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Kuncoro, Arnan

Sustainable Energy System and Policy Research Cluster, Universitas Indonesia

Purwanto, Wahyu, Widodo

Sustainable Energy System and Policy Research Cluster, Universitas Indonesia

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Analysis of Energy-Water Nexus Palm Oil Biodiesel Production in Riau Using Life Cycle Assessment and Water Footprint Methods

Arnan Kuncoro^{1,2}, Widodo Wahyu Purwanto^{1,2,*}

¹Sustainable Energy System and Policy Research Cluster, Universitas Indonesia, Indonesia

²Department of Chemical Engineering, Faculty of Engineering, Universitas Indonesia, Indonesia.

*Author to whom correspondence should be addressed:

E-mail: widodo@che.ui.ac.id

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Abstract: The purpose of this study is to conduct an analysis of the relationship between water and energy consumption in biodiesel production in Riau Province. The process simulation of biodiesel production at the refinery was done with Unisim Design R390.1 as part of Life Cycle Assessment (LCA) to evaluate the energy consumption and CO₂ emission. Water consumption in biodiesel production was calculated using water footprint method. The result showed that water footprints for Fresh Fruit Bunches (FFB), Crude Palm Oil (CPO), and biodiesel were 671 m³/t FFB, 3,292 m³/t CPO, and 3,432 m³/t biodiesel, respectively. The total energy consumption and CO₂ emission in biodiesel production was 14,252 MJ/t biodiesel and 608.6 kg CO_{2-eq}/t biodiesel. Compared to other energy production, biodiesel production in Riau in 2017 is the largest water consumer, around 99.3% of total water abstraction, and the second largest energy consumer, about 31.7% of total electricity to water supply for CPO and biodiesel productions.

Keywords: Energy-water Nexus, Palm Oil Biodiesel, Riau, Life Cycle Assessment, Water Footprint

1. Introduction

Indonesia is one of the fastest growing countries in terms of energy consumption. Between 2007 and 2017, energy consumption in Indonesia increases by almost 38%¹⁾ and is expected to increase further in the future. Currently, the fulfillment of energy demand in Indonesia is dominated by limited fossil fuels. Indonesia consumes 31 million liters of diesel fuel in 2015 and is estimated to increase by 4.9% between 2015 and 2025²⁾. The increase in diesel fuel consumption has triggered many researchers to develop biodiesel. As a country with the largest palm oil production in the world³⁾, Indonesia has the potential to develop biodiesel fuel from palm oil.

Palm oil biodiesel production consumes large amounts of water, especially at the plantation stage. According to Hoekstra and Chapagain, the plantation is the most water consumptive sector with a total of 85% of global water consumption⁴⁾. Water is not only needed in palm oil plantation, but also in the processing of palm oil to biodiesel. In addition, biodiesel production also consumes a considerable amount of energy both directly and indirectly. Indirect use of energy in biodiesel production includes withdrawal, purification, and distribution of the water needed for biodiesel production. The relationship

between energy and water use (energy-water nexus) in biodiesel production is very important to be analyzed in order to obtain an in-depth understanding of the effect of biodiesel production in the future.

There are several studies related to nexus system. Okadera, Chontanawat, and Gheewala⁵⁾ did a water-energy nexus analysis on energy production in Thailand using water footprint method. Pacetti, Lombardi, and Federici⁶⁾ analyzed water-energy nexus on biogas production from several feedstocks in three regions of Italia using life cycle assessment (LCA) and water footprint. Silalertruksa and Gheewala⁷⁾ analyzed a land-water-energy nexus on sugarcane production in two regions of Thailand with carbon, water scarcity, and ecological footprint methods. Egeskog and Scheer⁸⁾ evaluated the water and energy consumption on biodiesel production in Indonesia but they did not discuss the water-energy nexus.

The aim of this research is to analyze energy-water nexus on palm oil biodiesel production from the plantation, oil palm processing into crude palm oil (CPO), and biodiesel production from CPO in Riau Province, Indonesia. The methods used in this research are LCA and water footprint. Furthermore, this study assesses the link between energy and water consumption, the impact of

biodiesel production on the environment (CO₂ emission), and the comparison of biodiesel production with other energy production in term of water consumption.

2. Methodology

2.1 Process Simulation

The process simulation was carried out for biodiesel production (CPO processing into biodiesel) using Unisim

Design R390.1. The process flow diagram, input components, and operating conditions for simulation were based on process proposed and simulated by Zhang⁹⁾. CPO with a mass flow of 1,050 kg/h was used as a basis in the simulation. The total CPO consumed to produce biodiesel in Riau in 2017 was 1,256,724 ton. The main process of biodiesel production is transesterification. Fig. 1 shows the schematic diagram of biodiesel production used for simulation

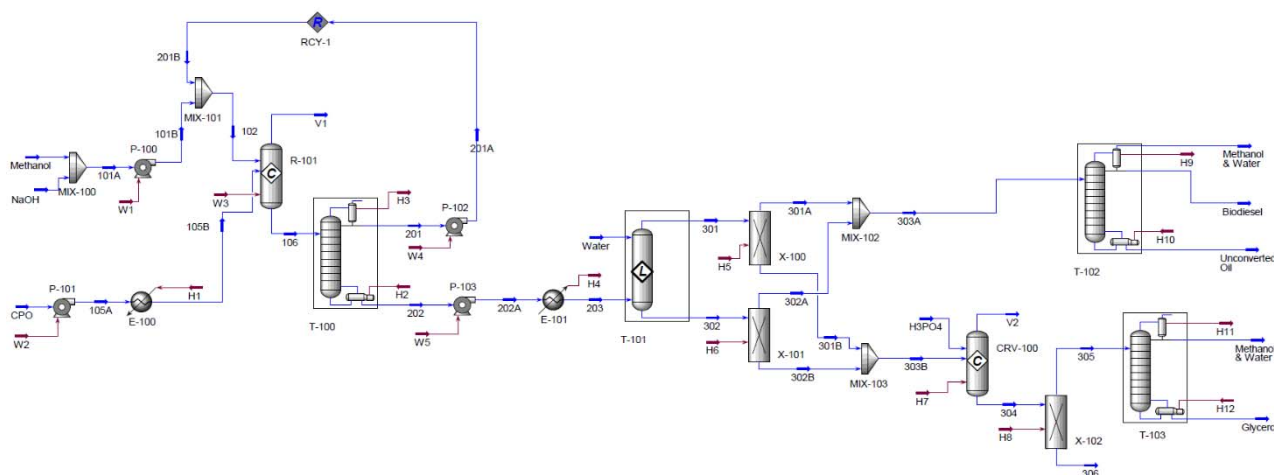


Fig. 1: Schematic diagram of biodiesel production

Transesterification reaction consist of transformations from triacylglycerol (triglycerides) to diacylglycerol (diglycerides), and eventually monoacylglycerol (monoglycerides) to become glycerin¹⁰⁾. The transesterification reaction occurred at 60°C and 400 kPa with 95% conversion, producing biodiesel and glycerol as a by-product. The product stream from the reactor was sent to a distillation column to recover excess methanol. Afterward, the bottom stream from the column was pumped into the water washing unit to separate biodiesel from glycerol and excess feedstocks using gravity settler. This step produced two streams of product. The first stream, which is mainly contained biodiesel, was distilled in the column, producing high purity (more than 96.5 wt%) biodiesel. The second stream, which is mainly contained glycerol, was sent to neutralization reactor to eliminate excess NaOH by adding H₃PO₄. The produced Na₃PO₄ salt was then removed from glycerol stream. Afterward, the glycerol stream was distilled in the column. Mass and energy balance resulted were used as LCA inventory in biodiesel refinery stage.

2.2 Water Footprint

The water footprint of a product is the total volume of water that is directly or indirectly used to produce a product and measured in the entire supply chain¹¹⁾. Water footprint consists of four steps: determine goal and scope, water footprint accounting, water footprint sustainability assessment, and water footprint response formulation¹¹⁾. In this study, only step 1 and 2 of the water footprint will

be carried out to calculate the amount of water needs in biodiesel production. The scope of the water footprint accounting includes oil palm plantation, CPO production, and biodiesel production. The water footprint of biodiesel production was calculated by using equations for water footprint of growing crop and a product based on water footprint assessment manual¹¹⁾. In the plantation stage, the crop water use (CWU) for green and blue water was calculated using CROPWAT 8.0. The climate data for calculation was obtained from Tambang and Sultan Syarif Kasim meteorological station in Riau Province in 2017¹²⁾. Other data for CWU and grey water calculation were taken from Chapagain and Hoekstra¹³⁾; Allen, Pereira, Raes and Smith¹⁴⁾; and Bulsink, Hoekstra, and Booij¹⁵⁾. The data used for water footprint accounting in CPO production stage are summarized in Table 1. For biodiesel production, the data were taken from simulation results. The results of the water footprint calculation were the amount of water consumption to produce FFB, CPO, and biodiesel.

Table 1. Data for Water Footprint Calculation in CPO Production

Data	Blue	Green	Grey	Unit	Source
WF _{proc} [p]	6.4	0		m ³ /t CPO	8)
	5.08	0	2.36	m ³ /t CPO	16)
WF _{proc} [p] avg	5.74	0	2.36	m ³ /t CPO	-
f _p [p,i]	0.19	0.19	0.19	-	13)
f _v [p]	0.93	0.93	0.93	-	13)

2.3 Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) is a measure of the impact of the system on the environment during its whole life cycle¹⁷⁾. Based on ISO 14040¹⁸⁾, LCA consists of four stages: goal and scope, inventory analysis, impact assessment, and interpretation. The scope for LCA included biodiesel production from plantation to biodiesel refining stage. The data for inventory analysis were taken from Harsono, Prochnow, Grundmann, Hansen and Hallmann¹⁹⁾; Pleanjai and Gheewala²⁰⁾; Archer, Murphy and Steinberger-Wilckens²¹⁾ research and process simulation outcome. The results of LCA were energy input and output, and CO₂ emission in biodiesel production.

In this study, a full chain energy analysis was carried out to determine energy-intensive processes in biodiesel production. The total energy input and output for each stage of biodiesel production are calculated by multiplying energy factor and quantity of input material or products. The products considered in energy output calculation were biodiesel, glycerol, shell, kernel, and biogas. From total energy input and output, the net energy balance (NEB), i.e. the difference between energy output and input, was determined. The impact assessment was carried out to determine the impacts of biodiesel production on the environment, especially CO₂ emission as global warming indicator. The CO₂ emission was calculated by multiplying the emission factor and quantity of input material.

2.4 Energy-Water Nexus

In order to analyze energy-water nexus, the amount of water needed for energy production and energy needed for water supply related to energy production in Riau Province were determined. The energy production considered in this study were all primary (oil, coal, natural gas and renewable) and secondary (fuels and electricity) energy production. The calculation was performed to find out how much water is supplied to produce energy, the contribution of each type of energy to the water supply, and the contribution of each activity in water supply to energy production. The data for water and energy needs calculation was taken from IEA²²⁾, ²³⁾; KPMG²⁴⁾; Spang, Moomaw, Gallagher, Kirshen, and Marks research²⁵⁾; and the results of water footprint accounting. Energy needs for water supply were calculated by using equation based on Gerbens-Leenes²⁶⁾ research.

3. Results and Discussion

3.1 Biodiesel Production Process Simulation

The simulation results of biodiesel production are quantity of feedstocks and products. The simulation showed that with 1050 kg/h of CPO as a basis, the process could produce 1004.5 kg/h of palm oil biodiesel and 102.6 kg/h of glycerol. The methanol and NaOH needed for

biodiesel production were 117.2 kg/h and 10 kg/h. Neutralization reaction required 9 kg/h of H₃PO₄ to remove excess NaOH from glycerol stream and produced 14.5 kg/h of Na₃PO₄ salt. Based on simulation results, the biodiesel production required 11 kg/h of water for the biodiesel washing process. Biodiesel produced from simulation had 99.8 wt % of fatty acid methyl ester (FAME) content with 0.05 wt% of methanol, triglyceride and water content, each. The energy required for pumping was 0.26 kWh. The heating and cooling duty were 2,689 and 2,324 MJ/h, respectively. The simulation results from this study are in line with previous studies⁹⁾, ²¹⁾ and can be used to calculate LCA.

3.2 Water Footprint of Palm Oil Products

Based on Fig. 2, the total water footprint for fresh fruit bunch (FFB), CPO and biodiesel were 671 m³/t FFB, 3,292 m³/t CPO, and 3,432 m³/t biodiesel, respectively.

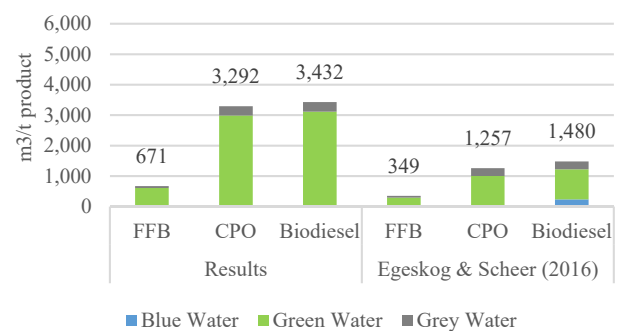


Fig. 2: The results of water footprint calculation compared to another study⁸⁾

For all three products, the component of water footprint with the largest contribution was green water. Oil palm can only grow in the tropic region with very high rainfall, such as in Indonesia. High rainfall can provide enough water for oil palm growth; thus, the water needs of the irrigation system can be reduced or eliminated. This causes the value of green water for FFB is very high (609.3 m³/t FFB) compared to blue water (0 m³/t FFB).

At the CPO production, the value of green and blue water was 2,982 and 5.3 m³/t CPO, respectively. The blue water is used in the process of FFB sterilizing and digesting in the form of steam to prepare FFB before oil extraction, and in the clarification stage to separate extracted oil from impurities. The value of green and blue water at biodiesel production was 3,107 and 8 m³/t biodiesel, respectively. The blue water consists of water consumption in the previous process and the biodiesel production process at refinery. In biodiesel production, water was used as cooling water or heating steam and also used to separate biodiesel from glycerol and other excess materials.

The value of grey water for FFB, CPO and biodiesel were 61.8 m³/t FFB, 304.7 m³/t CPO, and 317.4 m³/t biodiesel, respectively. At the plantation stage, the biggest contribution of grey water comes from the use of nitrogen

fertilizers. At CPO production, pollutants that have a significant contribution are Palm Oil Mill Effluent (POME) which has a high BOD and COD content. Based on Fig. 2, the water footprint results in this study have greater value than the other study⁸⁾. The difference in these results can be caused by several things, namely assumptions used, research location, time basis, and FFB yield. FFB yield data used in this study is 17.1 t FFB/ha (Riau Province data in 2017), while the other study⁸⁾ used yield data of 26 t FFB/ha. Lower FFB yield can generate higher water footprint based on the equation in water footprint manual¹¹⁾.

3.3 Energy Analysis and Impact Assessment

The total energy input for biodiesel production was 14,252 MJ/t biodiesel. The value is smaller than the results in Harsono, Prochnow, Grundmann, Hansen and Hallmann¹⁹⁾ research, which has values ranging from 18,240-19,970 MJ/t biodiesel for production in Sumatra. This is due to the inclusion of energy for fertilizer transportation and transportation within plantations in their research. Based on Fig. 3a, the stage that requires the most energy is biodiesel production at the refinery, followed by plantation, CPO production, and transportation.

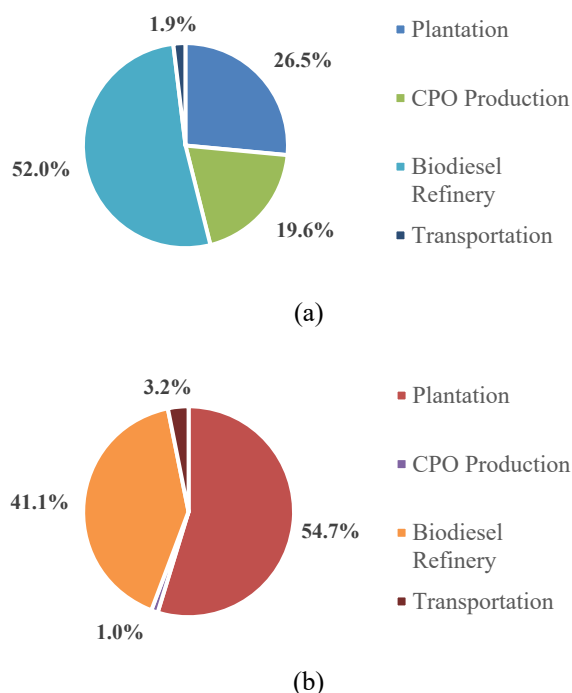


Fig. 3: Share of (a) Total Energy Input; (b) Total CO₂ Emission

Energy requirement in refinery comes from methanol production (59.2% of the total energy input at the refinery). This result is consistent with several other studies^{19), 20)}. At the plantation stage, the biggest contributor to energy

input was fertilizer production, which accounts for 84% of the total energy input at the plantation. In CPO production, about 90.8% of total energy input at CPO production was required to produce steam for sterilizing and digesting process. This is due to the high operating conditions of steam produced (15-45 psi, >100°C). Transportation required 1.9% of the total energy input, which comes from diesel production. The total energy output based on calculation was 56,989 MJ/t biodiesel. Biodiesel has the greatest energy content (69.5% of total energy output) compared to other products. In this study, the calculated net energy balance (NEB) was 42,737 MJ/t biodiesel.

The total of CO₂ emission in biodiesel production was 608.6 kg CO_{2-eq}/t biodiesel. This value is in accordance with the results of another study¹⁹⁾, which has values ranging from 522.13-746.47 kg CO_{2-eq}/t biodiesel for production in Sumatra. Based on Fig. 3b, the biggest contributor to CO₂ emission was biodiesel production at the plantation stage, followed by the refinery, transportation, and CPO production. The biggest emission contributor at the plantation was nitrogen fertilizer production, which accounts for 62.6% of total emissions in the plantation. Biodiesel production at refinery produced about 41.1% of total emissions, which mainly comes from the production of methanol. Transportation produced around 3.2% of total emissions from diesel production and combustion.

3.4 Water-Energy Interdependence

Fig. 4 shows the amount of water needed to produce energy in Riau in 2017. About 99.5% of groundwater was taken for crude oil extraction. The huge water demand is influenced by the oil recovery technology used.

In this study, the amount of water for oil extraction was calculated for secondary recovery technology, which needs water ten times more than primary recovery technology²²⁾. In coal production, water is most mainly used for mining activities, such as coal cutting, removal of coal dust, and coal washing. In oil refineries, water is needed for the cooling process and used as boiler feed to produce steam. Power plants need water for the cooling process. In this study, the cooling technology used is a cooling tower for coal and gas power plants. Diesel power plants need the least amount of water because water is only used to cool the radiator. Biodiesel production required the biggest amount of water (99.3% of the total water abstraction), which is dominated by rainwater. The annual rainfall of Riau Province in 2017 is 3,249 mm with a range of 137-503 mm per month¹²⁾. From calculation result, the rainwater supply can meet the water needs for oil palm cultivation in Riau, which is around 32% of rainwater supplied. However, the calculation does not include run-off water, water for other sectors, and water availability in Riau.

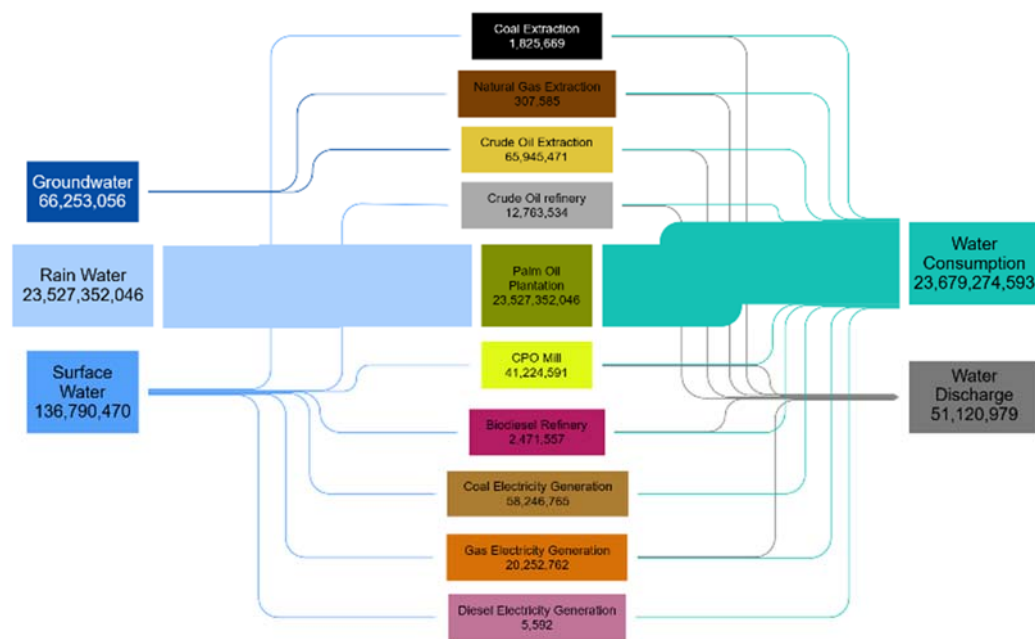


Fig. 4: Water consumption for energy production (m³)

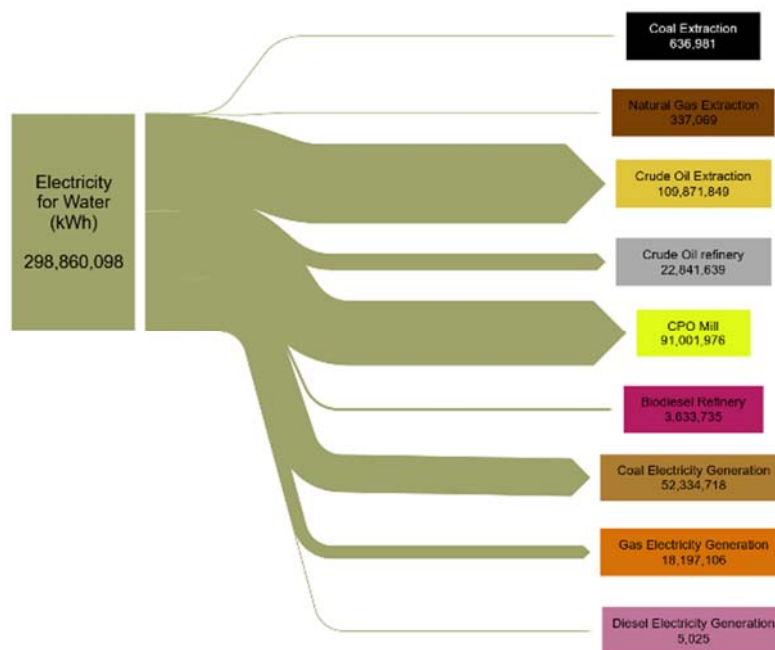


Fig. 5: Electricity consumption for water supply (kWh)

Based on Fig. 5, around 37% of the total electricity was used to supply water for oil extraction, which is dominated by wastewater treatment and water abstraction. Wastewater treatment is an energy-intensive process compared to other water supply activities. The source of water for oil extraction comes from groundwater, which needs energy seven times more than surface water pumping²³). Water supply in CPO production required 30.5% of total electricity, which is mainly used for wastewater (POME) treatment. In the power plant, the electricity is mainly consumed for distribution of water

from the treatment site to the power plant. In oil refineries, the most energy-intensive activities are wastewater treatment and water distribution, which accounts for 49.8% and 40.8% of the total electricity at the refinery. In biodiesel production at the refinery, the amount of electricity required is relatively small compared to other energy production (1,2 % of total electricity).

4. Conclusion

In this paper, the water and energy consumption, along

with CO₂ emission for biodiesel production had been evaluated. The total water footprints for FFB, CPO, and biodiesel in Riau Province were 671 m³/t FFB, 3,292 m³/t CPO, and 3,432 m³/t biodiesel, respectively. The biggest contributor to water footprint was green water in the plantation stage. The total energy input in biodiesel production was 14,252 MJ/t biodiesel with the largest energy were consumed at the refinery. Biodiesel production emitted 608.6 kg CO_{2-eq}/t biodiesel. In comparison to other energy production, palm oil biodiesel production required a large amount of water, and electricity to supply water. The large water consumption can be met from rainwater supply in Riau. However, due to the lack of data on water availability in Riau and water consumption for other sectors, the water scarcity of Riau cannot be evaluated.

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