Potency estimation of forest stands biomass in Gunung Walat Educational Forest, Sukabumi, West Java as fuel for electricity generation

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Abstract. The need for energy in Indonesia is increasingly growing into an inseparable part of the daily life of society. However, the limited availability of fossil fuel sources as raw materials for electricity and increased public awareness to preserve the environment lead to the need for an alternative source of renewable energy such as bioenergy, which is a renewable energy that utilizes biomass as its fuel source. Furthermore, this research was conducted to estimate the potential of biomass in Gunung Walat Educational Forest (GWEF) as fuel for electricity generation. Estimation of the potential of electrical energy has been carried out by using the biomass conversion approach to wood pellets (WP). The results showed that Pinus merkusii stands have the highest biomass content (12,828.62 tons with a total area of 104 Ha) and Swietenia macrophylla stands have the lowest biomass content (16.63 tons with a total area of 0.67 Ha) compared to other stands. The total biomass obtained from 358.24 Ha of eleven stands was 45,041.38 tons and it can produce electricity of 123,863.79 MWh, suggesting that the biomass in GWEF has the potential to be developed to fulfill the electricity needs of 10.6 MWh per year.

1. Introduction
Energy needs in Indonesia are increasingly developing into an inseparable part of people’s daily lives as indicated by Indonesia’s primary energy demand, which grew by 4.9% in 2018, well ahead of its average annual rate of 2.8% between 2007-17 [1]. The energy consumption, especially electricity, will continue to increase along with the increasing rate of population growth rates, welfare levels, and technological development. However, the limited availability of fossil energy sources as raw material for electricity and increasing public awareness to preserve the environment led to the need for alternative renewable energy sources that are environmentally friendly.

Renewable energy is energy generated from geothermal, wind, bioenergy, sunlight, water flow and waterfall, as well as movement and temperature differences in sea layers [2]. Renewable energy in Indonesia has considerable potential to be developed. Up to 2015, the potential for renewable energy includes 75,000 MW of hydropower, 950 MW of wind energy, 4.8 kWh/m2/day of solar energy, 17.96 GW of ocean currents, 1.9 GW of wave energy, 41 GW of sea heat, and 32.6 GW of bioenergy [3]. Most of the renewable energy power plants built from 2008-2018 came from geothermal sources (37%), large-scale hydropower (29%) and bioenergy (23%). However, since 2014, bioenergy power generators accounted for 51% of renewable energy power plants, followed by geothermal (32%) and mini/micro hydro (14%) [4].
suggesting that bioenergy acts as a potential driver of sustainable development, given sufficient economic and technological support.

Bioenergy is an energy from organic matter (biomass), i.e. all materials of biological origin that are not embedded in geological formations (fossilized) and include traditional biomass (example forestry and agricultural residues), modern biomass and biofuels [5]. Biomass from plants has a variety of forms, such as twig waste, which has the potential to be increased in efficiency when used in uniform processed forms such as wood pellets. Wood pellets have a smaller and drier form that can facilitate the storage, distribution, and combustion process. The ability of wood pellets to release heat equivalent to fossil energy will make wood pellets easily accepted because the world market is currently making efforts to reduce the effects of greenhouse gases through more environmentally friendly energy use.

The important thing in processing biomass (wood pellet) into electricity is an understanding of conversion technology, which is adjusted according to the type of biomass that will be used. Although various types of technology are available, a good understanding of the suitability of biomass types and technology types is needed to achieve maximum energy output from a biofuel [6]. In Indonesia, the abundance of biomass derived from plants is quite high due to the presence of large forests. Therefore, exploration of the potential of biomass in various forests in Indonesia is necessary. One interesting example of forest to explore is Gunung Walat Educational Forest (GWEF) in West Java, because the forest is evidence of a success history in Indonesia forest management [7] and surrounded by village settlements and intensive perennial/annual crops, creating a rural environment, so that if the biomass in this forest has the potential to produce enough electricity, then the community can reduce the use of electricity from non-renewable energy (fossil energy). However, the study of the potential of biomass in the forest has never been carried out. Furthermore, the aim of this study was to estimate the potential of biomass in Gunung Walat Educational Forest (GWEF), Sukabumi, West Java as fuel for electricity generation.

2. Materials and methods

2.1. Study site
The study was conducted on October 2017 in Gunung Walat Educational Forest (GWEF), Sukabumi, West Java, Indonesia. Since 1969, the forest has been managed by Faculty of Forestry, IPB university (Bogor Agricultural University), as an educational forest [7]. Geographically, GWEF is located between 6°54’23" S - 6°55’35" S and 106°48’27" E - 106°50’29" E and is administratively located in the Cibadak Subdistrict area, Sukabumi District, West Java [8]. The GWEF area has an area of 359 ha [7], and borders with several villages, namely Batununggul Village and Sekarwangi (North) Village, Cicantayan and Cijati Villages (East), and Hegaranmanah Village (South and West). GWEF is located at an altitude of 460-726 masl and parts of the mountains that line from east to west.

Vegetation in GWEF is dominated by Agathis stands (*Agathis loranthifolia*) planted in 1951, pine/pinus stands (*Pinus merkusii*) planted in 1960, and puspa stands (*Schima wallichii*) planted in 1968 [8]. The three species are native to Indonesia and planted with different area sizes i.e. 35 ha of agathis plantations, 35 ha of pine/pinus plantations, and 59 ha of puspa forest plantation [8]. The undergrowth was covered by various types of woody shrubs such as Calliandra calothyrsus, Ettlingera solaris, Clidemia hirta, Melastoma candidum, Sellaginella doederleinii, Cynodon dactylon, Curculigo latifolia, Claoxylum indicum, Lelea sambucina, Equisetum debile, and Coffea arabica [8]. Besides trees and shrubs, there are also ferns, epiphytes and various types of grass.

2.2. Vegetation analysis
Vegetation analysis was conducted by measuring the pole and tree level in eleven types of stands i.e. (1) the mixed stands of *Pinus merkusii* (pine/pinus) and *Agathis loranthifolia* (agathis), (ii) mixed stands of *Swietenia macrophylla* (mahogany) and *Schima wallichii* (puspa), (iii) pure stands of *Maesopsis eminii* (kayu afrika), (iv) pure stands of *A. loranthifolia*, (v) mixed stands of *A. loranthifolia*, *P. merkusii* and *S. wallichii*, (vi) mixed stands of *A. loranthifolia* and *S. wallichii*, (vii) pure stands of *P. merkusii*, (viii) mixed stands of *P. merkusii* and *M. eminii*, (ix) mixed stands of *P. merkusii* and *S. wallichii*, (x) pure stands of *S.
wallichii, and (xi) pure stands of *S. macrophylla*, using circular sampling plots of 0.1 ha with a plot radius of 17.8 m (figure 1). In addition, vegetation analysis of pure stands of *Calliandra calothyrsus* (Kaliandra) was also carried out using circular sampling plots of 0.01 ha as a comparison, because the timber of this species has been known as bioenergy sources [9]. The circular sampling plot is commonly used for vegetation surveys (including biomass or carbon stock) in relatively homogeneous forest such as temperate forests or plantations [10]. In total, ten circular sampling plots were established for eleven types of stands (figure 2), and one circular sampling plot was established for pure stands of *C. Calothyrsus*.

![Figure 1. The 0.1 ha circular sampling plot design in the observation plot.](image1)

Data taken during vegetation analysis were tree diameters at breast height (DBH), tree height, and clear-bole height. Data were analyzed quantitatively to determine the composition of the stand and the dominance of one species to another described by the Importance Value Index (IVI). The IVI value is the sum of the relative density (RDs), the relative frequency (RF), and the relative dominance (RDm) of a species, which can be calculated using equation 1 [11]:

\[
\text{IVI} = \text{RDs} + \text{RF} + \text{RDm}
\]
Absolute density of each species (ADs) = \[ \frac{\sum \text{individual of species}}{\text{total of sampling area}} \times 1 \text{ ha} \]

Relative density (RDs) = \[ \frac{\text{ADs}}{\text{total of all species}} \times 100\% \]

Absolute dominance of each species (ADm) = \[ \frac{\sum \text{coverage of species}}{\text{total of sampling area}} \times 1 \text{ ha} \]

Relative dominance (RDm) = \[ \frac{\text{ADm}}{\text{total of all species}} \times 100\% \]

Absolute frequency (AF) = \[ \frac{\sum \text{sampling plots where } k \text{ species found}}{\sum \text{sampling plots}} \]

Relative frequency (RF) = \[ \frac{\text{AF}}{\text{total of all species}} \times 100\% \]

Importance value index (IVI) = RDs + RDm + RF (for pole and tree level) \hspace{1cm} (1)

2.3. Estimation of biomass potential

Estimation of stand biomass was conducted by using allometric equations that are suitable for tree species and ecosystem types at the study site. The allometric equations used in this study were obtained from previous studies on estimating biomass of each tree species, so that the accuracy of the results can be tested. Allometric equations for estimating biomass using the DBH variables obtained from measurements carried out during vegetation analysis. The allometric equations used for *Agathis loranthifolia*, *Pinus merkusii*, *Swietenia macrophylla*, and *Schima wallichii* in this study are presented in Table 1.

| Species                | Allometric Equations | Sources |
|------------------------|----------------------|---------|
| *Agathis loranthifolia*| \[ W = 0.3406 D^{2.0467} \] | [12]    |
| *Pinus merkusii*       | \[ W = 0.206 D^{2.26} \]  | [13]    |
| *Swietenia macrophylla*| \[ W = 0.048 D^{2.68} \]  | [14]    |
| *Schima wallichii*     | \[ W = 0.4594 D^{1.9978} \] | [15]    |

The biomass measured in this study is above-ground biomass. However, the availability of allometric equations for estimating above-ground biomass for tree species in Gunung Walat Educational Forest (GWEF) was very limited, so that allometric equations used for the species that have no allometric equations references such as *Maesopsis eminii* and *Callicandra calothyrsus* were the universal allometric equations by Ketterings et al. [16], as shown in equation 2. The universal allometric equation was also used to estimate biomass of *C. calothyrsus* with DBH variables obtained from census measurements in the Tanabe Block and TVRI Transmitter Station. The equation uses variable diameters and wood density specifically for each species. The value of wood density for *M. eminii* that used in the calculation was 0.42 kg/cm³ [17]. While, the value of wood density for *C. calothyrsus* is 0.645 kg/cm³ [18].

\[ W = 0.11 \times \rho \times D^{2.62} \] \hspace{1cm} (2)

Where,
\[ W = \text{biomass (kg/tree)} \]
\[ \rho = \text{wood density (kg/cm³)} \]
\[ D = \text{diameter at breast height (cm)} \]
2.4. Estimation of electric energy potential

Estimation of the potential of electrical energy has been carried out by using the biomass conversion approach to wood pellets (WP), as shown in table 2.

| Table 2. Conversion of biomass to electricity |
|----------------------------------------------|
| **Biomass : WP (ton)** | **Heat Energy (MJ)** | **Electricity (kWh)** |
| 1.5 : 1 | 1 kg WP = 19.8 MJ | 3.6 MJ = 1 kWh |

The previous study by Sjodin et al. [19] showed that 1.5 tons of biomass are needed to produce 1 ton of WP. Furthermore, the WP conversion approach into heat energy was carried out with a yield of 19.8 MJ / kg [20]. Heat energy from WP was used to generate electricity by first converting the heat energy of WP (MJ) into electrical energy (kWh). Heat energy was converted into electrical energy with a value of 1 kWh = 3.6 MJ [21]. The engine efficiency used was 75%.

3. Results and discussion

3.1. Vegetation structure and composition in GWEF

The vegetation analysis carried out in this study was to determine the structure and composition of 5 species (P. merkusii, A. loranthifolia, S. macrophylla, S. wallichii, and M. eminii) in 10 observation plots that could be estimated by calculating the Important Value Index (IVI). This analysis can also determine the dominance of one species to another. The observation result showed that all 5 species can be analyzed for tree-level, but only 3 species (S. macrophylla, S. wallichii, and M. eminii) can be analyzed for pole-level indicating the absence of regeneration in other two species (P. merkusii, and A. loranthifolia).

Vegetation analysis at the tree-level (Figure 3) in 5 species revealed that IVI value was high in P. merkusii (64.1%), followed by A. loranthifolia (63.7%), S. macrophylla (62.7%), and S. wallichii (62.2%), while M. eminii have the lowest IVI value (47.4%) indicating that the presence of P. merkusii and A. loranthifolia in GWEF were quite dominant than other species at the tree-level. The dominance of P. merkusii and A. loranthifolia was due to the mass planting of A. loranthifolia in 1951/1952 and P. merkusii in 1969-1971. Both species were chosen to be planted in GWEF because the trees can produce resins that can be tapped and sold by the surrounding community [22]. In addition, wood biomass of P. merkusii can be used as a raw material for energy because it has good chemical and proximate properties [23]. The results of vegetation analysis at the pole-level in 3 species showed that S. macrophylla have a higher IVI value (207.9%) compared with S. wallichii (66.0%) and M. eminii (26.1%) suggesting that S. macrophylla dominates the pole vegetation.

![Figure 3. Percentage of IVI values in 10 plots with 5 different species in GWEF.](image)

3.2. Biomass potential in GWEF

In the present study, biomass potential in 10 observation plots was estimated by analyzing above-ground biomass following the the IPCC Guidelines [24,25]. Above-ground biomass is the total amount of organic matter living above the ground in trees including twigs, leaves, branches, main stems, and bark, which are
expressed in oven dry weight per unit area [26]. Above-ground biomass can also be defined as the weight of organic material per unit area at a certain time, which is associated with the function of the productivity system, stand age, and organic distribution [27].

The result of biomass estimation di GWEF showed that the largest average biomass content was found in mixed stands of *P. merkusii* and *A. loranthifolia* (263.05 tons/Ha) and the smallest was found in *S. macrophylla* stands (24.94 tons/Ha) (table 3). While, the result of biomass estimation for electrical energy showed that the largest biomass content was found in *P. merkusii* stand (12,828.62 tons) with a total area of 104 Ha. While the lowest biomass content was found in *S. macrophylla* stands (16.63 tons) with a total area of 0.67 Ha. The total value of stored biomass in eleven stands was 45,041.38 tons with a total area of 358.24 Ha (table 4). The biomass content in the *P. merkusii* stands has a higher value than other stands because this species have a larger planting area, larger tree volume size and have an older stand age compared to other species in the observation plot. The stored biomass is influenced by age, composition, and stand structure [27].

Biomass potential analysis also showed that 45,041.38 tons of total biomass contained in eleven different stands of 358.24 Ha can produce wood pellets of 30,027.59 tons (table 4). Heat energy contained in 30,027.59 tons of wood pellets was 594,546.20 GJ or equal to 123,863.79 MWh if converted into units used in electricity with engine efficiency of 75%. As a comparison, 0.01 Ha of *Calliandra calothyrsus* stands could produce 1.16 tons of biomass and 3.20 MWh of electricity (table 5).

| No  | Species                                       | Observed Biomass (ton/Ha) | Average (ton/Ha) |
|-----|-----------------------------------------------|---------------------------|-----------------|
| 1   | *P. merkusii* and *A. loranthifolia*          | 222.93                    | 263.05          |
| 2   | *P. merkusii* and *A. loranthifolia*          | 303.17                    |                 |
| 3   | *S. macrophylla* and *S. wallichii*           | 31.67                     |                 |
| 4   | *S. macrophylla* and *S. wallichii*           | 20.60                     |                 |
| 5   | *S. macrophylla* and *S. wallichii*           | 64.88                     | 54.46           |
| 6   | *S. macrophylla* and *S. wallichii*           | 96.51                     |                 |
| 7   | *S. macrophylla* and *S. wallichii*           | 58.63                     |                 |
| 8   | *M. eminii*                                   |                           | 57.18           |
| 9   | *M. eminii*                                   |                           | 42.26           | 46.05          |
| 10  | *M. eminii*                                   |                           | 38.71           |
| 11  | *A. loranthifolia*                            | 33.60                     | 139.70          |
| 12  | *A. loranthifolia*                            | 245.81                    |                 |
| 13  | *A. loranthifolia, P. merkusii, and S. wallichii* | 279.40                 |                 |
| 14  | *A. loranthifolia, P. merkusii, and S. wallichii* | 246.70                 | 224.57          |
| 15  | *A. loranthifolia, P. merkusii, and S. wallichii* | 147.59                 |                 |
| 16  | *A. loranthifolia* and *S. wallichii*         | 279.40                    | 213.50          |
| 17  | *A. loranthifolia* and *S. wallichii*         | 147.59                    |                 |
| 18  | *P. merkusii*                                 | 189.34                    | 123.35          |
| 19  | *P. merkusii*                                 | 57.37                     |                 |
| 20  | *P. merkusii* and *M. eminii*                 | 138.15                    | 192.43          |
| 21  | *P. merkusii* and *M. eminii*                 | 246.70                    |                 |
Table 4. Biomass potential in GWEF for electrical energy

| No | Species                          | Area (Ha) | Observed Biomass (ton) | WP (ton) | Heat Energy (GJ) | Electricity (MWh) |
|----|---------------------------------|-----------|------------------------|----------|------------------|-------------------|
| 22 | P. merkusii and S. wallichii    | 4.26      | 1,120.59               | 747.06   | 14,791.83        | 3,081.63          |
| 23 | P. merkusii and S. wallichii    | 9.42      | 513.10                 | 342.07   | 6,772.96         | 1,411.03          |
| 24 | S. wallichii                    | 7.42      | 341.60                 | 227.73   | 4,509.11         | 939.40            |
| 25 | S. wallichii                    | 27.43     | 3,832.00               | 2,554.66 | 50,582.36        | 10,537.99         |
| 26 | A. loranthifolia                | 7.96      | 1,787.55               | 1,191.70 | 23,595.60        | 4,915.75          |
| 27 | A. loranthifolia, P. merkusii, and S. wallichii | 54.05 | 11,539.51 | 7,693.01 | 152,321.57 | 31,733.66 |
| 28 | P. merkusii                    | 104.00    | 12,828.62              | 8,552.41 | 169,337.74      | 35,278.70         |
| 29 | P. merkusii and M. eminii       | 29.69     | 5,713.16               | 3,808.77 | 75,413.71       | 15,711.19         |
| 30 | P. merkusii and S. wallichii    | 23.88     | 4,707.90               | 3,138.60 | 62,144.25       | 12,946.72         |
| 31 | S. macrophylla                  | 89.46     | 2,640.72               | 1,760.48 | 34,857.48       | 7,261.98          |
| 32 | S. macrophylla                  | 0.67      | 16.63                  | 11.09    | 219.58           | 45.75             |
| 33 | S. macrophylla                  | 89.46     | 2,640.72               | 1,760.48 | 34,857.48       | 7,261.98          |
|    | Total                           | 358.24    | 45,041.38              | 30,027.59 | 594,546.20    | 123,863.79        |

Table 5. Potency of C. calothyrsus to be used as a source of electricity

| Species     | Area (ha) | Biomass (ton) | WP (ton) | Heat Energy (GJ/ton) | Electricity (MWh) |
|-------------|-----------|---------------|----------|----------------------|-------------------|
| C. calothyrsus | 0.01      | 1.16          | 0.78     | 15.36                | 3.20              |

Based on survey in the field, the use of electricity in GWEF every month ranges from IDR 661,600 to IDR 1,780,700, with an electricity rates of IDR 1,487 per kWh based on data from Perusahaan Listrik
Negara (PLN) in 2017. Therefore, the electricity demand in the GWEF area was around 0.88 MWh monthly or 10.6 MWh annually. In this study, electricity from eleven stands biomass was 123,863.79 MWh which can fulfill the electricity demand in GWEF for many years without replanting. While electricity from C. calothyrsus biomass of 3.20 MWh can fulfill the electricity demand in GWEF up to 3 months without replanting. This pattern suggested that GWEF has great potential to be developed as a sustainable source of biomass to generate electricity that can be used by a community who live surrounding the forest.

3.3. Biomass as fuel for electricity generation

Biomass needs to be processed first to facilitate its use as fuel. This processing is known as biomass conversion. In general, biomass conversion technology is divided into three types, namely direct combustion, thermochemical conversion, and biochemical conversion [28]. One example of a thermochemical conversion technique is gasification. Gasification is a process of changing thermochemically solid fuels into gas, where the required air is lower than the air used for the combustion process [29]. The gasification process starts from burning wood with limited oxygen in the reactor to produce fuel gas in the form of carbon monoxide gas (CO), methane gas (CH4), and hydrogen gas (H2), then cooled, purified, and mixed with air. Then, this gas enters the diesel engine to be converted into electricity (figure 4).

**Figure 4.** Gasification process diagram.

Figure 4 shows a diagram of the gasification process to produce a combustible gas, which is carried out through four stages, namely drying, pyrolysis, combustion, and reduction. The drying stage serves to change the water content in biomass to water vapor, which is also part of fuel gas. Furthermore, decomposition occurs in the pyrolysis stage of biomass so that it produces tar, CH4 gas, and charcoal. At the combustion stage, there will be an exothermic combustion reaction on the biomass substance in the form of carbon, hydrogen, and oxygen. Carbon will be burned into carbon dioxide and hydrogen will be burned to steam. At the reduction stage, there will be several reactions that will produce CO and H2 gas as the main component of fuel gas. However, the fuel gas produced from this process still contains water in the form of steam, tar, nitrogen gas, and unwanted dust particles. The effort that can be done to eliminate the unwanted content is through gas cleanup, as shown in figure 5.

Figure 5 shows the clean up gas circuit consisting of cyclone, water condenser, and washing gas. Fuel gas from the reactor will flow through the cyclone to reduce its solid particles. Furthermore, this gas is flowed to the water condenser to be cooled, reduced the content of the gas, and condensed the water content into liquid smoke. After passing through the water condenser, the fuel gas is flowed to the compartments containing water and diesel fuel bubbles to be cleaned. The water in the compartment functions to capture particles and the remains of tar, while the diesel fuel functions to capture the remains of particles.
Furthermore, fuel gas that has been cooled and cleaned can be used for diesel engines to be converted into electrical energy.

![Diagram of biomass gasification machine.](image)

Electricity needs per day in GWEF of 29.3 kWh can be fulfilled by installing a gasification engine with a capacity of 11 kW for 8 hours per day because it can produce 88 kWh of electricity per day with an efficiency of 75%. Within 1 hour, a maximum of 18 kg of biomass is needed. So that the use of 8 hours per day requires a maximum of 144 kg of biomass. This gasification machine can produce electrical energy of 32.12 MWh per year if used for 8 hours per day and requires a total biomass of 52.56 tons.

Total biomass from the three stands of 932.71 tons/ha can fulfill biomass needs for fuel gasification engines for up to 17 years without replanting. While the total biomass of *C. calothyrsus* amounted to 116.37 tons/ha can fulfill the needs of biomass for gasification engine fuel for 2 years without replanting. *C. calothyrsus* can be used as a raw material for gasification machines to fulfill electricity needs sustainably due to its fast-growing and easily adapted to wide range of environments, as well as the suitability of *C. calothyrsus* as wood energy, seen from its specific gravity which has a value of about 0.5-0.8 so that it dries quickly and burns quickly. In addition, the relatively high heating value, which is 4,600 kcal/kg of dry wood can also produce energy that meets commercial requirements. *C. calothyrsus* can also be cut after 1 year of growing before the rainy season at an altitude of 50 cm and then new shoots (coppiced wood) can appear from their stump [30].

Wood biomass used as a raw material can be in the form of pieces or can be changed first into a more solid form and uniforms such as wood pellets. The characteristics of wood pellets have a higher advantage compared to fossil fuels. Some of its advantages include easy handling, ignition and burning; uniform shapes and fuel properties; high energy density; and fewer toxic gas emissions [28].

4. Conclusions
The measurement of biomass content in GWEF which carried out in eleven types of stands showed that the content of biomass in *P. merkusii* stands higher (12,828.62 tons with a total area of 104 Ha) than other stands, while the content of biomass in *S. macrophylla* stands lower (16.63 tons with a total area of 0.67 Ha) than other stands. In addition, the total biomass obtained from 358.24 Ha of eleven studied stands was 45,041.38 tons and can produce electricity of 123,863.79 MWh suggesting that biomass in GWEF has the potential to be used as a fuel source for electricity generation for many years because electricity needs in GWEF are only 10.6 MWh per year. In addition, it is recommended to plant wood energy such as *C. calothyrsus* in special areas in GWEF to be used for biomass as fuel for electricity generation as this species could produce 1.16 tons of biomass in 0.01 Ha which can be used to produce 3.20 MWh of electricity. Furthermore, research on the chemical and proximate properties of *A. loranthifolia*, *S. macrophylla*, *S. wallichii*, and *M. eminii* to be used as a source of fuel for electrical energy is needed.
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