised in Table 13.  

### Table 13. Input data for contribution to GDP calculation.

<table>
<thead>
<tr>
<th>Lifetime of the plant (year)</th>
<th>15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Discount rate (%)</td>
<td>10</td>
</tr>
<tr>
<td>Inflation rate (%)</td>
<td>5.9</td>
</tr>
<tr>
<td>Internal rate of return (IRR) (%)</td>
<td>10</td>
</tr>
<tr>
<td>Minimum ethanol selling price (US¢/L)</td>
<td>68</td>
</tr>
<tr>
<td>Total ethanol production (ML/year)</td>
<td>24</td>
</tr>
<tr>
<td>Total capital investment (MMUSD)</td>
<td>55.5</td>
</tr>
<tr>
<td>Total operation and maintenance cost (MMUSD/year)</td>
<td>5.15</td>
</tr>
<tr>
<td>Excess electricity generation (GWh/year)</td>
<td>11</td>
</tr>
<tr>
<td>Income from selling electricity (MMUSD/year)</td>
<td>1.14</td>
</tr>
<tr>
<td>Income from selling ethanol (MMUSD/year)</td>
<td>14.64</td>
</tr>
<tr>
<td>Corporate tax (%)</td>
<td>25</td>
</tr>
</tbody>
</table>

* Taken from Trading Economics, “Indonesia Inflation Rate” http://www.tradingeconomics.com/indonesia/inflation-cpi.

b Since 2010, the corporate tax is 25 per cent, according to the Directorate General for Taxation http://www.pajak.go.id/content/seri-pph-tarif-pph-pasal-17 (in Indonesian).

### D. FOREIGN EXCHANGE SAVING

Since Indonesia is now a net-importer of crude oil, the gasoline replacement will prevent a part of oil import. This would save the national foreign exchange (FX). In addition, the surplus electricity sold to the state electricity company has a similar economic benefit, albeit to a lower extent, as major parts of Indonesian electricity are still powered by fossil fuel.

To calculate the FX savings, the crude oil equivalent is used to quantify the gasoline replacement, surplus electricity, and diesel consumption due to straw logistics (see Figure 8). Each litre of crude oil can

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30 MEMR Ministerial Regulation no. 04/2012 on Electricity Buying Price by PT. PLN from Electricity Generator Using Small and Medium Scale Renewable Energy or Excess Electricity (in Indonesian).
31 The discounted cash flow rate of return worksheet in Appx. Table 1 (see Appendix A).
produce 0.45 litre of gasoline and 0.24 litre of diesel fuel.\textsuperscript{32} The method computing the gasoline replacement and diesel consumption has been discussed in previous sections.

![Figure 8. Approach to determine foreign exchange savings.](image)

In the national electricity generation mix, coal, oil, and gas contribute, respectively, 45.9 per cent, 19.2 per cent, and 18.5 per cent (Ministry of Energy and Mineral Resources 2010, 33). These numbers are used as the allocation factor to the surplus electricity. Then corresponding portion is multiplied with the import prices of coal and oil. Natural gas does not lead to FX savings as Indonesia is a natural gas exporter.\textsuperscript{33} Table 14 summarises the input data for determining the FX savings of the project.

<table>
<thead>
<tr>
<th><strong>Table 14. Input data of foreign exchange saving.</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gasoline replacement</strong></td>
</tr>
<tr>
<td>Equivalency ratio of gasoline to 1-L crude oil (-)</td>
</tr>
<tr>
<td>0.45</td>
</tr>
<tr>
<td><strong>Diesel consumption</strong></td>
</tr>
<tr>
<td>Equivalency ratio of diesel fuel to 1-L crude oil (-)</td>
</tr>
<tr>
<td>Fuel economy of the truck (L/km) \textsuperscript{a}</td>
</tr>
<tr>
<td><strong>Surplus electricity</strong></td>
</tr>
<tr>
<td>Share of coal and oil to the electricity mix (-)</td>
</tr>
<tr>
<td>0.46 and 0.19</td>
</tr>
<tr>
<td>Imported coal price (USD/kg\textsubscript{coal}) \textsuperscript{b}</td>
</tr>
<tr>
<td>Oil price (USD/L) \textsuperscript{c}</td>
</tr>
<tr>
<td>0.91</td>
</tr>
</tbody>
</table>

\textsuperscript{a} Adapted from Delivand, Barz and Gheewala (2011)


\textsuperscript{c} One year forecast by Oil-Price.net, "Crude Oil and Commodity Prices." Accessed Apr 26, 2013. http://www.oil-price.net/. Units are modified.

E. Employment effects

Since unemployment and underemployment are the major cause of poverty, job creation is central in alleviating poverty (UN 2005). Job creation, therefore, is one of the main goals of the decision makers when they consider the implementation of an energy project. In Indonesia, poverty alleviation through


job creation is the first objective of the biofuel development (Legowo, Kussuryani and Reksowardjo 2007).

In this work, the employment effects related to the ethanol production are calculated in different categories: direct effects, indirect effect, induced effects, and unemployed benefit effects. The steps are shown in Figure 9.

![Figure 9. Approach to determine employment effects.](image)

Direct effects are associated with the labour force that directly work with the straw logistics, ethanol conversion process, construction and general operation and maintenance of the plant (Capros, Karadeloglou and Mentzas 1992). The amount of work is computed with the measure of working hours per person (Delivand, Barz and Gheewala 2011). To find the amount of direct jobs created, the total working hours needed is then divided by the average working hours in Indonesia, which is 40 hours per week (or about seven hours per day for six working days per week).

The input data of working hours in the straw logistics is shown in Table 15. For the straw conversion process to ethanol, the specific working hours is 3.10 h/t_{straw-db}, taken from the study of Delivand, Barz, et al. (2012). They obtained the value from questionnaires and interviews with experts who had experiences with biomass-to-ethanol projects.

<table>
<thead>
<tr>
<th>Driving speed (km/h)</th>
<th>40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Payload (t)</td>
<td>11</td>
</tr>
<tr>
<td>Driving time (h/t)</td>
<td>0.08</td>
</tr>
<tr>
<td>Stop time, loading and uploading bales (h/t)(^{a})</td>
<td>0.04</td>
</tr>
<tr>
<td>Baling time (h/t)</td>
<td>0.4</td>
</tr>
<tr>
<td>Hauling time and stacking time (h/t)</td>
<td>0.17</td>
</tr>
<tr>
<td>Delivery to gas station (h/t)(^{b})</td>
<td>0.09</td>
</tr>
</tbody>
</table>

\(^{a}\) Small-sized bales are preferred due to lower cost (Delivand, Barz and Gheewala 2011).

\(^{b}\) The round trip is assumed to be 153 km, i.e. the east-to-west span of the island.

The indirect effects refer to the labour required by external industries whose output will provide materials and services for the ethanol project. It includes the inter-industry effects generated by the local

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Decree of the Minister of Labour and Transmigration nr. 102/MEN/V1/2004 on Working Overtime and Salary of Working Overtime (in Indonesian).
expenditure of the ethanol plant and its supplier (Capros, Karadeloglou and Mentzas 1992). For instance, the purchase of RS can generate income for farmers or intermediate RS collectors.

The induced effects relate to the labour required to meet the demand for goods and services generated by increasing earnings due to direct and indirect effects. The wages given to the plant workers, for example, will be spent consequently to the local merchants.

To quantify these effects, the basic way is to use impact-evaluation multipliers (Hewings and Jensen 1986, Herzog and Olsen 1977, Urbanchuk 2006). The required data vary from information on the total regional and industrial economic structure to intersectoral dependencies. They are easy to estimate within limited cost, resource, and information. However, they have limitation regarding timing and local distribution of impacts. These multipliers, nevertheless, can be considered as estimates indicative of the anticipated employment impacts of energy projects (Capros, Karadeloglou and Mentzas 1992).

For this work, the values of indirect-induced effects are based on the estimated from a socio-economic aspect modelling study of biomass conversion in Slovenia and Croatia (Krajnc and Domac 2007). In that study, the ratios of indirect-induced employment to direct employment are 0.43 and 2.33, respectively for the wood biomass production and electricity production. Based on this, M. K. Delivand, M. Barz, et al. (2012) used 0.50 and 2.50 as the base values for indirect-induced ratio of, respectively, straw logistics and straw conversion. Due to the uncertainty, these multiplier input are ranged within ±30 per cent deviation.

In this work, nevertheless, some negating effects are neglected due to limitation of data. The first is the job displacement, as the labours required for the ethanol project might previously have job somewhere else. This work also ignores the reduction of external labour requirements due to the existence of the ethanol production (Capros, Karadeloglou and Mentzas 1992). The labour demand for oil production, for example, might decrease if gasoline was replaced by ethanol. In addition, the negating effects due to non-local inputs or outputs are ignored. It is assumed that the required material are supplied by local enterprises and the generated income is spent locally.

Furthermore, the employment effects provide benefits for the dependents—the unemployed children and elderly people—who are under the care of the labourers and thus benefitting from the aforementioned employment effects. The age dependency ratio, the ratio of the non-working-dependent population to the labour population, is used to quantify these dependent beneficiaries. According to the World Bank, the age dependency ratio of Indonesia in 2008-2012 is 48 per cent. The amount of the dependent beneficiaries, then, can be estimated with simple multiplication of the ratio with the jobs created due to direct, indirect, and induced effects.

The input data for employment effect is shown in Table 16.

<table>
<thead>
<tr>
<th>Working hours a</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Logistics (h/t)</td>
<td>0.63</td>
</tr>
<tr>
<td>Straw-to-ethanol conversion (h/t)</td>
<td>3.10</td>
</tr>
<tr>
<td>Employee working days (days/year) b</td>
<td>287</td>
</tr>
<tr>
<td>Indirect-induced ratio of logistics and production plant (-)</td>
<td>0.50 and 2.50</td>
</tr>
<tr>
<td>Age dependency ratio (-)</td>
<td>0.48</td>
</tr>
</tbody>
</table>

a See Table 15 for details.
b Adapted from Collective Decree nr. 5 year 2012, nr SKB.06/Men/VII/2012 and nr. 02 year 2012 on National Holidays and Collective Leave (in Indonesian).

VI. RESULTS AND DISCUSSIONS

A. GASOLINE REPLACEMENT

As mentioned in Table 3 above, there is about 39 per cent of RS that was not open-burnt, but used for some economic applications instead. In this case, probably the farmers will not sell the RS unless

good price was offered. Therefore, gasoline replacement calculation from the non-commoditised, supposedly open-burnt RS is also done.

The results are shown in Table 17. Each tonne of straw (dry) can produce ethanol, replacing 224 L of gasoline used in vehicles. Assuming all technically available RS is converted to ethanol, the amount of gasoline that can be replaced varies from 55 to 93 ML per year, depending on the RS yield. Only using non-commoditised RS, which is open-burnt by default, the amount of gasoline can be replaced varies from 33 to 57 ML.

Table 17. Results of gasoline replacement calculation.

| Specific gasoline replacement (L/t straw-db) | 224 |
| Gasoline replacement for all technically available RS (ML/year) | 55-93 |
| Gasoline replacement only by open-burnt RS (ML/year) | 33-57 |

*The values vary due to the RS yield range of 4.0-6.8 t/ha/year (Yasa 2011); collection efficiency of 0.40 is applied.

B. Lifecycle GHG Reduction

The estimated lifecycle GHG balance is shown in Table 18, with calculated net saving of 578.7 kg CO₂-eq/t straw-db. This is comparable with the result of Delivand, Barz and Pipatmanomai (2011), which is 504.9 kg CO₂-eq/t straw-db. The difference is mainly a result of higher electricity production in this work’s design. The major saving is due to the fossil fuel displacement, both in vehicles and electrical power generation. To the emissions, the chemical and enzymes used in the conversion are the major factor as they contribute the most. However, the total emissions is relatively small compared the savings obtained. Supposing whole technically available RS in Bali is converted (~244-415 kt/year), the lifecycle GHG reduction ranges from 19 to 32 kt CO₂-eq.

For this result, sensitivity analysis is done varying ethanol yield and the ratio of using open-burnt RS to commoditised (that is, non-open-burnt) RS for the ethanol plant. The former refers to the performance of the plant, whereas the latter refers to the fraction of converted RS that usually would have been open-burnt. Due to expectedly increasing demand of fermented RS for cattle feed, the commodification of RS might also escalate.

The ethanol yield range input for the sensitivity analysis is adapted from the technical sensitivity analysis for the ethanol yield reported by Humbird, et al. (2011, 80). The minimum and maximum values are determined by summing all, respectively, the negative and positive values of individual possible variations affecting the yield.

For the open burnt-to-commoditised RS ratio, the minimum value is set at 0.0, meaning the whole converted RS is commoditised from the first place. The base and maximum values are set to be 1.0, assuming all the converted RS is not commoditised and would have been open-burnt by default. As shown in Figure 10, the ethanol yield is more significant since it affects how much gasoline can prevent the fossil fuel burning. Additionally, the relatively small impact from the variation of the open-burnt-to-commoditised RS ratio implies that the use of commoditised RS is not a serious threat to environmental performance of the ethanol project.

Table 18. GHG emission balance.

<table>
<thead>
<tr>
<th>Emissions</th>
<th>(kg CO₂-eq/t straw-db)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Emissions</strong></td>
<td></td>
</tr>
<tr>
<td>Logistics</td>
<td>15.9</td>
</tr>
<tr>
<td>Chemical and enzymes</td>
<td>64.4</td>
</tr>
<tr>
<td>By-products combustion a</td>
<td>0.7</td>
</tr>
<tr>
<td>Ethanol user combustion b</td>
<td>13.3</td>
</tr>
<tr>
<td><strong>Savings</strong></td>
<td></td>
</tr>
<tr>
<td>Electricity displacement</td>
<td>-114.1</td>
</tr>
<tr>
<td>Straw open-burning avoidance c</td>
<td>-40.7</td>
</tr>
<tr>
<td>Fossil fuel displacement</td>
<td>-518.9</td>
</tr>
<tr>
<td><strong>Net GHG savings</strong></td>
<td>-578.7</td>
</tr>
</tbody>
</table>

* a, b, c CO₂ emission is considered neutral; only CH₄ and N₂O emissions are taken into account.
The calculated GDP contribution for 24-ML ethanol plant is 82.8 MMUSD, or 77 USD/t_straw-db. This value alters due to the variation of some parameters: ethanol yield, total capital investment (TCI), electricity feed-in-tariff (FIT), and RS buying price. Individual variations of these parameters are done to see the sensitivity of GDP contribution. As seen in Figure 11, the ethanol yield variation has the most impact. This is not surprising as ethanol yield directly affects the income from ethanol selling. The second largest impact is the variation of TCI, which directly linked to the NPV. As there has been no commercial RS-to-ethanol plant yet, there is not much certainty in both ethanol yield and TCI. Therefore, a cautious attention is needed in this regard when deciding to implement the project. Albeit the electricity is only a by-product, the government-driven FIT apparently plays an important role in affecting the economic yield of ethanol plant.

Guntoro (2013) estimates that the share of RS usage for fermented cattle feed might increase because 1) the Balinese cow population density is the highest in Indonesia while the availability of grass as cattle feed is limited, 2) human population—thus beef consumption—increases, and 3) the GOI limits beef imports to achieve self-sufficiency so local cow population is projected increasing. Besides, there have been efforts to shift the grass to fermented RS as cattle feed. These might lead to increasing RS price. However, the sensitivity analysis shows that even doubling the RS price (from the base price) does not affect much on the GDP contribution. This is because the feedstock price is a minor constituent of the operational cost.

The potential FX savings is 423 USD/t_straw-db, or 30 MMUSD/year for 24-ML capacity. Predictably, the varying import price of oil significantly impacts the FX savings (see Figure 12). Ranging crude oil price from USD 60 to USD 150 results in FX savings of, respectively, USD 234 to USD 582 for each tonne of processed straw. In an unstable or increasing price of oil, therefore, the ethanol project finds a stronger justification. Ethanol yield, again, has important impact on FX savings as the yield is immediately associated with the amount of gasoline production.
Figure 12. Sensitivity of foreign exchange saving for 24-ML ethanol production plant.

E. EMPLOYMENT EFFECTS

The total employment effects (direct, indirect, induced, and dependent), are found to be 5.8E-04 persons/t straw-dry in the 24-ML ethanol production plant. Given that all technically available RS in Bali is converted into ethanol with collection efficiency of 0.4, the total employment beneficiaries may reach 2,200-3,700 persons, corresponding to the technically available RS in Bali, ranging from 244 to 415 kt/year (see Figure 13). The error bars are due to the ±30 per cent variation of indirect-induced multipliers.

Figure 13. Total employment beneficiaries of straw-to-ethanol project converting all technically available RS in Bali with collection efficiency of 0.4.
VIII. CONCLUSION

In this work, environmental and socioeconomic benefits of rice straw-to-ethanol are assessed. Some indicators, which are the major concerns in implementing an energy project, are calculated. The overall results are shown in Table 19 for 24-ML plant capacity and for the whole technically available RS in Bali being converted to ethanol production, which ranges from 244 to 415 kt/year, depending on the RS yield.

Table 19. The calculated results of the environmental and socioeconomic indicators, for each tonne of rice straw and for technically available RS supply in Bali.

<table>
<thead>
<tr>
<th>Indicators</th>
<th>Values per tonne straw (dry basis)</th>
<th>Bali RS supply*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>~244 kt/year</td>
<td>~415 kt/year</td>
</tr>
<tr>
<td>Gasoline replacement (L)</td>
<td>224</td>
<td>5.5E+07</td>
</tr>
<tr>
<td>GHG emissions savings (USD)</td>
<td>579</td>
<td>1.4E+08</td>
</tr>
<tr>
<td>GDP contributions (kg CO2-eq)</td>
<td>77</td>
<td>1.9E+07</td>
</tr>
<tr>
<td>FX savings (USD)</td>
<td>423</td>
<td>1.0E+08</td>
</tr>
<tr>
<td>Jobs beneficiaries (persons)</td>
<td>5.8E-04</td>
<td>2.2E+03</td>
</tr>
</tbody>
</table>

* That is, technically available RS in the island with collection efficiency of 0.40, according to the RS yield of 4.0 to 6.8 t/ha/year.

A sensitivity analysis is done for some result parameters. The plant efficiency performance, in terms of ethanol yield, is found to be the most crucial parameter for the environmental performance of the ethanol plant. Also, it is found that there is only minor decrease in environmental performance in using commoditised RS, which would have been sold for certain economic applications. The probably fluctuating RS price is not a major threat for the financial viability of the plant. The total capital cost of the project is crucial for its contribution to GDP while RS price swing slightly affects. A supportive feed-in-tariff may also significantly help in yielding high GDP contribution. With regard to foreign exchange savings, increasing price for imported crude oil provides stronger justification for the implementation of the projects.

That said, the technology is not commercially available yet. However, many research and pilot projects are being undertaken around the world. Therefore, an apt anticipation by decision makers is needed to establish a clear research direction and also prepare a smooth technology transfer, knowing that Indonesia is, on the one hand, a major rice producer, and, on the other hand, an increasingly large energy consumer. This work can be a basis for further socioeconomic assessment on straw-to-ethanol project feasibility.

Finally, further studies are still needed to 1) upscale the scope of the study to national level and 2) compare the environmental and socioeconomic benefits between straw-to-ethanol and straw-to-electricity application in Indonesia.


Marsetyo. "Strategi pemenuhan pakan untuk peningkatan produktivitas dan populasi sapi potong." Seminar Nasional Pengembangan Sapi Potong Untuk Mendukung Percepatan Pencapaian Swasembada Daging...


UN. *The centrality of employment to poverty eradication*. Report of the Secretary General, UN, 2005.


APPENDICES

A. Discounted cash flow spreadsheet

In evaluating economic viability of the ethanol project, a cost benefit analysis through a discounted cash flow calculation is done. The values are averaged values taken from NREL report written by Humbird, et al. (2011, iv). Based on the calculated NPV, contribution to GDP is computed.

<table>
<thead>
<tr>
<th>Year</th>
<th>Total investment cost</th>
<th>Operational and maintenance costs</th>
<th>Revenues</th>
<th>Tax</th>
<th>Total CF</th>
<th>Disc. factor</th>
<th>Discounted cash flows</th>
<th>Cumulative cash flows</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-55.48</td>
<td></td>
<td></td>
<td></td>
<td>-55.48</td>
<td>1.000</td>
<td>-55.48</td>
<td>-55.48</td>
</tr>
<tr>
<td>1</td>
<td>-5.16</td>
<td>17.48</td>
<td>-3.08</td>
<td>9.24</td>
<td>0.963</td>
<td>0.963</td>
<td>8.90</td>
<td>-46.58</td>
</tr>
<tr>
<td>2</td>
<td>-5.16</td>
<td>17.48</td>
<td>-3.08</td>
<td>9.24</td>
<td>0.927</td>
<td>0.927</td>
<td>8.57</td>
<td>-38.02</td>
</tr>
<tr>
<td>3</td>
<td>-5.16</td>
<td>17.48</td>
<td>-3.08</td>
<td>9.24</td>
<td>0.892</td>
<td>0.892</td>
<td>8.25</td>
<td>-29.77</td>
</tr>
<tr>
<td>4</td>
<td>-5.16</td>
<td>17.48</td>
<td>-3.08</td>
<td>9.24</td>
<td>0.859</td>
<td>0.859</td>
<td>7.94</td>
<td>-21.83</td>
</tr>
<tr>
<td>5</td>
<td>-5.16</td>
<td>17.48</td>
<td>-3.08</td>
<td>9.24</td>
<td>0.827</td>
<td>0.827</td>
<td>7.64</td>
<td>-14.19</td>
</tr>
<tr>
<td>6</td>
<td>-5.16</td>
<td>17.48</td>
<td>-3.08</td>
<td>9.24</td>
<td>0.796</td>
<td>0.796</td>
<td>7.36</td>
<td>-6.83</td>
</tr>
<tr>
<td>7</td>
<td>-5.16</td>
<td>17.48</td>
<td>-3.08</td>
<td>9.24</td>
<td>0.767</td>
<td>0.767</td>
<td>7.08</td>
<td>0.25</td>
</tr>
<tr>
<td>8</td>
<td>-5.16</td>
<td>17.48</td>
<td>-3.08</td>
<td>9.24</td>
<td>0.738</td>
<td>0.738</td>
<td>6.82</td>
<td>7.07</td>
</tr>
<tr>
<td>9</td>
<td>-5.16</td>
<td>17.48</td>
<td>-3.08</td>
<td>9.24</td>
<td>0.710</td>
<td>0.710</td>
<td>6.57</td>
<td>13.64</td>
</tr>
<tr>
<td>10</td>
<td>-5.16</td>
<td>17.48</td>
<td>-3.08</td>
<td>9.24</td>
<td>0.684</td>
<td>0.684</td>
<td>6.32</td>
<td>19.96</td>
</tr>
<tr>
<td>11</td>
<td>-5.16</td>
<td>17.48</td>
<td>-3.08</td>
<td>9.24</td>
<td>0.658</td>
<td>0.658</td>
<td>6.09</td>
<td>26.04</td>
</tr>
<tr>
<td>12</td>
<td>-5.16</td>
<td>17.48</td>
<td>-3.08</td>
<td>9.24</td>
<td>0.634</td>
<td>0.634</td>
<td>5.86</td>
<td>31.90</td>
</tr>
<tr>
<td>13</td>
<td>-5.16</td>
<td>17.48</td>
<td>-3.08</td>
<td>9.24</td>
<td>0.610</td>
<td>0.610</td>
<td>5.64</td>
<td>37.54</td>
</tr>
<tr>
<td>14</td>
<td>-5.16</td>
<td>17.48</td>
<td>-3.08</td>
<td>9.24</td>
<td>0.588</td>
<td>0.588</td>
<td>5.43</td>
<td>42.97</td>
</tr>
<tr>
<td>15</td>
<td>-5.16</td>
<td>17.48</td>
<td>-3.08</td>
<td>9.24</td>
<td>0.566</td>
<td>0.566</td>
<td>5.23</td>
<td>48.20</td>
</tr>
</tbody>
</table>

NPV 48.20

IRR (after tax) 10.19%

Appx. Table 1. Discounted cash flow spreadsheet of the project (in MMUSD).
B. Ethanol Yield Calculation

Having been discussed in the methodology of calculating gasoline replacement (p. 18), the reactions and calculated mass of products are presented in Appx. Table 2 below. Taking account the losses, the conversion factors would result in of ~81 per cent of overall theoretical conversion yield, virtually equal to that of M. K. Delivand, M. Barz, et al. (2012), which is 82 per cent. The produced ethanol is then dehydrated through two-steps purification system; each has 99 per cent efficiency. The amount of produced ethanol is then divided by 99.5 per cent, which is the aimed purity. Finally, the volume of produced ethanol is determined with the density, resulting 335 L/t straw-db.

<table>
<thead>
<tr>
<th>Reactions</th>
<th>Conversion factor (%)</th>
<th>Product mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pretreatment</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Glucan)n + n H₂O (\rightarrow) n Glucose</td>
<td>Glucan to glucose</td>
<td>9.90</td>
</tr>
<tr>
<td>(Glucan)n + n H₂O (\rightarrow) non-fermentables</td>
<td>Glucan to non-fermentables</td>
<td>0.60</td>
</tr>
<tr>
<td>(Xylan)n + n H₂O (\rightarrow) n Xylose</td>
<td>Xylan</td>
<td>90.00</td>
</tr>
<tr>
<td>(Arabinan)n + n H₂O (\rightarrow) n Arabinose</td>
<td>Arabinan</td>
<td>90.00</td>
</tr>
<tr>
<td>Enzymatic hydrolysis</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Glucan)n + n H₂O (\rightarrow) n Glucose</td>
<td>Glucan to glucose</td>
<td>91.20</td>
</tr>
<tr>
<td>Unconverted glucose</td>
<td></td>
<td>100.00</td>
</tr>
<tr>
<td>Unconverted xylene</td>
<td></td>
<td>99.00</td>
</tr>
<tr>
<td>Unconverted arabinose</td>
<td></td>
<td>99.00</td>
</tr>
<tr>
<td>Fermentation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Glucose (\rightarrow) 2 Ethanol + 2 CO₂</td>
<td>Glucose to Ethanol</td>
<td>95.00</td>
</tr>
<tr>
<td>3 Xylose (\rightarrow) 5 Ethanol + 5 CO₂</td>
<td>Xylose to Ethanol</td>
<td>85.00</td>
</tr>
<tr>
<td>3 Arabinose (\rightarrow) 5 Ethanol + 5 CO₂</td>
<td>Arabinose to Ethanol</td>
<td>85.00</td>
</tr>
</tbody>
</table>

*This is the percentage of theoretical, stoichiometric yields of the reactions. The values are taken from Humbird, et al. (2011).

*See Table 9 for the gravimetric components of the rice straw.

*The ethanol yield from glucose has suffered losses from contamination in fermentation (3%) and saccharified slurry diversion for inoculation (10%).

Appx. Table 2. The reaction yield and product mass for converting 1-t RS.
C. Indonesian Economic Indicators

These figures below generally show some Indonesian economic indicators, conveying the role of agricultural sector in the country’s economy. The discussion is written in Introduction (p. 1).

![GDP shares per sector](image1)

Appx. Figure 1. GDP shares per sector.
Adapted from World Bank.\(^{37}\)

![Employment distribution share per sector, 2011](image2)

Appx. Figure 2. Employment distribution share per sector, 2011.
Adapted from World Bank.\(^{38}\)

![GDP and GDP growth from agricultural sector](image3)

Appx. Figure 3. GDP and GDP growth from agricultural sector.
Adapted from World Bank.\(^{39}\)

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\(^{38}\) Ibid.

\(^{39}\) Ibid.
D. Indonesian agricultural indicators

These indicators below point out the importance of rice in Indonesian agricultural sector. The complete discussion is delineated in the Introduction section (p. 1).

Appx. Figure 4. Production in 2011 (tonnes).
Adapted from FAO.\(^\text{40}\)

Appx. Figure 5. Share of crops in gross production value, 2011.
Adapted from FAO.\(^\text{41}\)

\(^{41}\) Ibid.