Design and evaluation of a zero-fossil fuel distiller for bioethanol

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Abstract. The study developed a Zero Fossil Fuel Distiller (ZFFD) to address environmental issues on bioethanol production from Nipa Sap. The Mariano Marcos State University had developed a distiller that can produce 95% fuel grade bioethanol powered by fuelwood. While burning woods provides a good heat source, this activity's byproducts are not good for the environment. The scarcity of fuelwood will also be a problem for bulk production. Hence, the development of a ZFFD integrated with the Internet of Things (IoT) technologies for easy monitoring, control, and configuration. A 10 kWp Hybrid Solar Photovoltaic System with battery backup was designed to power a 150 L capacity distiller. The power system is capable of storing excess harnessed energy to a battery and a grid for future use, as well as managing and monitoring the inflow and outflow of electricity on-site or remotely via IoT. Results show an average harnessed energy of 47.11 kWh to supply a 33.99 kWh required energy to distill 133 L of feedstock daily. The excess energy of 13.12 kWh is stored in the grid for future use. The developed ZFFD shows an improved regulation of the Kettle temperature, Column temperature, and Cooling System water flow.

Keywords: ZFFD, solar energy, bioethanol distiller, IoT

1. Introduction

1.1. Background

The Philippines Biofuel Act of 2006 was created to reduce dependence on imported fossil fuels and mitigate greenhouse gas emissions [1]. Through this Act, the market was created for biofuels through the required blend of bioethanol and biodiesel. Recognizing the challenge, the Mariano Marcos State University (MMSU) had developed a bioethanol distiller that can produce 95% fuel grade bioethanol way back in 2012 [2]. The said distiller was upgraded and was deployed in four different sites to establish a Village-Scale Bioethanol Industry in Pamplona, Cagayan, funded by the Department of Energy and the Sugar Regulatory Authority. The Bioethanol Industry produced more than 4,000 L of fuel-grade Hydrous Ethanol (95%) last year. To produce the said volume, about 16,000 m³ of fuelwood was consumed. If ethanol distillation from Nipa will be up-scaled and replicated to potential Nipa villages in the entire Philippines to augment the shortage of bioethanol needs of the country, it would require much fuelwood. Over time, it may cause forest degradation. Statistics also show that...
many people in the world still use wood as a primary fuel for heating needs, leading to significant health, economic, and environmental consequences. Moreover, the burning of wood emits carbon monoxide, benzo[a]pyrene, formaldehyde, nitrogen dioxide, and other particulate matter linked to severe diseases, like acute respiratory infections (ARI), chronic obstructive pulmonary disease (COPD) cancers, cataracts, and low birth weight for those exposed [3]. To address this, there is a need to reduce or eliminate dependence on fuelwood, plant trees, and to deploy distillers powered by renewable energy. Hence, the development of a Zero Fossil Fuel Distiller (ZFFD). This is to protect the environment, prevent health risks, and comply with the Biofuels Act of 2006.

Solar power generation technologies provide a major share of the clean and renewable energy needed nowadays [4] because it is abundant [5], cost-effective, simplest, and easiest [6] to install even in remote areas. Renewable energy such as solar energy has been used as an alternative to fossil fuel in biofuel productions and processing due to its greenhouse gas emissions and uneconomical methodology [5]. Besides, most biorefineries use fossil fuels to operate. Some research also says that greenhouse gas emissions from biofuel production and use might be higher than those generated from fossil fuels [7]. Therefore, using solar energy to supplement power to biorefineries lowers production costs and improves the net energy ratio [5].

With the rapid improvement of internet speed, the Internet of Things (IoT) [8][9] is becoming popular. By using IoT in solar energy, many problems and issues in solar farms can be solved with little effort and investment because IoT provides the ability to identify and fix problems in real-time. According to the observations of Spanias [10], this solar energy IoT system is currently programmable. It can: (i) provide mobile analytics, (ii) enable solar farm control, (iii) detect and remedy faults, (iv) optimize power under different shading conditions, and (v) reduce inverter transients. With IoT in solar energy farms, continuous monitoring and management of all equipment can be easily done according to Madbhavi [11] in one central control panel or by every authorized individual who may not be necessarily around but anywhere else with an internet signal. This implies that problems and issues can be easily detected and identified where the problem originated and dispatch a technician to fix it before it disrupts the entire system. Also, IoT simplifies the diagnosis and analysis process of the whole system [10]. Furthermore, IoT based technologies provide valuable information and intelligence to identify issues in real-time, as the error occurs so the source can be located and resolved quickly [12][13]. This means that the system will be more efficient, less susceptible to failures, and more secure. In other words, the main benefit of installing IoT in solar energy farms is near real-time remote monitoring and control of all the solar farm assets. One very simple popular, and secure IoT tool is the TeamViewer. It offers the convenience of being downloaded and installed on any computer, as well as access via the cloud, rendering it an easy-to-implement software [14]. TeamViewer provides easy monitoring and control of all the solar power system parameters for as long as connected to the internet.

1.2. Statement of the problem

The challenge here is to develop an optimized design of the Solar Power System to meet the distiller's energy requirement and maximize the use of the harnessed energy, especially during the off-season. Another challenging aspect of bioethanol production through reflux distillation is regulating the distiller kettle and column temperatures. The distiller column's temperature must be maintained at 78-80 °C as observed by Agrupis et al. [15] during the whole process of bioethanol production. To realize this, the amount of heat supplied to the distiller kettle must be controlled at all times so that it will not result in either overpressure or under power [16][17]. Control of the heat in the distiller kettle using firewood is laborious and not precise due to the different calorific value of fuelwood. Hence, the development of the ZFFD integrated with IoT for easy monitoring, control, and configuration of both the power source and the distiller.
1.3. Objectives
In general, this study developed a Zero Fossil Fuel Distiller to address some environmental issues and provide easy access to the distiller even remotely. Specifically, this study (i) design a solar power system for the ZFFD; (ii) assemble the ZFFD; and (iii) evaluate the performance of the ZFFD.

1.4. Significance
Bioethanol production through local resources supports the role of cleaner and increased availability of energy. Generally, reflux distillation [16][17] has many restrictions and are subject to many disturbances. Introduction of ZFFD [15][10][18] for distillation minimizes unwanted conditions from the effects of human lapses that lead to lowered production output by keeping the heating at the right values and applying appropriate control over the process. The Internet of Things enables technology developers to monitor operations and collect research data electronically to optimize the ZFFD further. Also, replacing finite fossil fuels [19] with renewable energy such as solar energy in bioethanol production helps in mitigating carbon footprints [7] and improves production [5]. In the future, deployment of ZFFD to potential nipa villages in the country supports the government’s effort in creating livelihood in rural areas [1] and reduces dependence on exhaustible naturals resources and unstable foreign fuel suppliers [1][7]. Eventually, through renewable energy, the production cost of bioethanol, which is energy-intensive [20], will be lowered [5].

2. Materials and Methods

2.1. Design Procedure
The design of the solar-powered energy ZFFD observes the Philippine Electrical Code (PEC) provisions [21]. The method was divided into three parts: (i) Computation of demand load and system requirements; (ii) assessment of the required materials and determination of the other components; and (iii) drafting of the blueprint.

2.1.1. Computation of loads. In designing a solar power system, it is essential to know all the system's loads. Electrical loads are weighed from the power rating of each device, the utilization frequency, and duration. The loads are composed of electric heaters, water pumps, and auxiliary loads.

2.1.2. Assessment of materials and components. The system is composed of solar equipment and other electrical auxiliaries. The following components compose the solar power system [22][23]:

- Solar Module – this is the main component of the solar power system. The solar cells harnessed energy from the sun then convert it to electricity. Specifications of the solar modules must be able to meet the demand.
- Battery – it is a device that stores energy for later utilization. The battery bank must be able to supply the needed energy to complete the distillation process during energy demand peaks, or cloudy days or during a power outage.
- Inverter with charge controller – converts direct current (DC) voltage into an alternating current (AC) voltage and synchronizes it with the grid frequency.
- Circuit Breakers – are a protective device that breaks or interrupts any abnormal current flowing in a system. It must automatically disrupt any current passing through whenever the circuit gets overload and prevents short circuits that can cause damage to the facility or harm people.
- Cables & connectors – this connects all components to make the system function. It must be able to handle all currents and power line losses during regular operation and in cases of faults.
2.1.3. **Layout Drafting**
To complete the design aspect, after the computation and assessment, drafting of the one-line diagram and layout of the components was next to come up with the whole blueprint of the solar power system.

2.2. **Installation Procedure**
After completing the design, the installation of all the components needed for the ZFFD was next. All applicable safety standards were observed during installations. Before the installation of the solar modules, a structural integrity assessment of the roof was done. Review and understanding of the product manual of the inverter were done before installing the inverter. Terminals of the solar panels, battery bank, inverters, and distiller were tested for a loose connection. In general, the inverters, the batteries, and the distiller were installed in an area where it is dry and well ventilated. The solar panels were installed on the roof of the Village-Scale Bioethanol Production Facility building.

2.3. **Evaluation Procedure**
To evaluate the performance of the developed ZFFD, ten trials of distillation processes were done, and the following was observed: (i) Energy harnessed and consumed during the distillation process; (ii) duration of distillation; and (iii) Regulation of the temperature of the kettle and the column.

Throughout the day, energy harnessed by the solar panels was measured and logged every minute by the instrumentation integrated into the installed inverters. Data on the harnessed energy during distillation were accessed on-site or remotely via Team Viewer. Energy consumed during the distillation processes were measured and logged by a power quality analyzer. Prior to actual data gathering, the readouts of the inverters’ internal instrumentation were validated using the power quality analyzer mentioned earlier. This is to ensure that biases in the instrument’s readings are minimized if not eliminated. Comparison of the harnessed energy and that of the consumed energy is analyzed statistically using simple mean, standard deviation (SD), difference, correlation, and goodness-of-fit measure.

3. **Results and Discussions**
3.1. **The ZFFD**
The demand load and system requirements of a 150 L capacity ZFFD are summarized in table 1 below. The computed total connected load is 11 kW comprising 10-1 kW electric heaters, 1-1 hp water pump, and auxiliary loads with a demand factor of 0.7. With an 8 kW demand load, a 10 kW solar power system is enough to supply the requirements of the ZFFD. With a Proportional–Integral–Derivative (PID) Fuzzy Logic Controller, control of power is easily attained, and there is no possibility that the power system will be overpowered.

|                          | Power (kW) | Energy (kWh) |
|--------------------------|------------|--------------|
| Connected Load           | 11         | -            |
| Demand Load              | 8          | 40           |
| System Requirement       | 10         | 50           |

The energy requirement for a distillation process of a 150 L ZFFD is 40 kWh, theoretically. This amount of energy can be supplied by a 10 kWp solar power system, generating average energy of 50 kWh daily.

Generally, the ZFFD composed of: (i) Reflux Distiller comprising of 150 L capacity stainless steel kettle and column where distillation takes place, 10-1 kW submersible electric heaters serve as the
source of heat to cause evaporation of ethanol, 1-1 hp water pump for the cooling tower and IoT capable solid-state relays serve as an actuator; (ii) Power Supply comprising of 36-275 Wp solar panels used to harness SunPower and convert it to electricity; 2-5 kW inverters with dual MPTT which serves as charge controller and link the system to the grid; 38 kWh battery bank where excess energy is stored for future use; protective devices and cables; and (iii) means of accessing the whole system remotely.

A “Hybrid Grid-tied with Battery back-up” topology was chosen over “OFF Grid” and “Grid-Tied” topologies, as shown in Figure 1. This ensures the power supply's reliability during distillation should there be a shortage of harnessed power from the sun due to the presence of clouds or power interruption from the grid. Directions of arrows show power flow and energy flow depending on weather conditions and availability of the grid. A double-ended arrow for the grid and battery bank means power and energy can flow in both directions. This means further that the grid will be utilized to store excess harnessed energy and will be used when there is a shortage. For this reason, the grid is net-metered, as shown. The system was configured in such a way that excess harnessed energy will be stored in the battery first before storing it to the grid. This means that the back-up battery bank is always full charge, ready to deliver power for distillation during a worse condition when there is power interruption from the grid, and at the same time, there is not enough power to harness from the sun due to weather condition like a cloudy sky.

The inverter and the distiller are equipped with a data logger and can be monitored remotely. All electrical parameters energy, power, voltage, current, and others are logged every minute. Report generation of data can be summarized yearly, monthly, and daily. All settings regarding power flow and energy flow and other configurations can be done on-site or remotely via Team Viewer for the Inverter and IoT based controller via MMSU i4.0 Platform for the distiller.

![Figure 1. One-line Diagram of the ZFFD](image-url)
3.2. **The ZFFD Performance**

The performance of the ZFFD was evaluated, and the results are shown in Table 2. Ten trials of different volumes and ethanol contents of feedstock was distilled. This was done to establish the relationship of ethanol yield to energy consumption per liter.

Generally, the average consumption to distill an average of 133 L of Sap is 33.99 kWh, and the average energy harnessed is 47.11 kWh. This proves that the designed power system is able to supply the required energy for a distillation process. The average energy stored on the grid is 13.12 kWh; this is slightly higher than the theoretical estimate. This means that the developed ZFFD is energy self-sufficient and does not use fossil fuel anymore.

It is notable that the actual energy consumed and harnessed varies so much and deviates substantially from the mean. This can be attributed to the ethanol concentration and volume of the feedstock to be distilled and of the weather condition, respectively. At 22.05 L SD of feedstock volume, the volume distilled varies from 85-152 L. Also, the 2.27% SD of the ethanol yield indicates that the feedstock's ethanol concentration distilled in the ten trials varies significantly. Further, the 6.46 kWh SD of the excess energy stored on the grid tells that the energy harnessed is always greater than the energy requirement during the ten observations and tells that the excess energy can be as high as 22 kWh, which is about one-third short of the required energy. This simply strengthens the claim that the developed ZFFD is powered by clean energy and thus provides a solution to the environmental concerns with a fuelwood powered distiller.

| Volume of Feedstock (L) | Percent EtOH Yield (V/V) | Energy Consumed (kWh) | Energy Harnessed (kWh) | Energy Stored to the Grid (kWh) | Duration of Distillation Process (hrs) |
|-------------------------|--------------------------|-----------------------|------------------------|-------------------------------|-------------------------------------|
| Average                | 133.00                   | 8.90                  | 33.99                  | 47.11                         | 4.62                                |
| SD                     | 22.05                    | 2.27                  | 5.95                   | 4.48                          | 0.81                                |

Further analysis of table 2 above resulted in a correlation between energy requirement and duration of distillation and percent yield shown in Figures 2 & 3. The time of the distillation process is highly correlated to the energy required. This is expected since the longer the distillation time, the higher the energy consumed.

**Figure 2.** Relationship of energy requirement and duration of distillation.

**Figure 3.** Relationship of energy requirement per ethanol feedstock concentration and percent yield.
To establish the relationship between the percent ethanol yield and energy consumption, it is necessary to even out the effect of the feedstock’s initial ethanol concentration. To do this, the energy per ethanol concentration for every liter of the feedstock was first determined then compared to the percent ethanol yield. Figure 3 shows that the higher the percent yield of the distillation process means the lower energy requirement for every liter of the feedstock's initial ethanol content. This means it is cheaper to distill feedstock with a high initial ethanol concentration because this will result in a higher ethanol yield.

Figure 4 below is the General User Interface (GUI) of the IoT controller. The temperature profile of the kettle and column condenser and current values of the temperatures, percent power utilization, and pump state is displayed for real-time monitoring purposes and further analyses of the ethanol distillation. The power utilization of 69% implies that the system utilizes a PID mode of control, which is the most common control algorithm used in industry and has been universally accepted in industrial control [24][25]. Moreover, the condenser's temperature profile and the kettle show that the regulation at 78 °C and below 100 °C, respectively, was achieved.

4. Conclusion
In the light of the above discussions, it is concluded that a 10 kWp Hybrid Solar Photovoltaic System with battery backup was designed to power a 150 L capacity distiller. The ZFFD was installed and evaluated and found to be effective in improving temperature regulation and control. The developed ZFFD is energy self-sufficient and does not use fossil fuel.

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