Design and energy assessment of a new hybrid solar drying dome – Enabling Low-Cost, Independent and Smart Solar Dryer for Indonesia Agriculture 4.0

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Abstract. Solar dryer is typically used for agricultural purposes in Indonesia. There are many economically important crops requiring storage or drying under particular environmental conditions such as temperature and humidity. High temperatures inside solar dryer prevents the growth of microorganism, and quickly reduce moisture content from the substance. A hybrid solar dryer is generally considered to provide the most optimum solution, however solar panels may be expensive and they still only provide heat or energy in the daytime. Hence, we propose here a new kind of hybrid solar dryer for 24/7 optimum conditions for crops – enabled by recent advances in energy technologies as well as Industry 4.0. This study aims to create an efficient, affordable and a self-sufficient intelligent energy system that will be applied to agriculture for storage or drying purposes by measuring the energy needs for the optimal drying system. Therefore, it is crucial to estimate and assess the critical energy needs for such new systems in order to optimize and design such smart solar dryer (SSD) system especially for Indonesia’s agricultural needs. We use design experience of our industry partner (PT Impack Pratama Industri, Indonesia) who has been working extensively on such solar dryer dome (SDD) based on polycarbonate material (only solar irradiation, no other technologies) and theoretical framework based on first principles in thermodynamics to estimate and assess critical energy needs for such dome with all the smart technologies. The calculation was performed based on Mollier diagram and the result still a rough estimation of energy required.

Keywords: solar dryer, crops, Mollier diagram, hybrid drying, thermodynamics
1. Introduction
There are many economically important agricultural crops in Indonesia (such as coffee, tea, chocolate, or copra) require storage or drying under certain environmental conditions especially in terms of temperature and humidity. This case is crucial for farmers, especially after harvesting their crops to store the crops before they can be transported and processed further in facilities that are more environmentally qualified. During the storage time, agricultural crops such as coffee are not at the ideal temperature and humidity 24/7 (24 hours per day, 7 days per week), then the coffee ore will decrease in quality. Thus, the decrease in the selling price of coffee ore products earlier caused our farmers to lose money or in the other words they don’t get the profits as they should. Coffee as one of the economically important agricultural crops requires an ideal temperature of about 15-20°C and relative humidity of about 60% for the storage system, 24/7 [1–3]. If farmers in remote areas or some areas in Indonesia often not connected by electricity, the situation will be aggravated because storage conditions (or drying) at certain temperatures and humidity require energy or electricity sources.

Indonesia is endowed with diverse and abundant energy sources – whether renewable (wind, water, solar, geothermal) or fossil-based. However, Indonesia’s geographical conditions are less than ideal for efficient energy distribution [4–6]. A centralized energy source is certainly less than ideal for geographical conditions in Indonesia. Energy production that is self-sufficient and decentralized from wind power sources, or local water or solar will be more appropriate. Many villages in remote area and other areas are not yet reached by the centralized electricity network of PLN (State Electricity Company), which leads to many agricultural/plantation operations in these areas that require electricity must use diesel fuel generators. An affordable self-sustaining energy system that can supply local electricity is required in order to achieve the important strategic significance for the Indonesian state in economic system, as well as an ecological/environmental system. Technology is the key that can make this system cheap, self-sufficient, and long-lived. This is where artificial intelligence algorithms can play a lot of roles to optimize energy production, storage system, usage or distribution, including optimizing the entire system so that it becomes a robust and durable system (reliable) [7]. These AI-based algorithms or software will be trained for each agricultural location (with environmental conditions – such as the intensity of sunlight, shading from clouds, certain types of plants, and others). This challenge is actually an opportunity for Indonesia to improve the resilience of the energy sector as well as the resilience of the agricultural sector and environmental/ecological development in a more sustainable manner [8,9]

Independent energy sources in these decentralized remote areas will reduce the cost of building complex electrical infrastructure networks which require large investment. However, this decentralized energy system requires accurate coordination and energy management, including ability to adapt to real-time conditions as well as adequate fail-safe mechanisms [10–12]. The concept of a decentralized energy system will be very impactful in view of the fact that it is smart, low-cost and self-contained, consisting of a solar panel system as a stable electricity source, local and reliable energy generator. The system is supported by an energy storage system (such as battery) and a software or an algorithm to organize and optimize the distribution of energy needs according to the usage and for storage system. These technological systems will enable self-sustaining, smart and low-cost energy systems with the aim that our farmers can store and dry their harvested crops at an ideal temperature and humidity during the day and nighttime. Control system technology will be used to predict energy requirements based on environmental conditions (load management) and optimize the distribution of energy from solar panels to storage system (drying system) as well as balancing it with storage to batteries, including maintaining the reliability of the battery through optimization of charging for each cell from a battery module to predict the maintenance of this entire energy system. These solar dryer systems will be supported by a consisting of sensors (for environmental conditions as well as storage/drying space conditions) that will be connected to each other to form a closed control system. This system has been built by PT Impack Pratama Industri as a dummy pilot design for the development of SDD in Sumedang with the aim to create an efficient, affordable and a self-sufficient intelligent energy system that will be applied to agriculture for storage or drying purposes by measuring the energy needs for the optimal drying system.
2. Literature Review

2.1 Drying

Drying is described as an operating system that thermally removes water content to produce products that have a low moisture content and tend to be solid. Moisture trapped in chemical combination structures or trapped in solid microstructures, which provides less steam pressure than pure liquids is referred to as bonded moisture. Excess moisture to exceed the bound moisture will be expressed as unbound moisture. When the solid undergoes a drying process, there will be two types of processes simultaneously, namely energy transfer and moisture transfer. Energy transfer converts a certain amount of energy into other forms (mostly thermal energy) of the surrounding environment to be able to evaporate moisture from the surface. The transfer of moisture occurs through internal processes from the interior of the product to the surface and from the surface to the surrounding air. This process converts energy into other forms, mostly into thermal energy. Based on the results of convection, conduction, or radiation, changes in energy (mostly heat) to wet solids can occur from the surrounding environment [13–15]. The drying process relies on external factors such as temperature, humidity and airflow, exposure to external environment, and pressure.

2.2 Solar Dryer

Systematically, the solar dryer produces a sufficient amount of heat to reduce moisture, thereby increasing the evaporation inside of the product and reducing the moisture content of the product. The level of air moisture carrying the capacity can be increased with a purpose to trigger a drying process. Air circulation is drawn through the dryer by natural or artificial convection such as using a fan. It is heated as it passes through the collector and then partially cooled as it captures moisture from the material. Warm water conditions will capture higher humidity compared to cold water. As a result, the reduced humidity level affects the temperature contained in the collector along with the absolute humidity of the air entering the collector [16–18]. The heat inside the dryer is generated by the conversion of energy from sunlight. The drying system will collect heat and isolate the air inside the dryer from the air outside of the dryer to maintain continuous temperature and humidity. This makes it possible to reach a stable temperature inside the dryer on cold and windy days [19,20]. The performance of a solar dryer is highly dependent on the weather conditions because the heat of drying systems is generated from solar heat and additional tools that require electricity such as fans and other heating systems. Therefore, weather conditions greatly affect the drying results and drying speed.

2.3 Solar Dryer Classification

Solar dryers are classified depending on the air circulation in the dryer or by the type of direct sun drying, indirect sun drying, and mix-type drying (see Figure 1). There are different types of air circulation such as natural circulation and also forced air circulation using fans or other air circulation regulators [21,22].

![Figure 1 Classification of solar dryers by drying modes](image-url)
Direct solar drying exposes dried substance/crops to direct contact with sunlight. For instance, the box-type dryer which has a transparent cover that can be directly exposed to sunlight. This model also come with insulated frames and black absorption surfaces to maximize sunlight absorption. The warm air will circulate through the hole in front of the drying rack then out through the hole behind the top of the drying rack. The advantage of this dryer is to reduce contamination caused by insects, animals, and human interference (see Figure 2) [23,24].

![Solar Dryer Model](image)

**Figure 2.** Solar Dryer Model, (a) Direct solar dryer, (b) Indirect solar dryer, (c) Mix-mode solar dryer [24,25]

Indirect solar drying has a solar collector to heat elements, and the heat from solar collector generates hot air, which is then transferred to the substance through a drying chamber until the substance is heated and dried. The solar collector uses a transparent cover and black absorption surfaces. The heat from the solar collector enters through the inlet and heats the air as the heating element (see Figure 2). The air circulation is provided by natural convection inside the drying chamber, and the hot air from the drying chamber is sucked in by the air outlet caused by the wind [13,24].

Mixed-mode solar drying has a combined photovoltaics (PV) and a transparent cover so that sunlight can directly contact the solar collector and the substance/crops. In this type of solar dryer, the drying process is carried out based on two types of dryers. Direct solar irradiance can support the drying process by using photovoltaics (PV) as a source of electricity for forced air circulation such as a fan (see Figure 2) [24–27].

**Advantages of solar dryer**
- It has a high temperature and quickly reduce the humidity level, thus speeding up the drying rate. High temperatures will prevent the occurrence of decay and prevent the growth of microorganism.
- It has a closed shape, so it is protected from external things such as dust and insects. Because it is closed and isolated, the solar dryer is waterproof so there is no need to move when it rains.
- Solar dryer material is relatively low-cost and easy to obtain.
Limitation of solar dryer

- It can only be used during the day when there is a sufficient frequency of sunlight.
- Limitation of skilled personnel for solar dryer maintenance.
- Additional heating system is recommended to maintain a stable temperature and humidity during night time.

These limitations of solar dryer are based on the observation by PT Impack Pratama Industri with over 2,000 SDD installed in remote areas all over Indonesia.

2.4 Solar energy in Indonesia

The geographical condition of Indonesia that makes up the territory of Indonesia is very suitable as agricultural land, making agricultural business one of the high livelihoods in Indonesia. The location on the equator makes Indonesia one of the tropical countries, meaning that Indonesia gets longer sunlight throughout the year than other countries outside the equatorial region. Therefore, the utilization of solar power in drying becomes one of the considerations (see Figure 3). Solar drying was the modification from the traditional sun drying which is very common for all agricultural commodities [29]. The biggest problem especially for agricultural drying/storage systems is that solar power alone cannot supply energy during the day and night. During the nighttime, there is no solar energy produced. The solar energy during the day can be stored in the battery using solar panels considering the needs of additional tools that require electricity to maintain the temperature and humidity for the drying process [19]. On the contrary, solar panels need to be lightweight and affordable, considering Indonesia's vast and wide geographical area in order to facilitate transportation and installations in remote areas.

3. Methodology

3.1 Pilot systems for data collection

Through the construction of several pilot systems in several locations in Indonesia, the locations have significantly different conditions in terms of local energy sources, climate conditions, and agricultural needs. Some pilots will collect specific data from each location, such as energy demand, weather data, and local infrastructure to get the best solution. The collected data will be used to form the energy supply and consumption for rural agriculture. This will increase the selling value of smallholder farmers and thus increasing local socio-economic activities. Depending on the season, plantations/farms usually have certain energy requirements that will be adjusted according to the conditions of the area.
3.2 Design and construction
The design and construction will utilize cost-effective solar cell technology to ensure the optimal energy yield and reliability, with a correlation to climate and geographical conditions of the installation site. The temperature difference and very high irradiance during Indonesia’s expansion from west to east will change the specifications of the installed solar cell modules, so that further details of the power/energy system specifications need to be determined at a later stage (after determining the location of the pilot and the next initial data collection). As a large number of clouds and pollution can reduce the performance and reliability of the module, there are several considerations, including the use of glass-framed solar cell modules to improve the reliability and the use of bifacial PV modules to increase energy production [5,8,30].

3.3 Calculation of energy needs
In order to obtain appropriate energy requirements, several things must be considered, including cooling/heating, humidification or de-humidification based on enthalpy, and air circulation. In addition, it is also necessary to consider the actual temperature and humidity points based on the temperature/humidity development and the estimated electrical capacity required by the battery as an electrical capacity (see Figure 4). A Mollier diagram with mass and heat energy balance can be used to calculate the energy needed with help of the following Eqs. 1 – 5 [31].

![Figure 4. Drying system diagram.](image)

\[
G_1 = G_2 = G_3 = G \text{ kg dry air/h} \\
wx_{in} + Gx_2 = wx_{out} + Gx_3 \\
G = w \frac{x_{in} - x_{out}}{x_3 - x_2} \\
\]

Since all air that comes in also goes out, the air flow measured in kg dry air/ h remains constant and thus G1 equals G2 equals G3 equals G and get the water mass balance Eq. (2). Where G is evaporation rate, w is air flow, x is specific humidity from the Eqs. 1 – 3 [31]. From the G value which will then be used to calculate the energy needed with energy balance with help of the following Eqs. 4 – 5.

\[
GH_1 + Q = GH_2 \\
Q = G(H_2 - H_1) \\
\]

Evaporation rate input is given by using the G value from Eq. (3) and get the energy balance with the help of following Eqs. 4 – 5 where H is the entalphy and Q is the amount of energy. Based on Eq. (5) [31] it will get the amount of energy needed to evaporate water in the dryer system for estimating the energy usage.
4. Critical Design Considerations and Energy Analysis

4.1 The solar dryer dome

The physical solar drying Dome (SDD) size is designed in accordance with the optimization that has been done by PT Impack Pratama Industri. The height of the dome reaching 3.5 m, the area is 6 m x 8 m and the volume of the dome is approximately 125 m$^3$. To make it Smart Solar Dome (SSD), there are several considerations including the energy needs for operational purposes. The power that will be required for all SSD operational purposes are internal ambient conditioning, sensing external environmental conditions, the energy stored in the battery for nighttime usage, closed control system, data processing and analytics, and all other mechanical/electronic components. There are several design considerations for solar dryer dome; the solar dome’s longitudinal axis in general must be aligned to the N-S axis, so that when the sun moves from east to west, the solar irradiation received by the dome will be maximized while the solar panels in general need to be facing the east to maximize photons (with the preferred wavelength) and also sunlight intensity in the morning.

![Figure 5. Solar dryer dome design.](image)

4.2 Energy calculation for drying process

The energy required for drying requires several parameters such as the mass of the substance/crops, humidity, temperature, and the effectiveness of the drying system. The parameters used to perform calculations are still temporary guesses. Calculated parameters will be adjusted with Mollier diagram. The energy that will be calculated is the energy needed for the heating and cooling process of solar drying performance in Indonesia and the calculation with the help of the following Eqs. 6 – 9 [31,32]. For instance, in drying process of coffee beans at night, with the initial temperature condition is 28 °C, relative humidity is about 60%, and water content is 0.7 kg water/kg dry matter. Air content will be heated until the air temperature increases to 40 °C and water content of 0.6 kg water/kg dry matter. In this calculation, the relative humidity is assumed to be 100% and incoming air-drying goods (coffee beans) is 23.4 kg dry matter/h. The calculation of energy and air flow can be calculated with the help of following Eqs. 6 – 7. This calculation shows that the target’s condition of the dummy pilot design should reach 40 °C temperature and 60% relative humidity.

Based on Mollier diagram, the values of water content are $X_1 = 0.0148$ kg water/kg dry air, $X_2 = 0.0148$ kg water/kg dry air, $X_3 = 0.020$ kg water/kg dry air and also the values of the enthalpy are $H_1 = 65$ kJ/kg dry air, $H_2 = 77$ kJ/kg dry air, $H_3 = 78$ kJ/kg dry air, and $w = 23.4$ kg dry matter/h. The air flow on $X_3$ contains more water vapor than $X_2$ and thus the value of enthalpy on $X_3$ slightly larger than $X_2$ (see Figure 6).

\[ G = w \frac{x_{in} - x_{out}}{x_3 - x_2} \]  \hspace{1cm} (6)

\[ G = 23.4 \frac{0.7 - 0.6}{0.020 - 0.0148} = 450 \text{ kg dry air/h} \]  \hspace{1cm} (7)

Based on the calculation obtained, the $G$ value will then be used to calculate the energy needed using energy balance with help of the following Eqs. 8 – 9 [31].
Figure 6. Air drying with Mollier diagram.

\[ Q = G(H_2 - H_1) \]  \hspace{1cm} (8)

\[ Q = \frac{450}{3600}(77 - 65) = 1.5 \text{ kW} \]  \hspace{1cm} (9)

From this calculation, the energy requirement is 1.5 kW. Assume the time taken of the drying process is 10 hours during the night-time. Thus, the energy needed for one night is 15 kWh. Based on calculations, resulting an assumption amount of the energy value for upper bound conditions.

4.3 Electrical Design

The electrical system will use off grid system, which means it is not directly connected to the main electricity system, PLN (State Electricity Company). Ambient conditioning settings devices from inside and outside will be measured and adjusted through sensors that are connected to the heaters and moisture regulators. Inside ambient conditioning and outside sensing parameters will depend on crops and agricultural location. The estimated energy usage and calculation are still conservative. Assume that two hours of running portable air conditioner for ambient conditioning where the energy needed for portable air conditioner is 4.1 kW and it is used for two hours at noon so the energy consumption is approximately 8.2 kWh. During the night, the energy consumption is approximately 15 kWh as calculated by Mollier diagram (see Section 4.2). For the control system, the energy needed for sensors and Arduino controllers is 1.5 A \times 12 \text{ V} = 20 \text{ VA/h}. Thus, the energy consumption for control system per day is 480 VA/h (0.48 Wh) \sim 0.5 \text{ kWh}. As a result, the energy required for a day is approximately 23.7 kWh. It will be able to
be met by 8 solar panels (500 Wp each per panel, effectively 6 hours per day of peak sunlight intensity) and several battery units (depending on battery specifications and technology).

5. Conclusion
Solar dryer dome can reduce moisture and also protect the crops from external things such as insect, dust, and birds. High temperatures inside solar dryer will prevent the occurrence of decay, prevent the growth of microorganism, and quickly reduce moisture content from the substance. Based on obtained result, the average value of daily solar radiation in Indonesia region is ranged between 3.0 kWh/m² to 5.6 kWh/m². From the calculation, we can conclude that the energy required for drying process is approximately 23.7 kWh. Based on calculations, resulting an assumption amount of the energy value for upper bound conditions. As a result, the required water content of the substance/crops could be reach quickly in solar dryer dome with the help of external heating/cooling, humidifier/de-humidifier, and sensors to help sensing the ambient condition from inside and outside.

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