UTRECHT UNIVERSITY, COPERNICUS INSTITUTE OF SUSTAINABLE DEVELOPMENT

Sugar Palm: A Novel Bio-Ethanol Feedstock

A life cycle assessment of bio-ethanol production from the Indonesian sugar palm (Arenga pinnata)

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Abstract

The village hub is a small-scale factory, designed to support Indonesian rural communities in their development and to preserve local biodiversity. The main product of the village hub is sugar syrup based on the juice from the sugar palm tree. The village hub includes ethanol production. A life cycle assessment was performed to assess the environmental performance of ethanol production based on sugar palm juice. Additionally, an initial economic assessment was performed. Data was provided by the Masarang foundation, which developed the village hub, regarding sugar palm cultivation. This data was supplemented with measurements performed on key processes in the ethanol lifecycle as well as literature sources and the Ecoinvent database.

The lifecycle assessment reveals that ethanol produced by the village hub has a poorer performance than fossil natural gas. However, this environmental performance can be improved to below natural gas levels by reducing the energy use in two key processes: juice processing and distillation. Sugar palm ethanol production has a good performance regarding climate impact and natural resource depletion while it performs poorer in the categories respiratory health and carcinogenic effects. When implementing ethanol production at a village hub, care needs to be taken to prevent additional environmental impacts caused by land use change resulting from an increase in juice production.

It is likely that sugar palm ethanol will be expensive to produce compared to the retail price of natural gas. To lower the price of ethanol for the consumer, a subsidy will be required. The cost of juice has a large contribution to the overall production costs. When waste juice is used, the production costs are considerably decreased and a subsidy might not be required.

Both the environmental as well as the economic performance of ethanol production is the best when waste juice is used. Using waste juice should be the preferred option for ethanol production.

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List of abbreviations

CO_{2eq}	Carbon dioxide Equivalent emissions
DALY	Disability-adjusted life years
DLUC	Direct Land Use Change
Ha	Hectare
ILUC	Indirect Land Use Change
IRD	Integrated Rural Development
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LHV	Lower Heating value
LUC	Land Use Change
MJ	Mega joule
MMT	Million Metric Tons
NMVOC	Non-Methane Volatile Organic Compound
OGC	Organic Gaseous Carbon
PAHs	Polycyclic Aromatic Hydrocarbons
PDF	Potentially Disappeared Fraction
PM_{tot}	Total Particulate Matter
Tkm	Ton kilometer
Vol%	Percentage by volume

1. Introduction

The village hub is an Integrated Rural Development (IRD) project designed by the Masarang foundation. It is a small-scale factory, designed to support Indonesian rural communities in their development and to preserve local biodiversity. The village hub project is in the demonstration phase. One pilot unit is built in the city of Tomohon located in North Sulawesi, Indonesia. The goal is to expand the project by building additional village hubs in North Sulawesi and Kalimantan. The sugar palm tree (*Arenga pinnata*) is a key crop in this project.

Sugar palm trees are cultivated in an agroforestry setting. According to Nobel and Dirza (1997), agroforestry systems “combine trees with an understory of annual or perennial crops and sometimes livestock”. Agroforesters ‘tap’ this tree to collect sugary juice. Sugar palm trees are of great importance to the livelihood of many agroforesters. The sugar palm tree yields a diversity of products (juice, fruits, leaves, fibers, starch) which complement the livelihood strategy of agroforesters of ‘income diversification, risk spreading, efficient labor, and land use’ (Martini *et al.*, 2011).

Agroforesters who participate in the project supply juice to the village hub. There, the juice is processed into a thick syrup and prepared for sale on the national and international sugar market. Juice processing is the core activity of the village hub. Additionally, depending on the needs of the community, its activities can be expanded to produce clean drinking water, cattle feed, organic fertilizer, electricity, biogas and/or bio-ethanol.

The first goal of the village hub is to support rural development. The village hub directly benefits rural agroforesters by providing access to a larger sugar market. It intends to increase the income of the agroforesters and add to the economic activity of the community. The village hub also supports the welfare of the rural community by providing additional services mentioned previously.

The second goal of the village hub project is to prevent land conversion of forests and agroforests to monoculture cultivation such as the oil palm. Agroforestry support a higher biodiversity than regular agriculture (Mcneely and Schroth, 2006, Nobel and Dirza, 1997). The large-scale expansion of intensive agriculture, especially in the form of palm oil plantations has led to the deforestation of biodiverse Indonesian rainforests (Fitzherbert, 2008) with negative consequences for the climate (Wicke, 2011; Danielsen, 2008).

When agroforesters maintain their economic livelihood from agroforestry practices they have a stake in retaining their land instead of selling it. Moreover, the informal nature of land ownership in rural Indonesia has often led to conflicts between rural communities and palm oil companies (Obidzinski *et al.*, 2012) and allows for land acquisition against the interests of informal land users (Sirait, 2009; Marti, 2008). In efforts to formalize land ownership, the village hub project mandates associated agroforesters to formally delineate their land boundaries with adjacent land owners and local community leaders.

One service, which the village hub can offer, is the production of bio-ethanol. Access to affordable, clean energy is a major problem in rural Indonesian communities. Collecting solid fuels is a time consuming task that reduces the economic productivity of a household (Cabraal *et al.*, 2005). In 2007, almost 80% of rural Indonesians were not using modern cooking fuels; instead, they relied on solid fuels such as wood-based biomass, agricultural residues, and dung (World Bank, 2011). Making use of solid fuels for cooking with traditional methods result in poor indoor air quality that leads to serious adverse health effects for women and children (WHO, 2009; World Bank, 2011). Moreover, without proper indoor lighting, the productive day of a household ends after sundown which reduces the time spent on income generating activities and educational activities for children (Buragohain, 2012).

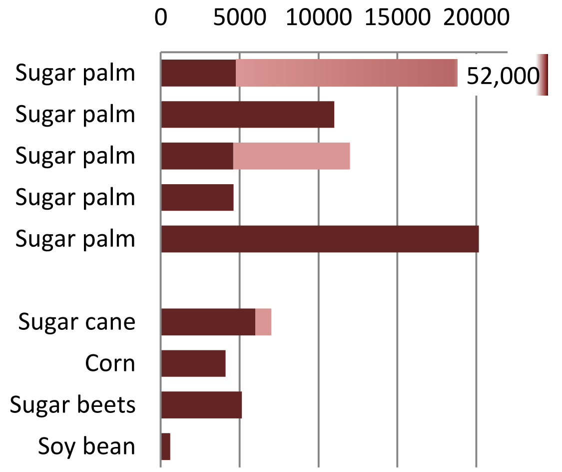
The use of ethanol instead of solid fuels for lighting and cooking would represent a great improvement in quality of life. In order to produce ethanol, the village hub is expanded with a fermenter and a distiller that uses sugar palm juice as a feedstock.

Staaij & van den Bos *et al.* (2011) performed an investigation into the economic feasibility of large-scale sugar palm-based ethanol production. They found that large-scale sugar palm cultivation is economically feasible. Ethanol yields and worker wages were the most important parameters in their cost analysis. The authors expect that sugar palm ethanol reduces GHG emissions when compared to fossil fuels, pointing to the high yields, the positive Land Use Change (LUC) impacts when planting on Imperata grasslands and the limited application of fertilizers and pesticides. However, this analysis applies to large-scale plantation aimed to produce ethanol, which is currently not practiced. Whether sugar palm ethanol production is also economically attractive in a small-scale setting such as village hub is so far not investigated. Addressing this knowledge gap is one of the goals of this research.

Even though the characteristics of sugar palm cultivation have been investigated in a number of instances, little is also known about the environmental performance of sugar palm ethanol production. Many sources describe sugar palm characteristics like juice yields, sugar concentration, the tree lifecycle, tree morphology, the tapping process and other properties of the sugar palm tree (Mogea *et al.*, 1991; Dalibard, 2007; Staaij & van den Bos *et al.,* 2011; Elberson and Oyen, 2009). All sources indicate the high sugar juice producing capacity of sugar palm trees. The high sugar yields have spurred investigations into the potential ethanol yields of a sugar palm based plantation compared to conventional bio-ethanol crops. However, it is unknown whether the yields from a single tree are a good indicator of potential sugar yields in a plantation setting. Estimates of potential ethanol yields reflect this uncertainty since different assumption yields greatly different results (table 1).

Table 1: The ethanol yield for sugar palm cultivation and the ethanol yield for a selection of other crops (liters dehydrated ethanol per year). The table (left) and the figure (right) depict the same values. The dark red and light red bars denote upper and lower estimates for the yields. An axis break is used for the upper limit for Staaij & van den Bos *et al.* (2011) which is 52,000 liters.

Source	Crop	Yield (liter/ha)
Staaij *et al.* (2011)	sugar palm	4,780-52,000
Dalibard (1995)	sugar palm	11,000[A]
Van Dam (2009)[B]	sugar palm	4,600-12,000
Fact Sheet (2010)	sugar palm	4,610
Effendi (2010)	sugar palm	20,160
CGEE (2012)	Sugar cane	6,000-7,000
FAPRI [C] (2012)	Corn	4,106
FAPRI [C] (2012)	Sugar beet	5,163
FAPRI [C] (2012)	Soy bean	589



A: The source states a yield of 20,000 kg of sugar per hectare. This sugar yield is converted to an ethanol yield considering an 80% fermentation efficiency.

B: Confidential report; information cited in Staaij & van den Bos *et al.* (2011)

C: FAPRI (2012)

In order to assess the environmental impacts of ethanol production in the village hub a Life Cycle Assessment (LCA) is performed on the current ethanol production system in the pilot village hub in Tomohon (ISO 14040, ISO 14044). For this purpose, measurements were performed between February and April 2013 on the pilot village ethanol module and the juice processing equipment used by the tappers and the village hub. The Masarang foundation and Dr. W. Smits supplied additional data. Four different variations of ethanol production by the village hub are analyzed. Their environmental performances are compared between systems, with other biofuels and with natural gas.

To address the economic viability of the village hub, a cost analysis is performed to provide a first estimate of the production cost of sugar palm ethanol. For this purpose, data was gathered from the Tomohon region on fossil fuel prices, prices of juice related products and other inputs for the production of juice related products.

Following this introduction, chapter two provides the necessary background on sugar palm, sugar palm tapping, and the village hub. Chapter three outlines the research questions and sub-questions. In chapter four the methods used to carry out the environmental and economic assessment are presented. Chapter five gives an overview of the data used to do the analyses and refers to the relevant appendices where much of the data analysis is documented. In chapter six the results of the LCA are presented. Chapter seven discusses other aspects of the environmental performance of sugar palm ethanol not included in the LCA. The strengths and weaknesses of the LCA and the cost analysis are discussed, too. Lastly, chapter eight concludes this report with an overall assessment of the performance of sugar palm village hub ethanol.

2. Background

2.1 Sugar palm tapping and juice collection

Sugar palm grows in natural forests across South- and Southeast Asia in India, Thailand, Cambodia, Malaysia, Indonesia (north Sumatra, west Java, east Borneo, and north Sulawesi) and the Philippines (Dalibard, 1995). Sugar palms can only propagate through the dispersal of its fruit which contain seeds. The trees as well as their seeds are known to survive forest fires and dominate the land thereafter. Sugar palm tapers sometimes actively plant additional sugar palm trees although this practice is rare (Martini *et al.*, 2011; Mogea *et al.*, 1991). Martini *et al.* (2011) found that tappers who make an effort to plant additional sugar palms on their land had an overall lower monetary return due to high labor requirements, which explains why tappers prefer natural propagation. Mogea *et al.* (1991) found that sugar palm trees were sometimes used to demarcate land boundaries and to help stabilize rocky slopes.

The sugar palm tree produces multiple male and female flowers, which are clustered separately at the end of different stems i.e. the inflorescences. The male inflorescence produces spores, the female inflorescence bears fruit. In north Sulawesi, the sugar palm's main product is sugar juice which is tapped from the male inflorescence. The female inflorescence is never tapped since it produces much less juice. The male inflorescence appears at the top of the tree underneath the crown when the tree is maturing. Maturation of a sugar palm tree takes around 9-10 years or longer depending on the growing conditions such as light availability (Mogea *et al.*, 1991).

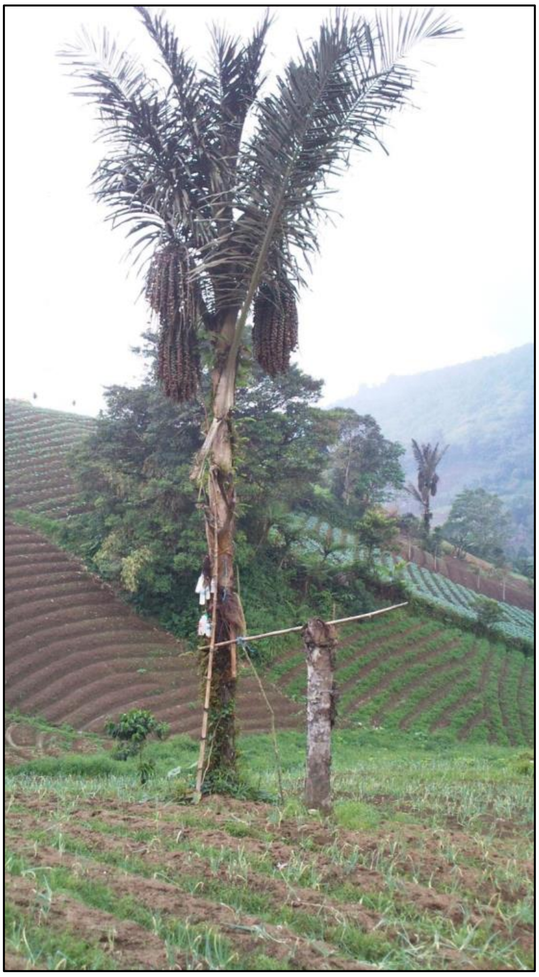


Figure 1: A freestanding sugar palm tree. The forest surrounding the tree has disappeared. Fruits from the female flower are hanging at the top. A male inflorescence is tapped in the middle. Plastic bottles collect the juice. A bamboo ladder is used to reach the inflorescence.

The male inflorescence needs to be prepared before it can be tapped. The base of the inflorescence is beaten by the tapper with a wooden mallet every day for around 1.5 months. This causes the base to swell up. After preparation, the inflorescence is cut off leaving a swollen stump. The wound at the end of the stump starts dripping sugary juice which is collected by the tapper into a jerrycan suspended underneath the tree via a construction involving bamboo or empty plastic bottles.

Tapping the sugar palm tree for the production of sugar is especially prevalent in the North Sulawesi area of Indonesia where this practice has a long history and juice yields are generally high (Mogea *et al.*, 1991). Lantemona *et al.* (2013) found that sugar palm juice yields are strongly correlated with altitude: palm trees growing at an altitude of >500 meters above sea level produced on average 22.5 liters of juice per day whereas comparable trees growing at sea level produced on average 8.9 liters of juice per day. The pilot village hub in Tomohon is located at an elevation of 500-1,500 meters which falls within the highest yield category.

The juice is collected from the tree at least once every day and processed as soon as possible to prevent quality degradation from microbial growth. Upon collection, the wound of the stump needs to be reopened to keep the juice flowing. After 3-4 months of tapping the juice yields are significantly lower than at the start and tapping of this inflorescence is abandoned. The next male inflorescence appears lower on the stem and the last one appears almost at ground level. The first inflorescence produces the highest volume of juice with the highest concentration of sugar and produces for the longest period. The yields of consecutive inflorescences decrease thereafter. One sugar palm tree yields 6-9 male inflorescences over its lifespan of up to 30 years.

2.2 Estimate of sugar palm ethanol yield

The sugar palm tree produces between 1,600-2800 kg of sugar over its productive lifetime of 12-16 years (See Appendix I). Therefore, the yearly productivity is in the range of 105-227 kg/year. Based on these values, it is possible to estimate the potential sugar palm ethanol yield, adding to the wide range of estimates presented in the introduction. Considering a present day fermentation efficiencies in the Brazilian sugar cane ethanol industry of 91.36% (CGEE, 2012), the yearly production of dehydrated ethanol (99 vol%) of a tree would be 66-143 liters (see Appendix I).

Translating the yields of one tree to the potential yield per hectare is the most difficult step since it is unknown what the relation is between tree density and sugar yields of the trees. Palm oil plantations usually have a planting density of 143 palms/ha since this gives the highest palm oil yields per hectare over the lifetime of a plantation; a higher tree density leads to a lower yield per tree and an overall lower yield per hectare (Breure, 2010). Martini *et al.* (2011) reports of a plot with sugar palm trees planted at an 8x8 meters spacing which results in 156 palms per hectare. Sumadi (1988) mentions that the optimal density is with trees planted at 10x10 meters interval, or 100 trees per hectare.

Multiplying a low ethanol yield of 66 liters per tree per year with a density of a hundred trees per hectare results in an ethanol yield of 6,609 liters ethanol/ha/year. Conversely, multiplying the high yield of 142 liters per tree per year with a tree density of 156 palms per hectare results in an ethanol yield of 22,289 liters/ha/year. The uncertainty of the sugar yield of sugar palm trees in a plantation setting, together with the uncertainty in the optimal tree density of a sugar palm plantation lead to a wide range in the ethanol yield of such a plantation. However, even an ethanol yield of >6,000 is higher than most other ethanol crops (see table 1 in the introduction) and the prospect that sugar palm could produce up to 22,000 liters of ethanol per hectare indicates that the sugar palm tree might be an attractive crop for the production of ethanol.

2.3 Agroforestry and biodiversity conservation

In Indonesia a rapid process of intensification from agroforestry to mono-culture has occurred for the so called ‘boom crops’; cocoa, coffee, rubber and oil palm (Feintrenie *et al*., 2010). Even though agroforestry farmers have some sentimental attachment to the forest, this does not prevent them from pursuing economic options associated with agricultural intensification. Feintrenie *et al.* (2010) explains the popularity of these crops in Indonesia because of their `high profitability and the opportunity that they represent for isolated forest people and poor farmers to escape poverty and marginalization’. Figure 1 shows the steep increase of production volumes for these boom crops in the last five decades.

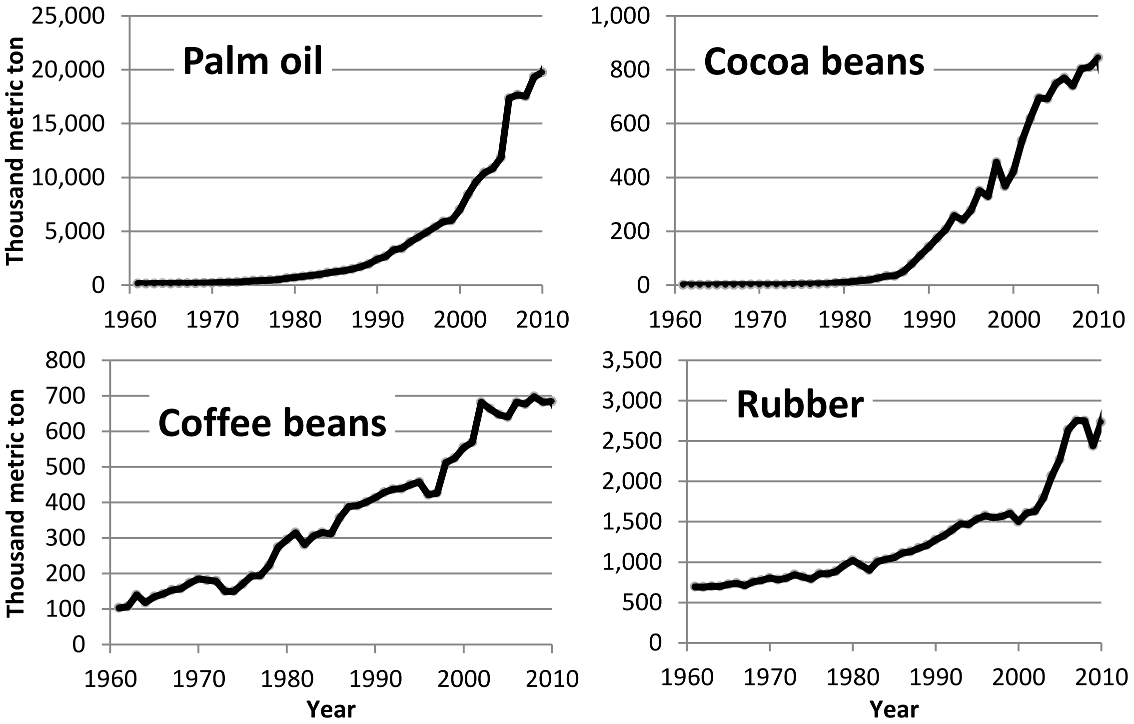


Figure 2: Production volume of palm oil, cocoa beans, fresh coffee beans and natural rubber in Indonesia from 1962 to 2010. Source: FAO (2013).

That the practice of agroforestry cultivation in Indonesia is declining has consequences for the environment and for rural communities. Since agroforests support a higher biodiversity than intensive agriculture (Nobel and Dirza, 1997), the conversion of agroforestry land to mono-culture cultivation is at the cost of biodiversity (see figure 3).

Figure 3: Left: sugar palm trees in an agroforestry setting. Right: the agroforest has been converted to mono-culture agriculture, only some trees remain.

Moreover, agroforests near natural forests provide additional ecological functions: they provide secondary habitat for species that tolerate a certain level of disturbance, they connect otherwise isolated populations in dispersed natural habitats and they buffer for natural forests against the conversion to grasslands or monoculture (Mcneely and Schroth, 2006; Nobel and Dirza, 1997). These environmental functions and the capacity for livelihood improvement of the rural poor make agroforestry a valuable asset for both conservation and development projects (Mcneely and Schroth, 2006).

2.4 Sugar palm juice products

Sugar palm tappers in the Tomohon area have different options for generating income from sugar palm juice. Their first option is to sell their juice to the Masarang sugar factory of the village hub. Tappers have to boil the juice after it is produced so that it does not degrade due to natural fermentation and other microbial growth before it arrives at the village hub. Boiling the juice requires that the tapper collects firewood and starts a fire every day. The juice is collected with a truck, every morning on weekdays, by the factory employees at a rendezvous point near the tappers' land. There, the factory employee measures the volume of the juice, as well as the sugar concentration and its acidity, which is an indicator of quality. If the acidity is adequate, then the juice is accepted and taken to the factory. At the end of the week the tappers are paid for their juice deliveries. The payment is based on the amount of sugar in the juice delivered; i.e. liters of juice times sugar concentration.

The second option for the tapper is to produce sugar directly. In this case the tapper will boil the juice until most of the water is evaporated. While still hot and fluid, the sugar is packed in empty coconut shells where the sugar solidifies as it cools. These solid halve moon shaped sugar packages weigh around 600 grams and have a dark brown color. The families of the tappers sell this sugar on the market or to a trader. This product is more accurately called jaggery since the molasses and other solid materials are not separated from the sugar crystals. Sugar palm sugar is used in various local traditional dishes.


Figure 4: Sugar palm sugar is sold on the local market

The third option for tappers is to produce Sagwer, an alcoholic beverage. Sagwer is produced when the juice is allowed to ferment naturally. Many tappers reserve one tree for Sagwer production. Since natural fermentation is the intended application for the juice, this tree is tapped only once every day or every two days and the juice is allowed to ferment while still in the jerrycan. Even though Sagwer is mostly for personal consumption and is only a small part of a tapper's overall juice production, occasionally a tapper will produce more Sagwer to sell to an interested buyer.

The fourth option for the tapper is to produce Capticus, which is a strong liquor with ~40 vol% ethanol. To produce Capticus, the tapper first produces Sagwer and then distills it in a used oil barrel with a bamboo distillation column. The ethanol concentration increases when the bamboo column is longer and when the fire is burned at the optimal temperature. Producing Capticus requires an investment in this distillation equipment and requires the collection of significant amounts of juice and fuel wood to supply one distiller. Therefore, three to four tappers work together with one distiller. Capticus is a popular drink in the Christian North Sulawesi area where alcohol consumption is more accepted than in the otherwise mostly Muslim population of Indonesia. However, Capticus production is illegal as it breaks laws regarding the production of alcoholic beverages.

2.5 Juice processing to ethanol

When juice is processed into ethanol at the village hub, the tapper boils the juice before delivery to sterilize it so that the quality does not deteriorate before it arrives at the village hub. The second purpose of boiling the juice is to increase the sugar concentration which makes the juice easier to transport. Moreover, after fermentation, it reduces the heat required for distillation. An example of this effect is shown in Stampe *et al.*, 1983.

Sugar boiling is traditionally performed by the tapper in a large, round, shallow wok pan over a fire pit. Tappers also use this method to boil the juice to produce sugar.

The Masarang foundation has developed a more efficient system to boil juice which makes use of the rocket stove system. The rocket stove includes a stove where wood is combusted. A pan is placed in the 'chimney' of the stove with only a small volume between the pan and the chimney's inner walls. This way the exhaust of the fire passes over the whole length of the pan, thereby allowing for a long period of heat transfer. The rocket stove design employed by the village hub has a capacity of 500 liters of juice (batch process) which requires multiple tappers to combine their juice for boiling. The expected effect is that less fuel wood is required by the tappers for juice processing.

After the juice is boiled, it is transported from the tapper to the village hub by a Toyota Dyna Long 4000 truck with a capacity of 4,700 kg. The main input in this process is the consumption of transport fuel. Next, the juice is inoculated with baker's yeast and allowed to ferment in a large tank. After fermentation, the wine is loaded into the distiller. The distillation process produces the desired ethanol with a concentration of ~85 vol%.

2.4.1 The ethanol module


Figure 5: The ethanol module at the village hub

The ethanol module consists of a fermenter and a distiller. The pilot village hub has three large tanks for juice fermentation. After the tanks are filled with juice, baking yeast is added and the lid is sealed with an air lock to allow for anaerobic fermentation. Fermentation is visible by the CO_2 bubbles that escape through the airlock. When fermentation is finished, the tank is attached to the distillation unit. A manual valve allows the juice to flow from the tank to the first column of the distiller. Under the first column is a stove where fire wood is burned to heat up the wine and start the distillation process. Water and ethanol vapor escape at the top of the first column into the second column.

The vapor that escapes from the second column is cooled and collected in a jerry can. At first the ethanol has a high concentration >90 vol%. However, over time the concentration of the ethanol drops as more water is produced. When the concentration of the final product reaches the intended concentration of 85 vol% the process is stopped, the columns are emptied and the first column is refilled with wine. The ethanol is distributed locally as a clean biofuel for cooking and lighting.

2.6 Other sugar palm products

Besides juice-related products, the sugar palm yields other products. For instance, the sugar palm yields fruits (Kolang Kaling) which can be eaten after processing. However, harvesting fruits is known to decrease juice production and therefore simultaneous fruit and juice harvesting from one tree is rare. The trunk of the sugar palm tree is covered in a thick mesh of fibers which can be used, together with sugar palm leaves, as roofing material. The fibers can also be spun into a rope. These fibers are mostly harvested for personal use of the tapper. The trunk of the tree contains a starchy center called sago which can be eaten. The tree needs to be felled to harvest the sago. Sago harvesting is not compatible with juice and fruit production since sago yields are highest when the tree is young, before juice or fruits can be harvested.

In north Sulawesi, sugar, wine and liquor are the most produced sugar palm products. Kolang Kaling and fibers are harvested and processed occasionally. The harvesting of sago is rare; this practice is seen more often on other Indonesian islands such as Java. Wood from the sugar palm trunk is rarely processed for timber or firewood since it is relatively wet and difficult to process.

2.7 The village hub

Currently the village hub in Tomohon is the only village hub that exists. It is not in use for commercial purposes. If the project is implemented broadly, more hubs will be built in Indonesian villages across the country. They will all produce sugar palm syrup as their main product. The syrup from different villages will be aggregated, processed if necessary at another location and then sold to consumers nationally and internationally.

Tappers who partner with the village hub in their area are supported in their livelihood: they gain an additional income option when they supply juice to the village hub. Additionally, these tappers are supported by the village hub with education programs that teach best practice cultivation techniques and with a supply of high-yielding sugar palm seedlings.

Depending on local circumstances, a village hub can be expanded with additional modules to provide services to the local community. The additional modules are: a water filter, an electricity generator, a composting mound, an algae pond, a bio-methane unit and an ethanol unit. Many of these modules make use of waste products from another process. For example, the algae are fed to livestock and in turn the manure of the livestock is returned to the bio-methane unit. The sludge from the bio-methane unit then goes to the composting mound. In this fashion the village hub strives for a zero-waste system.

3 Research questions

The goal of this research is to assess the performance of sugar palm based ethanol produced in the village hub from an environmental perspective and a rural development perspective.

1. What is the environmental performance of sugar palm ethanol production in the pilot village hub in Tomohon, Indonesia?
    1.1. What are the cradle-to-gate environmental impacts of sugar palm ethanol production in the pilot village hub in Tomohon, Indonesia?
    1.2. How can these impacts be reduced by taking improvements into account?

2. What are the economic conditions required in a village for successful production of ethanol in a village hub?
    2.1. What is the cost structure of sugar palm ethanol?
    2.2. What is the production cost of ethanol in the pilot village hub?
    2.3. What is the value of ethanol when compared to fossil fuel prices?

4. Methods

4.1 Life Cycle Assessment

4.1.1 System Boundaries and functional unit

To assess the environmental impacts of ethanol production in the pilot village hub in Tomohon, a cradle-to-factory gate life cycle assessment is performed (ISO, 2006). The ethanol produced at the village hub has an ethanol concentration of 85 vol%; the remaining 15% is practically water. The functional unit is the heating value of one liter of this ethanol which is 16.7 MJ.

The impacts from ethanol production are due to inputs to and outputs from the system, commonly referred to as environmental interventions. The processes involved in the production of ethanol are depicted in figure 6 below. The tappers use agroforestry land to produce juice with a sugar concentration of 15 °Brix[1], fuel wood, as well as additional agroforestry products. Juice boiling takes place in a pan over a fire pit on the tapper's land. Combustion from the fuel wood results in the production of flue gasses and ash. The intermediate product is juice with an increased sugar concentration of 20 °Brix. A diesel truck is used to transport the concentrated juice to the village hub. Exhaust gasses are produced in this process. At the village hub, the juice is fermented to wine. This wine is distilled which requires additional fuel wood from local wood producing lands. The distillation products of the wine are ethanol and vinasse which is used as fertilizer in rice paddies. Additionally, the waste products flue gasses and ash are formed during distillation.

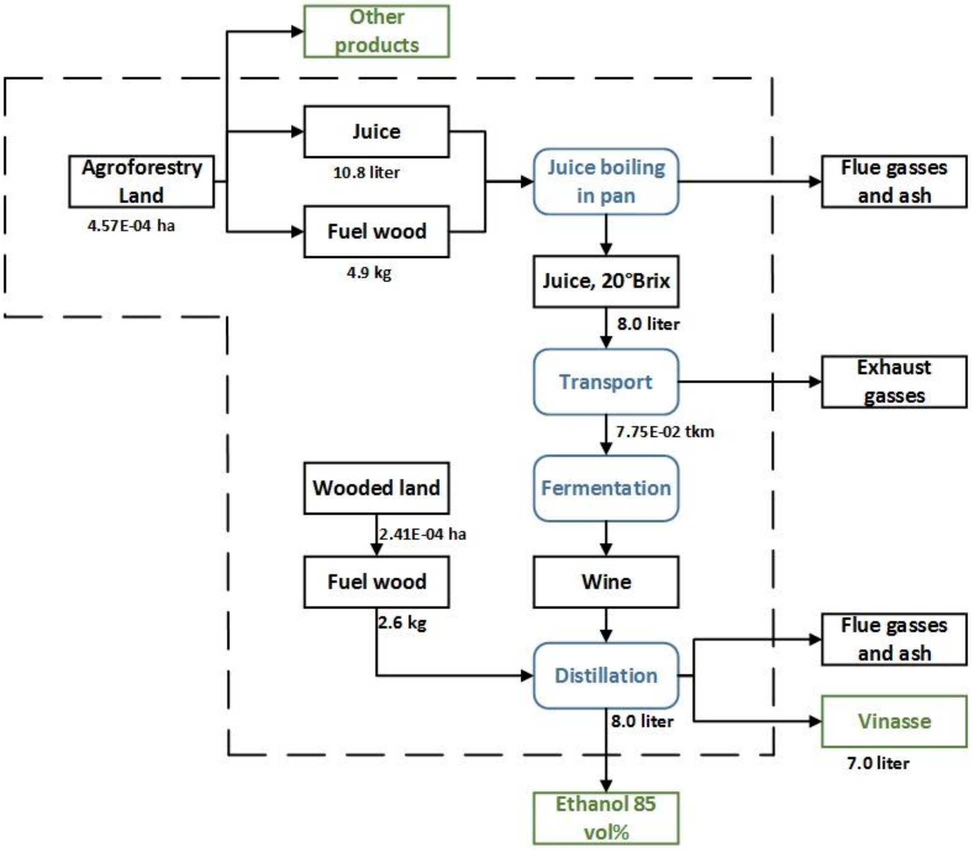


Figure 6: The cradle-to-gate lifecycle of sugar palm ethanol. The black rectangles denote inputs, outputs, intermediate products and waste outputs. The blue rounded rectangles represent processes. The final products are represented in green rectangles. The processes within the dashed line are under investigation in this work. The values indicate the amount of inputs and outputs associated with the production of one liter of ethanol.

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[1] °Brix expresses the concentration (by weight) for solid materials (in this case sugars) in a fluid.

4.1.2 Multifunctionality

The reference system yields multiple products: ethanol, vinasse and agroforestry products. To determine the environmental impacts of the co-products, system expansion is the preferred option in the ISO standard (ISO 14044). If this is not possible, allocation needs to be performed.

In the agricultural phase, agroforestry land yields processed juice (which requires the input of fresh juice and fuel wood for processing) and additional agroforestry products (which vary between tappers and can include different kinds of fruits, vegetables and herbs as well as chicken, fibers and timber). Expanding the system to address the multifunctionality of the land requires additional quantitative data on all agroforestry products which are not available and inherently variable. Allocation based on mass, energy content or carbon content is also not possible for the same reason. Instead, allocation is performed based on the economic value of processed juice on the one hand and all other agroforestry products on the other hand.

Martini *et al.* (2011) calculated the contribution of sugar production as a fraction of the total income of sugar palm tappers in the Batang Toru region in North Sumatra. Their work is the only thorough and quantitive examination of the livelihood of sugar palm tappers. They calculated that sugar contributes 39-50% of the income of a tapper, the other part coming from other agroforestry products such as sugar palm fruits, sugar palm fibers, rubber, petai and durian fruit. The tappers in the Tomohon produce most of the same products as the tappers in the Batang Toru region, with the exception of rubber which is not produced by tappers in the Tomohon area. The 'Wild sugar' cultivation type investigated by Martini *et al.* (2011) is the one practiced also in Tomohon where 50% of the income comes from sugar. Therefore, 50% of the land used by the tappers is allocated to processed juice production (through juice and fuel wood cultivation), the other half is allocated to other agroforestry products.

The second multifunctionality issue results from the distillation process. Both ethanol and vinasse are produced. Allocation between vinasse and ethanol is performed based on the economic value of the products.

The value of vinasse is based on its function as a fertilizer. The vinasse substitutes synthetic fertilizer in rice paddies. The amount of fertilizer vinasse substitutes is based on the nutrient content of the vinasse. The nutrient content of the vinasse can be determined based on the nutrient content of the *juice* which is taken from literature (i.e. Lantemona *et al.*, 2013). It is assumed that all the nutrients in the juice end up in the vinasse after distillation and not in the ethanol. The value of fertilizers is fixed by the government through a subsidy scheme. The fertilizer function of vinasse has a value of Rp.14 for every liter of ethanol that is produced (See Appendix III).

Ethanol with 85 vol% concentration is not a common product and a retail price is not available. Therefore the value of ethanol is based on the value of natural gas by correcting for the heating value of the two fuels. The resulting value is Rp.2,081 per liter (see Appendix IV). Since the value of ethanol is two orders of magnitude larger than the value of vinasse, the exact value of ethanol does not influence the LCA results much. Based on the relative monetary values of vinasse and ethanol, ethanol accounts for 96.7% of the environmental impacts and vinasse accounts for the remaining 3.3%. When considering the two allocation procedures together, the allocation values are as follows:

Table 2: Allocation values for ethanol, vinasse and other agroforestry products in the agroforestry cultivation and juice processing-distillation phase.

Phase	Product	Allocation (%)
Agroforestry cultivation	Ethanol	48.3
	Vinasse	1.7
	Other agroforestry products	50
Juice processing - distillation	Ethanol	96.7
	Vinasse	3.3
	Other agroforestry products	0

4.1.3 Alternative systems

The system described above is the reference system based on the pilot village hub system in Tomohon and the current juice processing practices of tappers. However, one of the goals of this work is to propose improvement to the ethanol lifecycle and to assess the effects of these improvements. There are three alternative systems which improve on one or more of the processes in the ethanol lifecycle. These systems are discussed in the paragraphs below. The reference system is hereafter referred to as system 1. The alternative systems are numbers from 2-4.

4.1.3.1 System 2: Rocket stove

The juice boiling process in the reference system is performed by the tappers in a traditional fashion using a fire pit with a large round pan to boil the juice. The village hub project offers the tappers an alternative system to boil the juice: the rocket stove. The rocket stove is designed to require less fuel wood. Measurements have been performed to determine the fuel wood use for juice boiling in the traditional pan and in the rocket stove.

4.1.3.2 System 3: Larger scale distillation

The distiller of the pilot village hub has a very small capacity. The design capacity is 100 liters of ethanol per day. However, the actual capacity is closer to 30 liters per day. This capacity makes it the smallest fuel ethanol distillery found in literature. For example, Ortega *et al*. (2006) refers to small rural ethanol distillation in Brazil with a capacity of 500 liters per day.

This alternative scenario assumes that the pilot village hub distiller is replaced with a batch distiller as described in Stampe *et al.* (1983) with a yearly capacity of 170,000 liters (92.2 vol%) ethanol per year (approximately 500 liters per day) and a process energy consumption of 3.88 MJ/liter. This distiller used corn 'beer' with an ethanol concentration consistent with that of sugar palm wine of 10 vol%. At the village hub the boiler system of the syrup module can be used for this purpose. When correcting for a boiler efficiency of 68% for a wood-fired boiler (see paragraph 5.1.9) this translates to primary energy use of 5.71 MJ/liter.

Stampe *et al.* (1983) report that their energy use is 'slightly lower than has been reported in other comparable systems'. However, this was considering the state of technology in 1983 when small-scale ethanol production received extensive attention in the American scientific community.

For juice processing in this system, the rocket stove is also used.

4.1.3.3 System 4: Use of waste-juice and syrup

The main activity of the village hub is the processing of juice into syrup. The juice produced for the village hub syrup module follows the same route (agroforestry land, juice processing and transportation) as the juice for the ethanol module. The capacity of the syrup module is many times larger than that of the distillery (Appendix V). It is likely that there will be instances where either juice or syrup is rendered useless. For example, if the syrup unit goes offline unexpectedly and the juice cannot be processed on time, this juice soon starts to spoil and is wasted. The same applies if there is some delay in the transport of juice from the tapper to the hub. Another possible situation is when produced syrup is contaminated by insects or from improper storage. Syrup or juice which is rendered unusable for consumption can instead be fermented and used to produce ethanol.

How much juice and syrup will be wasted at an operational village hub is unknown. However, considering that the syrup module has a juice processing capacity which is 6.9 times larger than the ethanol module (see Appendix V). A waste volume of 5% of the syrup module capacity is enough to supply the ethanol module. Whether enough waste sugar will be available will be known after a village hub has been operational for a while.

The environmental impacts resulting from the production of wasted juice or syrup is attributed to syrup production. If it is used to produce ethanol, this feedstock is considered to be free of its previous environmental impacts; the environmental impacts resulting from juice production and transportation are neglected.

The flow chart for this system is depicted below in figure 7. The allocation procedure is also different since it does not include the sugar palm cultivation phase. Therefore, the allocation for the whole system is only between ethanol for 96.7% and vinasse for 3.3%.

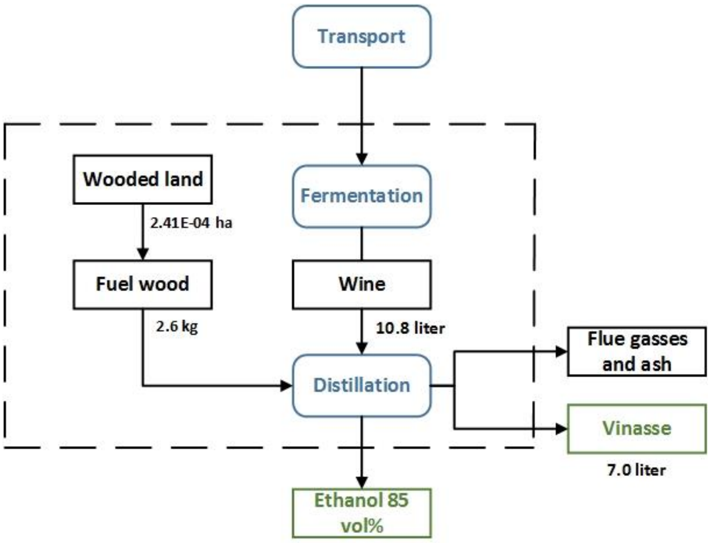

Figure 7: The cradle-to-gate lifecycle of sugar palm ethanol for system 4: waste juice and syrup. The agroforestry phase and transport processes are excluded from the assessment. The values indicate the input required to produce one liter of ethanol.

4.1.3.4 Summary: overview of systems

The systems are different regarding three processes in the ethanol lifecycle. Juice processing can either be performed with pan boiling or the rocket stove. For feedstock, processed juice can be used or waste juice and syrup. For distillation, either the village hub module is used or a larger scale distillery. Which processes are included in which system is described in table 3 below.

Table 3: Overview of the juice processing practices, feedstocks and ethanol modules of the four systems analyzed.

System #	**Juice processing**	**Feedstock**	**Ethanol module**
System 1: 'Reference'	Pan boiling	Processed juice	Village hub module
System 2: 'Rocket stove'	Rocket stove	Processed juice	Village hub module
System 3: 'Larger scale'	Rocket stove	Processed juice	Larger scale distiller
System 4: 'Waste juice'	-	Waste juice and syrup	Village hub module

Based on these variations, two other systems could be analyzed. A system with a large-scale distiller which makes use of pan boiling is excluded. This system does not make sense since the 'rocket stove' improvement is relatively easy to incorporate into the ethanol lifecycle and leads to a relatively large improvement.

A system that makes use of waste juice and syrup and includes a larger scale distiller is also excluded because it is unlikely that there will be enough waste juice and syrup to supply a larger scale distiller.

4.1.4 Impact assessment

Based on the values calculated for the inputs and outputs associated with the production with one liter of ethanol, a Life Cycle Inventory (LCI) is created with the use of the Simapro 7.3 software. Based on this LCI, the environmental impacts are determined using the *ReCiPe Midpoint (H) V1.05 / World ReCiPe H* and the *Eco-indicator 99 (H) V2.08 / Europe EI 99 H/H* impact assessment methods.

4.1.5 Biogenic carbon

In this system, biogenic carbon is stored in the juice and the fuel wood. This carbon is captured from the atmosphere and incorporated into the biomass of the wood and the sugars of the juice. This sequestered carbon is released later in the ethanol lifecycle; during combustion of the wood, combustion of the ethanol and during fermentation. Over the whole lifecycle of ethanol, the net effect of this biogenic carbon for the climate is zero. However, this study is based on the cradle to factory gate lifecycle of ethanol. At the factory gate, there is still biogenic carbon sequestered in the ethanol. If this were accounted for, the net CO_2 emissions would be negative. Instead, sequestered carbon is not included in the analysis as is customary for biofuels. This way, a comparison with other biofuels gives consistent results.

However, not accounting for biogenic carbon sequestration leads to inconsistent results when comparing to fossil gas. This gas contains fossil carbon which *does* have a climate impact. However, in a cradle to factory gate analysis the carbon is not yet released and the climate impact is zero. To account for the difference in climate impact between biogenic and fossil carbon, the carbon emissions of natural gas from combustion are included in the environmental impacts, even though these technically occur after the factory gate.

4.1.6 Land use impacts

Land use impacts result from the production of processed juice in the agroforestry phase as well as for the production of fuel wood for distillation. Ideally, the land use would be measured before and after the start of village hub operations to determine the land use impacts. For example, the tree density on the tappers` lands could be measured at the start of village hub operations and after one year of operations. Therefore, direct measurements of the method of fuel wood harvesting for distillation would be ideal.

Since direct measurements of land use impacts are not possible, assumptions have to be made about the LUC effects. The type of land use effects that are assumed are outlined in the next two sections. Other assumptions regarding land use would lead to different results. This is addressed in the results and discussion section.

4.1.6.1 Agroforestry land

The juice and fuel wood input for the production of processed juice requires the cultivation of agroforestry land. The increased demand for processed juice for ethanol production can lead to different scenarios of land use change. For this analysis, it is assumed that juice is purchased from tappers who would otherwise use this juice to produce sugar. Therefore, the land use of the agroforesters does not change.

This assumption is based on two observations. First, sugar palm tapping activities are declining in the Tomohon area since the tapping activities of parents are often not continued by children. Against a background of declining sugar palm cultivation, it is not likely that the village hub will completely reverse this trend and that the agroforestry cultivation of sugar palm starts expanding in the area. The second observation is that tappers cannot produce more juice from their lands by intensifying sugar palm cultivation. The productivity of tappers is in the first place constrained by their own labor input (Martini *et al.*, 2011). When tappers start supplying their juice to the village hub, their agricultural output will decline for some other product. This decline in output is most likely for sugar since tappers are also limited in the amount of fuel wood available on their land to process juice. Tappers who are producing sugar are already using more fuel wood than their land can supply (Results section 6.1.1). Even though most tappers could produce more juice on their land (Appendix VI), they would not have enough fuel wood to process the juice.

Therefore, a reduced production of sugar is the most probable effect if the village hub in Tomohon would start ethanol production. In this scenario, there are no direct land use change (DLUC) impacts for juice production. Instead, a reduced sugar production leads to indirect land use change (ILUC). What types of ILUC occurs in this scenario and the concurrent environmental consequences are discussed in the discussion chapter.

4.1.6.2 Wooded land for fuel wood

It is assumed that the land belonging and adjacent to the pilot village hub is used for fuel wood production. This land is a reforested hillside slope. Harvesting fuel wood from this land would require the management of this land to allow for a continuous production of wood.

By first reforesting this land and consecutively harvesting the land for fuel wood, the net environmental impacts in terms of biodiversity or carbon storage heavily depend on the practices employed. Here it is assumed that the net effect is zero. Therefore, the environmental impacts are only expressed in land occupation. The effects of this methodological choice are also addressed in the discussion chapter.

4.1.7 The emissions from wood burning

Burning fuel wood for the processing of juice and for distillation leads to emissions to air as well as solid waste in the form of ash. For fuel wood combustion in the boiler used in system 3, the following Ecoinvent dataset is used: 'Heat, hardwood logs, at furnace 30kW/CH S'. This dataset describes the lifecycle inventory for the production of one MJ of heat from a wood-fired boiler with 69% thermal efficiency. The thermal efficiency of the boiler system of the village hub is unknown and is therefore assumed to have the same efficiency. Included in this dataset is also the construction of the boiler, as well as the sourcing of the wood. These inputs, as well as all infrastructure inputs are excluded from the analysis.

For wood combustion for juice processing and distillation in the other scenarios, there is no dataset of a similar system in Ecoinvent. Therefore, for these systems, the LCI values of the furnace dataset are used with adjusted values based on the emissions data from Pettersson *et al.* (2010). How the Ecoinvent dataset is used and how the dataset is adjusted to approximate the other wood burning processes and why Pettersson *et al.* (2010) is used for this purpose is outlined in Appendix XV.

4.1.8 Natural gas

The environmental impacts of sugar palm ethanol are compared to those of natural gas and of other biofuels to provide a frame of reference. When comparing the environmental impacts of different fuels, a comparison based on the LHV is most appropriate. For example, Whitaker *et al.* (2010) and De Vries *et al.* (2010) compare the environmental impacts of different biofuels on a per MJ basis.

For the comparison with natural gas, the environmental impacts of on liter of sugar palm ethanol with 16.7 MJ is compared with a corresponding amount of natural gas. The environmental impacts of natural gas production are based on the 'Natural gas' Ecoinvent dataset. The natural gas used in Tomohon is produced in Indonesia since Indonesia is a producer and net exporter of natural gas. Transport over sea is not included in the analysis. However, transport over land *is* included. The weight of 16.7 MJ of natural gas corresponds with 0.31 kg. Natural gas for retail sale is transported in canisters. Therefore, to transport 0.31 kg of natural gas, an additional 0.16 kg of canister is transported. The transport over land from Manado to Tomohon is 30km. Therefore, the land transport input is 1.41E-02 tkm/liter ethanol equivalent of natural gas.

The fossil carbon contained in natural gas is not released in the cradle to factory gate analysis. However, because of the methodological choices regarding biogenic carbon where carbon sequestration is disregarded, this leads to an uneven comparison between natural gas and sugar palm ethanol. To address this, the carbon emissions which would occur during natural gas combustion are added to the environmental impacts of natural gas (5.03E-02 kg CO_2/MJ natural gas, based on: IEA 2013), even though these emissions occur outside of the system boundaries.

4.2 Production costs of ethanol

The production cost of ethanol is an important factor influencing the successful implementation of ethanol production in current and future village hubs. Rural communities that use solid biomass fuels for cooking will benefit from the availability of a clean liquid fuel. However, natural gas is already a widespread and clean fuel. People who use solid biomass apparently cannot or are unwilling to invest in a more expensive fuel. For ethanol production to be effective, its price should be lower than natural gas. If the production cost of ethanol production is higher than the retail price of natural gas, ethanol production has to be subsidized to make it attractive for consumers.

Because so far there has not been any commercial ethanol production from a village hub, the cost of ethanol production is unknown. To determine the cost, an estimate is made based on the following cost factors: processed juice, transportation (fuel cost, depreciation of truck and labor), the ethanol unit, labor for operating the ethanol unit and the cost of the fuel wood. Other costs factors which are not included: the cost the rocket stove, maintenance cost for the distiller, maintenance cost for the trucks, different types of overhead costs (administration, management) of the village hub, insurance costs (if any), and many other costs associated with an organization.

Estimating the future production costs of ethanol production, as well as its value, is very complicated and uncertain. The price of juice has seen a steep increase in the Tomohon area. The cost of labor is unpredictable in Indonesia since the minimum wage has increased unexpectedly and with large percentages over the last years. In addition, the prices of (subsidized) fuels are likely to continue to rise unpredictably as they have done in the past.

Because both the production cost of ethanol as well as the value of ethanol is likely to change greatly over the lifetime of the village hub distillation unit, these values are only calculated for the first year of operations based on current price levels. Investment costs for equipment that only occur at the start of operations are divided by the estimated lifetime of the equipment.

5 Data

5.1 LCA data

The parameters used for the life cycle inventory are summarized in the table below.

Table 4: Parameter values for the different processes included in the ethanol LCA.

Process	Value	Unit	Source
Village hub capacity			
Ethanol concentration in product	85	Vol%	Reference product
Load factor module	260	Days/year	Considering work days
Daily ethanol production	32.2	Liters/day	Appendix VII
Yearly ethanol production	8,378	Liters/year	
Larger scale capacity			
Ethanol concentration in product	85	Vol%	Reference product
Load factor module	260	Days/year	Considering work days
Daily ethanol production	500	Liters/day	Ch. 4.1.3.2
Yearly ethanol production	130,000	Liters/year	
Sugar palm cultivation intensity			
Juice yields	64,672	Liters juice/ha	Ch. 5.1.1; Appendix VI
Sugar concentration of juice			
Sugar concentration of juice	15.0	°Brix	Ch. 5.1.2; Appendix IX
Juice boiling			
Minimum energy for boiling to 20°Brix	1.272	MJ/liter fresh juice	Ch. 5.1.3; Appendix X
Juice boiling in pan			
Pan energy efficiency	20	%	Ch. 5.1.3; Appendix XI
Pan energy consumption	6.70	MJ/liter juice	Ch. 5.1.3; Appendix XI
Pan energy consumption	73	MJ/liter ethanol	
Juice boiling in rocket stove			
Rocket stove energy efficiency	50	%	Ch. 5.1.3; Appendix II
Rocket stove energy consumption	2.55	MJ/liter juice	Ch. 5.1.3; Appendix II
Rocket stove energy consumption	27.6	MJ/liter ethanol	
Transport			
Average route distance	18.5	Km	Appendix VIII
Juice transport volume	1272	Liters juice per trip	Appendix VIII
Average transport input	12.7	Tkm/trip	Appendix VIII
Fuel wood properties			
Wood LHV air-dried	14.9	MJ/kg air-dried wood	Ch. 5.1.4; Appendix XII

Moisture content air-dried wood	18.8	%	Ch. 5.1.4; Appendix XII
Production land yield			
Wood yield of production forest	25	M^3 fresh wood/ha/year	Ch. 5.1.5; Appendix XIII
Wood yield of production forest	10,666	Kg air-dried wood/ha/year	Ch. 5.1.5; Appendix XIII
Energy yield of forest	158,934	MJ/ha/year	Ch. 5.1.5; Appendix XIII
Fermentation			
Fermentation efficiency	75	%	Ch. 5.1.6; Appendix XIV
Ethanol concentration of wine	10.6	Vol%	Ch. 5.1.6; Appendix XIV
Distillation			
Energy use pilot village hub distiller	38.4	MJ/liter ethanol	Ch. 5.1.7; Appendix XII
Energy use system 3 distiller	5.7	MJ/liter ethanol	Ch. 4.1.3.2
Juice - ethanol ratio	7.99	Liters juice (20°Brix)/liter ethanol	Ch. 5.1.7
Juice - ethanol ratio	10.8	Liters juice (Fresh)/liter ethanol	Ch. 5.1.7
Natural gas			
Lower heating value	53.6	MJ/kg	Ch. 5.1.8
Land transport	1.41E-02	Tkm/16.7 MJ equivalent	Ch. 5.1.8
CO_2 emissions	50,3	Gram CO_2/MJ	Ch. 5.1.8

These values are used to calculate the LCI and the average environmental impact of ethanol production for the four systems. Moreover, an upper limit and lower limit for the environmental impacts is determined. These upper and lower limits are based on a life cycle inventory that makes use of adapted values for the table above. The parameters that are varied influence many values downstream. Therefore, these parameters have the largest impact on the final environmental impacts. As long as possible, the high and low impact parameters are based on the variability of the underlying data. However, in part they are based on educated estimates.

Table 5: Parameter values for the 'high', 'average' and 'low' impact scenario.

Input	Unit	High impacts	Average impacts	Low impacts
Average transport input	Tkm/trip	6	13	20
Fermentation efficiency	%	60	75	90
Sugar concentration juice	°Brix	12	15	18
Energy yield of forest	MJ/ha/year	100,000	158,934	200,000
Pan efficiency	%	10	20	30
Rocket stove efficiency	%	40	50	60
Distillation heat input village hub	MJ/liter ethanol	56	38	20
Distillation heat input system 3	MJ/liter ethanol	10	5.7	4

When these parameters are changed, other parameters change with them. The heat requirement for juice boiling is affected by the sugar concentration in the juice and the boiling efficiency. The agroforestry land requirement is in turn affected by the heat requirement for juice boiling, the fermentation efficiency and the energy yield of forests. The wooded land requirement is affected by the distillation heat input and by the energy yield of forests.

The effects of these parameters compound to greatly increase or decrease the environmental impacts. Therefore, the results for these high and low impact scenarios can effectively be regarded as upper and lower limits of the environmental impacts of the four scenarios.

5.1.1 Sugar palm cultivation intensity

The Masarang foundation performed an extensive survey of 91 sugar palm tappers in the Tomohon area with a combined total of 60.7 hectares of land. The survey was performed between 12-06-2011 and 19-09-2011. Among the data that was collected from the sugar palm tappers was the amount of sugar palm trees on their land. Every palm tree counted on the tapper's land was furthermore categorized as 'young tree', 'adult tree which is tapped', 'adult tree which is not tapped' and 'spent, previously tapped tree'. The amount of land in their possession in hectares was determined and an estimate was made of their yearly juice production. Since this is data collected from functioning sugar palm lands, it gives a clear picture of the properties of current agroforestry sugar palm cultivation practices. A breakdown of this information is presented in Appendix VI.

Based on this survey:

- The average size of a farmer's plot is 0.6 hectare;
- The average sugar palm tree density: 111 trees/ha;
- The average tapping intensity is 12 trees tapped/ha;
- The average juice yields is 64,672 liters juice/ha;
- The maximum sugar palm tree density is between 150-300 palms/ha.

5.1.2 Sugar concentration of juice

The Masarang sugar factory kept records of the juice volumes they purchased from tappers collected in November 2011. This record includes a breakdown of the amount of juice purchased per individual tapper for every day and the °Brix of the juice for each delivery. In total during these 30 days, 29.8 hectoliter of juice was collected from 21 tappers. Based on this raw data, the distribution of °Brix values measured for the purchased juice was determined. The breakdown of this information is presented in Appendix IX.

Based on this data, sugar palm tappers in the Tomohon area produce sugar with an average sugar concentration of 15.0 °Brix with a standard deviation of 2.3 °Brix.

5.1.3 Juice boiling

Two tappers measured how much wood they used to boil their juice in a pan. They also recorded the volume of the juice and the sugar concentration at the start of boiling. The amount of heat *added* was calculated based on the LHV of wood of 14.9 MJ/kg multiplied with the amount of wood burned. The amount of heat *required* was calculated based on the heat capacity of juice and the heat of evaporation of water. The method for calculating the heat required for boiling is outlined in Appendix X.

The average efficiency of boiling juice in a pan was found to be 19.8%. Heating of the juice starts almost immediately after the fire starts. Therefore, the relation between heat added and heat required is:

$$Heat\ added\ \left(\frac{MJ}{liter}\right) = 5.051 * Heat\ required\ \left(\frac{MJ}{liter}\right)$$

Juice boiling in the rocket stove was measured on three occasions. Using the method outlined in Appendix X, the boiling efficiency was determined to be 50%. However, first the rocket stove itself is heated before heat is transferred to the juice. Therefore, the relationship between heat added and heat required is the following:

$$Heat\ added\ \left(\frac{MJ}{liter}\right) = 124.8\ \left(\frac{MJ}{liter}\right) + \left(1.4768 * Heat\ required\ \left(\frac{MJ}{liter}\right)\right)$$

Based on these equations, the rocket stove is more efficient at boiling juice when over 52 liters of juice is processed.

5.1.4 Fuel wood properties

Fresh wood has a moisture content of 50% with a density of 0.62 kg/liter (Agus and Van Noordwijk, 2005). One M^3 of fresh wood therefore weighs approximately 620 kg. The moisture content of air-dried wood was determined to be 18.8% for typical fuel wood used by tappers (Appendix XII). After drying, the moisture content is decreased from 50% to 18.8% on average. Therefore, 31.2% of the weight of the wood is lost and 68.8% of the weight remains. Therefore, one M^3 of fresh wood weighs 620 kg * 0.688 = 427 kg after drying.

The lower heating value of 14.9 MJ/kg of air-dried is determined based on literature values. The calculations to determine the heating value are outlined in Appendix XII.

5.1.5 Production land yield

The amount of fuel wood that is produced per hectare of agroforestry land and from production land is an important parameter in the analysis to determine the land requirements. Fuel wood yields are the constraining factor for the processed juice yield of the agroforestry land. Therefore, the fuel wood availability directly translated to agroforestry land requirements.

Determining the fuel wood productivity of agroforestry lands is a difficult task. The value used for the fuel wood productivity comes from Dr. W. Smits who measured the volume of all the trees in a ten-year-old forested stand in the Tomohon area. This measurement showed that the above ground biomass totaled 250 m^3 of wood indicating that the yearly biomass increment was on average 25 $m^3ha^{-1}year^{-1}$. A review of the literature (Appendix XIII) shows that the yearly wood productivity of 25 $m^3ha^{-1}year^{-1}$ for natural forest or a production forest is appropriate. After air drying this wood, one hectare yields 10,666 kg fuel wood or 158,934 MJ.

5.1.6 Fermentation efficiency

The fermentation efficiency was determined by the village hub operators to be 75%. How the fermentation efficiency is defined is outlined in Appendix XIV as well as the formula that relates sugar concentration, fermentation efficiency and ethanol concentration. Based on this fermentation efficiency, juice with 20°Brix yields wine with 10.6 vol% ethanol.

5.1.7 Distillation

The heat required to produce ethanol from the distiller was measured on three occasions. The heat input per liter produced depends on three variables: the start-up energy required, the heat per liter produced after start-up and the volume produced before distillation is stopped. The heat required for distillation is determined to be between 30.0 and 46.2 MJ/liter with an average of 38.1 MJ/liter. The measurements performed on the distiller and the distillation process, as well as the calculations are outlined in Appendix VII.

After distillation, the wine is spent and ethanol and vinasse remain. For every liter of ethanol that is produced, 85/10.6 = 7.99 liters of wine is required. For every liter of wine, 1.36 liters of fresh juice is required (since the juice is boiled, some volume is lost). Therefore, for every liter of ethanol which is produced, 10.8 liter of fresh juice is required as input.

5.2 Cost analysis data

The following table summarizes the values used for the cost analysis. Background information is provided below the table in the different sections belonging to the various cost factors. The values are all based on 2013 price levels.

Table 6: Values used for the ethanol cost analysis calculations.

Cost factor	Unit	Value	Source
Juice costs			
Estimated cost for 2013 price levels	Rp	1,503	Ch. 5.2.1; 6.2.1
Truck costs			
Average truck lifetime	Km	289,608	Ch. 5.2.2
Truck cost	$	20,120	Ch. 5.2.2
Transport fuel costs			
Diesel cost	Rp/liter	5,500	Ch. 5.2.3
Wages			
Minimum hourly wage	Rp	8,942	Ch. 5.2.4
Labor for transportation per route	Hours	4	Ch. 5.2.4
Labor for module operation per day	Hours	3	Ch. 5.2.4
Cost of modules			
Small-scale module	$	11,000	Ch. 5.2.5
Large-scale module	$	151,000	Ch. 5.2.5
Wood costs			
Wood requirements small-scale unit	M^3/year	51	Ch. 5.2.6
Wood requirements large-scale unit	M^3/year	117	Ch. 5.2.6
Wood cost	$\$/m^3$	10	Ch. 5.2.6
Currency conversion rate			
Currency conversion rate Indonesian Rupee - US Dollar	$/Rp	1.03356E-04	Ch. 5.2.7

5.2.1 The cost of juice

The cost of juice is a large contributor to the cost of ethanol production. However, juice prices in the Tomohon area have been volatile. This juice price started with Rp.700 at the opening of the factory in 2007 (Rp.950 at 2013 price levels) and increased to Rp.1,200 in the year 2012 (Rp.1,278 at 2013 price levels). When juice prices continued to rise in the Tomohon area, the sugar factory stopped production. Current juice prices are an estimated to be between Rp.1,503 – Rp.2,500 based on the price of processed sugar and Sagwer (see Results chapter 6.2.7).

5.2.2 The costs of the vehicle

The cost of transportation is based on the transport fuel cost, the cost of the truck and labor cost. A new Toyota Dyna truck of the type which is used in the pilot village hub costs Rp.219,250,000 new based on the 2013 price offered on the Indonesian Toyota website. The assumed lifetime of this truck is assumed 179,954 miles (289,608 km) average light truck lifetime in the US (Davis, 2013).

5.2.3 The cost of transport fuel

The amount of fuel used is calculated for the LCA analysis (based on transport route length, fuel efficiency and truck load factor; see Appendix VIII). One transport trip transports 2,772 liters of juice and requires 2.5 liters of diesel. Subsidized diesel costs Rp.5,500 per liter.

5.2.4 The cost of wages

The Indonesian minimum monthly wage is different per province. For North Sulawesi, the minimum monthly wage is Rp.1,550,000 for 2013 (Wage indicator, 2013). Converting to an hourly wage considering a 40-hours work week yields a minimum hourly wage of Rp.8,942.

Operating the village hub distiller requires a minimum amount of effort. It only requires lighting the stove and checking the process every half hour which can be done by regular village hub personnel. Preparing the equipment and lighting the stove requires approximately half an hour which is performed twice every day. Additional time has is spent to keep the stove burning and to check the fluid levels. Labor costs for operating this distiller are therefore estimated to be three hours of work per day at a cost of minimum wages.

Batch distillation units found online have automated procedures to distill one complete batch. Operation of these units will require some preparation work before distilling and some work afterwards. The labor input for the distillation processes is assumed to be one hour per batch. With three batches distilled per day, the total labor investment is three hours per day as well.

5.2.5 The cost of the modules

The cost of the village hub ethanol unit is not available. However, the costs of distillation units with a comparable capacity are readily available online. A cost for the distillation equipment is assumed to be $10,000 which is the price of small-scale distillation units offered online by Chinese companies like the Wenzhou Onway Machinery Company and the Zhejiang Dayu Light Industrial Machinery Company. Another $1,000 is assumed for shipping costs oversees from Shanghai to Jakarta to Manado (worldfreightrates.com). A lifetime of 20 years is assumed for this equipment.

For the larger scale ethanol distillation with a capacity of 500 liters per day, a cost of $150,000 is assumed which is based on distillery prices with a similar capacity offered online by the Wenzhou Onway Machinery Company. Another $1,000 is assumed for shipping costs oversees from Shanghai to Jakarta to Manado (www.worldfreightrates.com). The lifetime of this unit is assumed to be 20 years.

5.2.6 The cost of fuel wood

The amount of fuel wood required for the production of ethanol in the small and large-scale module is calculated in the LCA. The cost of Indonesian fuel wood is assumed to be $10 per m^3 (Martini *et al.*, 2011).

5.2.7 Currency conversion rate

Most of the prices listed above are price levels observed between February and April of 2013. Cost inputs that are expressed in US Dollars are converted to Rupiah according to the exchange rate between these currencies for the first of March 2013. The currency conversion rate from Rupiah to American Dollar is taken from the website www.xe.com which is based on the exchange rate of the Mid-market rates on 2013-03-01 17:00 UTC. Whenever a currency conversion from dollars to rupees is performed, a conversion rate of 1.03356E-04 $/Rp., or 9675.3 Rp./$ is used.

6 Results

The results are presented in two parts for the LCA in chapter 6.1 and the cost analysis in chapters 6.2.

6.1 LCA Results

Paragraph 6.1.1 presents the results regarding the processed juice yields in the agroforestry phase that is limited by fuel wood availability instead of fresh juice production capacity. Next, paragraph 6.1.2 reports the performance parameters calculated for the different system and shows how these parameters are translated to create the LCI with the use of Ecoinvent datasets and literature sources. Paragraph 6.1.3 presents the midpoint environmental impact results for the four ethanol systems and for natural gas. In paragraph 6.1.5, the GHG emissions of sugar palm ethanol are compared to the emissions from other biofuels. Paragraph 6.1.6 presents the endpoint environmental impact results and a comparison of the weighted scores for the four systems and natural gas.

6.1.1 Agroforestry land use

Before moving on to the LCI results, the mass flow calculations revealed an interesting property pertaining to the agroforestry land use: processing all the juice produced from the agroforestry lands require more fuel wood than the land can support. The consequence is that the processed juice yield of the agroforestry lands depends on their fuel wood productivity. The following sections show that processed juice yields are limited by the fuel wood availability.

Based on the Masarang survey (Appendix VI), tappers produce on average 64,672 liters of fresh juice per hectare per year. Moreover, there is a large variation in juice productivity with some tappers producing more than twice that amount.

Chapter 5.1, Appendix X and Appendix XI reveal that the energy requirement for juice processing with a pan requires 6.2 MJ/liter and with the rocket stove requires 2.4 MJ/liter. Considering that agroforestry land yields an estimated 158,934 MJ/ha/year (Appendix XIII), at most 23,732 and 62,344 liters can be processed with the systems. This is less juice than can be produced on this land. The rocket stove is more than twice as efficient as pan boiling and therefore requires less than that half of the amount of agroforestry land.

This result also indicates that tappers who are producing sugar are producing more juice than they can process. Sugar production requires more energy than processing the juice to 20 °Brix. Producing juice into sugar requires 2.6 MJ/liter (using calculations from Appendix X). Therefore, considering a juice boiling efficiency of 20% using a pan (Appendix XI), a tapper can produce sugar from 11,493 liters of juice per hectare. Since most of the tappers in the Masarang survey were producing more juice than that, they were either using fuel wood harvested from outside of their land or they were processing the juice into a product that requires less fuel wood such as Sagwer.

6.1.2 Life cycle inventory

A life cycle inventory (LCI) contains all the inputs to and outputs from the system. The LCI is the basis of the impact assessment. The complete list of the life cycle inventory is very long. However, there are five parameters for each of the systems studied that are translated by Simpro and the Ecoinvent database into the LCI. These parameters are: agroforestry land use (ha), wooded land use (ha), juice transport (tkm), heat use stove (MJ) and heat use boiler (MJ). The values for these parameters are presented in the table below. For the values, allocation has already been taken into account as outlined in paragraph 4.1.2.

Table 7: Background data for the LCI.

		System			
Parameter	**Unit**	**System 1**	**System 2**	**System 3**	**System 4**
Wooded land use	Ha/liter	2,34E-04	2,34E-04	3,48E-05	2,34E-04
Agroforestry land use	Ha/liter	2,22E-04	8,43E-05	8,43E-05	0
Juice transport	Tkm/liter	7.75E-02	7.75E-02	7.75E-02	0
Heat use stove	MJ/liter	108	64.0	26.8	37.2
Heat use boiler	MJ/liter	0	0	5.54	0

These results already reveal a lot about the relative performance of the four systems. System 2 performs better than the reference system concerning total land use and wood combusted. Since the other inputs of these systems are equal, system 2 has a better environmental performance than the reference system. System 3 performs better than system 2 since wood combusted in the boiler has a lower environmental impact than wood combusted in a stove, and overall less wood is combusted. System 4 performs better than the reference system and system 2. The only unknown is whether system 3 or four performs better.

Some of these parameters are directly responsible for environmental impacts. The Eco-indicator 99 environmental impact assessment method includes 11 environmental impact categories. The 'forest occupation' input contributes to the 'land use' environmental impact indicator.

For the other parameters, eco-invent datasets are used. These datasets are LCIs for the processes they describe. These LCIs are then translated to environmental impacts via the environmental impact assessment methods. The datasets that are used are presented in the table below.

Table 8: The Ecoinvent datasets and inputs which are used to build the LCI for the sugar palm ethanol lifecycle.

Input	**Unit**	**Ecoinvent dataset/input**
Wooded land use	Ha	'Forest land occupation'
Agroforestry land use	Ha	'Forest land occupation' (50%) and 'Arable land occupation' (50%)
Juice transport	Tkm	'Small lorry transport, Euro 0, 1, 2, 3, 4 mix, 7,5 t total weight, 3,3 t max payload'
Heat use stove	MJ	'Heat, hardwood logs, at furnace 100kW/MJ/CH', with adjusted emissions based on Pettersson *et al.* (2010) and 'Forest land occupation' removed
Heat use boiler	MJ	'Heat, hardwood logs, at furnace 100kW/MJ/CH', with 'Forest land occupation' removed

For the LCI dataset regarding wood combusted in a stove, the 'forest land occupation' environmental input is removed since this input is already calculated separately. Moreover, the most important emissions are adapted based on the measurements performed by Pettersson *et al.* (2010) to more accurately account for the higher emissions of a stove compared to a boiler (see Appendix XV). For wood combusted in a boiler, the same dataset is used including the original emission values while also excluding the 'forest land occupation' input. When the LCA is performed, the inputs of infrastructure are not included since for many processes the infrastructure lifecycle is unknown; for example for the village hub distillery and the rocket stove. The land use for fuel wood production is included separately as 'forest land occupation'. For the agroforestry land use, equal amounts of 'forest land occupation' and 'Arable land occupation' are used since agroforestry is a combination of forest and agriculture.

6.1.2.1 Natural gas

For natural gas, the following Ecoinvent datasets and values are used.

Table 9: The Ecoinvent datasets and inputs that are used to build the LCI for the natural gas lifecycle.

Input	**Unit**	**Amount**	**Ecoinvent dataset**
Natural gas extraction	MJ	16.7	'Natural gas'
Natural gas transport	Tkm	1.41E-02	'Transport, lorry >28t, fleet average/CH S'
Combustion CO_2 emissions	Kg	0.842	'Carbon dioxide emission, fossil, high population'

6.1.3 LCA midpoint impact results

Based on the LCI, the environmental impacts are calculated using the *ReCiPe Midpoint (H) V1.05 / World ReCiPe H* impact assessment method. The midpoint environmental impacts are presented in the table below. System 3 outperforms system 2 in all categories which in turn outperforms system 1 in all categories. System 4 and system 3 are tied in performance; they have a better score in 9 out of 18 categories. In the categories where system 3 has a better performance, the difference is usually small whereas the difference is larger when system 4 has a better performance. Natural gas outperforms sugar palm ethanol in 16 out of 18 environmental impact categories. The two exceptions are the climate change and fossil depletion impact category.

Table 10: The midpoint LCA impact results for one liter of sugar palm ethanol production by system 1-4 and for an equal amount (based on the LHV) of natural gas. The red cells indicate the highest impact in that category. The lowest (best) impact score is marked green. The systems in between are colored orange and yellow, with increasing amounts of green for better scores.

Impact category	**Unit**	**System 1: Reference**	**System 2: Rocket stove**	**System 3: Larger capacity**	**System: 4 Waste juice**	**Natural gas**
Climate change	kg CO_{2eq}	7,35E-01	4,90E-01	3,05E-01	2,10E-01	1,00E+00
Ozone depletion	kg CFC-11_{eq}	2,07E-07	1,93E-07	1,83E-07	1,20E-08	3,19E-10
Human toxicity	kg 1,4-DB_{eq}	4,34E+00	2,60E+00	1,34E+00	1,48E+00	2,73E-04
Photochemical oxidant formation	kg NMVOC	3,23E-02	1,97E-02	1,04E-02	1,07E-02	1,70E-04
Particulate matter formation	kg $PM10_{eq}$	2,45E-03	1,55E-03	1,33E-03	7,62E-04	3,63E-05
Ionising radiation	kg $U235_{eq}$	4,00E-01	2,45E-01	1,33E-01	1,32E-01	1,67E-04
Terrestrial acidification	kg $SO2_{eq}$	6,34E-03	4,03E-03	2,77E-03	1,97E-03	9,10E-05
Freshwater eutrophication	kg P_{eq}	3,58E-04	2,13E-04	1,08E-04	1,24E-04	1,84E-07
Marine eutrophication	kg N_{eq}	3,08E-03	1,94E-03	1,40E-03	9,71E-04	6,16E-05
Terrestrial ecotoxicity	kg 1,4-DB_{eq}	2,99E-02	1,78E-02	9,00E-03	1,03E-02	2,37E-07
Freshwater ecotoxicity	kg 1,4-DB_{eq}	1,04E-02	6,23E-03	3,18E-03	3,59E-03	5,24E-06
Marine ecotoxicity	kg 1,4-DB_{eq}	1,41E-02	8,47E-03	4,36E-03	4,83E-03	5,53E-06
Agricultural land occupation	m2a	4,56E+00	3,19E+00	1,19E+00	2,34E+00	7,87E-06
Urban land occupation	m2a	1,15E-01	6,85E-02	2,87E-02	3,98E-02	1,85E-05
Natural land transformation	m2	9,58E-04	5,70E-04	2,88E-04	3,31E-04	7,08E-07
Water depletion	m3	5,24E-03	3,47E-03	2,18E-03	1,51E-03	8,35E-06
Metal depletion	kg Fe_{eq}	9,63E-02	5,97E-02	3,30E-02	3,13E-02	1,04E-04
Fossil depletion	kg oil_{eq}	1,45E-01	1,04E-01	7,38E-02	3,53E-02	4,19E-01

The results in a table below are presented in graph form. The impacts are normalized to 100%. Most of the impacts follow the same distribution where the reference system has the 100% score, system 2 has a ~60% score, system 3 and 4 have a ~35% score. Natural gas has a ~0% score for most of the impacts. Notable exceptions are climate change and fossil depletion where natural gas has the 100% score. Another exception is the ozone depletion impact where system 4 only has a 6% score since transport is responsible for most of this impact which is absent in this system.

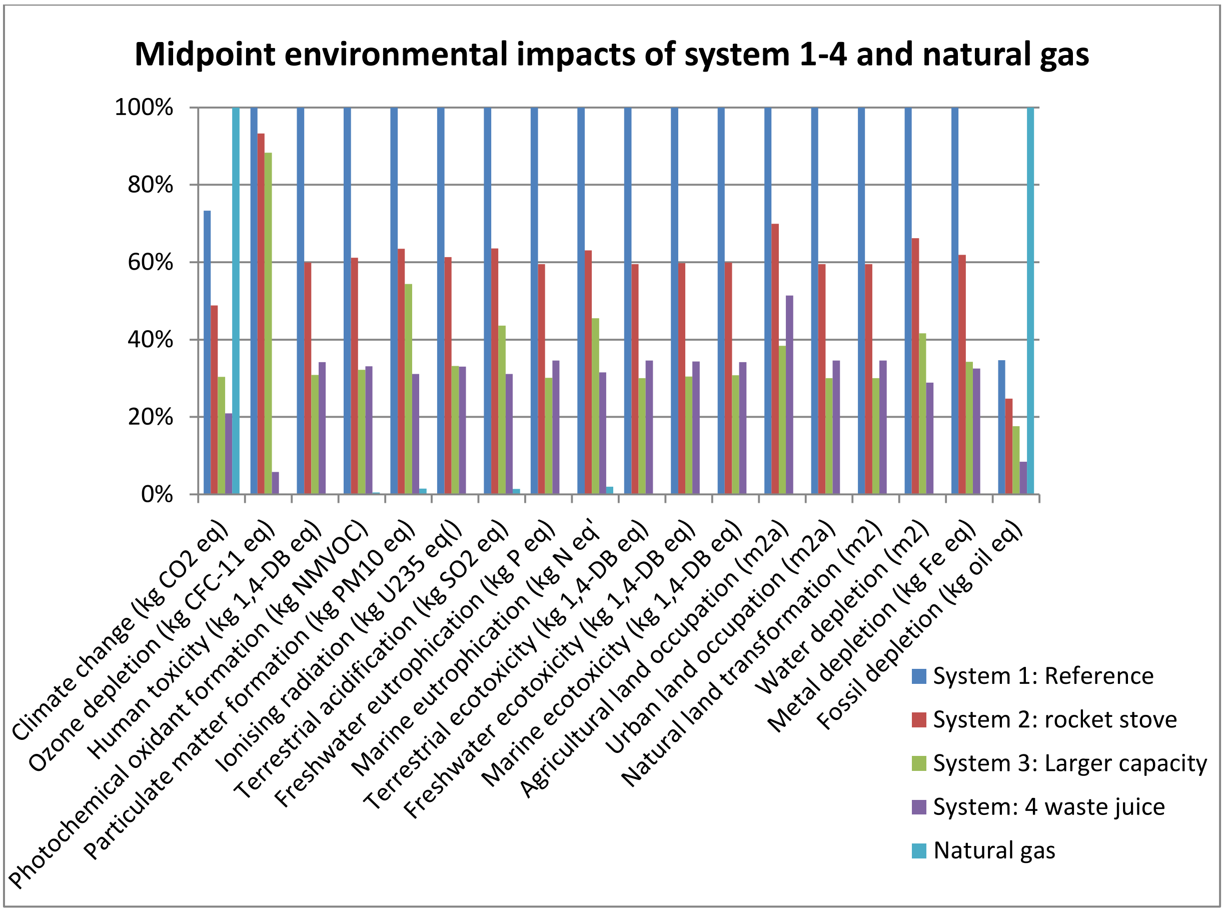

Figure 8: The normalized, midpoint environmental impact results (%) of system 1-4 and natural gas.

6.1.3.1 Process contributions results

Almost all of the environmental impacts are due to fuel wood burning from juice processing and distillation. These processes contribute the most to 16 out of 18 environmental impacts. The first exception is for the ozone layer depletion impact where transport contributes the most. The second exception is for the agricultural land occupation impact where agroforestry and wooded land use contribute the most.

The relative contributions of processes in the ethanol lifecycle to the environmental impact scores are depicted in the figures below. Scenario 4 only has two inputs which contribute to environmental impacts: distillation and wooded land use. The distillation input is therefore responsible for 100% of the impact score in 17 out of 18 impacts, with wooded land use responsible for the impact score in agricultural land use. Therefore, scenario 4 is not depicted in a graph.

When comparing the differences in the relative contribution of the processes to the environmental impacts, the first observation is that the contribution of transport increases in scenario 2 and 3. The explanation for this is that the absolute contribution from transport is the same for the three systems whereas the contribution from the other processes decreases as improvements are implemented.

Juice processing is the single largest contributor to most environmental impacts categories for system 1 and 3. In scenario 2, distillation is the largest contributor.

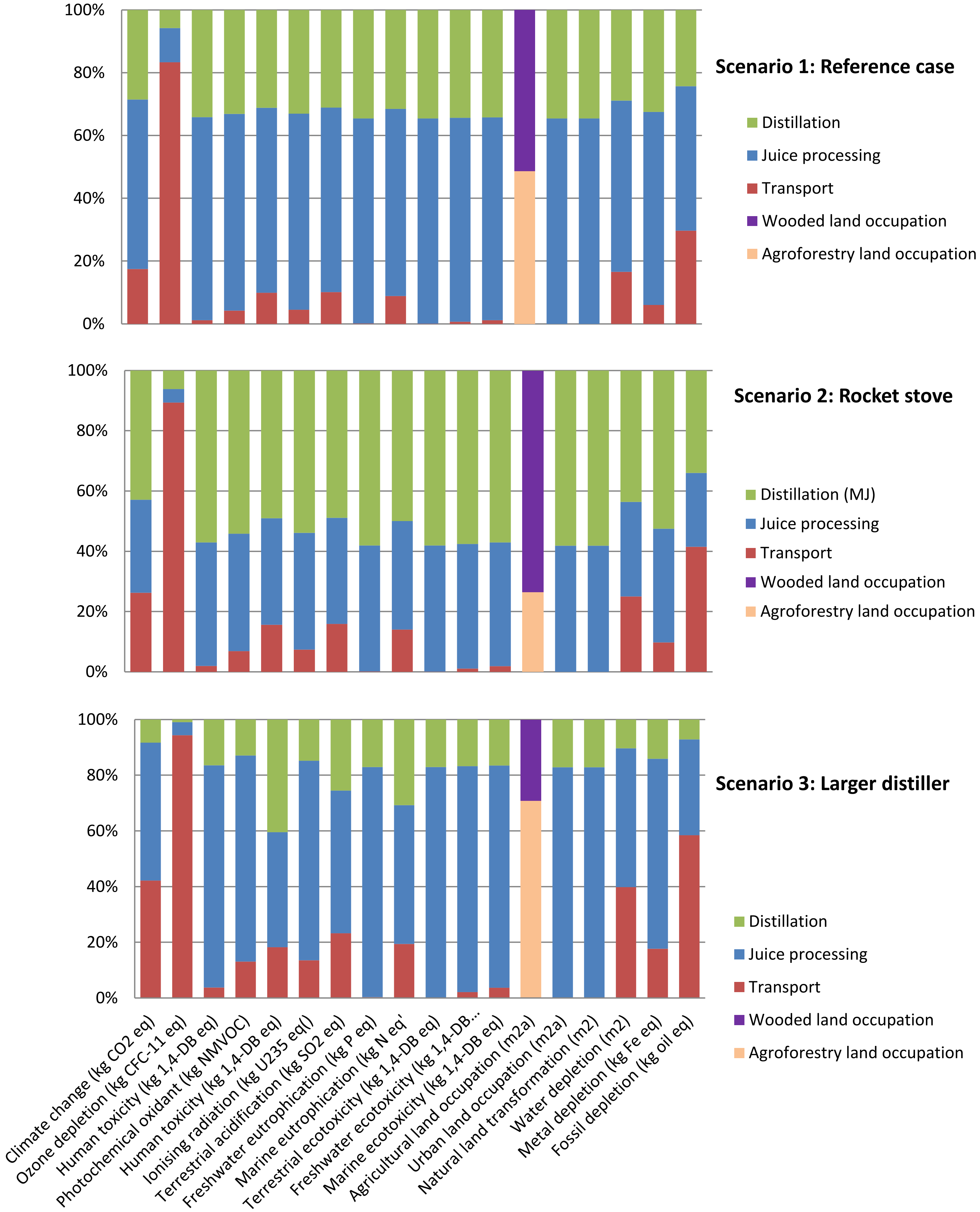

Figure 9: The normalized midpoint environmental impact results (%) of scenarios 1-3. The figures compare the relative contribution of the processes to the 18 environmental impacts.

6.1.5 Comparison with other biofuels

The GHG emissions are an important part of the environmental impact. The climate change impact varies greatly between different biofuels, depending in large part on the type of feedstock used and the use of waste products. Similarly, there is a large difference between the climate change impacts of sugar palm ethanol in the different scenarios. The graph below compares the GHG emissions of a large selection of biofuels based on the aggregated results of two scientific works (Whitaker *et al.* 2010; De Vries *et al.* 2010).

The GHG emission of sugar palm ethanol in scenario 1 is relatively high and comparable to the emissions of wheat, sugar beet and cassava bioethanol as well as rapeseed biodiesel. The GHG emissions of sugar palm ethanol in scenario 4 are relatively low and comparable to second generation biofuels such as biodiesel from recycled vegetable oil or bioethanol produced from wheat straw. The GHG emissions of sugar palm ethanol in scenario 2 and 3 are intermediate and comparable to those of biofuels such as sugar cane ethanol, palm oil biodiesel and bioethanol produced from energy grasses.

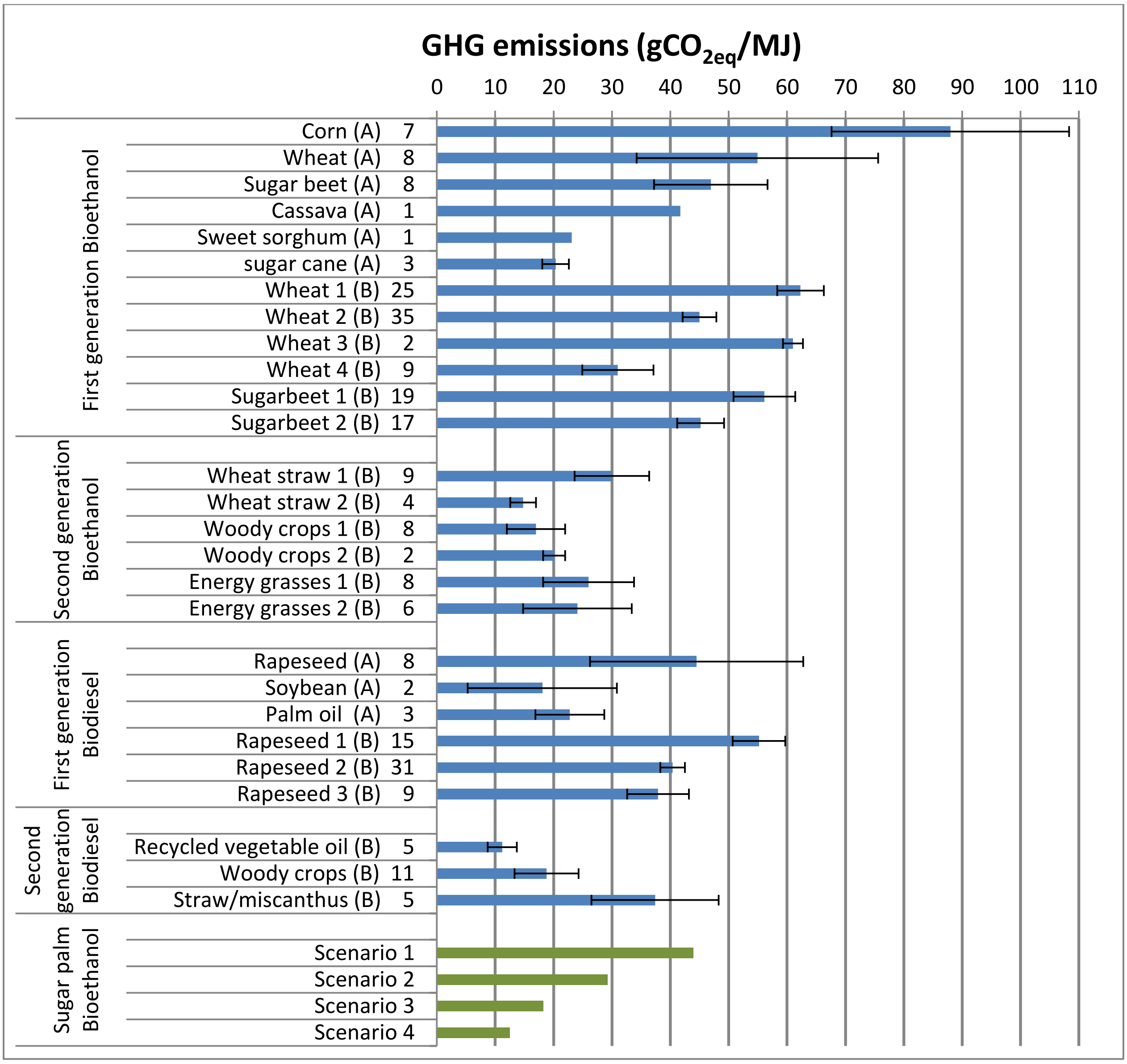

Figure 10: The GHG emissions of a selection of biofuels including those of sugar palm ethanol. The GHG emissions are adapted from two scientific sources indicated by (A) which indicate De Vries *et al.* (2010) and (B) which indicates Whitaker *et al.* (2010) as the source. The value listed after the crop type and literature source indicates the amount (N) of LCA sources which were used by the sources to compile the average and standard deviation of the GHG emissions for this biofuel. The lifecycle GHG emissions calculated by De Vries *et al.* (2010) are based on a cradle to factory gate analysis and

exclude infrastructure contributions. The biofuels analyzed by this source only include first generation biofuels cultivated in different regions: maize (USA), wheat (Northwest Europe), sugar beet (Northwest Europe), cassava (Thailand), sweet sorghum (China), sugarcane (Brazil), rapeseed (Northwest Europe), soybean (USA) and oil palm (Malaysia). The GHG emission values are based on LCA results which make use of system expansion to deal with multi product systems.

The GHG emissions calculated by Whitaker *et al.* (2010) include infrastructure contributions and the distribution of the biofuel to the consumers (well to tank analysis). The biofuels analyzed by this source include first and second generation biofuels ‘which could be cultivated in the United Kingdom or northern Europe’. The values listed by this source are aggregated from results using different allocation methods. However, different values are reported per biofuel type based the utilization of by-products. These different types are indicated by the number after the feedstock. They are for wheat: no co-products (1), dried distiller grains (2), straw (3), dried distiller grains and straw combined (4); for sugar beet: no co-products (1), animal feed (2); for wheat straw: no co-products (1), surplus electricity and acetic acid (2); for woody crops: no co-products (1), surplus electricity and acetic acid (2); for energy grasses: no co-products (1), surplus electricity and acetic acid (2); for rapeseed: no co-products (1), glycerin and rapemeal (2), glycerin and rapemeal and straw (3).

6.1.6 LCA endpoint impact results

The Eco-indicator 99 (Version 2.08) is used to translate the LCI to endpoint environmental impacts. This impact assessment method uses 11 impact indicators. The results for the average results for the four systems and for natural gas are shown in the table below. The units for the impact categories are ‘Disability-adjusted life years’ (DALY), the ‘Potentially Disappeared Fraction*m^{2}yr’ (PDF*m^{2}yr) and the ‘MJ surplus’.

Table 11: The LCA results: scores for system 1-4 and natural gas in the 11 impact categories of the Eco-indicator 99 impact assessment method. The red cells indicate the highest impact in that category. The lowest (best) impact score is marked green. The systems in between are colored orange and yellow, with increasing amounts of green for better scores.

Impact category	**Unit**	**System 1: Reference**	**System 2: rocket stove**	**System 3: Larger capacity**	**System: 4 waste juice**	**Natural gas**
Carcinogens	DALY	9.96E-07	5.96E-07	3.08E-07	3.41E-07	1.91E-10
Resp. organics	DALY	1.72E-08	1.06E-08	5.17E-09	5.64E-09	7.84E-11
Resp. inorganics	DALY	2.30E-06	1.41E-06	9.36E-07	7.65E-07	1.49E-08
Climate change	DALY	1.53E-07	1.02E-07	6.41E-08	4.32E-08	2.06E-07
Radiation	DALY	8.40E-09	5.15E-09	2.79E-09	2.78E-09	3.52E-12
Ozone layer	DALY	2.24E-10	2.10E-10	2.00E-10	1.21E-11	3.34E-13
Ecotoxicity	PDF*m^{2}yr	2.01E-01	1.26E-01	7.16E-02	6.38E-02	4.97E-05
Acid./ Eutrophication	PDF*m^{2}yr	4.98E-02	3.13E-02	2.21E-02	1.58E-02	9.07E-04
Land use	PDF*m^{2}yr	1.77E+00	8.58E-01	6.05E-01	2.97E-01	2.78E-05
Minerals	MJ surplus	5.26E-02	3.25E-02	1.79E-02	1.72E-02	3.58E-05
Fossil fuels	MJ surplus	6.71E-01	4.93E-01	3.63E-01	1.52E-01	2.64E+00

In the figure below, the results are normalized such that the highest value for the impact is set to 100%.

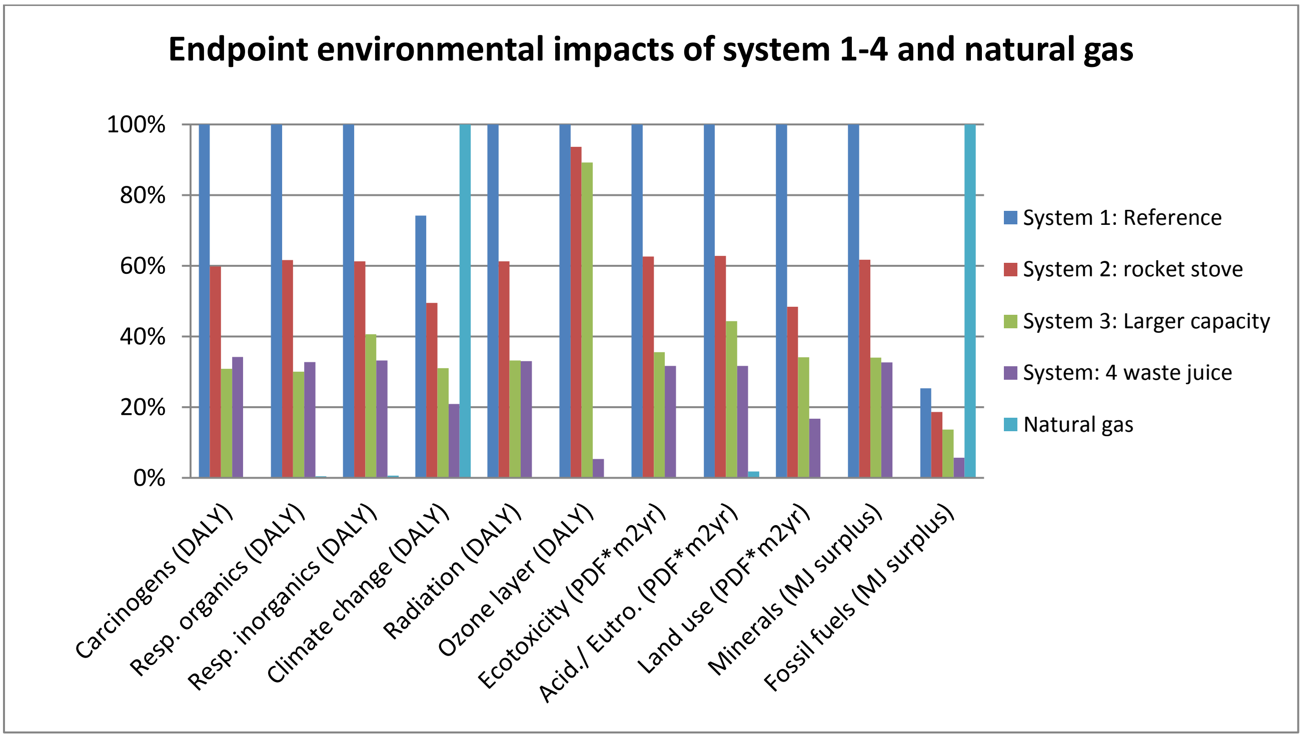

Figure 11: The normalized, endpoint environmental impact results (%) for system 1-4 and natural gas.

For most impact indicators the scores are in the following order: System 1> System 2> System 3 > System 4 > Natural gas. The notable exception are the fossil fuels consumption and climate change impacts where natural gas scores the highest. These results are similar to the midpoint environmental impact results.

6.1.5 Weighed impact scores

The different impact categories are compared with each other by weighing the units. The impact assessment method includes normalization values and weight factors for the different categories. Weights are applied and all the impacts are added up into a single score as shown in the figure below.

Table 12: The default, hyrarchist normalization values and weights used by the Eco-indicator 99 impact assessment method to translate the environmental impact score to weighted damage factors (Goedkoop and Spriensma, 2000)

	Normalization	**Weights**
Human Health (DALY)	1.54E-02	400
Ecosystem Quality (PDF*m^{2}yr)	5.13E+03	400
Resources (MJ surplus)	8.41E+03	200

The single weighted results are presented in the figure below. The error bar represent the scores when using the ‘optimistic’ and ‘pessimistic’ parameters as outlined in paragraph 5.1.1.

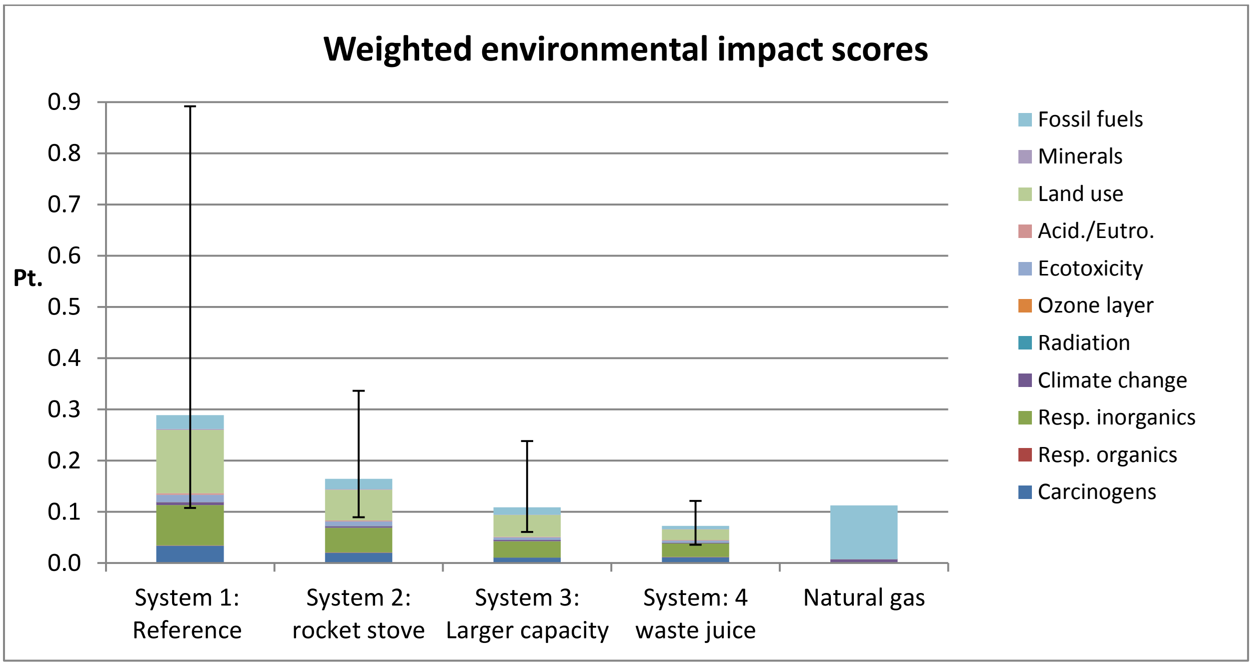

Figure 12: The weighted environmental impact scores (unit less) of system 1-4 and natural gas. The upper and lower limits of the error bars denote the impact scores for the 'high impact' and 'low impact' scenarios.

The results show that all systems potentially perform better than natural gas when considering the optimistic parameter values. However, most likely, only for system three and 4 are the environmental impacts less than for natural gas. Impacts to human health in the form of carcinogenic and respiratory effects have a large contribution to the environmental impacts. This is due to the effect that fuel wood burning has on air quality. Another large impact is land use.

By normalizing and weighing in this fashion, it is possible to show which categories have the highest contribution to the overall environmental impact. For all four systems, the contribution from land use is the highest, followed by respiratory inorganics and carcinogens. Since all four systems are similar in this respect, only the contribution analysis for the reference case is presented in the figure below.

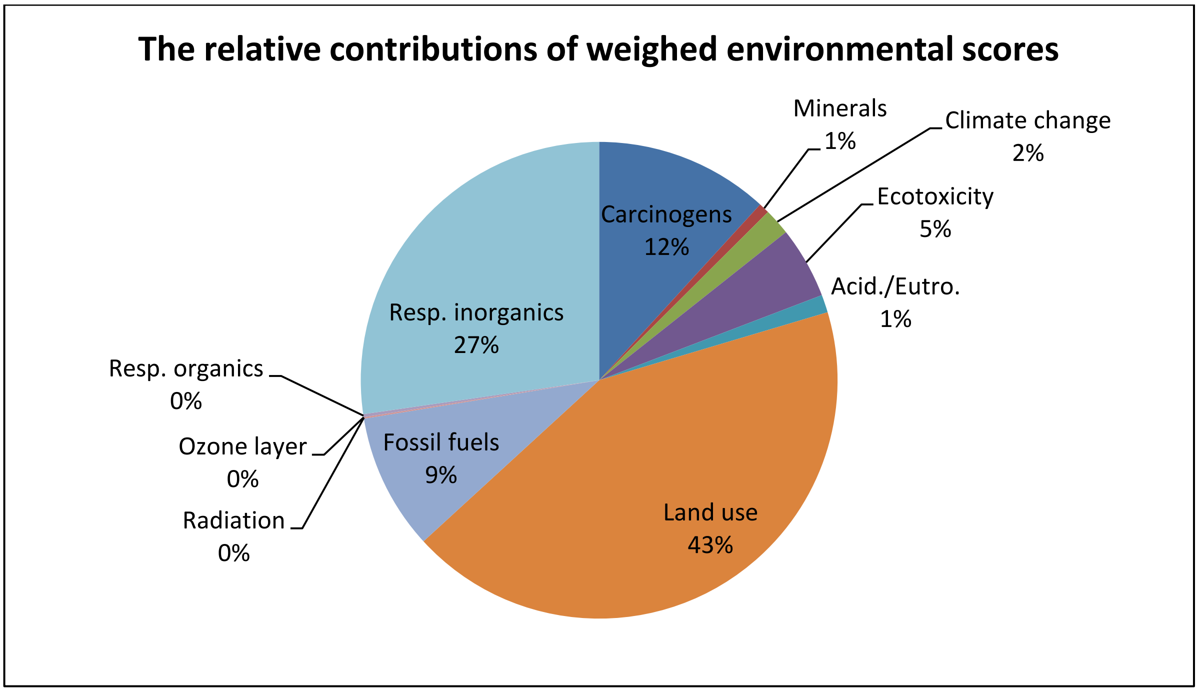

Figure 13: The relative contributions (%) of impact categories to the overall weighed environmental score for the reference system

6.2 Sugar palm ethanol: cost of production and retail value

6.2.1 Value of sugar palm juice and juice related products

An important input to the cost analysis is the cost of juice. Since the pilot village hub is not operational, the cost of juice needs to be estimated based on the value of other juice related products. The tapper has the option to process the juice into four different products: sugar, Sagwer, Capticus, or boiled juice for the village hub to process into ethanol (See Chapter 2.4 for background information on the different juice products and the production processes involved). For these products, different amounts of juice are needed as input. A larger input of juice requires a greater effort for the tapper to produce one unit of product. The processing of these products (boiling, distilling) requires additional effort as well on behalf of the tapper. These inputs are outlined in table 13. For fresh juice, a sugar concentration of **15.0°Brix** is applied, based on results from Appendix IX. For Capticus, an average ethanol concentration of 40 vol% is applied.

Table 13: A comparison of different sugar palm juice based products and their input of juice, fuel wood and equipment in relation to the value of juice.

Products	Unit	Income for tapper[A]	Value per liter juice eq.	Juice input	Fuel wood input[C]	Equipment input[F]
		Rp	*Rp/liter juice eq.*	*Liter juice/unit product*	*Amount*	
Village hub juice	1 Liter	1,200[B]	1,200	1.0	Small	Wok pan and fire pit
Sugar	1 Kg	10,000	1,503	6.7[D]	Medium	Wok pan and fire pit
Sagwer	1 Liter	2,500	2,500	1.0	-	-
Capticus	1 Liter	20,968	3,354	6.3[E]	Large	Distillation equipment[G]

A: Based on price levels of February-April 2013, with the exception of boiled sugar (see note B).

B: Based on purchasing price of juice by the Tomohon sugar factory in 2012.

C: The fuel wood required for distillation is larger than for sugar production. Even though for sugar production all the water is evaporated (whereas for distillation only part of the water evaporates), the distillation process requires a longer, slower fire which consumes more fuel wood.

D: 6.7 liters of juice are required as input for one kg of sugar based on 100°Brix for sugar divided by 15.0°Brix for the juice = 6.9.

E: Based on a sugar concentration of the juice of 15.0°Brix and a fermentation efficiency of 61% (see Appendix XIV) which results in a wine of 6.4 vol% ethanol concentration. Dividing 40 vol% ethanol concentration of the Capticus with 6.4 vol% of wine results in 6.3 liters juice per liter Capticus.

F: The equipment listed here refers to equipment required in addition to equipment required for the tapping process such as jerry cans, machetes and rope.

G: The distillation equipment usually consists of an oil drum above a fire pit attached to an elaborate construction of bamboo distillation columns.

Producing one liter of Capticus requires the most effort from the tapper because of the high amount of juice input, the large amount of fuel wood input and the complicated distillation equipment required. Producing sugar requires the second largest effort because of the amount of juice and fuel wood required followed by juice production for the village hub and Sagwer which requires virtually no additional effort after tapping.

A tapper who invests effort into producing a higher quality product like Capticus can expect a higher return for this product. Over the past decade in the Tomohon area, many tappers have switched from producing sugar and juice for the sugar factory to producing Captikus. This switch was most likely driven by an increase in demand for alcoholic beverages with corresponding high prices.

Sagwer requires the least amount of effort and still has a per liter value higher than sugar. When possible, tappers will sell their juice as Sagwer. However, there is a limited and seasonal demand for Sagwer which means that tappers cannot exclusively focus on this product.

Currently, there is no production processed juice for the village hub or sugar factory. The Rp.1,200 is too low to for the tappers to produce juice for the sugar factory. Therefore, the juice value based on the value of sugar (Rp.1.503) is the best estimate of the current price which the village hub would have to pay for juice.

6.2.2 Production cost of ethanol

The estimated production cost of ethanol in the pilot village hub module is Rp.14,206 per liter ethanol when considering juice prices of Rp.1,503 per liter (See paragraph 6.2.1). If juice prices are zero in the case that waste juice is used for the production of ethanol, production costs are Rp.2,203 per liter. In comparison, based on the LHV of ethanol, its value in comparison to natural gas is an estimated Rp.2,082 per liter (Appendix IV).

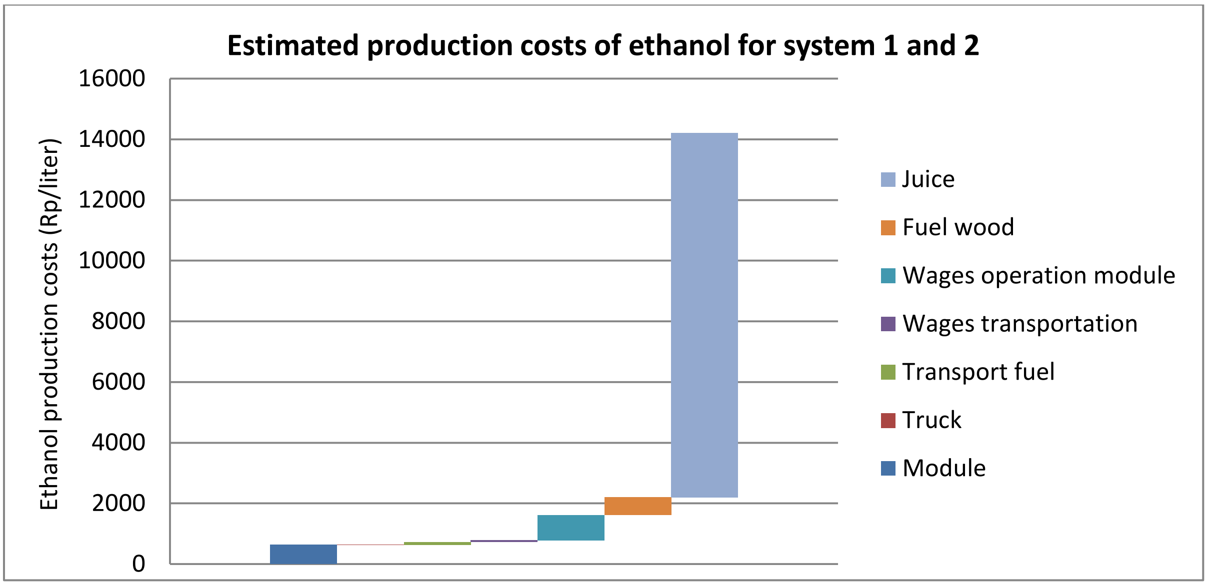

Figure 14: A breakdown of the production costs of ethanol for the pilot village hub. The total production costs are Rp.14,206.

The production costs with a larger scale distiller is an estimated Rp.12,857 per liter ethanol. When considering the case where the juice is free of costs, the ethanol production costs drops to Rp.853 per liter. However, the situation that the larger scale distillery can solely make use of waste juice is unlikely. The following cost factors are the same as for the pilot village hub scenario: Truck costs, transport fuel costs, wages for transport and operation and the juice cost. The fuel wood cost is reduced because of a lower energy requirement in distillation. Operation costs of the module are also less because the labor for operating the module is assumed to remain the same on a per day basis which means it is decreased on a per volume basis. The cost of the module is also slightly reduced on a per volume basis.

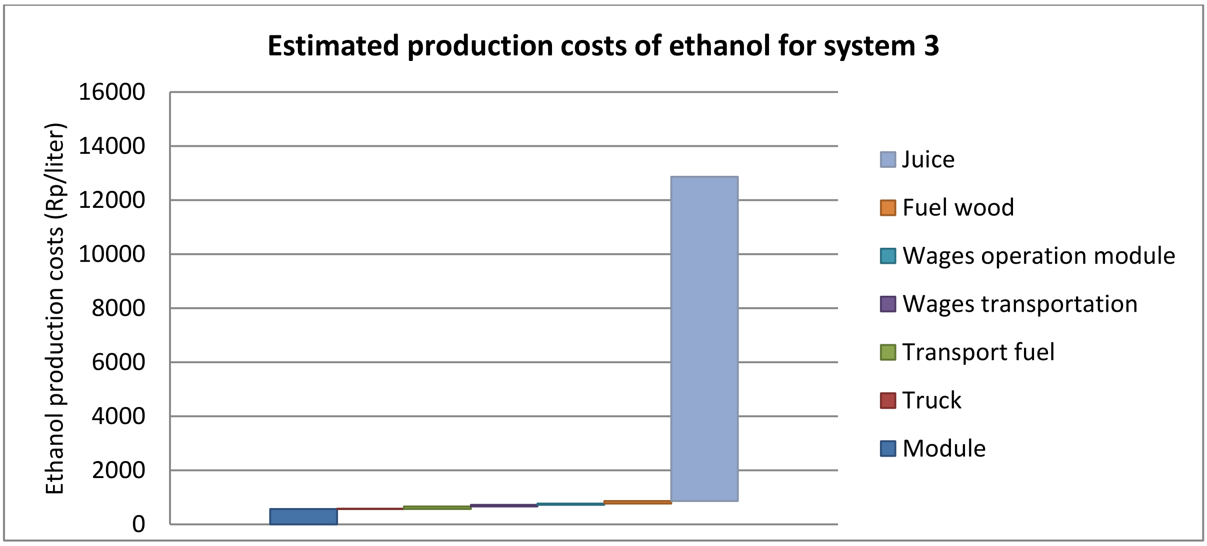

Figure 15: A breakdown of the production costs of ethanol for system 3: larger scale. The total production costs are Rp.12,857.

The cost of juice is the largest cost factor. The cost of ethanol scales linearly with the cost of juice. In the larger scale ethanol production scenario, the break-even point for ethanol production occurs when juice prices are Rp.154. These results suggest that ethanol cannot be produced at competitive prices when the cost of juice is included in the production cost. This either means that ethanol production needs to be subsidized or that waste juice is used.

7 Discussion

Chapter 7.1 relates the differences in the environmental impact results with differences in their designs. Other possible designs are discussed and what their environmental performance would be. Moreover, the importance of the GHG emissions to the overall environmental performance is highlighted as well as the role of the choice of functional unit to the results. Moreover, paragraph 7.1.2 discusses the importance of LUC effect to the environmental performance of sugar palm ethanol.

Chapter 7.2 discusses how the cost analysis results can be refined and what the cost analysis results mean for the implementation of ethanol production at a village hub.

7.1 LCA discussion

The village hub is in the demonstration phase. Now, there is one pilot village hub in Tomohon which is used for testing and as a proof of concept. For future village hubs, this LCA can help the Masarang foundation in their decision process when they consider adding ethanol production to a village hub. That the pilot village hub is in the demonstration phase has shaped this research. Parameters such as the energy use of the distiller, of juice boiling, the transport distance, the capacity of the distiller and the fermentation efficiency are based on direct measurements of the individual processes instead of on long term records of day to day operation performance of the village hub.

Next, in paragraph 7.1.1., the relative performance of the four systems is discussed. In paragraph 7.1.11, the significance of the choice of functional unit is discussed. Since the LUC effects potentially have a large impact on the environmental performance, paragraph 7.1.2. discusses the role of LUC for the environmental performance.

7.1.1 The environmental performance of sugar palm ethanol

System 1 has a poor environmental performance compared to the other systems and compared to natural gas. System 1 makes use of low efficient pan boiling for juice processing. Large amounts of juice need to be processed per liter of ethanol. Therefore, the low energy efficiency of pan boiling translates to a very large heat requirement of 71 MJ/liter ethanol.

System 2 improves on that performance by reducing heat requirements for juice processing. The rocket stove significantly lowers the amount of heat required to 27 MJ/liter. Moreover, since juice processing is constrained by fuel wood availability, the land use for juice production is also significantly lower. Further improving the rocket stove to increase the juice processing efficiency will be difficult.

Other solutions might be available. Boiling the juice to 16-19 °Brix would require less energy while still disinfecting the juice. However, this will result in a higher heat requirement for distillation since the ethanol concentration in the wine will be decreased. Finding the optimal balance between juice boiling and distillation efforts could lead to an overall reduction in energy use and environmental impacts.

System 3 improves upon system 2 with a significantly lower heat input for distillation. To accomplish this reduction in heat requirements, a larger sized distiller is required with a larger capacity. Moreover, the wood is combusted in a boiler instead of a stove which leads to lower emissions. There is a large size difference between the distiller of system 3 and the village hub distiller. An intermediate sized distiller is also an option, with intermediate capacity and energy use. The environmental impacts of such a system would be in between those of system 2 and 3. The optimal size of the distiller needs to be determined based on a set of criteria regarding energy use (and corresponding environmental impacts), cost factors, the local demand for ethanol and other practical considerations.

System 4 makes use of waste juice. The only process involved in this system is the fermentation and distillation processes. Therefore, system 4 has the best environmental performance. Because the juice is free of costs, it produces ethanol at the lowest cost. Moreover, it is the only system which avoids LUC impacts

When available, all systems are recommended to first make use of waste juice, thereby lowering their overall environmental impact. Whether enough waste juice exists to completely cover the demand of a village hub ethanol unit is unknown. The village hub distiller has a juice capacity of 5% compared to the syrup modules (Appendix V). Experience with an operational village hub will reveal whether this amount of waste juice exists.

7.1.1.2 The role of the functional unit

The functional unit of the LCA is one liter of ethanol of 85 vol% produced at the village hub. However, a good extension of the present work is to include the use phase of ethanol. The functional unit including the use phase could be, for cooking: ‘preparing one standard Indonesian meal’; or for lighting: ‘providing an x amount of lux over a certain period of time’. Including the use phase might lead to different results.

Ethanol and natural gas cooking were briefly compared with simple test. This revealed that cooking with natural gas was easier and faster than cooking with ethanol. This can be explained by a difference in heating value: 22 MJ/kg for ethanol (85 vol%) and 53,6 MJ/kg for natural gas. The use phase was not included in the present analysis because that would have required extensive lab experiment or field measurements, which were outside of the scope of this project. Furthermore, generic efficiency values for natural gas cooking and lighting, specifically with 85 vol%, are difficult to find. However, it is to be expected that when the use phase is included, the environmental performance of sugar palm ethanol relative to a higher quality fuel will decrease.

7.1.2 LUC effects

The present analysis assumes that juice production for the village hub is performed by tappers who were already cultivating sugar palm on their land. The result is that the tappers do not change their cultivation practice and that DLUC does not occur. However, tappers abandon the production of sugar, a food product, to supply juice to the village hub. The use of food crops for the production of biofuels is under heavy debate because it might leads to higher food prices and to ILUC.

The general assumption is that when food is redirected to produce biofuels, this leads to the agricultural expansion elsewhere at the expense of forests. ILUC would also occur when tappers switch from liquor production or vegetable production to produce processed juice. In both cases, the loss in food production needs to be compensated by an increase in agricultural land somewhere else.

That ILUC causes large impacts has been shown in many scientific works (Lapola *et al.,* 2010; Fargione *et al.,* 2008; Searchinger *et al.,* 2008). This relatively new insight has also prompted the European Parliament to vote for proposals which limit the use of first generation biofuels (Lepage, 2013).

ILUC does not occur when *additional* juice is produced for the purpose of ethanol production, for example when unproductive lands are used for the production of sugar palm juice. In this case, DLUC effects occur which can be positive or negative. For example, when sugar palm cultivation expands into natural forests, the DLUC from fuel wood harvesting will have a negative impact on the environment. Conversely, when cultivation is expanded onto degraded lands, this will have positive effects on the environment.

Coupling sugar palm expansion with a reforestation effort might be a successful combination. The tappers could manage the newly created forest and prevent another round of deforestation while producing biofuels for the local community. However, the costs for such a project could not be covered by ethanol production. Moreover, sugar palm cultivation requires the removal of large amounts of fuel wood which would negatively impact this newly created forest.

This combination of reforestation and consecutive fuel wood removal already occurs with the wooded land next to the village hub used for fuel wood production for distillation. This land was previously degraded and through the efforts of the Masarang foundation is now reforested.

However, when this forest is harvested for fuel wood, the improvements from reforestation are reduced. The methodological question this raises is whether the positive effects of reforestation should be attributed to ethanol production, or the negative effects due to the removal of fuel wood.

In this analysis, neither positive nor negative LUC effects are included for the land used, only the 'forest land *occupation*' environmental input is included.

In conclusion, redirecting juice from sugar production leads to environmental impacts through ILUC. Moreover, it could increase the local price of sugar. Increasing overall juice production leads, through the removal of large quantities of fuel wood, to DLUC environmental impacts.

These negative impacts do not occur when ethanol production is coupled with a reforestation effort. However, it might not be reasonable to attribute the positive LUC impacts to the ethanol if the costs for reforestation are not covered by ethanol production.

Since the village hub is in the pilot phase, the land use effects were especially difficult to include. What type of LUC occurs depends on the local dynamics in a new village where a village hub starts operations. However, in all these cases, LUC impacts speak against the sugar palm ethanol production of system 1-3.

7.2 Cost analysis discussion

That the village hub, and ethanol production, has not been implemented yet has motivated the cost analysis. Besides environmental considerations there are also monetary considerations. If the village hub wants to contribute to access to energy of local communities, the ethanol has to be available to the community at competitive prices.

The analysis only gives a first indication of cost since several costs inputs are not added. Moreover, the costs are highly region dependent and prices will be different for a different village hub. Lastly, when considering investing in an ethanol module, the cost analysis should be performed over the whole lifetime of the module, including accounting for varying costs over time. A true economic assessment would give a much more detailed picture of the financial side of ethanol production at the village hub.

However, even though the accuracy of the analysis is rather rough, the cost analysis shows that the production costs are far greater than the value of ethanol. The input of juice represents the largest cost factor for ethanol production. For system 1-3, the village hub is therefore unlikely to be able to make a profit by producing ethanol. In this case, ethanol production needs to be subsidizing if it is to be implemented.

When the cost of juice is considered to be zero when using waste juice, the production costs are very near the value of ethanol. This indicates that production costs might be competitive compared to natural gas for this system.

8 Conclusion

The cultivation of sugar palms in an agroforestry setting supports a higher biodiversity than intensive agriculture. While the expansion of palm oil cultivation leads to a loss of forests, the cultivation of sugar palms can take place in a natural forest setting.

The village hub is a means to support agroforestry practices to prevent the loss of forests and the spreading of monocultures. At the same time, the village hub aims to contribute to rural development. Tappers who sell their juice to the village hub for ethanol production are supported in their livelihood. They have an incentive to continue the agroforestry cultivation of their land.

The intended effect of ethanol production in the village hub is the preservation of the biodiversity of agroforests. However, the direct effect is that large quantities of fuel wood are removed from the land with negative consequences for biodiversity. When new lands come under sugar palm cultivation due to an increase in the demand for juice, the land is affected negatively or positively depending on the previous land type.

Alternatively, the impacts could occur somewhere else when juice for sugar production is diverted to the production of ethanol. When choosing a location for a village hub, care should be taken that ethanol production does not lead to the local loss of natural forests or a decrease of sugar production. This can be achieved by combining ethanol production with a reforestation effort.

Beside the land use impacts, the environmental impacts of sugar palm ethanol production in the pilot village hub (system 1) are larger than the impacts of natural gas. Only the environmental impacts regarding climate change and the depletion of fossil resources are lower. Overall, the higher impacts in the other categories outweigh these benefits. The environmental impacts decrease significantly when the energy requirement for juice processing is reduced by making use of the rocket stove (system 2).

The overall environmental impacts are only lower compared to natural gas when the energy use for distillation is also reduced (system 3). To accomplish this, a large distiller is required. Moreover, the village hub boiler should be used instead of a separate stove.

The environmental impacts of the first three systems can be further decreased when waste juice is used. A system that solely uses waste juice (system 4) has the lowest environmental impact in comparison to the other systems and natural gas.

To contribute to the access to energy of the local community and to support its development, ethanol needs to be competitively priced. The cost analysis shows that sugar palm ethanol production is more expensive than the use of natural gas. A subsidy on ethanol would be required to reduce the price for consumers. Juice is the largest cost factor for ethanol production. Therefore, the use of waste juice, which is essentially free, greatly reduces the production costs. In this scenario, the production costs of ethanol might be able to compete with natural gas without subsidy.

In conclusion, the environmental performance of ethanol produced in the pilot village hub is poorer compared to natural gas, while it is more expensive. When the energy use of juice processing and distillation is reduced, the environmental impacts of the ethanol are lower. However, this requires the use of a larger distiller and a subsidy on the ethanol to make it attractive for consumers.

The use of waste juice greatly reduces the environmental impacts *and* the production costs. Moreover, there are no land use impacts. Therefore, when available, the use of waste juice should be the preferred option.

Appendix I: Sugar palm lifetime yield

The sugar palm tree lifecycle consists of a maturation (growth) period, followed by a mature period where tapping can take place. After all the male inflorescents have been tapped; the tree can survive for over a decade longer. Sugar palm trees can live for more than 30 years.

Dr. Willie Smits used yield data of several trees, as well as his expert knowledge of the sugar palm, to determine the yield of an average sugar palm tree over its lifetime. This average sugar palm tree yields juice from 6 flowers over its lifetime. The first flower produces the highest amount of juice, for the longest period, with the highest sugar concentration. Every consecutive flower yields less juice with a lower sugar concentration.

Table 14: Average lifetime sugar yield of the sugar palm tree based on average daily juice yield (liter) and sugar concentration (°Brix) for consecutive flowers. Source: Smits, 2013.

Flower #	**Days tapping/Flower**	**l/day**	**°Brix**	**Liters**	**Kg sugar**[A]
1	200	35	13.5	7000	957
2	160	30	13	4800	631
3	130	25	12	3250	393
4	100	20	11.5	2000	231
5	100	20	10.5	2000	210
6	100	20	10	2000	200
Total	790			21050	2729

The average yield of the sugar palm tree as proposed by Dr. Willie Smits produces 2,622 kg of sugar over its lifetime. The average sugar concentration of the produced juice is 12.3 °Brix. Note that the days and months that the tree is tapped is not necessarily continuous and two flowers can produce at the same time. The actual time between the first and last tapping is discussed in the following section.

The Pentagono Design team interviewed 10 locals with expert knowledge of sugar palm productivity. The interviewees were three sugar palm nursery employees, three Kolong Kaling farmers and four sugar palm tappers. They observed a large variation in tree productivity which is represented here with a high, low and medium productivity scenario. In medium yield scenario, the sugar palm tree yields six flowers for tapping. Each flower can be tapped for five months. However, after three months of tapping the juice yield of the flower is decreased. The low yielding scenario is similar, with the difference that only five flowers can be tapped. In the high yield scenario, all six flowers are tapped as in the medium yield scenario, with an additional two months of production per flower, with a lower yield and a lower sugar concentration of 8 °Brix.

Table 15: Average juice yield (liters) of the first six flowers of the sugar palm tree for a low, medium and high yield scenario. A flower has a period of high yields at first, followed by a second and, in the high yield scenario, third period of consecutively lower yields. Source: Pentagono design team.

	Medium yield		**Low yield**		**High yield**	
Flower #	**Months**	**Liters/day**	**Months**	**Liters/day**	**Months**	**Liters/day**
1	3	37	3	37	3	37
	2	16	1	16	2	16
	-	-	-	-	2	16
2	3	28	3	28	3	28
	2	13	1	13	2	13
	-	-	-	-	2	13
3	3	23	3	23	3	23
	2	12	1	12	2	12

	-	-	-	-	2	12
4	3	19	3	19	3	19
	2	10	1	10	2	10
	-	-	-	-	2	10
5	3	15	3	15	3	15
	2	8	1	8	2	8
	-	-	-	-	2	8
6	3	15	-	-	3	15
	2	8	-	-	2	8
	-	-	-	-	2	8

The Pentagono team did not ask for °Brix values of the juice. So to calculated the lifetime sugar yield in these three scenarios the °Brix values for flowers in table 14 is used (with the exception of the last two months of production for flowers in the high yield scenario).

Table 16: The average lifetime juice yield (liters) and sugar yield (kg) of the sugar palm tree based on the low, medium and high yield scenarios of the Pentagono design team compared to the findings of Dr. W. Smits.

	Medium	**Low**	**High**	**Dr. W. Smits**
Lifetime juice yield (liter)	16,577	12,927	20,653	21,050
Lifetime sugar yield (kg)	2,110	1,684	2,446	2,729

Sugar palm tree lifetime sugar production

The lifetime juice and sugar yields were discussed previously. However, sugar palm trees have a maturation period of many years. When considering the per year productivity of an sugar palm tree, or an area of land with multiple sugar palm trees, it is important to know how long the lifecycle of the sugar palm tree is. Dividing the lifetime yield of the tree with its lifetime yields the per year productivity. After how many years sugar palm palms reach maturation varies greatly based on a literature review:

- Mogea et al 1991: ‘The sugar palm can be tapped at an age of 10-12, sometimes at an age of only 5-7 years.’
- Staaij & van den Bos *et al.* (2011): *‘The period from seedling to full grown sugar producing palm (when the first flowers appear) varies between 5 – 12 years. The importance of a high temperature shows from the slow growth at higher altitudes. At sea level, flowering begins after 5-7 years and at 900m altitude after 12-15 years (Martin, 1999)’* However, this Martin 1999 source does not contain this information so the actual source is unknown. For their calculations they assume an average of 9 years maturation and three years tapping which they appear to assume as the average lifecycle.
- Dalibard 1997: ‘*sugar palm Arenga pinnata can be tapped when they are between 12-15 and more than 30 years old; then they can be cut for sago production (Sumadi 1988).’* This Sumadi 1988 source could not be found for more details.
- Pentagono design team 2013: Maturation is between 9-11 years under light conditions, 12-17.5 years in shade conditions. Tapping can take place for 2-5 years after maturation. Another round of tapping is possible when all the female fruits have ripened after ~30 years.

Table 17: The lifetime (years) of the sugar palm tree based on literature sources and personal investigations. The lifetime of the sugar palm tree is a combination of the maturation period (vertical axis) and the tapping period (horizontal axis). Note that the tapping period includes non-productive periods between the development of flowers and cannot be used to estimate lifetime juice yields. The colored cells represent the reported lifetime of a certain source for a certain growing condition. The colors of the cells in the table match the colors of the cells on the right with the source information. The Pentagono team gave a range of lifetimes for the sugar palm tree. These ranges include sugar palm lifetime estimates of other sources. Otherwise, there is no overlap.

Maturation period	**Tapping period (years)**

(years)	**2**	**3**	**4**	**5**
5	7	8	9	10
6	8	9	10	11
7	9	10	11	12
8	10	11	12	13
9	11	12	13	14
10	12	13	14	15
11	13	14	15	16
12	14	15	16	17
13	15	16	17	18
14	16	17	18	19
15	17	18	19	20
16	18	19	20	21
17	19	20	21	22

Mogea *et al.* (1991): `Short maturation period`

Staaij & van den Bos *et al.* (2011): `Best estimate`

Pentagono team: `Sunny growing conditions`

Mogea *et al.* (1991) : `Average maturation period`

Pentagono team: `Shade conditions`

Dalibard (1997)

Based on these sources, under normal conditions, sugar palm trees have produced their maximum amount of juice between the ages of 12-16 years.

Assuming that the lifetime productivity is unaffected by the length of the lifecycle of the tree, *yearly* juice and sugar productivity can be calculated. Based on a lifetime of 12-16 years and a lifetime sugar production of 1,684-2,729 kg, the yearly productivity is in the range of 105-227 kg/year. What the relation is between maturation time, tapping time and juice yields is unknown and is an important area for future investigation.

Appendix II: Sugar boiling in rocket stove

Three measurements were performed with the rocket stove to determine its efficiency for juice boiling. However, in two instances no fresh juice was available and water was used instead. The procedure for calculating the heat input and heat required at different intervals is outlined in the methods section under 'juice boiling efficiency calculations'. The results are shown in figure 16 below.

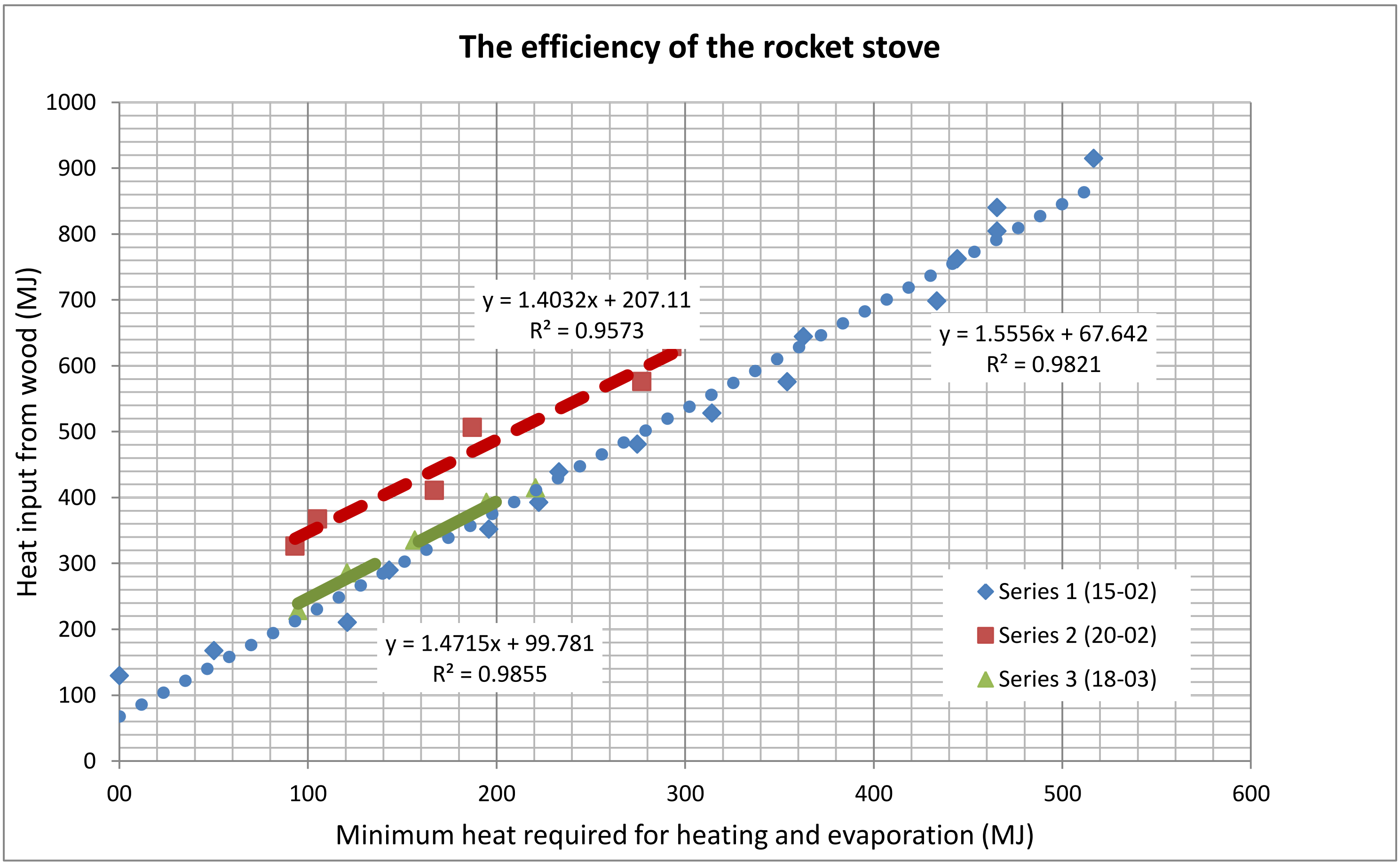

Figure 16: The effective heat used for heating and evaporation of the juice in relation to the heat added to the rocket stove in the form of combusted wood.

The measurements were performed on a rocket stove located in the pilot village hub in Tomohon. The heat added is calculated from the wood that is burned plus some (~200 ml) lighter fluid that is used to light the fire (using a LHV of 30.4 MJ/liter). These trend lines do not intersect the origin. This indicates that there is a start-up energy requirement before heat is transferred to the juice. The initial expenditure to start the rockets stove is between 68-207 MJ based on the intersection of the trend lines with the Y-axis. This initial expenditure of energy comes from the heat capacity of the rocket stove itself, which is considerable due to the brick insulation of the stove. This initial expenditure depends heavily on circumstances like the temperature of the rocket stove and the juice, the presence of wind and rain and how quickly a good fire is started.

After the start-up period of the rocket stove, the energy efficiency is between 1.40-1.56 MJ input/MJ required. Therefore the longer the rocket stove is used, the more efficient evaporation becomes since initial energy expenditure only has to be expended once. The energy efficiencies at the end of boiling for the three measurements are 56%, 47% and 53% for series 1-3 respectively. On average the efficiency is therefore 52%.

The relation between the heat added and the heat required, based on an initial expenditure of energy of 124.8 MJ and an energy input to minimum heat required of 1.4768 (the averages of the three trend lines in figure 16) the relationship would be:

$$Heat\ added = 124.8 + (1.4768 * Heat\ required)$$

Comparison between pan boiling and the rocket stove

When comparing the energy efficiency of pan boiling with boiling in the rocket stove, we find that at low juice volumes the pan is more efficient because of the initial energy expenditure in the rocket stove. However, at higher volumes and longer boiling times, the rocket stove becomes more efficient. Based on the relation between heat added and heat required of the two systems, the break-even point is at a heat required of:

$$\frac{124.8\ (MJ\ input)}{(5.051 - 1.4768)\left(\frac{MJ\ input}{MJ\ required}\right)} = 35\ (MJ\ required)$$

Therefore, when boiling more than 52 liters of juice, the rocket stove is more efficient. When boiling less than 52 liters of juice, pan boiling is more efficient.

Appendix III: Value of vinasse as a fertilizer

Vinasse can be used as a fertilizer since it contains the three most important minerals needed for plant growth: Nitrogen (N), Phosphor (P) and Potassium (K). The amount of minerals present in vinasse produced from the village hub distiller was not measured directly because the composition of vinasse will change from batch to batch. There are two reasons why the mineral concentration can vary over time. First of all, the mineral concentration in the juice varies depending on the season (Lantemona *et al.* 2013). Secondly, the mineral concentration in the juice varies from tree to tree. Therefore, every batch of wine which is distilled will yield different compositions of vinasse. Measurements of the mineral concentrations in village hub vinasse therefore have to be performed over a longer period of at least a year and from vinasse produced from a representative sample of sugar palm trees. Such a measurement was outside of the scope of this research.

However, the average mineral concentration of minerals in vinasse can be estimated based on the mineral concentration in sugar palm juice, as measured by Lantemona *et al.* (2013). They determined different sugar palm juice properties of a sample of 12 Aren palm trees found in the Tomohon area. For every tree, five measurements were performed in the rainy season and another five in the wet season. For the measurements of mineral concentration, these values are averaged since both seasons take approximately half a year. Therefore, every value is the average of 120 measurements.

In the following calculations it is assumed that all the minerals in the juice are transferred to the vinasse after distillation, instead of ending up in the ethanol. The first reason behind this assumption is that for every liter of ethanol which is produced, approximately 11 liters of vinasse is produced which means based on volume most of the minerals would be transferred to the vinasse. The second reason is that it is assumed that the minerals are separated from the ethanol during the distillation process.

The authors report the value for phosphor in % by weight in the juice. For Potassium the values are reported in ppm (by weight) which are converted to concentration in percent by multiplying with 10,000. These values are multiplied with the density of juice at 13.12 °Brix which is the average sugar concentration of the juice in their samples. For nitrogen however, the *protein* concentration is reported. To translate the protein concentration to nitrogen concentration, a conversion factor of 4.4 kg protein per kg nitrogen is applied, based on Milton and Dintzis (1981).

To perform the economic allocation between ethanol and vinasse, the value of the minerals in the vinasse need to be determined. The Indonesian government subsidizes fertilizes so the prices are for 2013 are fixed. The price of Urea (a N-fertilizer) is Rp.1,800, the price of superphosphate-36 (a P-fertilizers) is Rp.2,000 (Sidik 2013). Determining the value of potassium is difficult because fertilizers which include potassium usually also include one or both of the other minerals. However, potassium does not significantly add to the value of the vinasse because the concentration of potassium in sugar palm juice is almost zero; even when using a high value for potassium this only influences the allocation values by 10^{-2} per cent.

Urea contains 0.46 kg of nitrogen per kg of fertilizer. Therefore, the value of nitrogen in vinasse is Rp1800/0.46 = Rp.3,913 per kg nitrogen. Superphosphate-36 contains 0.36 kg of phosphorus pentoxide (P_2O_5) per kg fertilizer. Out of this phosphorus pentoxide, 43,6% is phosphorus by (atomic) weight. Therefore, the value of phosphorus in the vinasse is Rp.2,000/(0.36*0.436) = Rp.12,742 per kg phosphorus.

Table 18 outlines the concentration of minerals in the juice, the amount of minerals produced per liter of ethanol, the value of the minerals per kilogram and the value of the minerals produced per liter of ethanol. The total value of the minerals in the vinasse amount to Rp.72 per liter of ethanol produced.

Table 18: Summary of the calculation of the value of vinasse per liter of ethanol produced.

	Percentage in juice	Weight per liter ethanol	Value	Value
Unit	% by weight	Kg/l	Rp/kg mineral	Rp/liter ethanol

Nitrogen (N)	1.295E-01	1.667E-02	3,913	65
Phosphor (P)	4.000E-03	5.146E-04	12,742	6.6
Potassium (K)	2.115E-04	2.721E-05	-	-
				72

Appendix IV: Value of ethanol and other fuels

Energy consumers have the option to purchase energy carriers from different sources. Ethanol produced from sugar palm has to compete with fossil energy carriers, especially natural gas for cooking. Alternatively, people who are cooking with biomass could switch to sugar palm ethanol. In both cases, in order for people to start purchasing sugar palm ethanol, it has to be more attractive than fossil alternatives in terms of price competitiveness, ease of use and reliability of supply. Ideally the production cost for ethanol should be therefore be lower or equal to market prices of fossil alternatives.

To correctly compare the price competitiveness of sugar palm ethanol with fossil alternatives, the cost of one liter of fuel needs to be corrected for its energy content. For cooking purposes, the LHV is the appropriate heating value to use since the heat of evaporation for water is not reclaimed when cooking. Finding a source for the LHV of ethanol with 85 vol% ethanol was surprisingly unsuccessful. Therefore the LHV was calculated from the HHV. The HHV of ethanol is 28.1 MJ/kg. Multiplying with the density of 0.789 yields a HHV of 22.18 MJ/liter. The difference between the HHV and the LHV is the heat of evaporation of the water in the mixture and of the water which is produced in the combustion reaction. For every mol of ethanol which is combusted, three mols of water are produced. The molar weight of water is 18gram/mol, the molar weight of ethanol is 46 gram/mol. The LHV at 85 vol% is therefore:

$$HHV_{85\,Vol\%} = HHV_{100\,Vol\%} * 0.85$$

$$LHV_{85\,Vol\%} = HHV_{85\,Vol\%} - 0.15 * 2.252\left(\frac{MJ}{l\ ethanol}\right) - 0.85 * 0.789\left(\frac{kg\ ethanol}{l\ ethanol}\right) * \left(\frac{18*3}{46}\right)\left(\frac{kg\ water}{kg\ ethanol}\right) * 2.26\frac{MJ}{kg\ water}$$

Filling in the formula yields an ethanol LHV with 85 vol% of **16.74 MJ/liter**.

In comparison: gasoline has a LHV of 44.4 MJ/liter and natural gas 53.6 MJ/kg. A competitive ethanol price would be:

$$Competatice\ ethanol\ Price\left(\frac{Rp}{Liter}\right) = Fossil\ Fuel\ Price\left(\frac{Rp}{Unit}\right) * \frac{LHV_{Ethanol}\left(\frac{Mj}{Liter}\right)}{LHV_{Fossil\ Fuel}\left(\frac{Mj}{Unit}\right)}$$

Table 19: Indonesian fuel prices in relation to the value of ethanol when correcting for a difference in the lower heating values.

Energy carrier	Unit	Price	LHV	Ethanol price
		Rp	MJ/unit	Rp/liter ethanol
Gasoline with subsidy	Liter	6,500^{A}	44.4	2,449
Gasoline w.o. subsidy	Liter	10,000	44.4	3,768
Gas (for cooking)	Kg	6,667^{B}	53.6	2,081
A: Price of subsidized, 'Premium', gasoline as of 22-06-2013 B: Price level at February-April 2013				

Appendix V: Juice demand of the village hub

Capacity of the Syrup module

The capacity of the village hub syrup module is 1,000 kg sugar per day. One liter of juice has on average 15.03 °Brix with a density of 1.06 kg/liter (see Appendix IX). One liter of juice therefore has on average of:

$$0.1503 \frac{kg\ sugar}{kg\ juice} * \ 1.06 \frac{kg\ juice}{liter juice} = 0.159\ \frac{kg\ sugar}{liter juice}$$

Dividing the capacity of a 1,000 kg of sugar per day with this number yields a daily capacity of ~6,275 liters juice per day for the syrup module.

Capacity of the ethanol module

The capacity of the ethanol unit is 32.2 liters of ethanol at 85 vol%. As outlined in paragraph 5.1.7, 10.8 liters of juice input is required per liter ethanol. Therefore, the capacity of the ethanol module is 30*10.8 = 328 liters of juice per day. This is 5% compared to the total juice demand of the village hub.

Juice production capacity in the Tomohon area

The Masarang sugar palm tappers cooperative has 6,250 members. The tappers included in the Masarang survey produced on average 124 liters of juice per day. This translates to an estimated total production of 772,000 liters of juice produced per day in the Tomohon area by all the tappers combined. The syrup module would require 0.81% of the total production and the ethanol unit would require another 0.12%. This means that current production capacity of juice in the Tomohon region could be met without the expansion of sugar palm cultivation.

Appendix VI: Properties of sugar palm cultivation

The Masarang foundation performed an extensive survey of 91 sugar palm tappers in the Tomohon area with a combined total of 60.7 hectares. The survey was performed between 12-06-2011 and 19-09-2011. This survey reveals five properties of sugar palm tapping practices in the Tomohon area. These five properties are:

- The average size of a farmer's plots is 0.6 hectare
- The average sugar palm tree density: 111 trees/ha
- The average tapping intensity is 12 trees tapped/ha
- The average juice yields is 64,672 liters juice/ha
- The maximum sugar palm tree density is between 150-300 palms/ha, with up to 32 trees tapped/ha which results in 136.000 liters juice produced per hectare and up to 21.672 kg sugar produced per hectare per year

A more detailed breakdown of these properties of sugar palm tapping is presented in the following paragraphs.

Size of farmer's plots

The average plot size of the tappers in the survey is 0.6 hectare per tapper.

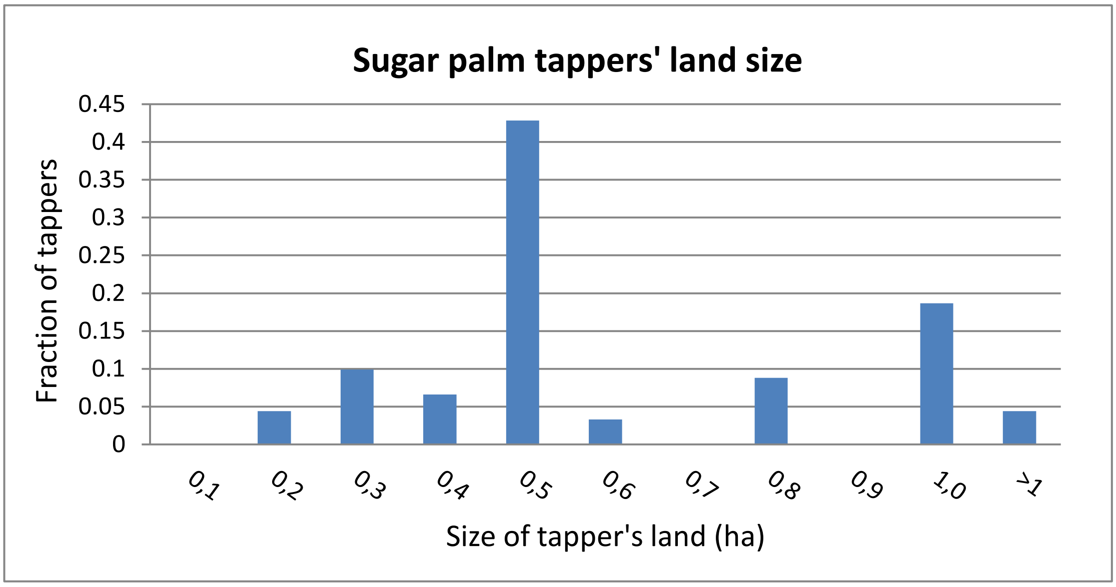

Figure 17: Distribution of sugar palm tappers` land size as determined by the Masarang foundation for 91 participating sugar palm tappers in the Tomohon area. The average land size is 0.6 hectare.

Sugar palm tree density

The amount of sugar palm trees growing on the land of the tappers was counted. All sugar palm trees, including young trees were counted. The amount of trees on the tappers` land is then divided by the size of this land to yield the tree density. The average tree density was 111 trees/ha although most commonly the tree density was between 50-75 trees/ha. The highest amount of sugar palms per hectare was measured to be 821 on the land of a tapper with 197 sugar palm trees on only 0.24 hectares of land.

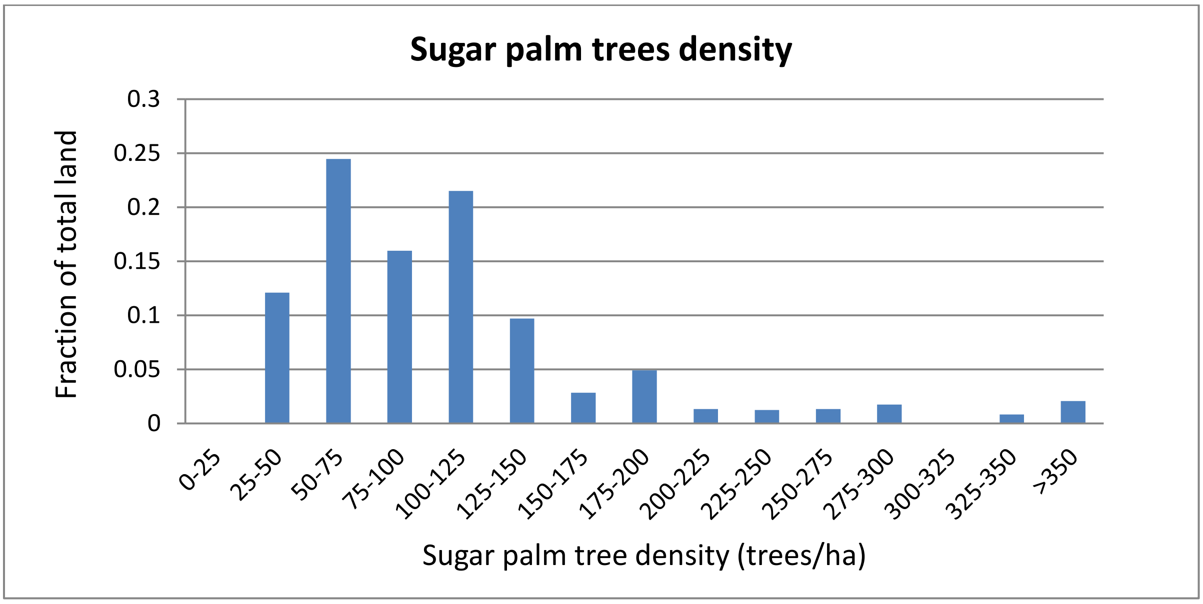

Figure 18: Distribution of sugar palm tree densities of the tappers` land of 91 Sugar palm tappers involved in the Masarang survey.

Tapping intensity

Of these 111 trees per hectare, an average of 12 trees/ha and 11% of all the trees were tapped. From the distribution of the amount of tapped trees per hectare, up to 18 tapped trees per hectare is not uncommon.

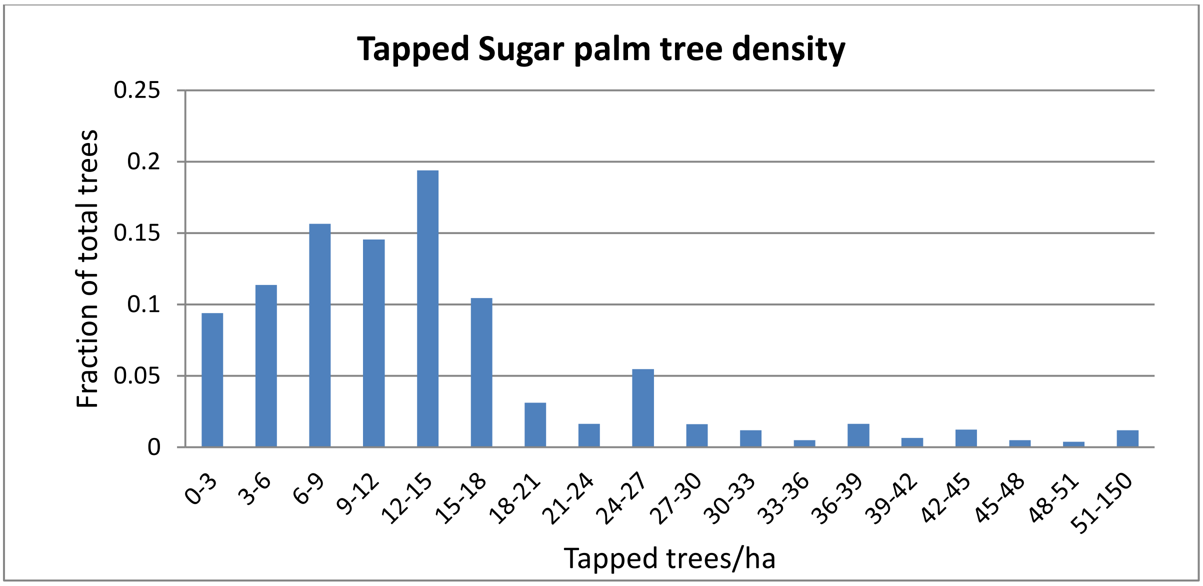

Figure 19: Distribution of tapped sugar palm tree densities of the tappers` land of 91 sugar palm tappers involved in the Masarang survey.

Sugar juice yields

The surveyors from the Masarang foundation have expert knowledge of the productivity of sugar palm trees. They assumed that a tapped tree produces on average 16.25 liters per day. Multiplying this juice yield with the amount of sugar palm trees being tapped, they estimated the daily and yearly juice yield per tapper. Dividing this yearly production by the amount of hectare of the tapper's parcel yields the juice production per hectare as shown in the figure below. The average production is 64,672liters juice per hectare per year.

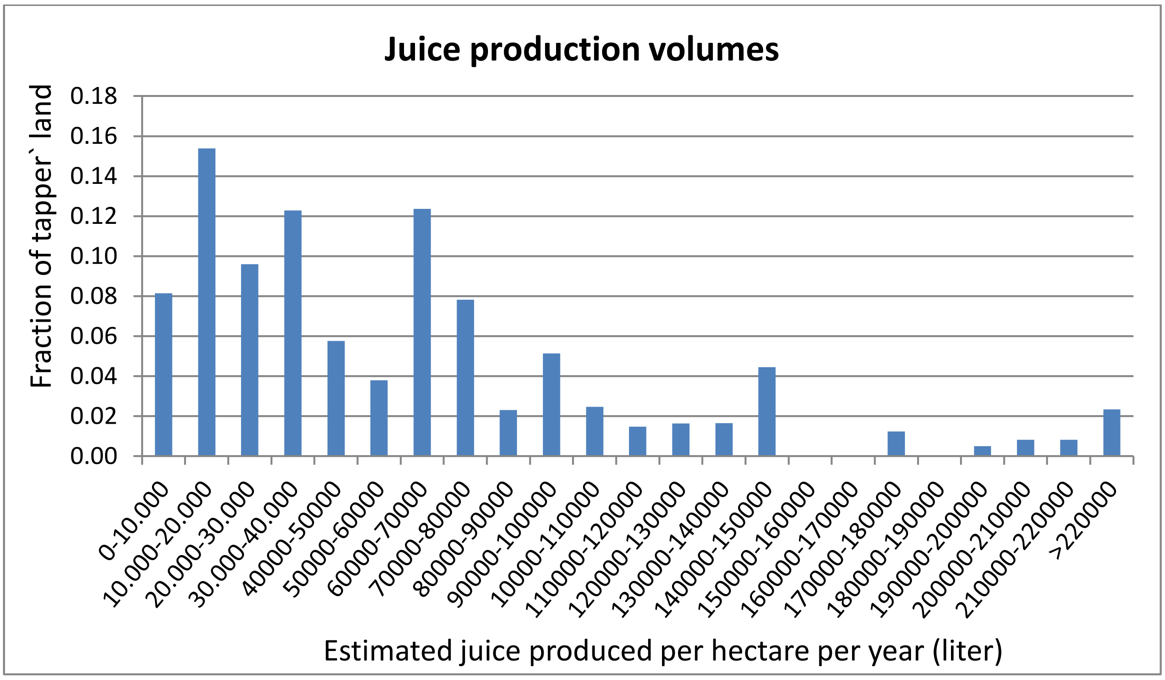

Figure 20: Distribution of estimated juice production volumes of the tappers` land of 91 sugar palm tappers involved in the Masarang survey.

There is a wide variation in the juice production of tappers. There can be many reasons for this variation, including seasonal variability in the production capacity of tappers, differences in the skill of tapping and differences in effort invested into tapping. Based on these results, a per hectare production of up to 100,000 liters per year is not uncommon.

Upper limit of tree density and tapping intensity

With 111 trees per hectare and 11% of trees being tapped, on average 12 trees per hectare are tapped. To increase sugar yields, more trees per hectare need to be tapped. This can either be accomplished by increasing the amount of trees per hectare and tapping more trees. However, at higher tree densities, there is a greater competition for light, water and nutrients. At some point this will start affecting juice yields of these trees. The relationship between tree density and juice yields oculd not be determined. Furthermore, at high tree densities, the maturation period of trees might lengthen, reducing the fraction of trees which can be tapped. The relationship between tree density and the fraction of tapped trees *could* be determined. The figure below shows the relation between tree density and the fraction of tapped and young trees.

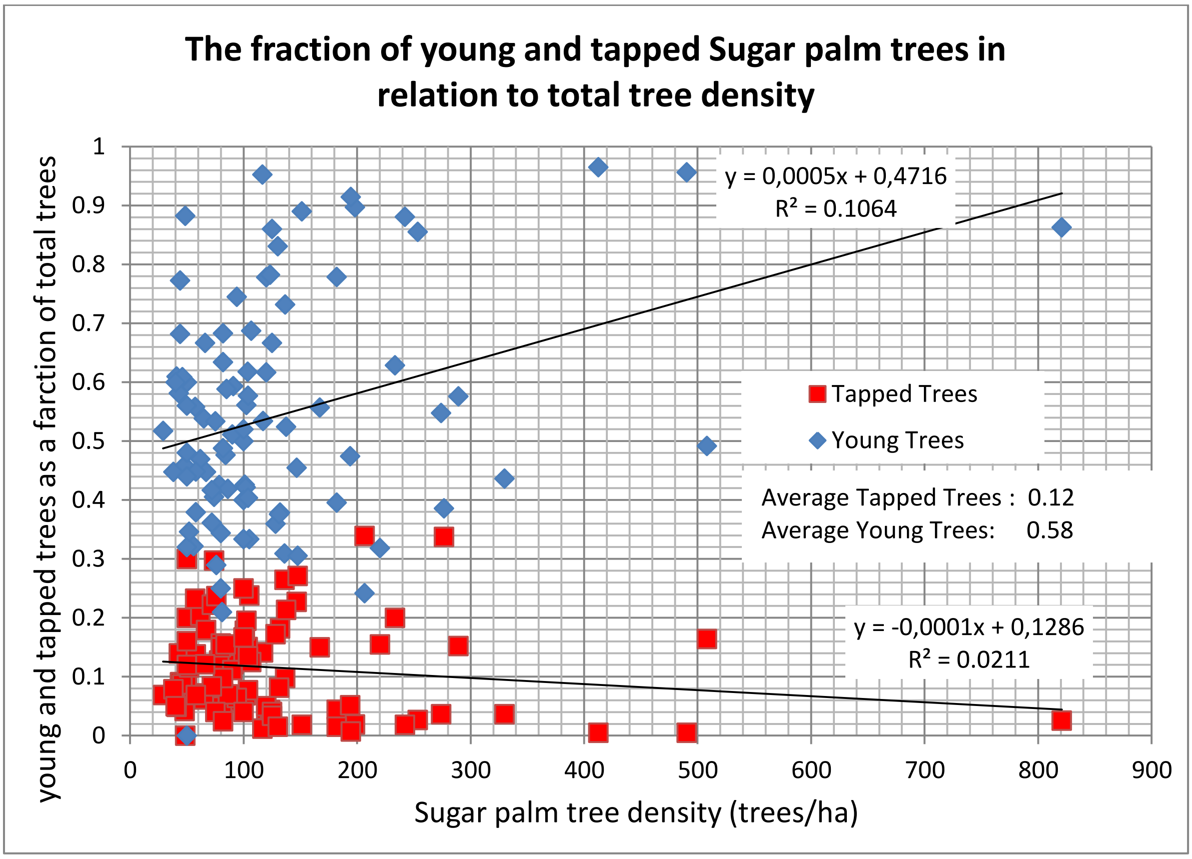

Figure 21: Relation between the tree density and the fraction of young and tapped sugar palm trees. Note that every blue data point has a corresponding red data point below. There is no significant correlation between tree density and age composition. However, the likely trend is an increase in young trees at higher tree densities. A visual interpretation of this data indicates that the fraction of trees available for tapping is unaffected up to tree densities of 150-300 trees/ha.

The trend is that at higher tree densities, the fraction of trees which can be tapped slightly decreases, although this trend is not statistically significant. A logarithmic fit does not improve the R^2.

Conversely, one might expect that at higher tree density, the fraction of immature (and thus smaller) trees might increase. The fraction of immature trees is plotted against tree density in blue. There is a trend of an increased amount of immature trees at higher density, however this trend is not statistically significant as well. Based on these results it is not possible to determine an upper limit for tree densities. However, the data becomes sparser at tree densities above 200 trees/ha which makes it unclear if the trends really continue beyond that point. Since few tappers have sugar palm tree densities of above 200 trees per hectare, this in itself suggests that this might be a feasible upper limit.

Therefore, the maximum density where the fraction of tapped trees is unaffected is between 150-300 trees/ha. This translates to a likely amount of 16 to 21 trees being tapped per hectare. Whether juice yields also remain unaffected at these intensities is unclear. If juice yields up to 21 tapped trees/ha remains unaffected, this would translate to 136.000 liters juice per hectare or up to 21.672 kg sugar per year.

In summary, an average tapper has 0.6 hectare of land. The land of a tapper has on average 111 sugar palm trees per hectare of which 12 are tapped. This produces 65,000 liters of juice per year or 9.8 tons of sugar per hectare per year.

Appendix VII: Distillation Energy use and capacity

The distiller consists of two distillation columns and a cooling unit. The fermenter is attached to the first distillation column. When the valve between these two units is opened, wine flows from the fermenter into the first column. The fluid level inside the column can be read from a transparent tube connected to the column on the outside. Underneath the first column is a wood stove which heats the column and the wine inside.

As the first column heats up, the distillation process commences; a water-ethanol mixture evaporates from the wine and exits from the top of the column into the second column. At the beginning of the distillation process, the second column is still cool and all of the vapor condenses and collects there. However, after about an hour of heating, vapor is produced from the second column as well. Vapor leaving the second column enters the cooling unit where it condenses and flows into a jerry can. This is the ethanol product.

The first ethanol that is produced has the highest concentration. Afterwards, more and more water is produced and the ethanol concentration slowly decreases. Distillation is stopped when the ethanol concentration drops to a certain minimum.

At the start of distillation, the first column is filled with +/- 35 liters of wine. Later, as the water table decreases, additional wine can be loaded into the first column. The ethanol concentration of the wine from the fermenter can vary. A new batch of fermented juice has concentration of around 10 vol%.

However, after distillation, the ethanol concentration in the second column might still be significant. In the first two measurements performed, the ethanol concentration in the second column was actually higher than the feed. This 'vinasse' can be fed back to the feed for another round of distillation. The ethanol concentration of the feed therefore increases as more distillation operations have been performed.

Three measurements were performed to assess the energy use of this distiller. The first two measurements were performed with an almost depleted tank of feed with an elevated ethanol concentration. The first experiment used a feed with 43 vol% and produced 17.5 liters of ethanol with 72 vol% over a period of 6:06 hours. Measurements started when ethanol production started. Therefore, the amount of fuel wood combusted to start the distillation process was not measured in this case. The second measurement used feed with 45 vol% and produced 7.75 liters of ethanol with a concentration of 87 vol% over a period of 4:47 hours. The third experiment used a feed of 8.7 vol% (from a new batch of wine). It produced 0.55 liters of ethanol with 82 vol% before distillation was halted due to extreme weather.

To compare the produced ethanol with different concentrations, the volumes of ethanol are converted to '*ethanol 85 vol% equivalent liters*' in the following way:

$$Volume\ ethanol_{85\ Vol\%\ equivalent} produced\ =\ Volume\ produced_{Actual\ Vol\%} * \frac{Actual\ Vol\%}{85}$$

This conversion to 85 vol% ethanol is a simplification which allows the comparison between ethanol mixtures of different concentrations. This simplification ignores the fact that more heat is required to produce ethanol with higher concentrations. However, for concentrations close to 85 vol% the assumption is this conversion is a good approximation of the amount of heat input required.
The results are summarized in the table below.

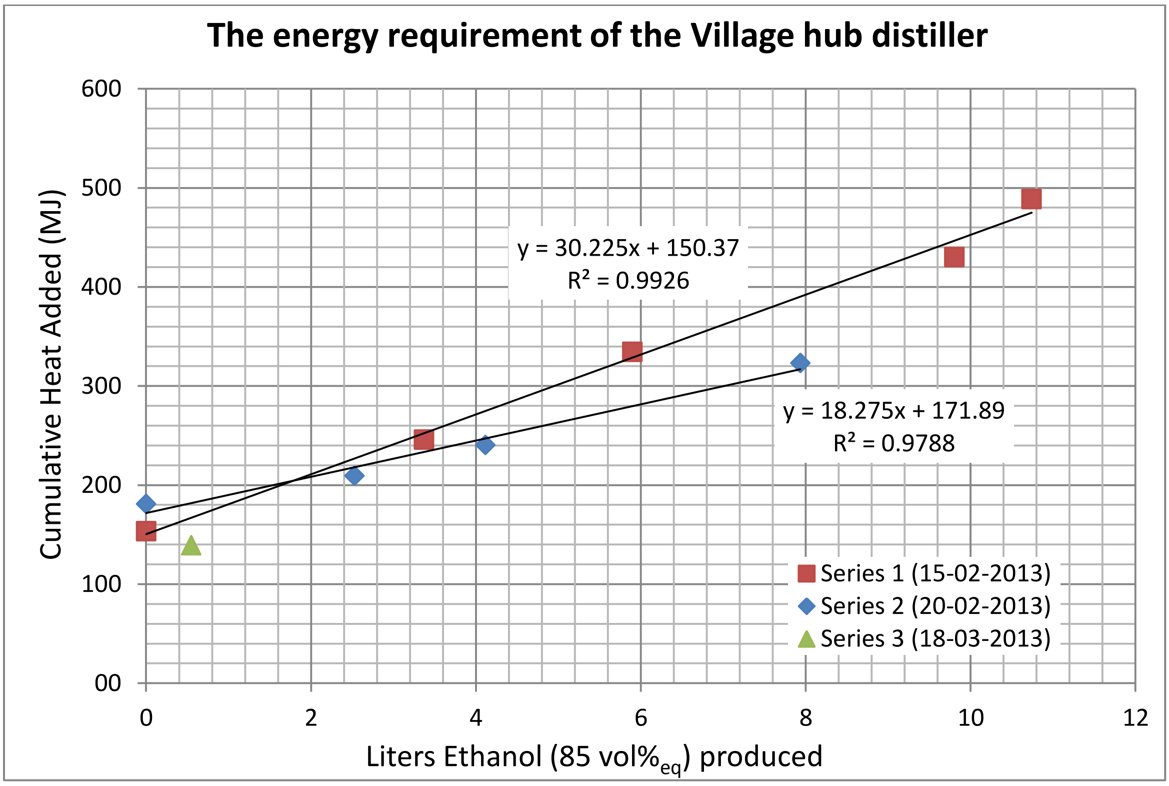

Figure 22: Three measurements were performed to determine the heat requirement of the village hub distiller. At different intervals, the heat added was measured based on the amount of fuel wood which was combusted, as well as the volume of the ethanol which was produced. The production volume was then converted to liters 85 vol$\%_{eq}$ based on the ethanol concentration.

The slope of the trend lines show that after an initial start-up of the distiller, between 18-30 MJ is required to produce one liter of ethanol of 85 vol$\%_{eq}$. Taking the average slope of these measurements, then extrapolating backwards for the third measurements, 126 MJ of heat is required for ethanol production to start. At the second measurement, the start-up heat was 172 MJ. Therefore, for the first measurement (where the beginning amount of wood added was not measured), an average start up energy of 149 MJ is assumed. Afterwards, an average of 24.3 MJ of heat is required per liter that is produced.

The first measurement produced 10.7 liters of ethanol 85 vol$\%_{eq}$. This is considered the average volume of ethanol produced per batch. At most three batches can be produced per day yielding 32.1 liters of 85 vol$\%_{eq}$. The average amount of heat required to produce one liter of 85 vol$\%_{eq}$ ethanol would then be:

$$Heat\ input\ per\ liter = 24.3\frac{MJ}{liter} + \frac{152\ MJ}{10.7\ liter} = 38.4\frac{MJ}{liter}$$

Based on these results, it is clear that there is a large variation in energy use for distillation and that more measurements, over a longer period, need to be performed to get a more accurate value. However, a reasonable lower limit can be calculated from these results by combining the lower value of start-up energy and per liter energy input. Conversely an upper limit can be calculated. This gives a range of 30.5-46.2 MJ/liter ethanol produced. The results are summarized in the table below.

Table 20: Parameters which describe the energy requirement of the village hub distiller in terms of start-up energy, energy required after start-up per liter ethanol and the overall energy requirement per liter ethanol for a high, medium and low estimate.

Lower limit of energy use for distillation		
Slope trend lines	MJ/liter	18.3
Start-up energy	MJ	132

Volume produced	Liters	10.7
Total heat used	MJ/liter	30.5
Upper limit of energy use for distillation		
Slope trend lines	MJ/liter	30.2
Start-up energy	MJ	172
Volume produced	Liters	10.7
Total heat used	MJ/liter	46.2
Average energy use for distillation		
Slope trend lines	MJ/liter	24.3
Start-up energy	MJ	152
Volume produced	Liters	10.7
Total heat used	MJ/liter	38.4

Appendix VIII: Transportation

The pilot village hub is located next to the Masarang sugar factory. This sugar factory is served by sugar palm tappers for the supply of fresh juice. From the sugar factory, there are two routes for transport trucks to visit affiliated tappers to pick up fresh juice in the mornings. These routes are 21 and 16 km long based on readings of the vehicles kilometer meters. On average these routes are therefore 18.5 km.

The Masarang foundation uses two Toyota Dyna Long 4000 trucks with a capacity of 4,700 kg of juice. The average juice transported per trip, based on the Masarang sugar factory records was 1,272 liters per trip which weighs 1,376 kg. When a truck leaves to pick up the juice it is empty and when it returns it contains 1,376 kg. Therefore, it is assumed that during the trip the average load of the truck was 1,376/2 = 688 kg or 0.688 tons. The eco-inventory datasets includes environmental impacts for the transportation loads of different types of vehicles. These datasets require calculate the environmental impacts based on the amount of goods transported in ton-kilometer (tkm). The average transport input for juice is therefore 0.688 tons * 18.5 km = 12.7 tkm per trip.

Appendix IX: Sugar in juice

The sugar in sugar palm juice consists almost exclusively of sucrose with small fractions of glucose and fructose (Smits, 2013; Itoh *et al.*, 1984). Besides sugar, juice contains small amounts of protein and ash, as well as different kinds of organic acids and minerals (Lantemona *et al.,* 2013; Itoh *et al.*, 1984).

Sugar concentration

Based on records kept by the Masarang foundation of juice purchases by the Masarang sugar factory from tappers, the average concentration of the juice delivered to the Masarang factory was 15.0 °Brix. The standard deviation is 2.3 Brix. Interestingly, the °Brix values of the juice collected are not normally distributed around the mean as might be expected but they are strongly skewed towards higher values as can be seen from the figure below.

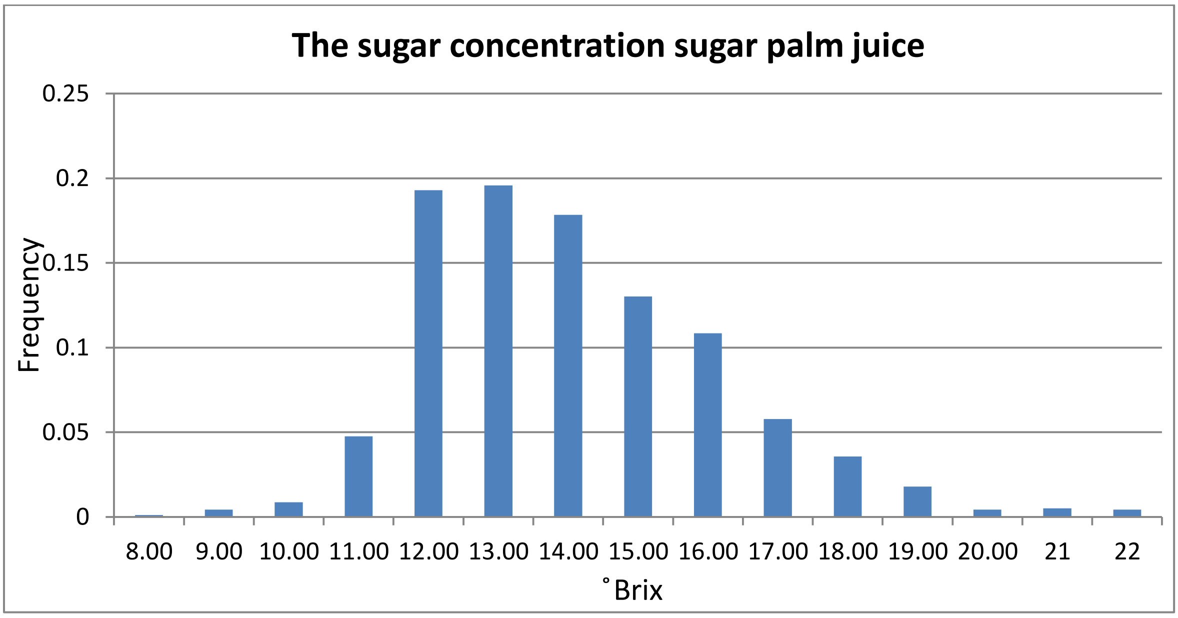

Figure 23: Distribution of sugar palm juice Brix values, based on 29.8 hectoliter of juice collected in November 2011 from 21 sugar palm tappers in the Tomohon area. They provided juice to the sugar palm sugar factory. The average Brix for this sample is 15.0. The standard deviation is 2.3 Brix.

The distribution is skewed for higher °Brix values. This can be explained if tappers abandon trees which produce juice with low sugar concentration. This graph suggests that sugar °Brix could be normally distributed around 13 °Brix and that tappers have a strong preference for trees that yield at least 12 °Brix juice. These findings largely concur with other reported juice concentrations:

- Staaij & van den Bos *et al.* (2011) report a range of 12-17 °Brix with additional outliers
- Mogea *et al* 1991 reports a range of 12-15°Brix
- A smaller sample of 476 liters of juice collected from multiple tappers for the purpose of measurements on the rocket stove had a sugar concentration of 14.1°Brix
- Lantemona *et al.* (2013) recorded the yields of 12 mature sugar palm trees in the Tomohon area and found that the average °Brix was 12.64±0.50 during the wet season and 13.53±0.58 during the dry season

Density juice

Quantities of juice are usually expressed in volume. However, the sugar concentration is expressed in °Brix which is a percentage by weight. Therefore, the volume of juice has to be converted to the weight of juice by multiplying with the density. For sugary juice, the density is usually >1. Therefore, neglecting to correct for the density of the juice could lead to significant errors.

There are some online tools that calculate sugar juice density based on the °Brix value. However, these standard tools might not be accurate for sugar palm sugar which has a unique composition. Therefore, measurements were performed to determine the density of sugar palm juice both at room temperature as well at near-boiling temperature (which is required for the juice boiling measurements). Samples with different sugar concentrations were produced by dissolving sugar palm sugar into water. The volume and weight of these samples were carefully measured. Based on these measurements, a relation between density and °Brix was determined by fitting the samples using the Microsoft Office Excel trendline functionality. One extra data point was added for the zero-°Brix value based on standard densities of water at room and boiling temperatures. The measurements, including the functions relating °Brix and density are presented in figure 24 below:

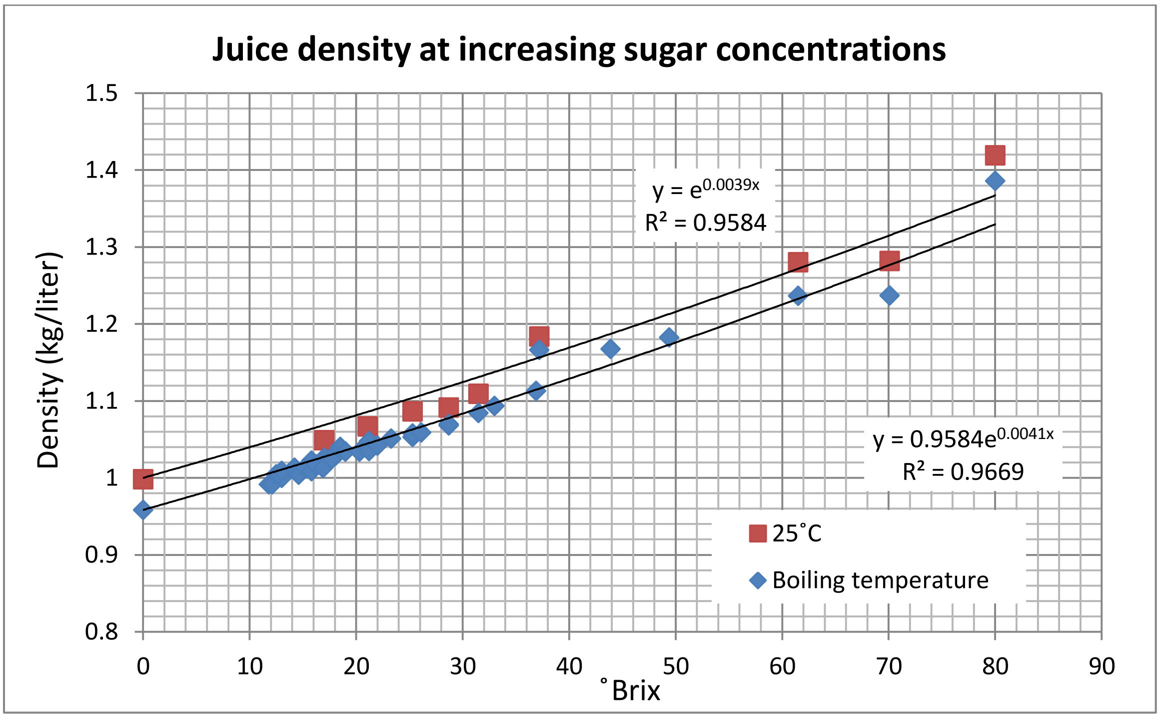

Figure 24: Density (kg/liter) of sugar palm juice for increasing sugar concentrations (˚Brix). The red data points refer to measurements of juice at room temperature. The blue data points refer to measurements taken of juice immediately after boiling. The densities at 0˚Brix are taken from the website theengeneeringtoolbox.com. The trendlines are forced through these data points at 0˚Brix since these values should be accurate.

Appendix X: Juice boiling efficiency calculations

The efficiency of juice boiling (expressed in heat required for boiling divided by heat added) is calculated for juice boiling in a pan (used in System 1: reference case) and in a rocket stove (used in System 2 and 3). The heat added is calculated from the amount of wood which was burned in the boiling process. The heat required, in a one-stage evaporation process, is combination of the temperature increase to boiling temperatures and the heat of evaporation of the water in the juice. The procedure of the efficiency calculations are described in this section.

Before boiling, the °Brix, the temperature and the volume of the juice are measured. During boiling only the °Brix and the temperature are measured. The initial weight of the juice is calculated as follows:

$$Weight\ juice_{start} = Density\ juice_{start} * Volume\ Juice_{start}$$

With:

$$Density\ juice_{25-50°\mathrm{C}} = e^{0.0039*BRIX}$$

$$Density\ juice_{>50°\mathrm{C}} = 0.9584 * e^{0.0041*BRIX}$$

The weight of the juice is comprised of water and sugar. The weight of these can be calculated as follows:

$$Weight\ sugar = Weight\ juice * \frac{Brix}{100}$$

$$Weight\ water = Weight\ juice - Weight\ sugar$$

In the rocket stove juice boiling measurements, the volume of juice was measured directly by measuring the depth of juice in the barrel. At the start, there is no wood burned yet and therefore no heat added and no heat required for water evaporated or temperature increase. At the next interval (T) a certain amount of wood has been burned to boil the juice. The amount of heat added is therefore:

$$Cumulative\ heat\ added_T = \sum_{Start}^{T} Wood\ burned * LHV\ wood$$

When the added wood has released its heat of combustion is of course impossible to determine exactly. For the measurements it is assumed that when wood is added, the previously added wood is completely combusted. This is a simplification which is necessary to be able to analyze the relation between heat added and juice evaporated over time during boiling. However, this simplification does not affect the first and last measurements since either no wood has burned yet or all the wood is completely combusted.

The new °Brix and the temperature of the juice are measured. The amount of sugar in the juice is unchanged since the sugar does not evaporate or disappear.

$$Weight\ sugar_T = Weight\ sugar$$

However, some water has evaporated and the weight of the juice has decreased. For measurement of juice boiling in a pan, it was not possible to directly measure the weight or volume of the juice while boiling occurred. Therefore, the °Brix of the juice, which has a direct relation to the weight of the juice was used to calculate the weight of the juice:

$$Weight\ of\ juice_{(T)} = \frac{Brix_T}{Weight\ sugar} * 100$$

In the rocket stove juice boiling measurements, the volume of juice was measured directly by measuring the depth of the juice in the barrel with a measuring tape. The weight of the juice could therefore be calculated directly in the following way:

$$Weight\ juice_{(T)} = Density\ juice_{(T)} * Volume\ Juice_{(T)}$$

With:

$$Density\ juice_{(25-50°C)} = e^{0.0039*BRIX}$$

Or:

$$Density\ juice_{(>50°C)} = 0.9584 * e^{0.0041*BRIX}$$

The weight of the water is recalculated as previously:

$$Weight\ of\ water_{(T)} = Weight\ juice_{(T)} - Weight\ sugar$$

In two out of three measurements with the rocket stove, water was used for boiling instead of actual juice since no fresh juice was available. In these instances, the weight of the water is determined by measurement of the volume of water multiplied with the density:

$$Weight\ of\ water_{(T)} = Volume\ water\ _{(T)} * Density\ water$$

For cold water (~25°C) a density of 0.9982 kg/liter is assumed, for hot water (~100°C) 0.9854 kg/liter is assumed (theengeneeringtoolbox.com).

Heat has been used to evaporate the lost water. The amount of heat required to evaporate this water is calculated as follows:

$$Heat\ of\ evaporation_{(T)} = (Weight\ of\ water_{(T-1)} - Weight\ of\ water_{(T)}) * Heat\ of\ evaporation$$

If the temperature of the juice has increased over this time interval, additional energy was consumed. This is calculated as follows:

$$Heat\ of\ temp.increase_{(T)} = \left(Temp_{(T)} - Temp_{(T-1)}\right) * \frac{Weight\ of\ juice_{(T)} + Weight\ of\ juice_{(T-1)}}{2} * Heat\ capacity\ of\ water$$

The heat capacity of water is used since the heat capacity of juice only decreases slightly as the °Brix value increases. Moreover, after an initial heating of the juice at low °Brix values, the temperature levels off around 100°C and the energy consumption halts. In case the measurements only contain two intervals, the start and the end, the heat of temperature increase reduces to:

$$Heat\ of\ temp.increase_{(T)} = \left(100 - Temp_{(start)}\right) * Weight\ of\ juice_{(start)} * Heat\ capacity\ of\ water$$

In this case it is assumed that all the juice is heated to 100°C first and that only then evaporation starts.

The total amount of heat that was used to increase the temperature and evaporate the water at this point is:

$$Cumulative\ heat\ required_T = \sum_{Start}^{T} Heat\ of\ evaporation + \sum_{Start}^{T} Heat\ of\ temp.increase$$

By dividing the cumulative heat required with the total heat added, the efficiency of the juice boiling process can be determined.

$$Efficiency\ juice\ boiling = \frac{Cumulative\ heat\ required_{(end)}}{Cumulative\ heat\ added_{(end)}}$$

Appendix XI: Sugar boiling in pan

To determine the efficiency of sugar boiling in a pan, a tapper monitored the boiling process on two occasions as he boiled his juice in a pan on the fire pit on his land. This tapper measured the temperature of the juice, the °Brix of the juice and the amount of wood added to the fire at different intervals during boiling. Based on this data, and following the procedure as outlined in the methods section and Appendix X, the results are plotted in the graph below.

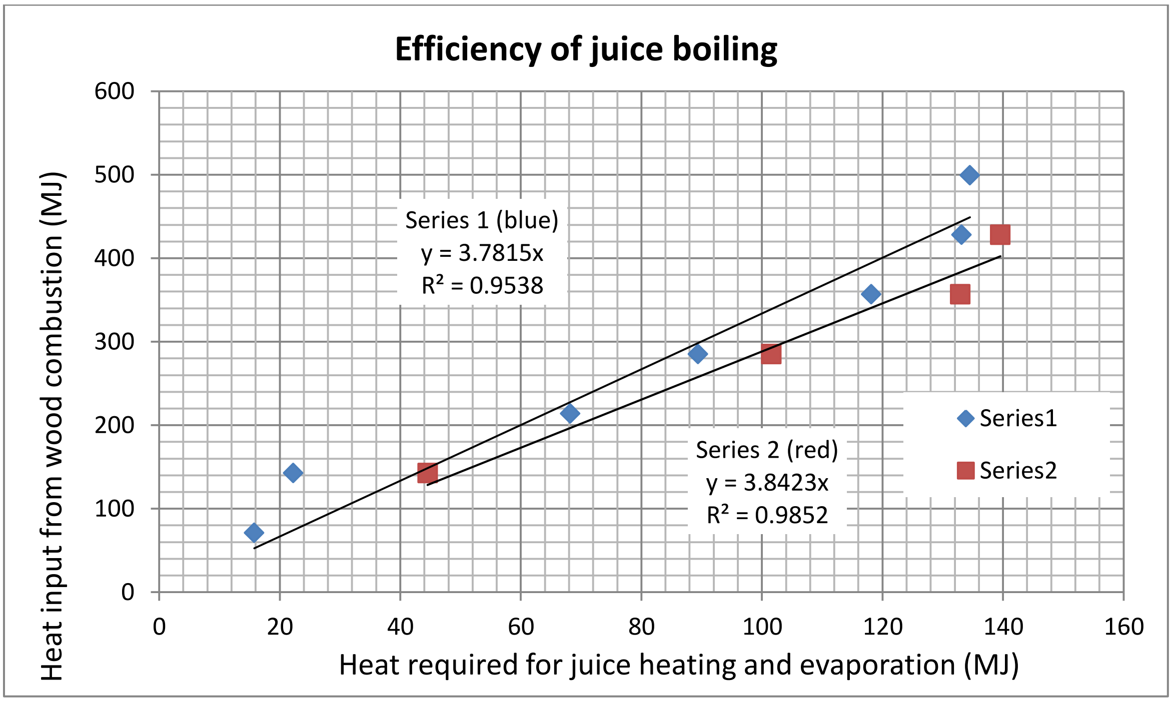

Figure 25: The amount of heat (MJ) which was released from combusting wood for the purpose of juice boiling with a pan in relation to the minimum heat required. The minimum heat required for the boiling process (MJ) is based on the temperature increase of the juice and the amount of juice evaporated.

The efficiency for the boiling series one was 27.0%, for series 2 it was 32.4%. The trend lines intersect the origin as is expected, where zero heat is added and zero initial energy is required. What these trend lines show is that immediately after heat is added, this led to the heating and evaporation of the juice.

Additional measurements were performed by this and another tapper on additional boiling processes. In these instances, measurements were only performed at the beginning of boiling and on the total wood use at the end. Using the same method as previously, the efficiency of boiling is calculated and the results are shown in the table below. The first two measurements from tapper 1 are the measurements analyzed before.

Table 21: Measurement data, intermediate values and final efficiency values for the sugar palm juice boiling process of Tapper #1.

Tapper 1													
Volume of juice	**Liter**	56	58	26	30	30	27	30	30	30	30	30	30
Sugar concentration	**°Brix**	10.2	11.4	11.2	11.1	11.2	12.2	12.2	12.1	11	11.1	11.2	11.2
Wood burned	**Kg**	35	30	27	30	30	27	30	30	29	29	30	30
Density before boiling	**Kg/liter**	1.04	1.05	1.05	1.04	1.05	1.05	1.05	1.05	1.04	1.04	1.05	1.05
Weight sugar	**Kg**	5.9	6.9	3.0	3.5	3.5	3.5	3.8	3.8	3.4	3.5	3.5	3.5
Weight juice	**Kg**	58	61	27	31	31	28	31	31	31	31	31	31
Weight of water	**Kg**	52.3	54	24	28	28	25	28	28	28	28	28	28
Heat of evaporation water	**MJ**	118	121	54	63	63	56	62	62	63	63	63	63
Heat for heating juice	**MJ**	17	17	8	9	9	8	9	9	9	9	9	9
Total heat required	**MJ**	135	139	62	72	72	64	71	71	72	72	72	72
Total heat input from wood	**MJ**	499	428	385	428	428	385	428	428	414	414	428	428
Wood burned	**Kg/liter**	0.63	0.52	1.04	1.00	1.00	1.00	1.00	1.00	0.97	0.97	1.00	1.00
Efficiency boiling by farmer	**%**	**27.0**	**32.4**	**16.2**	**16.8**	**16.8**	**16.7**	**16.7**	**16.7**	**17.4**	**17.4**	**16.8**	**16.8**

Table 22: Measurement data, intermediate values and final efficiency values for the sugar palm juice boiling process of Tapper #2.

Tapper 2											
Volume of juice	**Liter**	50	65	60	60	52	50	54	53	48	50
Sugar concentration	**°Brix**	10	9	9	9	8	9	9	9	9	9
Wood burned	**Kg**	37	47	48	46	42	40	42	42	50	50
Density before boiling	**Kg/liter**	1.04	1.04	1.04	1.04	1.03	1.04	1.04	1.04	1.04	1.04
Weight sugar	**Kg**	5.2	6.1	5.6	5.6	4.3	4.7	5.0	4.9	4.5	4.661
Weight juice	**Kg**	52	67	62	62	54	52	56	55	50	52
Weight of water	**Kg**	47	61	57	57	49	47	51	50	45	47
Heat of evaporation water	**MJ**	106	138	128	128	111	106	115	113	102	106
Heat for heating juice	**MJ**	15	19	18	18	15	15	16	16	14	15
Total heat required	**MJ**	121	158	146	146	127	121	131	129	116	121
Total heat input from wood	**MJ**	528	671	685	656	599	571	599	599	714	714
Wood burned	**Kg/liter**	0.74	0.72	0.80	0.77	0.81	0.80	0.78	0.79	1.04	1.00
Efficiency boiling by farmer	**%**	**22.8**	**23.5**	**21.2**	**22.2**	**21.2**	**21.2**	**21.9**	**21.4**	**16.3**	**17.0**

The average boiling efficiency of the first tapper is 19%, that of the second tapper is 21%. All the measurements together have an average efficiency of 20%. However, the data from the first tapper suggests that there might have been a significant amount of rounding in the values of the amount of juice processed and the amount of wood burned. However, the tapper in question reports that this was not the case. These tappers have a daily routine of juice boiling which they have performed for several decades; this could explain the regular values in their boiling procedure.

The relation between the heat added and the heat required, based on an efficiency of 19.8% would be:

$$Heat\ added = 5.051 * Heat\ required$$

Appendix XII: Moisture content and heating value of fuel wood

Fuel wood is combusted in the production of sugar palm ethanol in both the sugar juice boiling phase as well as in distillation. Measurements have been performed to determine the amount of fuel wood (in kg) which is used in these processes. However, expressing the amount of fuel wood used in these processes in terms of energy (MJ) is informative because it allows for a better interpretation of the results. Moreover, the Ecoinvent database expresses the environmental impacts of wood combustion per MJ. Therefore the fuel wood measurements are translated to the energy released in the fuel wood in MJ.

Cempaka (*Magnolia champaca*) and Pakoba (*Eugenia stipitata*) are popular hard wood trees which are cultivated in the Tomohon area. They were used at the pilot village hub as fuel wood. Tappers make use of any fuel wood available to them but a small questionnaire with 12 tappers revealed that they also used Cempaka if it was available. Both the village hub and the tappers generally dry their wood before combustion.

Air-dried logs of Cempaka and Pakoba were tested to determine their moisture content. From each wood type, three samples of saw dust were produced over the complete length of the logs (including equal amounts of inner and outer layers) and weighed on a very sensitive scale. These samples were then dried in an oven for ~24 hours at ~100˚C and weighed again afterward. After oven drying, the moisture content is reduced to an estimated 0.4% (based on Reeb and Milota, 1999). The moisture content is calculated as follows:

$$Moisture\ contennt\ (\%) = \frac{Weight\ loss\ from\ drying}{Weight\ before\ drying} \times 100 + 0.4\%$$

The results of the weight measurements are presented in table 23 below.

Table 23: Measurement data and the calculated moisture content for six samples of air-dried fuel wood.

		Pakoba			**Cempaka**		
	Sample	1	2	3	4	5	6
Weight before drying	**Gram**	4.8663	4.8992	5.0511	4.3553	3.6359	3.6753
Weight after drying	**Gram**	3.7681	3.834	3.9965	3.6908	3.0872	3.1263
Moisture content	**%**	22.97	22.14	21.28	15.66	15.49	15.34

The average moisture content of all six samples is 18.8%.

Telmo and Lousada (2011) determined the LHV of a sample of tropical hardwoods to be 16.8482 MJ/kg. These samples had a moisture content of 9.7% .Generally, wood has very similar heating values when correcting for the moisture content. To correct for the moisture content, the heating value of completely dry wood is calculated first. The relationship between dry wood and wood with moisture is expressed in the following formula, adapted from Sokhansanj (2011):

$$LHV_{wet} = LHV_{dry} \times (1 - moisture\ content) - 2.443\ \left(\frac{MJ}{kg}\right) \times\ moisture\ content$$

Rearranging gives:

$$LHV_{dry} = \frac{LHV_{wet} +\ 2.443\ \left(\frac{MJ}{kg}\right) \times\ moisture\ content}{1 - moisture\ content}$$

Using the rearranged formula the heating value of completely dry (0% moisture) tropical hardwood is calculated to be 18.92 MJ/kg. Using the original formula again to translate the heating value to wood with 18.8% moisture gives a LHV of 14.9 MJ/kg, which is the value used in this study.

Appendix XIII: Fuel wood productivity of forests

Natural forest

The analysis of a ten year old plot of secondary forest grown in Tomohon (North Sulawesi) revealed that the above ground biomass totaled 250 m^3 of wood indicating that the yearly biomass increment was on average 25 $m^3ha^{-1}year^{-1}$ (W. Smits, unpublished data). Hertel *et al.* (2009) found that the yearly above ground increment of biomass in a natural rainforest in the Central Sulawesi area to be 5.62 Mg $ha^{-1}year^{-1}$ of dry biomass (D. Hertel *et al.* 2009). Taking an average moisture content of 50% and a density of 0.62 $g_{(wet)}/cm^3$ (Agus and van Noorwijk 2005) this equals a yearly increment of 18.1 $m^3ha^{-1}year^{-1}$. When including the leaves and other fine litter the above ground biomass increases to 42 $m^3ha^{-1}year^{-1}$. However the leaves and litter are generally not collected when harvesting fuel wood.

Production forest

Brown *et al.* 1997 reports that 25 $m^3ha^{-1}year^{-1}$ is the upper limit for Pine plantations in Brazil and Chile and exceeds yields of Eucalyptus plantations in Brazil and South Africa with 18-20 $m^3ha^{-1}year^{-1}$. Other sources report a yearly biomass increment of 15-30 $m^3ha^{-1}year^{-1}$ for Pine and Eucalyptus plantations, depending on subspecies, growing condition and rotation length (Ugalde and O Pérez, 2001; Huy, 2004).

Sustainable wood removal from existing forests

The establishment of a production forest can either have a positive or negative effect on biodiversity depending on the former land use (Huy 2004). Sustainable wood removal from an existing natural forest is also possible at lower intensities. Sista *et al.* (2002) find that a sustainable wood removal from mixed dipterocarp forests in Kalimantan (Indonesia) is 1.6 $m^3ha^{-1}year^{-1}$ with no more than 80 m^3ha^{-1} harvested at once, implying an optimal rotation cycle of 50 years. W. Bisschoff *et al.* (2005) looked, among other things, at the recovery of secondary forest in Kalimantan after logging and found that logging practices often exceeded this 80 m^3ha^{-1} with actual logging practices ranging between 60-174 m^3ha^{-1} of wood removed per rotation. Assuming that the state mandated rotation cycle of 60 years is applied (Sabah Forestry Department, 1989; in Pinard and Cropper, 2000) the past logging practices result in a 1.0-2.9 $m^3ha^{-1}year^{-1}$. These low quantities of annual wood removal from natural forests result in very large areas of forest needed to meet energy demand for the distillery and the associated transport distances. Furthermore, the harvested wood is of a high quality better suited for timber uses instead of being used as firewood.

Conclusion

Completely cutting natural forests to meet energy demand for ethanol production is not an option. Sustainable wood harvesting yields are too low for to meet fuel wood use. Moreover this wood would be better suited as furniture and building material. Production forests with fast-growing species have high yields and can have a positive effect on biodiversity depending on former land use. The fuel wood yield of 25 $m^3ha^{-1}year^{-1}$ is used in this analysis which is supported by measurement of Dr. W. Smits as well as literature sources.

Appendix XIV: Fermentation efficiency, °Brix and ethanol concentration

The chemical equation for the fermentation of sugar (sucrose) to ethanol is the following:

$$C_{12}H_{22}O_{11} + H_2O \rightarrow 4\ C_2H_5OH + 4\ CO_2$$

The molar weights of sucrose and ethanol are 342.0 and 46.07 g*mol^{-1}. Therefore, one gram of fructose can at the most yield 0.51143 gram of ethanol:

$$\frac{4\left(\frac{mol\ Ethanol}{mol\ Sucrose}\right) * 46.07\left(\frac{gr\ ethanol}{mol\ ethanol}\right)}{342.30\left(\frac{gr\ sucrose}{mol\ sucrose}\right)} = 0.53836\left(\frac{gr\ ethanol}{gr\ sucrose}\right)$$

When multiplying ethanol by its density of 0.789 gram/ml we get a ratio of 0.68234 ml ethanol produced per gram sugar. This is however considering a 100% efficiency of fermentation. In practice the fermentation is lower than a 100% because the yeast incorporates some fructose into its biomass and because usually some sugars are left at the end of fermentation. The average fermentation efficiency in sugarcane ethanol production in Brazil was 80% in 1975 and is a maximum of 91.36% currently (CGEE 2012).

To calculate the ethanol concentration of wine after fermentation, the following formulas are used:

$$Ethanol\ concentration\ (Vol\%) = \frac{Volume\ ethanol\ (liter)}{Volume\ wine\ (liter)} * 100$$

$$Volume\ ethanol\ (liter) = \frac{Mol\ ethanol\ (mol) * Molar\ weight\ ethanol\left(\frac{gram}{mol}\right)}{Ethanol\ density\ \left(\frac{gram}{liter}\right)}$$

Four moles of ethanol are produced from the fermentation of one mole fructose:

$$C_{12}H_{22}O_{11} + H_2O \rightarrow 4\ C_2H_5OH + 4\ CO_2$$

Therefore, the amount of moles ethanol produced is as follows:

$$Mol\ ethanol\ (mol) = Mol\ fructose\ (mol) * 4 * \frac{fermentation\ efficiency}{100}$$

$$Mol\ fructose\ in\ juice\ (mol) = \frac{concentration\ fructose\ \left(\frac{kg\ fructose}{kg\ juice}\right) * \ density\ wine\ \left(\frac{kg\ juice}{liter\ juice}\right) * volume\ wine\ (liters\ juice)}{molar\ weight\ fructose\ \left(\frac{kg\ fructose}{mol\ fructose}\right)}$$

$$Concentration\ fructose = \frac{Brix}{100}\ \frac{\left(\frac{decigram\ sugar}{kg\ juice}\right)}{\left(\frac{decigram\ sugar}{kg\ sugar}\right)}$$

Combined the formulas are:

$$Ethanol\ concentration\ (Vol\%) = \frac{Brix * \ density\ juice\ * 4 * fermentation\ efficiency * molar\ weight\ ethanol}{molar\ weight\ fructose\ * \ ethanol\ density * 100}$$

For example, a juice with 20 °Brix and a fermentation efficiency of 74.8% yields the following ethanol concentration:

$$Ethanol\ concentration\ = \frac{20 * \ 1.04\ * 4 * 74.8 * 46}{342\ * \ 0.789 * 100} = 10.09\ (Vol\%)$$

Natural fermentation efficiency

The ethanol concentration of six samples of 'Sagwer', naturally fermented juice was determined. Since Sagwer is carbonated and contains some sugar a direct of the alcohol concentration using a buoyancy based device was not possible. Therefore, the whole sample of ~100 ml was distilled in a small laboratory setup. The effect of this distillation was to dispel the carbon and to separate the ethanol from the sugar. After distillation was >95% complete, the product was then measured using a standard alcohol measuring device which uses the buoyancy as an indicator of the ethanol concentration. This concentration was then corrected based on the relative volumes of the sample before and after distillation. This procedure was repeated four times on sample six with very similar results ranging from 5.3-5.57 vol%. The results are presented in table 2 below.

Table 24: Ethanol concentration of six samples of Sagwer.

Sample #	Ethanol concentration (%)
1	6.83
2	5.78
3	4.90
4	6.56
5	8.87
6	5.44
Average	**6.4**

Based on the average of 15.0 °Brix in juice before fermentation, the fermentation efficiency of these samples would be 67%. This calculation of this fermentation efficiency is not very robust since the °Brix of the juice before fermentation was not measured, only based on averages. However, this natural fermentation efficiency does not affect any of the results and these measurements were part of an initial investigation.

Appendix XV: Emissions from fuel wood burning

Measurements have been performed on the emissions of various types of stoves and cooking equipment. However, their results vary greatly depending on experimental conditions such as type of wood used, moisture content of the wood, the size of the logs used and the length of time measured (Roden *et al.* 2009). Moreover, large differences are observed between measurements performed in laboratory conditions or in the field (Roden *et al.* 2009; Pettersson *et al.* 2010).

All three processes in the ethanol lifecycle where fuel wood is burned make use of unique systems which cannot be directly related to systems analyzed in literature. The rocket stove used for juice boiling has a unique design and is considerable larger than conventional rocket stoves used for cooking. The stove of the distiller is also of a unique design and more resembles a brick stove used for heating than a stove used for cooking. The sugar boiling processes of the tapper uses a fire in a hole in the ground with a large round pan suspended above. This method is not practical for conventional cooking purposes and does not resemble traditional cooking methods such as for example the ‘three stone fire’. Matching any of these cooking systems with systems analyzed in literature was therefore unsuccessful.

Moreover, different works which analyzed similar systems still find different average values for emissions. Therefore, using emission data from varying authors would already lead to biases. For example, ‘three stone fire’ which is studied by MacCarty *et al.* (2010) is similar to the ‘improved open fire’ studied by Ballard-Tremeer and Jawurek (1996). However, even though these sources analyzed very similar systems they still found very different emissions for CO (Carbon Monoxide) and PM_{tot} (Total Particulate Matter).

Table 25: The CO and PM_{tot} emissions from wood burning as reported by two sources.

		MacCarty *et al.* (2010)	**Ballard-Tremeer and Jawurek (1996)**
CO	g/kg_{fuel}	52	19
PM_{tot}	g/kg_{fuel}	1.3	0.83

Therefore, emission measurements from one good source are used to account for the emissions of all three systems. The emissions data used come from measurements performed on a natural-draft wood stove used for space heating by Pettersson *et al.* (2010). There are two reasons why their measurement are preferred above those performed by others.

The first reason is that their measurements are particularly thorough and include six types of emissions which can be used for the analysis: besides CO and PM_{tot} which are commonly measured in emissions literature, Pettersson *et al.* (2010) also measured NOx (Nitrogen Oxides), NMVOCs (Non-Methane Volatile Organic Compounds), Methane and PAH_{tot} (total Polycyclic Aromatic Hydrocarbons).

In comparison, most other works usually only include two types of emissions (CO and PM). The wide range of emissions measured allows for a more complete translation to environmental impacts.

Secondly, the heating activity of the measurements in this work are similar to wood burning practices in the ethanol lifecycle, in terms of length of heating as well as amount of wood burned per cycle. Pettersson *et al.* (2010) measured emissions over two combustion cycles. Measurements started after kindling of the fire and the first batch of wood was burning. When the first batch was dwindling a second batch of wood was added. Measurements continued until this second batch was also burned out. One cycle of measurements took around six hours which is comparable with one distillation cycle or one rocket stove cycle. In total, six kg of wood was burned during the cycle of measurements whereas between 27 and 60 kg of wood was burned in one cycle of distillation or juice boiling. In comparison, other sources often use the standard water boiling test which requires the combustion of only around 1 kg of wood. Because such a test has a much shorter cycle, the start-up (kindling) phase has a relatively greater contribution to emissions. Moreover, those tests include a low intensity burning phase (for simmering the food) which does not occur in juice boiling or distilling.

The Pettersson *et al.* (2010) measurements of ‘mode 1 and 2’ are used which describes normal wood stove operation. The emissions values are used to replace the corresponding values in the Ecoinvent dataset ‘Heat, hardwood logs, at furnace 100kW/CH S’. The PM values in Ecoinvent are subcategorized based on the size of the particles. When the emission data for the stoves is inserted these categories are removed and a new PM_{tot} (which also exists in Ecoinvent) is added with the correct value.

Table 26: A comparison of the emission factors of wood burning as reported by Pettersson *et al.* and the corresponding values from the Ecoinvent dataset.

Emissions type	Average emissions (Pettersson *et al.*, 2010)	Corresponding emission category in Ecoinvent dataset	Emission value in Ecoinvent dataset
	kg/MJ		Kg/MJ
CO	2.40E-03	Carbon monoxide, biogenic	4,8482E-04
NOx	4.90E-05	Nitrogen oxides	1,8250E-04
NMVOC	1.00E-04	NMVOC, unspecified origin	9,2436E-06
Methane	6.80E-05	Methane, biogenic	2,0023E-05
PM_{tot}	1.10E-04	Particulates, unspecified[A]	4,73629E-05[A]
PAH_{tot}	3.60E-06	PAH	1,5920E-08

A: In Ecoinvent the PM_{tot} emissions are separated in three emission categories: Particulates, < 2.5 um (high pop.), Particulates, > 10 um (high pop.), and Particulates, > 10 um (high pop.). The values listed in the table are the sums of these three emissions. When the emission values from Pettersson *et al.* (2010) are used, the three categories are deleted and the ‘Particulates, unspecified’ category is inserted with the corresponding value.

Appendix XVI: Environmental impacts of high and low impact scenarios

The following environmental impacts are for the high and low impact scenarios which make use of different parameters sets as detailed in paragraph 5.1.

Low impact scenario

Table 27: The endpoint environmental impacts of ethanol production under the low impact scenario.

Impact category	Unit	System 1: Reference	System 2: rocket stove	System 3: Larger capacity	System: 4 waste juice	Natural gas
Carcinogens	DALY	1.39E-02	1.00E-02	5.23E-03	6.09E-03	6.54E-06
Resp. organics	DALY	2.40E-04	1.76E-04	8.03E-05	1.01E-04	2.68E-06
Resp. inorganics	DALY	3.20E-02	2.34E-02	1.69E-02	1.36E-02	5.11E-04
Climate change	DALY	2.11E-03	1.63E-03	9.87E-04	7.70E-04	7.06E-03
Radiation	DALY	1.17E-04	8.57E-05	4.61E-05	4.95E-05	1.21E-07
Ozone layer	DALY	3.04E-06	2.90E-06	2.73E-06	2.15E-07	1.14E-08
Ecotoxicity	PDF*m^{2}yr	5.70E-03	4.23E-03	2.37E-03	2.33E-03	3.48E-06
Acidification/ Eutrophication	PDF*m^{2}yr	1.41E-03	1.05E-03	7.98E-04	5.76E-04	6.34E-05
Land use	PDF*m^{2}yr	4.06E-02	3.97E-02	2.80E-02	8.88E-03	1.94E-06
Minerals	MJ surplus	8.49E-04	6.26E-04	3.41E-04	3.55E-04	1.42E-06
Fossil fuels	MJ surplus	1.07E-02	8.75E-03	6.23E-03	3.15E-03	1.05E-01

High impact scenario

Table 28: The endpoint environmental impacts of ethanol production under the high impact scenario.

Impact category	Unit	System 1: Reference	System 2: rocket stove	System 3: Larger capacity	System: 4 waste juice	Natural gas
Carcinogens	DALY	8.09E-02	3.35E-02	1.96E-02	1.70E-02	6.54E-06
Resp. organics	DALY	1.39E-03	6.04E-04	3.34E-04	2.82E-04	2.68E-06
Resp. inorganics	DALY	1.86E-01	7.97E-02	5.92E-02	3.82E-02	5.11E-04
Climate change	DALY	1.20E-02	6.01E-03	4.18E-03	2.16E-03	7.06E-03
Radiation	DALY	6.78E-04	2.92E-04	1.79E-04	1.39E-04	1.21E-07
Ozone layer	DALY	1.56E-05	1.39E-05	1.34E-05	6.03E-07	1.14E-08
Ecotoxicity	PDF*m^{2}yr	3.29E-02	1.48E-02	9.42E-03	6.51E-03	3.48E-06
Acidification/ Eutrophication	PDF*m^{2}yr	8.16E-03	3.67E-03	2.87E-03	1.61E-03	6.34E-05
Land use	PDF*m^{2}yr	5.05E-01	1.61E-01	1.13E-01	4.58E-02	1.94E-06
Minerals	MJ surplus	4.92E-03	2.15E-03	1.33E-03	9.95E-04	1.42E-06
Fossil fuels	MJ surplus	5.96E-02	3.50E-02	2.78E-02	8.82E-03	1.05E-01

References

1. Agus, F. and M. van Noordwijk (Editors), 2005, *Alternatives to Slash and Burn in Indonesia: Facilitating the Development of Agroforestry Systems: Phase 3 Synthesis and Summary Report*, World Agroforestry Centre, Southeast Asia, Bogor, Indonesia
2. Ballard-Tremeer, G. and H.H. Jawurek, 1996, *Comparison Of Five Rural, Wood-Burning Cooking Devices: Efficiencies And Emissions*, Biomassa and Energy Vol. 11, No. 5
3. Breure, C.J., 2010, *Rate of Leaf Expansion: A Criterion for Identifying Oil Palm (Elaeis guineensis Jacq.) Types Suitable for Planting at High Densities,* NJAS - Wageningen Journal of Life Sciences, Vol. 57, Issue 2
4. Brown, A.G., E.K.S. Nambiar and C. Cossalter, 1997, *Plantations for the Tropics – Their Role, Extent and Nature*, in: Tiarks, A., E.K.S. Nambiar, and C. Cossalter, 1999, *Site Management And Productivity In Tropical Forest*, Center For International Forestry Research (CIFOR), Indonesia, Occasional Paper No. 16
5. Buragohain, T., 2012, *Impact of Solar Energy in Rural Development in India*, International Journal of Environmental Science and Development, Vol. 3, No. 4
6. Cabraal, R.A., D.F. Barnes and S.G. Agarwal, 2005, *Productive Uses of Energy for Rural Development*, Annual Review of Environmental Resources, No. 30
7. Dalibard, D., 1997, *The Potential of Tapping Palm Trees for Animal Production*, Animal Production Officer, Feed Resources Group France
8. Dam, van, J.E.G., 2007, *Validation Arenga Palm Sugar Production*, WUR-Agrotechnology and Food Science Group; Reported in: Staaij, van de, J., A. van den Bos, C. Hamelinck, E. Martini, J. Roshetko and D. Walden, 2011, *Sugar Palm Ethanol, Analysis of Economic Feasibility and Sustainability*, Ecofys and Winrock
9. Danielsen, F., H. Beukema, N.D. Burgess, F. Parish, C.A. Brühl, P.F. Donald, D. Murdiyarso, B. Phalan, L. Reijnders, M. Struebig and E.B. Fitzherbert, 2009, *Biofuel Plantations on Forested Lands: Double Jeopardy for Biodiversity and Climate*, Conservation Biology. No. 23
10. Davis, S.C., S.W. Diegel and R.G. Boundy, 2013, *Transportation Data Book Energy*, Ed. 32, Oak Ridge National Laboratory for the U.S. Department Of Energy
11. Effendi, D.S., 2010, *Prospek Pengembangan Tanaman Aren* (Arenga Pinnata Merr) Mendukung Kebutuhan Bioetanol di Indonesia, Perspektif, 9
12. European Parliament, 2009, *On the Promotion of the Use of Energy from Renewable sources*
13. Fargione, J., J. Hill, D. Tilman, S. Polasky and P. Hawthorne, 2008, *Land Clearing and the Biofuel Carbon Debt*, Science, Vol. 319
14. Fitzherbert, E.B., M.J. Struebig, A. Morel, F. Danielsen, C.A. Brühl, P.F. Donald and B. Phalan, 2008, *How will Oil Palm Expansion Affect Biodiversity?*, Trends in Ecology & Evolution, Vol. 23, Issue 10
15. Food and Agricultural Policy Research Institute (FAPRI), 2012, *Biofuel Conversion Factors*
16. Food and Agriculture Organization (FAO), 2013, *Food and Agriculture Organization of the United Nations Statistics*, Accessed 22 October 2013
17. Goedkoop, M. and R. Spriensma, 2000, The Eco-Indicator 99, *A damage Oriented Method for Life Cycle Impact Assessment: Methodology Report*; *Second Edition*, The Dutch Ministry of Housing, Spatial Planning and the Environmentl
18. Hertel, D., G. Moser, H. Culmsee, S. Erasmi, V. Horna, B. Schuldt and C. Leuschner, 2009, *Below- and Above-ground Biomass and net Primary Production in a Paleotropical Natural Forest (Sulawesi, Indonesia) as Compared to Neotropical Forests*, Forest Ecology and Management. No. 258.
19. Huy, L.Q., 2004, *Fast-Growing Species Plantations – Myths & Realities and their Effects on Species Diversity*, College of Forestry, Dr. Y.S. Parmar University of Horticulture and Forestry
20. International Energy Agency (IEA), 2013, *Frequently Asked Questions: How Much Carbon Dioxide (CO_2) is Produced When Different Fuels are Burned?*, Website, Link: http://www.eia.gov/tools/faqs/faq.cfm?id=73&t=11

21. ISO 14040, 2006, *Environmental Management — Life cycle assessment — Principles and Framework*
22. ISO 14044, 2006, *Environmental management — Life cycle assessment — Requirements and Guidelines*
23. Itoh, T., C.H. Widjaja, A. Matsuyama, M.Z. Nasution and J. Kumendong, 1984, *Compositional Characteristics of Nira - Palm Juice of High Sugar Content From Palm Tree*, Faculty of Agricultural Engineering and Technology, Agricultural University, Bogor, Indonesia
24. Lantemona, H., A.L. Abadi, A. Rachmansyah and J. Pontoh, 2013, *Impact of Altitude and Seasons to Volume, °Brix Content, and Chemical Composition of Sugar Palm Sap in North Sulawesi*, IOSR Journal Of Environmental Science, Toxicology And Food Technology (IOSR-JESTFT), Vol. 4, No. 2
25. Lapola, D.M., R. Schaldach, J. Alcamo, A. Bondeau, J. Koch, C. Koelking and J.A. Priess, 2010, *Indirect Land-Use Changes Can Overcome Carbon Savings from Biofuels in Brazil*, PNAS, Vol. 107, No. 8
26. Lepage, C., 2013, *Proposal for a Directive by the European Parliament and the European Council*, Amending Directive 98/70/EC *on the Quality of Petrol and Diesel Fuels and Directive 2009/28/EC on the Promotion of the Use of Energy from Renewable Sources*
27. MacCarty, N., D. Still and D. Ogle, 2010, *Fuel Use and Emissions Performance of Fifty Cooking Stoves in the Laboratory and Related Benchmarks of Performance*, Energy for Sustainable Development, No. 14
28. Marti, S., 2008, *Losing Ground: The Human Rights Impacts of Oil Palm Plantation Expansion in Indonesia*, Report by Friends of the Earth, LifeMosaic and Sawit Watch
29. MCneely, J. A. and G. Schroth, 2006, *Agroforestry and biodiversity conservation – traditional practices, present dynamics, and lessons for the future*, Biodiversity and Conservation 15
30. Milton, K. and F.R. Dintzis, 1981, *Nitrogen-to-Protein Conversion Factors for Tropical Plant Samples*, Biotropica, Vol. 13, No. 3
31. Mogea, J., B. Seibert and W. Smits, 1991, *Multipurpose Palms: The Sugar Palm (Sugar Palm Arenga Pinnata (wurmb) merr.)*, Agroforestry Systems, No. 13
32. Noble, I. R., R. Dirzo, 1997, *Forests as Human-Dominated Ecosystems*, Science vol. 277
33. Obidzinski, K., R. Andriani, H. Komarudin and A. Andrianto, 2012, *Environmental and Social Impacts of Oil Palm Plantations and their Implications for Biofuel Production in Indonesia*, Ecology and Society, No. 17
34. Ortega, E., M. Watanabe and O. Cavalett, 2006, *Production Of Ethanol In Micro And Mini-Distilleries*, Laboratory of Ecological Engineering, Campinas, Brazil
35. Pentagono Design Team: I. Costariol, J. Jansen, C. Ruiz, P. Shen and O. Weller, 2013
36. Pettersson, E., C. Boman, R. Westerholm, D. Boström and A. Nordin, 2010, *Stove Performance and Emission Characteristics in Residential Wood Log and Pellet Combustion*, Part 2: Wood Stove, Energy Fuels 2011, No. 25
37. Reeb J. and M. Milota, 1999, *Moisture Content by the Oven-Dry Method for Industrial Testing*, Oregon State University, Corvallis
38. Roden, C.A., T.C. Bond, S. Conway, A.B. Osorto Pinel, N. MacCarty and D. Still, 2009, *Laboratory and Field Investigations of Particulate and Carbon Monoxide Emissions from Traditional and Improved Cook Stoves*, Atmospheric Environment, No. 43
39. Sabah Forestry Department, 1989; Reported in: Pinard, M.A. and W.P. Cropper, 2000, *Simulated Effects of Logging on Carbon Storage in Dipterocarp Forest*, Journal of Applied Ecology, No. 37
40. Searchinger, T., R. Heimlich, R.A. Houghton, F.A. Dong, A. Elobeid, J. Fabiosa, S. Tokgoz, D. Hayes and T.H. Yu, 2008, *Use of U.S. Croplands for Biofuels Increases Greenhouse Gases through Emissions from Land-Use Change*, Science, Vol. 319
41. Sidik, A., 2013, *Kebutuhan Dan Harga Eceran Tertinggi Pupuk Bersubsisi*, Website, link: http://bpbtphpacet.com/?p=444

42. Sirait, M. T., 2009, *Indigenous Peoples and Oil Palm Plantation Expansion in West Kalimantan*, Indonesia, Cordaid Memisa, The Hague
43. Sista, P., N. Picard and S. Gourlet-Fleury, 2002, *Sustainable Cutting Cycle and Yields in a Lowland Mixed Dipterocarp Forest of Borneo*, Annals of Forest Science. No. 60
44. Smits, W., 2013 (*Personal communication*)
45. Sokhansanj, S., 2011, *The Effect of Moisture on Heating Values*, Biomass Energy Data Book 2011
46. Staaij, van de, J., A. van den Bos, C. Hamelinck, E. Martini, J. Roshetko and D. Walden, 2011, *Sugar Palm Ethanol, Analysis of Economic Feasibility and Sustainability, Ecofys and Winrock*
47. Stampe, S., R. Alcock, C. Westby and T. Chisholm, 1983, *Farm-Scale Ethanol Distillation System*, Energy in Agriculture, Vol. 2
48. Sumadi, G., 1988, *Arenga Pinnata: A Palm for Agroforestry*, In: Proceedings of an International Workshop Held in Pataya, Thailand, 2-5 November 1987; Reported in: Dalibard, D., *The Potential of Tapping Palm Trees for Animal Production*, 1997, Animal Production Officer, Feed Resources Group France
49. Telmo, C. and J. Lousada, 2011, *Heating Values of Wood Pellets from Different Species*, Biomass and Bioenergy, No. 35
50. Vries, de, S.C., G.W.J. van de Ven, M.K. van Ittersum and K.E. Giller, 2010, *Resource Use Efficiency and Environmental Performance of Nine Major Biofuel Crops Processed by First-Generation Conversion Techniques*, Biomass and Bioenergy, No. 34
51. Wage Indicator Foundation, 2013, Link: www.wageindicator.org/main/salary/minimum-wage/indonesia
52. Whitaker, J., K.E. Ludley, R. Rowe, G. Taylor and D.C. Howard, 2010, *Sources of Variability in Greenhouse Gas and Energy Balances for Biofuel Production: A Systematic Review*, GCB Bioenergy, No. 2, Issue 3
53. Wicke, B., R. Sikkema, V. Dornburg and A. Faaij, 2011, *Exploring Land Use Changes and the Role of Palm Oil Production in Indonesia and Malaysia*, Land Use Policy, No. 28
54. World Bank, 2011, *One Goal, Two Paths: Achieving Universal Access to Modern Energy in East Asia and Pacific*