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Feasibility Study, Design, and Installation of Solar PV Tree to Cover the Electricity Demand at Mangrove Park

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Abstract. To mitigate climate change, transitioning from fossil fuels to renewable energy sources and expanding carbon sinks such as forests and mangroves are essential strategies. This study explores the integration of solar photovoltaic (PV) tree technology to achieve a net-zero emission concept within the mangrove conservation area at Science Techno Park (STP), Teluk Awur, Jepara, Indonesia. Mangroves play a critical role in carbon sequestration, yet limited land availability for conventional solar panels in such ecosystems necessitates innovative solutions. Solar PV trees, designed with a capacity of 50 Wp per unit and 10 Wp panels per leaf, are deployed to supply electricity for LED lighting (6 W) and mobile charging stations. A total of 70 units, yielding 3500 Wp, are planned for the mangrove boardwalk. Several factors influencing system performance, including non-optimal solar incidence angles, ambient temperature, and dust accumulation, are analysed due to their potential to reduce efficiency and induce hotspot formation. The installation of a prototype banana-style solar PV tree results in a Net Present Cost (NPC) of USD 828 and a Levelized Cost of Energy (LCOE) of USD 1.080/kWh. The findings demonstrate that solar PV trees offer a feasible and sustainable solution to meet local energy needs while enhancing renewable energy implementation in ecologically sensitive areas.

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1. Introduction

Energy is very important to human life as it runs all the system of the living things as well as its supporting system. Till this date the dominant energy source came from fossil energy that will undoubtedly decrease with continued usage and lack of regeneration. In Indonesia the fossil energy such as coal dominantly uses for the electricity generation. In fact, it contributes to almost 50% of the total carbon emission that caused the global warming and climate change[1]. There are several ways to reduce the carbon emission, one of them is to shift the energy source into the renewable energy such as solar energy, wind energy, biomass-based energy, hydropower. These initiatives are part of the world agendas to achieve Sustainable Development Goals in 2030 especially SDG 7 Affordable and Clean Energy and SDG 13 Climate Action. In addition, through Paris Agreement, many countries in the world have agreed for global to shift toward a low carbon future through many programs and initiatives especially in the renewable energy shift and the growth and conservation of carbon-absorbing plants[2].

Mangrove Park is one of the support forms for carbon sequestration and green open spaces. Mangroves, as carbon sequestration sites, are very important for the surrounding ecosystem[3]. Nevertheless, due to careless deforestation and land degradation, the current state of mangrove forest is concerning. Universitas Diponegoro and the Ministry of Research, Technology and Higher Education collaborated in the development of the Science Techno Park that includes a mangrove conservation area. Based on UU Number 5 of 1990 about the Conservation of Living Natural Resources and their Ecosystems, the conservation of living natural resources is the wise management and utilization of resources in order to ensure the harmony of their supplies while maintaining and increasing the quality of their diversity and value[4]. Considering that, maintaining the conservation area is mandatory, which includes providing electricity as a source of energy that is clean and sustainable such as electricity that generated from the sun (solar based energy). By that it is necessary to conduct feasibility study, design, and installation of solar PV tree to cover the electricity demand in Mangrove Park, Teluk Awur, Jepara, Indonesia.

Solar PV trees can be an alternative source of energy in the mangrove conservation area that is mainly used for lighting and charging stations. Additionally, solar panels installation also has the potential to lowering the temperatures beneath the installations and raise local thermal heterogeneity. In the place where solar panels are installed, it means moisture and moisture heterogeneity can rise. This effect provides benefits to the surrounding ecosystem[5–7].

On the other hand, the global horizontal irradiation in Teluk Awur, Jepara is 4.907 kWh/m2/day, this value is higher than the average value of Indonesian solar irradiation, which is 4.5 kWh/m2/day[8]. Thus, from the irradiation data alone, the possibility of sunlight utilization as an energy source is feasible to be converted into electricity in Mangrove Park area. However, feasibility study is needed to confirm the hypothesis as well as suitable design and evaluation. This paper discussed the feasibility study, design, and installation of solar PV in the model of tree as an electricity source in Mangrove Park, Teluk Awur, Jepara, Indonesia. In addition, the techno economy analysis also reported for the implementation of solar PV tree as an alternative renewable energy source in the coastal area.

2. Methodology

2.1. Location

The research was conducted in a mangrove area in Teluk Awur, Jepara, Indonesia with an area of 17.527 m2, the shoreline is 1.1 km with estimated width 1.5m (Figure 1.). According to its abundance and distribution, red mangroves are dominant with 100 and 75 individuals in the front zone and in the middle zone respectively within the area of 400m2.

Figure 1. Science Techno Park (MSTP) project area

2.2. Research Framework and Methodologies

The research framework of the feasibility study, design, installation, and evaluation of solar PV Tree in Teluk Awur, Indonesia is designed as depicted in the Figure 2.

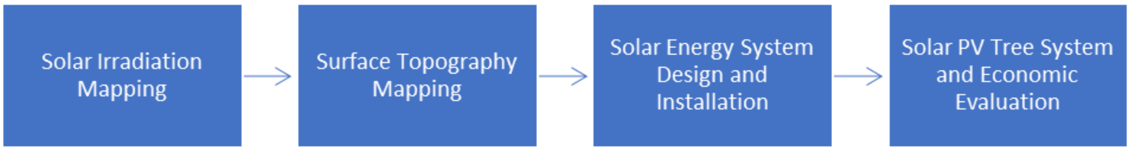


Figure 2. Framework of the study

2.3. Mapping solar irradiation intensity

The feasibility of Solar PV Tree installation in the Mangrove Park, Teluk Awur Jepara, Indonesia was analyzed by solar irradiance measurements. Solar irradiance data can be divided into three categories namely: Direct Normal Irradiance (DNI), Diffuse Horizontal Irradiance (DHI) and Global Horizontal Irradiance (GHI). In this study the mapping was conducted by DNI method which is the radiation received on a surface perpendicular to the incoming radiation rays[9].

2.4. Mapping surface topography of Mangrove Park, Teluk Awur, Jepara, Indonesia

The feasibility of Solar PV Tree installation in the Mangrove Park, Teluk Awur Jepara, Indonesia is not only analyzed by solar irradiance measurements but also the surface topography. The purposes of the mapping were to determine the contour of areas affected by shading effects[10]. Accurate information regarding the contour of the Solar PV Tree installation area is very important [11].

2.5. Design and Installation of Solar PV Tree

The design of the Solar PV Tree was generated based on solar irradiation and surface topography data. The surface and contour of the area can affect the illumination angle and shadowing from local horizons. Design and installation of Solar PV Tree consist of several components include artificial tree, solar panel, solar irradiation tool, transmitter, inverter 1600W, battery and cable. The solar power system consists of the following four main parts[12,13]: (i) Photovoltaic cell array (solar panel), consists of photovoltaic batteries in series and parallel, which is often seen in the everyday life of solar panels. This is a very important core part of the solar power systems, ensuring that solar energy is converted into electrical energy. Electrical energy can be stored in the storage battery pack; (ii) Photovoltaic Controller, located in the unidirectional current channel between the photovoltaic cell array and the inverter, and it is bi-directionally connected with the storage battery pack to control the working status of the system. When the temperature difference between day and night is in a large area, the controller can also provide temperature compensation.

In addition, the PV controller also has many other features, such as the choice of light control switch or time switch, the system providing electronic short circuit protection, overload protection, or unique anti-reverse protection; (iii) Storage battery pack, this part can store electrical energy, in case there is less or no solar energy in winter, on rainy days or nights when a photovoltaic cell array cannot produce electricity; Inverter, it can change DC power into AC power.

2.6. Solar PV Tree System and Economic Evaluation

The evaluation of the solar PV tree that has been installed involves testing it as lighting in the mangrove track. Calculating the luminous flux is the first step in calculating the number of lamps required along the mangrove track, using equation as below[14]:

$$E = \frac{I}{r^2} \quad (1)$$

where the illumination is expressed by E (lux), I is luminous intensity (candela) and r is distance of the surface from the source (m2).

$$I = \frac{\varphi}{\omega} \quad (2)$$

where I is luminous intensity (candela), φ is luminous flux (lumen), and ω is solid angle (steradian).

The standard of lighting intensity for pedestrian paths has not been regulated in SNI. Based on the DIN EN 13201 standard regarding the selection of lighting classes, garden paths are classified under type E2. Where the average horizontal illuminance is 3 - 20 lux and the minimum illuminance is 0.6 - 8 lux[15]. The lighting used for the PV trees placed in the mangrove track is a 6-Watt LED lamp with a 12 VDC input with a lamp flux of 430 lm.

Meanwhile, the techno-economic evaluation can be assessed through several indicators such as Levelized Cost of Energy (LCOE) and Net Present Cost (NPC). LCOE is a measure of the average current cost of electricity, which is used over its lifetime, expressed as follows[16]:

$$LCOE = \frac{I_0 + \sum_{t=1}^{n} \frac{A_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{Q_t}{(1+r)^t}} \qquad (3)$$

where I0 is Initial cost, At is annual operating cost, Qt is the estimated energy provided (kWh/year), r is the interest rate, n is the estimated system lifespan. Meanwhile, NPC is the present value of installing and operating costs over the life of the project, which is reduced by the present value of all income earned during the life of the project, that can be expressed[17]:

$$NPC = \frac{C_{total}}{CRF(i + P_T)} \qquad (4)$$

$$CRF(i, n) = \frac{i(1+i)^n}{(1+i)^n - 1} \qquad (5)$$

where Ctot is the total annualized cost of the entire system in $/year, CRF is the capital recovery factor, PT is project lifetime, i is the interest rate (%), n is the number of years.

3. Results and Discussion

3.1 Solar irradiation intensity

Solar irradiance measurements are the first step in the installation of solar panels on the mangrove track MSTP Teluk Awur, Jepara, Indonesia. Solar irradiance data can be divided into three categories namely: Direct Normal Irradiance (DNI), Diffuse Horizontal Irradiance (DHI) and Global Horizontal Irradiance (GHI). DNI: is the radiation received on a surface perpendicular to the incoming radiation rays[9]. This number can enhance the amount of irradiation that the surface receives annually by keeping it normal to incoming radiation. This amount is very useful for centralizing solar panel setups that can track maximum sun radiation[18]. DHI is the total radiation that has been scattered and then reflected by clouds, gases (N2, CO2, O2, etc.), and water vapor[9].

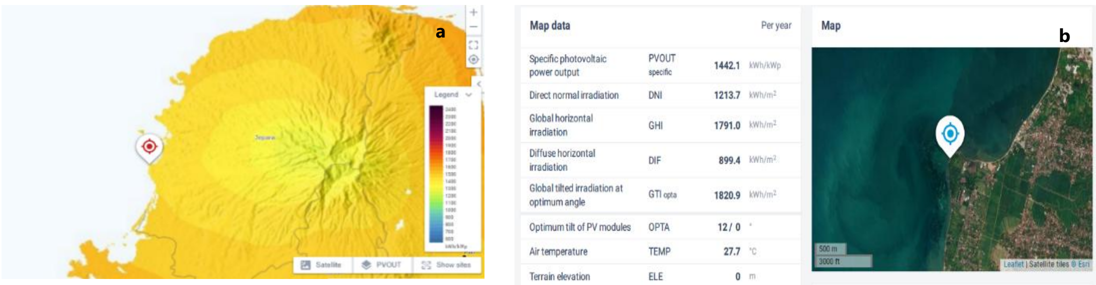


Figure 3. Solar irradiation (a and b) in MSTP Teluk Awur[19]

Average hourly profiles

Direct normal irradiation [Wh/m^2]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0 - 1												
1 - 2												
2 - 3												
3 - 4												
4 - 5												
5 - 6	3			4	3				13	18	28	9
6 - 7	57	50	89	131	152	135	136	153	207	175	151	80
7 - 8	110	128	213	265	309	310	334	371	394	318	252	142
8 - 9	163	178	289	364	419	416	457	503	516	426	327	204
9 - 10	208	238	337	408	486	481	537	585	584	471	349	243
10 - 11	222	276	381	389	475	502	567	613	593	447	317	252
11 - 12	235	264	356	350	434	468	548	588	544	396	253	236
12 - 13	248	259	310	313	388	428	510	538	522	394	223	212
13 - 14	226	240	293	287	347	406	476	506	488	365	220	183
14 - 15	190	183	262	249	306	358	417	449	434	301	196	152
15 - 16	132	136	196	189	242	282	326	364	326	215	139	103
16 - 17	81	82	116	105	136	167	198	215	172	102	76	62
17 - 18	28	29	18	10	7	11	18	20	12	5	6	8
18 - 19												
19 - 20												
20 - 21												
21 - 22												
22 - 23												
23 - 24												
Sum	1902	2062	2862	3066	3703	3964	4526	4904	4806	3633	2537	1888

Figure 4. Direct Normal Irradiation in MSTP Teluk Awur

GHI: The total amount of shortwave radiation that a horizontal surface reflects from the sun and transmits to the ground[18]. GHI is a combination of DNI and DHI, can be express[20] as below:

$$GHI = DHI + DNI . \cos \theta \qquad (6)$$

where θ is the solar zenith angle.

Conventional interpolation and extrapolation techniques can be used to make solar irradiation measurements; other techniques include modelling techniques such as Multilayer Perceptron (MLP), Gradient Boosting Machine (GBM), Random Forest (RF), and Support Vector Regression (SVR)[21] are also applicable. In this paper, the use of secondary data of solar radiation to retrieve solar irradiance statistics by inputting the solar PV tree's installation position is used as illustrated in Figure 3. Data on solar radiation for SPVT systems can currently be obtained with greater efficiency. However, the simulation also takes into account as a number of variables that lead to energy loss[22]. These variables include: (i) Static: PV module mismatch, cable losses, and pollution on the module surface; (ii) Dynamic: These losses depend on the irradiance and temperature, which change during the day and during the seasons.

Data obtained included GHI of 1791kWh/m2/year then Direct Normal Irradiation of 1213.7 kWh/m2, Diffuse Horizontal Irradiation of 899.4kWh/m2. Solar irradiation data, especially Direct Normal Irradiation, can provide information in the form of average hourly profiles (Figure 4). Thus, it can help to find out the maximum time for solar energy to be obtained. Figure 4 shows that August-September are the months with the highest solar irradiation when compared to other months. August to September is the peak of dry season in Indonesia, especially Teluk Awur, Jepara. The optical route length through the earth's atmosphere for electromagnetic radiation from sunlight to reach the surface of the planet is determined by the air mass (AM) coefficient in relation to the vertical path length. Universally, the spectrum between $0.3\mu m \leq \lambda \leq 2.5\mu m$ is called The AM1.5 is a character of the solar spectrum[23–25].

Solar irradiance AM1.5 can be converted into a form of electrical and thermal energy using technology such as photovoltaic[25–28], solar thermo-chemical reaction[25,29,30], and concentrated solar power[25,31–35]. Range wavelength band of VIS is $0.4\mu m \leq \lambda \leq 1.2\mu m$, then IR has wavelength band is $1.2\mu m \leq \lambda \leq 2.5\mu m$. However, the IR range is the solar spectrum not absorbed by the c-Si cell for PV conversion. The electromagnetic spectrum is divided into various spectrums, the spectrum that is owned by solar irradiance namely Infrared (IR), Visible (Vis), Ultraviolet (UV). IR has a shorter wavelength than Vis, then

UV has a longer wavelength than Vis. Visible light is a spectrum that can be converted to generate electricity, through being absorbed by the semiconducting materials of a solar cell[25].

In the development of solar panels, the materials used are semiconductors. The use of silica as a material is based on its non-toxicity and high stable efficiency[36]. In the first type of is single-crystal silicon, which has an efficiency in the range of 16–17%, even up to 20%, but the price is very high. In the second type there is a type of polycrystalline silica, this type is relatively cheaper, unfortunately the efficiency of polycrystalline silica is low, namely 13-15%[37].

The incident of solar irradiation is the result of variations in the topography of the area, and the distance between trees[38–42], which is common in mountain forests[43,44]. The mapping was carried out in the mangrove area, where the position of the tree also affects the solar irradiation incident (position social roles in plant ecology)[45,46].

3.2 Surface topography

The purposes of surface topography mapping can determine the contour of areas affected by shading effects[10]. Accurate information regarding the contour of the Solar PV Tree installation area is very important[11]. Therefore, it must considered the solar PV Tree installation tends to be in flat locations, if it is installed in more complex terrain, hills and slopes it requires a design and engineering that is not simple; terrain horizon can estimate energy losses due to its effect on the shading hills or mountains; at high altitudes might require the use of more durable materials (due to UV factor); and whether on the coast or along the rivers, from terrain analyses provide information on the potential risk of flooding.

Based on Figure 5, it can be seen that some of the solar irradiance is obstructed by topography, which will affect the capture of solar irradiance by the solar panel. Generally, the obstruction is caused by the slope itself (shading) or nearby terrain (shadowing). Figure 6 shows the height of the MSTP area using drone photos. The topographical area of MSTP Teluk Awur which is located on the coast has a flat slope (0-8%). From Figure 6, it is known that the height of the land is 10 m, 20 m, and 30 m, and it can be seen that the difference in height is not significant. This is also seen in Figure 6, which indicates that Teluk Awur, Jepara, has a terrain elevation of 0 meters. This minimal difference in elevation is preferred for the placement of solar panels because it allows for low construction costs[47].

Based on the mapping results, it is known that the mangrove area in Teluk Awur is far from the mountains or hills. The presence of mountains affects the height of an area, which results in suboptimal solar irradiance acceptance. Thus, the shadow effect can be neglected.

3.3 Solar PV tree design

Solar PV trees installed in the Teluk Awur mangrove area, Jepara, where Global Positioning System coordinates the Latitude: 6°37'17.05"S and Longitude: 110°38'19.89"E, are expected to be able to provide electricity supply around the conservation area. It has a total of 5 PV panel leaves, which have a width of 240 mm and a length of 360 mm (Figure 7), where the output power is 10 wp for each PV panel. The distance between PV tree installations is 15 m, and a total of 70 light points can be installed along the mangrove tracking with a total installed power capacity for tree solar of 3500 Wp. According to the calculation on equations 1 and 2, the amount of illumination for the installed 6-Watt LED lamp for the PV tree is 4.872 lux. This value is suitable with DIN EN 1302 standard for E2 classification, in which the standard minimum of illumination for pedestrians is 0,6 - 8 lux. Since the mangrove conservation area, the electricity demand is relatively small, the PV tree is used for supplying lighting on the mangrove track and can also be used as a cellphone battery charging station.

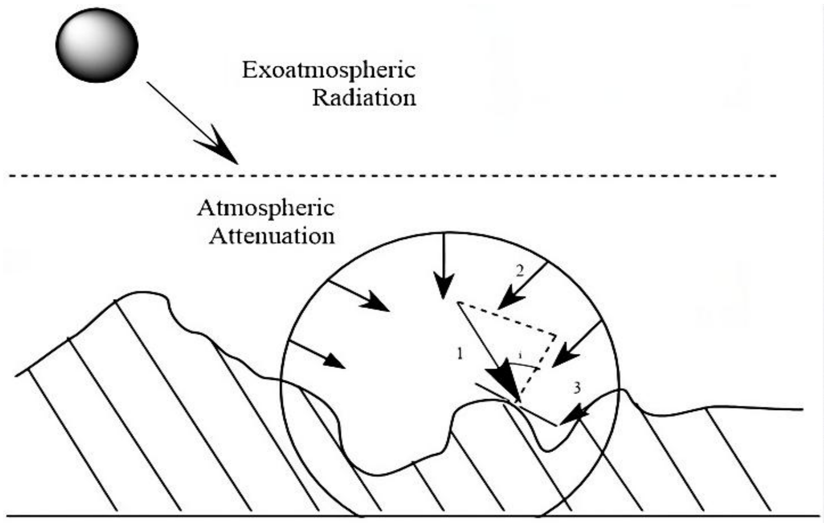


Figure 5. Solar radiation (1) direct irradiance, (2) diffuse irradiance from the sky, where the surrounding terrain can block some of the overlapping hemispheres, and (3) irradiance reflected from the surrounding terrain[48].

3.4 Comparison between solar PV tree and flat/traditional panel solar PV

A Banana solar PV tree only requires an area of 20 cm2, when compared to flat solar PV panels, which require a larger area. Because flat panel solar PV has a greater need to capture sunlight, its design consumes more area. Other than that, because their panels are oriented to face the sun directly during peak sunlight hours, flat-panel solar PV has less shading effect[49]. However, in the existing design in Teluk Awur, Jepara, the panels are installed without any shadow effect.

Installing solar pv trees in the mangrove track as a base of providing space-saving electricity in conservation areas. The height of the solar PV tree is 2800 mm, so that its presence does not become an obstacle for the surrounding ecosystem. Choosing a banana tree design to be used with solar PV, because it has many advantages including the potential to capture more sunlight (3D structural) and prevent the effect of shadowing from other objects[50]. Besides that, it has an aesthetic appearance when compared to flat solar PV panels. The design integrates aesthetic allure with functional geometry through a specified tilt angle that complies with recognised solar PV installation requirements. This is executed to mimic the natural form of banana trees and reduce ecological disruption in the mangrove habitat. This design is officially protected by industrial Design Registration No. IDD000070803. The registered design encompasses a straight photovoltaic panel configuration, an integrated rod mounting mechanism, and a root-like framework structure specifically engineered for the soft mud substrate typical of mangrove ecosystem. Nevertheless, that panels are positioned differently and not all of them face the Sun directly during the peak Sunshine hours, thus the amount of absorb sunlight is relatively lower[50,51].

The angle of incidence of sunlight should be perpendicular to the panel to gain maximum energy[49,50,52]. Sometimes clouds[53] and wind speed[54] effect of the angle of incident sunlight. At first the incident sunlight was 100%, then reflected by the clouds by 20% and also absorbed by 3%[53,55].

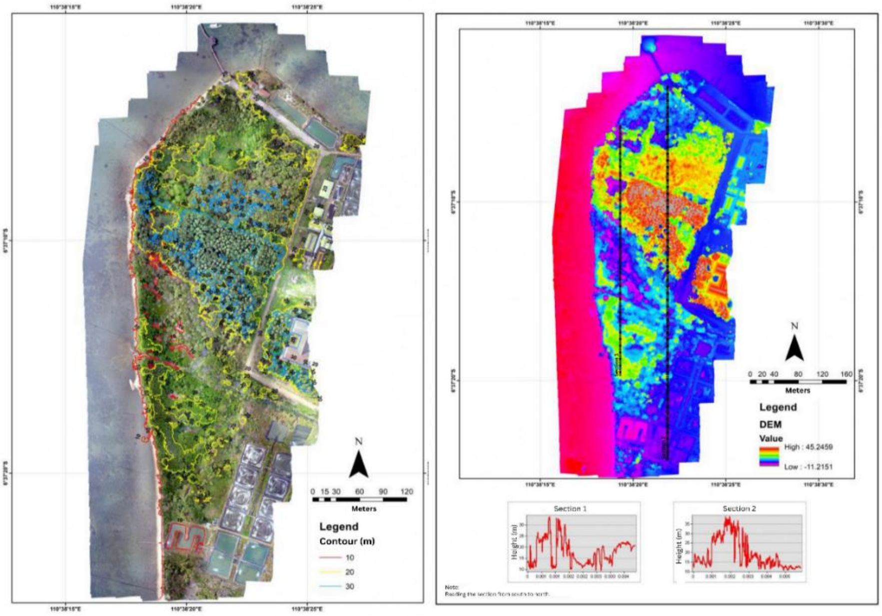


Figure 6. Mapping of surface topography on MSTP, Teluk Awur, Jepara

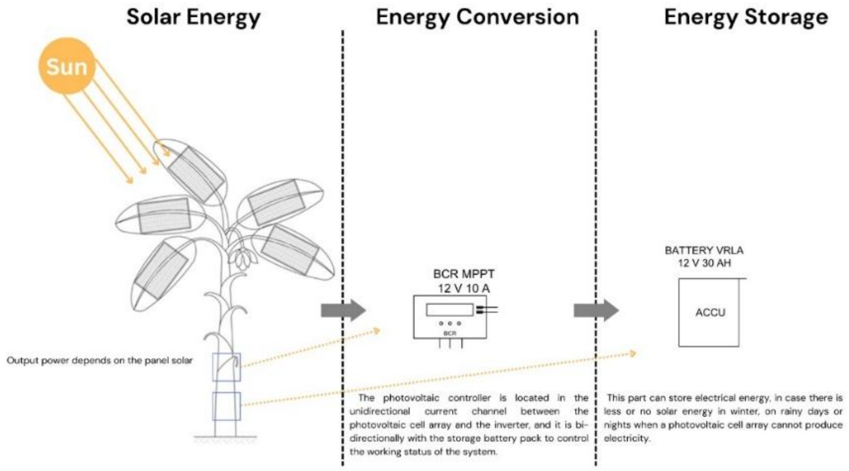
In PV systems, ambient temperature and dust accumulations plays an important role in the power output and efficiency of the PV module[56–58]. In Teluk Awur, the ambient temperature of 27.7°C is quite low when compared to the installation of a PV system in the Middle East[59].

If the ambient temperature increases, the impact of increasing the PV panel's temperature causes a decrease in the output voltage of the module, which lowers the PV system's output power[58,60,61].

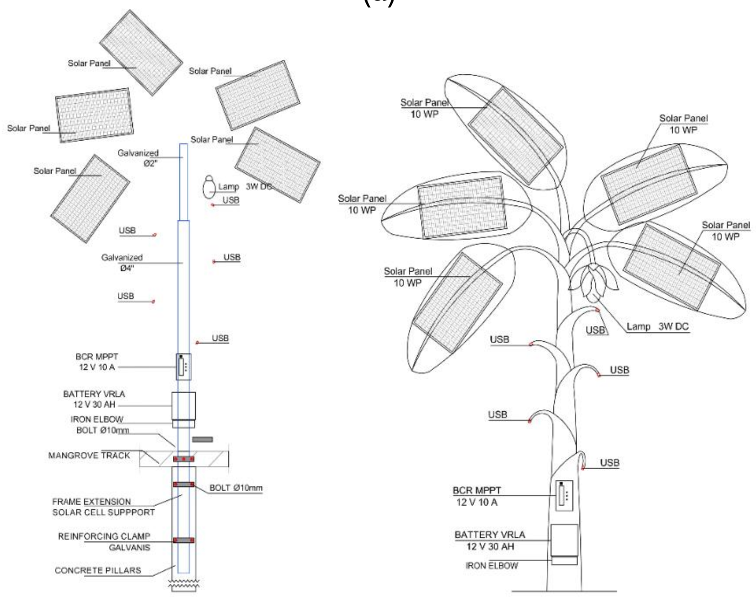
Dust is composed of up of various particles, such as pollen grains, bacteria, smoke, haze, and soil[62]. Besides the fact that the PV system is located in a mangrove area, which is far from anthropogenic causes (construction, transportation, and other human activities)[63], this has an impact on reducing the accumulation of dust that sticks to the PV system, so it will produce maximum power output.

However, the material used for the banana solar PV tree is single-crystal silicon (Mono-crystalline), which is quite sensitive to dust accumulation when compared to amorphous silicon[64]. The existence of dust accumulation prevents light transmittance from reaching the PV module[62,63], caused the dust that blocks the photovoltaic modules is deposited to form a layer of dust so that solar irradiance is absorbed or reflected[65]. Furthermore, affecting the performance of solar PV modules, it also affects the life of the PV system. The life span of the PV system will decrease because it affects the strength of solar irradiance, surface temperature, and the production of partial shadowing[66]. The surface temperature of solar PV modules will rise if dust is blocking them[66–68].

Dust accumulation on the surface of the PV module causes damage to the battery. The battery will become a nuisance to other batteries, and the electricity consumed will become hot, thereby increasing the temperature of the PV modulus. This high temperature creates a hotspot effect, causing irreparable damage to the PV system[69].



(a)



(b)

Figure 7. (a) The Main components of the banana solar PV (b) Design of banana solar PV tree.

Cleaning can be done frequently on each panel in order to get maximum power output. A cleaning combination involving water, a rubber brush, and cleaning with a cloth was found to reduce pollutants to less than 1%. Ash and other volatile contaminants are cleaned using sodium and alcohol solutions[61].

3.5 Techno-economic analysis

A banana solar PV tree is known to have an initial cost of $ 1948 and an annual operating and maintenance cost (O&M) of $ 80 per year. A total net present cost (NPC) of $828 and a levelized cost of energy (LCOE) of 1.080 $/kWh. Depending on the stability of the national economy, the cost of energy is dependent on a variable interest rate in the range of 1% to 14%[70]. It is known that the operation and maintenance costs of solar PV trees are low or even non-existent, but the initial costs are relatively large.

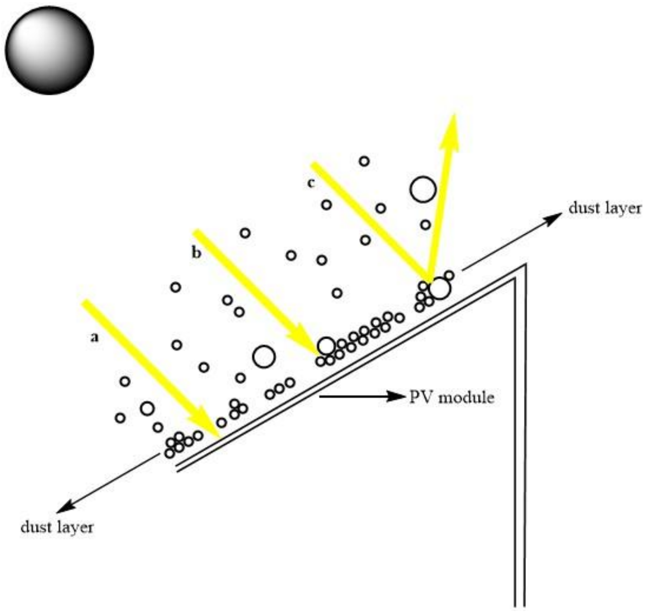


Figure 8. Illustration of the dust layer effect on the PV module by solar irradiation a) transmission b) absorption c) reflection

Table 1 Techno-economic data on solar panels

Parameters	**Units**	**Value**
Initial cost	$	1948
Operating and maintenance cost (O&M)	$/year	80
Net present cost	$	828
Levelized cost of energy (LCOE)	$	1080
Electricity	kWh/month	151.2
Annual electricity cost	$	168

The electricity required for lighting in the mangrove area is 151.2 kWh per month. Electricity is currently provided by the National Electricity Company, and the amount that must be paid is $14/month. Therefore, it is possible to reduce annual electricity costs by $ 168. Obviously, the payback period will be longer when compared to the initial investment, which is 12 times more than the saved funds. But the fundamental issue is the enormous influence on the environment, the usage of renewable energy, and energy security.

4. Conclusions

Feasibility study, design, and installation of solar pv tree to cover the electricity demand in Mangrove Park, Teluk Awur, Jepara, Indonesia has been successfully conducted. When compared to flat panel solar PV, banana solar PV trees are superior in several categories, such as a smaller installation area, no shadow effect between panels, and an aesthetic shape. The capacity of the installed banana solar PV tree is 50 Wp consisting of 10 Wp solar panels for each leaf. Along the 1.1 km mangrove path, around

70 tree solar points can be installed which function as lighting and cellphone battery charging stations. The angle of incidence of sunlight that is not perpendicular affects the panel to gain maximum energy. High ambient temperatures and dust accumulation cause damage to the PV system due to the formation of hotspot areas on the PV modules. Furthermore, implementing a banana solar PV tree might result in annual savings of $168.

The implementation of solar PV tree systems substantially enhances energy sustainability. This contribution is evidenced by technology-driven mangrove restoration, carbon footprint mitigation, instructional resources, renewable energy advancements, and further initiatives. The initiative functions as a prototype that integrates renewable energy with mangrove conservation.

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Authors Contribution

K: Conceptualization, methodology, design and installation, formal analysis, writing—original draft, **D.N.S.**: supervision and review, **A.A.** and **P.D.L.**; writing and editing, project administration.

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