Life Cycle Assessment of Cane-sugar in Indonesian Sugar Mill: Energy Use and GHG Emissions

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Abstract. This paper presents the life cycle assessment (LCA) of sugar cane production at PG Ngadirejo, that is consist of sugar cane cultivation, transportation and sugar processing. The objective of the study was to identify and review the critical areas of potential Global Warning Potential (GWP) environmental impacts in sugarcane life cycle on PG Ngadirejo. Energy consumption in the sugarcane life cycle is 116,562.52 MJ/ton sugar where the largest consumption in coal energy usage 87%. The relative contribution of CO₂ emission contributor, sugar processing contributes the biggest GHG emission of 96.4% (10.728 ton CO₂/ton of sugar) with the use of fossil fuels reaching 9,344 ton CO₂/ton sugar (87%). In sugarcane cultivation, fertilizer manufacture contributed the largest environmental impact of 0.29 tons CO₂/ton of sugar 73.48%, pesticide manufacture 22.5%, and mechanization 4%. The emission reduction from bagasse that replaces fossil fuels in sugar production is 2.43 tons CO₂-eq/ton of sugar, reaching 25% of total CO₂/ton sugar emissions. Some options for the environmental performance improvement of sugarcane including the optimal use of fertilizers and pesticides, the concentration of sugar mills, co-generation project implementation.

1. Introduction
Sugarcane is a consumer as well as an energy producer. Indirect energy includes energy contained in seeds, fertilizers, and pesticides while direct energy includes electricity and diesel fuel used in the process of sugar production. Because it is closely related to greenhouse gas emissions, the energy balance involved in the cycle is also expected to calculate emissions. Evaluation of carbon emissions from the preparation of sugarcane raw materials, transportation, sugar production and the use of waste to produce electricity in accordance with the cradle-to-gate approach, described in ISO 14040 [18]. To find out the emission quantization is done by identifying the use of raw materials, energy flow and environmental impacts of carbon emissions in the form of GHG emissions at each life cycle of LCA.

PG Ngadirejo is an industry that moved in white crystal sugar processing field from cane by grinding capacity get up to 6.000 Ton Cane Day (TCD). The large of cane field is 11,427.6 ha with land productivity until 87.6-ton cane/ha/year. Production of sugar is 82,264.6 ton with cane productivity 0.0828-ton sugar/ton cane/year. The resulting waste is 297,233.54 ton with productivity 0.30 ton bagasses/ton cane. Energy resource is from cane cultivation (seed, fertilizer, pesticide), transportation (diesel), processing cane uses fossil energy and biomass (electricity, diesel, coal, waste, chemist material). Source of GHG emission is from the uses of seed, fertilizer, pesticide, fuel burning of fossil boiler, and biomass, electricity use, diesel use for mechanism and manufactory. The resulting base in industry process is cane and bagasses, filter mud and molasses. Generally, result side is used as fuel for
produce steam and electricity for industrial processes alone and having a potential for producing excess electricity [12,1]. PG Ngadirejo uses result side in the form of waste as boiler fuel. Except for dregs, is also uses added fuel of Industrial Diesel Oil (IDO) and coal to meet energy achievements.

The purpose of the study was to assess energy use and greenhouse gas emissions (GHG) in the sugar life cycle PG Ngadirejo use LCA method. This research is focused on calculating the accumulated emissions resulting from sugarcane plantation activities, transportation and production of sugar from sugarcane raw materials and processing of waste as energy. Evaluation of environmental impacts with consideration of the entire product life cycle through LCA from the acquisition of raw materials to the sugar factory (cradle to gate), by using four steps of LCA: definition purpose and scope, inventory analysis, effective assessment, and interpretation. Now, LCA is considered as the best tool for assessing environmental sustainability from different technology choices, because it considers all impacts on ecosystems and populations that endanger the present and future generations [2,3].

2. Materials and Methods

2.1. Time and Research Place
The research was conducted at the Ngadirejo Kediri sugar factory in East Java.

2.2. Research Stage
This research is identification of the product life cycle of GKP using LCA, comparing the environmental impact of factual conditions with the recommendations for improvement. The presentation of the results of the research in this paper is the Life Cycle Assessment research in the sugar industry.

2.3. Energy Excretion and Greenhouse Gas Emission
The method used for energy estimation is by conversing energy changed to standard energy unit (Joule). Getting the value of emerging need in every production of sugar GKP is used equation 1 [6]. This method explains energy input and material that is needed to develop result and side result and emission happened during the production process. Three main greenhouse gases consist of CO₂, CH₄ and N₂O resulting from agricultural activities, industrial production processes, land burning, burning of fossil fuels, waste handling, and processing. Source of CO₂ emissions from activities in the environment based on the Intergovernmental Panel on Climate Change (IPCC) method, with the calculation of CO₂ emissions.

2.4. Life Cycle Assessment
The aim is to identify and measure the potential environmental impacts of the Global Warming Potential (GWP) in the form of GHG emissions at the PG Ngadirejo. To find out the emission quantization is done by identifying the use of raw materials, energy flow and the environmental impact of carbon emissions in each life cycle of the LCA (Life Cycles Analysis) process of sugar production. In this study, the system boundaries are shown in Figure 1 includes sugarcane cultivation, sugar cane milling, and sugar conversion according to other studies [8,11,18]. The sugarcane cultivation stage includes sources of GHG emissions derived from the supply of seeds, fuel used for agricultural machinery, transportation, production of fertilizers and pesticides. The industrial phase includes milling and sugar conversion including emissions from electricity generation, the use of fuels and chemicals.

A functional unit is one ton of sugar cane produced by PG Ngadirejo. The function unit used is kg CO₂ eq/ton of sugar. The energy unit used is Joule describing the energy produced by sugar during its life cycle. The total life-cycle energy consumption is the total energy consumed from the whole stage of the life-cycle, starting from sugarcane cultivation, transportation, and sugar production processes. The global warming potential of CO₂, CH₄ and N₂O greenhouse gases is 1, 25 and 298 respectively [22]. Other greenhouse gases are not considered because they only contribute a small portion of global emissions of around 2% [6].
3. RESULTS AND DISCUSSION

3.1. Energy Consumption and Potential

Inventory mass equilibrium is shown in Table 1. Some sources note the mass balance of sugar production, as Brazil produces sugar, bagasses, and molasses 14.3%, bagasse 28% and molasses 2.8% [14], Mauritius produces sugar, bagasse, filter mud and molasses 11%, 30.8%, 3% and 3% [20] and Nepal produce molasses ranging from 4%-4.6% [8]. Production of sugar cane as the main product and bagasse as a byproduct of producing electricity contributes to the environment in the form of GHG emissions. Energy flow is calculated in terms of energy requirements in sugarcane cultivation, transportation and sugar production including fuel and electricity as the main energy, and additional energy used in the production of chemicals used in agricultural and industrial processes.

![Figure 1. LCA scope (Cradle to Gate)](image)

Information:
- **----**: Scope of Research
- **→**: Material flow

### Table 1 Mass balance of 1 ton of sugar

| Product               | Quantity | % of sugar cane |
|-----------------------|----------|-----------------|
| Sugarcane             | 12,165.45| 100.00          |
| White crystal sugar   | 1,000.00 | 8.20            |
| Bagasses              | 3,613.14 | 29.70           |
| Filter mud            | 312.65   | 2.57            |
| Molasses              | 575.43   | 4.73            |

Through this research can be known the consumption of resources and greenhouse gasses emissions in the sugar industry. Energy use includes external electricity 7.3 kWh/ton sugar cane, diesel consumed in the garden and in the factory 0.4 liters/ton, 0.06 liters/ton sugar cane in a row, coal 0.3 tones/ton sugar cane and 0.17 ton/ton sugarcane bagasses. The biggest consumption of sugar production in sugar mills reaches 97% with the biggest energy in fossil energy use by 87%. In sugarcane cultivation, the use of...
fertilizer contributes the greatest energy, 69% followed by pesticides 22%. Energy consumption throughout the life cycle is 116,562.52 MJ/ton sugar. Mauritius energy consumption of 14.235 MJ/ton of sugar with fossil energy share of 14% [12], while PG GMP Indonesia consumes the energy of 41,310 MJ/ton of sugar [19]. The high energy used by the Ngadirejo PG is because it takes into account the use of coal fuel in 2011-2012. The energy consumption of the resources of each sugar life cycle is shown in Figure 2.

Sugar mills have the potential to produce electricity through the burning of bagasses which produces steam in the boiler [13]. The burning of the bagasse is done to produce a certain amount of steam that is used to rotate the grinding machine, heat the steam engine and drive the alternator turbine as a power plant. The calorific value of bagasse is calculated using equation 1 [17].

\[
\begin{align*}
\text{NCV} &= 4250 - 12s - 48.5w \\
\text{GCV} &= 4600 - 12s - 46w
\end{align*}
\]

Information:
- \( s \) = Sucrose content of the bagasse (%)
- \( w \) = bagasse moisture (%)

The waste used as PG Ngadirejo's boiler fuel has an average bagasse of 13.36% with 50% humidity. Using the NCV heating value, the bagasses used as PG Ngadirejo boiler fuel has a heating value of 1,664.68 kcal/kg equivalent to 6.97 MJ/kg waste and 1.94 kWh/kg waste. Coal energy with a carbon content of 65% is 26 MJ/kg [21]. The potential of a power plant of 1 kg of coal is 7.22 kWh which is equivalent to 6,209.99 kcal/kg can be produced from 3.7 kg of bagasses.

PG Ngadirejo uses 310,243.8 tons of coal fuel requires an energy of 8,066.34 TJ equivalent to 2,241.29 GWh. Based on the average data, PG Ngadirejo (2011-2015) used waste is 170,133.7 tons and the remaining waste that is not utilized is 127,099.9 tons. The remaining waste has energy potential 246.07 GWh can replace coal 34,351.3 tons so as to reduce coal use by 11%.

![Figure 2. Energy consumption of sugar’s life cycle](image)

**Energy Consumption of Sugarcane Cultivation**
- Transportation: 6.17%
- Pesticide: 21.99%
- Fertilizer: 68.57%
- Seedlings: 3.27%

**Energy Consumption of Sugar Factory**
- Fossil Fuel: 86.95%
- Drags: 12.97%
- Chemical Substances: 0.07%
- 0%

3.2. Impact assessment on sugar life cycle

Emission that significantly produced is carbon dioxide (CO\(_2\)), nitrous oxide (N\(_2\)O), and methane (CH\(_4\)). Emission of CO\(_2\), N\(_2\)O, and CH\(_4\) are converted to be equivalent with CO\(_2\) (CO\(_2\)-eq) using the global warming potential (GWP) that states the relative contribution of gas to global warming. GWP of each (with the range of time 100 years) CO\(_2\), N\(_2\)O, and CH\(_4\) is 1.21, and 310 [6]. The emission of CO\(_2\)-eq for each gas (CO\(_2\), N\(_2\)O, and CH\(_4\)) are summed for giving the total CO\(_2\)-eq. Table 2 summarizing the consumption of natural sources and emission in a production of a ton of sugar. The relative contribution of CO\(_2\) in each of sugar life cycle is shown in table 3. The processing of sugar contributing the emission of Global Warming Gas, the largest amount of it is up to 96.4% (10.728 tons CO\(_2\)/tons of sugar), with the using of fossil fuel is up to 9.344 tons CO\(_2\)/tons of sugar (87%). In sugar cane cultivation, the making
of fertilizer contribution the environmental effect in the largest amount of 0.29 tons CO$_2$/tons of sugar (73.48%) followed by the pesticide making (22.5%) and the mechanization (4%).

Table 2 Consumption of sources and emission per ton sugar

| Process/Material                                      | Sources Consumption |
|-------------------------------------------------------|---------------------|
| Area of cultivation area (ha/ton sugar)               | 0.14 Ha             |
| Sugar cane                                            | 12.17 Ton           |
| Fossil fuel consumption                               | 98,611.08 MJ        |
| Energy consumption total (fossil and drags fuel)       | 113,293.34 MJ       |

Emission GHG

| CO$_2$        | 9,455.54 Kg       |
| CH$_4$        | 0.98 Kg           |
| N$_2$O        | 1.07 Kg           |
| Total CO$_2$-eq | 9,807.18 Kg      |

The combustion of dregs fuel producing the steam as the electric generator for PG Ngadirejo. This thing is, of course, can reduce the emission of global warming gas because all of carbon contained is recycled, so that the production of sugar contributes the gas emission of CO$_2$ by the input of fossil fuel, fertilizer, and chemical substances, steam, and electric. The total emission of sugarcane cultivation and sugar producing is 9.81 tons CO$_2$/tons of sugar. The emission of CO$_2$ produced by PG Ngadirejo is in the category of high amount compared to PG Mauritius that produce 233 kg CO$_2$/ton sugar [12]. This happens because of still using coal as an energy source and not optimal use of bagasses in sugar processing.

The remaining bagasses of 127,099.9 tons/year is able to replace coal at 34,351.31 ton so that the emission reduction potential is 85,093.39 tons CO$_2$/year. The energy consumed in the sugar factory process consists of fossil fuels and by-products (bagasses). Emissions from fossil fuel use are estimated by multiplying the amount of energy consumed with specific fossil fuel (natural gas) emission factors. CH$_4$ and N$_2$O emissions are taken into account in the use of bagasses for electricity generation [6].

Electricity potential from waste can replace coal so greenhouse emissions are also lower and reduce environmental pollution. Potential of waste is 3.61 tons/ton of sugar producing energy equivalent to 0.98 tons of coal. Coal potential CO$_2$ emissions of 2.48 tons CO$_2$/ton coal. So, reducing emissions from bagasses that replaces fossil fuels in the manufacture of sugar is 2.43 tons of CO$_2$-eq/ton of sugar. This shows that if the potential of waste is used all the emissions that can be avoided are 25% of the total CO$_2$ emissions/tons of sugar [12]. stated that the use of bagasses as energy in PG Mauritius resulted in a reduction in CO$_2$ emissions reaching 45% of fossil fuels.

Power plants using coal fuel have the largest emission factor of 660-1050 kg CO$_2$-eq / MWh followed by 530-900 kg CO$_2$/MWh diesel and 8.5-130 kg CO$_2$/MWh biomass. This shows, that to produce the same electrical energy, coal produces the largest CO$_2$. Optimizing the use and quality of bagasses as a power plant will reduce the impact of GHG emissions. In sugarcane cultivation, fertilizer production is found as the biggest hot spots in the impact category studied. Precision farming involving rational fertilizer management programs is not only cost effective but also benefits the environment because it will greatly reduce the impact of emissions due to sugar production, will reduce the transport distance and decrease the use of diesel energy so that the GHG impact also decreases.

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Table 3 Relative contribution each subsystem with Functional Unit 1 ton sugar

| Process/Material                             | Energy MJ/Functional Unit | Energy (%) | Global Warning kg CO$_2$-eq/Functional Unit | Global Warning (%) |
|---------------------------------------------|---------------------------|------------|---------------------------------------------|-------------------|
| Sugarcane seeds and harvest                 | 117.30                    | 0.10       | 15.75                                       | 0.14              |
| Fertilization and pesticides                | 3,074.89                  | 2.64       | 372.92                                      | 3.35              |
| Transportation                              | 203.28                    | 0.17       | 2.08                                        | 0.02              |
| Sugar processing and electricity generation  | 113,167.05                | 97.09      | 10,728.08                                   | 96.49             |

3.3 Interpretation and Improvement Analysis

Based on inventing analysis and result of impact assessment, main conclusion and recommendation how to fix performance of sugarcane industry environmental that resulted from this resource is as follows:

1. Cultivation and sugarcane harvesting, fertilizer manufacture and pesticide founded as hot spots to impact category that researched. Better residual recycling management could reduce substantially from chemistry fertilization.
2. Implementation of power plant project from sugar factory byproduct (waste), increase boiler efficiency, centralizing sugarcane milling activities can save energy and reduce the impact of greenhouse gas emissions, especially CO$_2$.
3. The implementation of policies to provide incentives on sugar industry that able to use energy efficiently in sugarcane need to be considered.
4. Improvement of the sugar factory condition includes increasing the calorific heat value, decreasing consumption on the main driver of sugar manufacturing equipment, reducing the consumption of process heat in heating and evaporation.
5. Global warming. This category impact mainly depends on fossil fuels utilization especially coal.
6. Appropriateness of commercial sugar industry is not only depending on sugar, but the energy of waste could increase industry income. Energy production also estimated to increase in the future because of possibility of sugar cane harvesting and utilization of trash as fuels.

4. RESULTS AND DISCUSSION

This research evaluates the utilization of energy and greenhouse gas emissions in the sugar life cycle and considers the byproducts like a waste as power plants. The biggest energy use in sugar production is on sugar factory that reaches 97% with fossils energy use more than 84%. The main source of greenhouse gas emissions in sugar production is fossils fuels consume more than 96% of emission total. Sugar cane as sugar producer has advantage related to reducing of fossil fuels that not renewable and greenhouse gas emissions, waste availability could use as a renewable fuel for replacing fossil fuel
resource. LCA result show aspect of sugar producing process in factory give the biggest contribution for environmental impact. Waste utilization as resource produces emission reduction 25%. This information could use for guide environmental management effort by industry. The effort to fix the environmental production profile and sugar cane management is maximizing utilization of waste byproduct to decrease environmental impact.

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