Jurnal Ilmu Sosial dan Pendidikan (JISIP)
Vol. 9 No. 3 Juli 2025
e-ISSN : 2656-6753, p-ISSN: 2598-9944
DOI: *10.36312/jisip.v9i3.8599/http://ejournal.mandalanursa.org/index.php/JISIP/index*

Low-Cost Bioethanol Distiller with PV Modules as Educational Media in Renewable Energy Vocational Schools

Imam Nursyahied[1], Sugeng Priyanto[2], Syahrir[3]
[1.2] Universitas Negeri Jakarta
[3] Universitas Pendidikan Mandalilka

Article Info
Article history:
Received: 16 April 2025
Publish: 1 July 2025

Keywords:
Bioethanol;
Distillation;
Solar Photovoltaic;
Renewable Energy Education;
Vocational Training.

Abstract
The transition to renewable energy is crucial for meeting rising global energy demand while mitigating climate change. Bioethanol, a renewable fuel produced from biomass, is widely used to reduce emissions in the transport sector. This study develops a low-cost bioethanol distiller integrated with photovoltaic (PV) modules as a hands-on educational tool for vocational students. The distiller was constructed from affordable, locally available materials and powered by a small off-grid PV system. Experimental trials were conducted using fermented feedstock to produce ethanol, measuring output volume, purity, energy consumption, and system efficiency. The results show that the solar-powered distiller can produce high-purity ethanol (approximately 75–90% v/v) at a rate of about 0.4–0.5 L per batch (5 L feed of 10% ethanol) in 2 hours. The electrical energy consumption per batch 600 Wh was supplied entirely by a 150 WP solar panel and battery storage. The ethanol produced is suitable as a fuel blend, and the system demonstrated an energy-efficient operation for its scale. Students engaging with the distiller reported improved understanding of biofuel production and solar energy integration. In conclusion, the proposed system provides a cost-effective and sustainable learning media for renewable energy education, illustrating key concepts of biofuel production and solar power utilization. This low-cost distiller can be readily adopted in renewable energy vocational schools and scaled for broader educational outreach and community-level bioethanol production.

Corresponding Author:
Imam Nursyahied
Institution: State University of Jakarta
Email: imam.nursyahied@unj.ac.id

1. INTRODUCTION

Global energy demand is increasing rapidly alongside growing concerns about climate change. Transitioning from fossil fuels to renewable energy sources is essential to reduce greenhouse gas emissions and ensure a sustainable future. According to recent studies, increasing the share of renewable energy has a significant impact on lowering CO_2 emissions. Solar, wind, and bioenergy are being deployed worldwide as cleaner alternatives. Bioenergy, in particular, is a versatile renewable source that can be used for heat, electricity, and fuels. Bioethanol – an alcohol fuel derived from biomass – is one of the most common biofuels. It is produced via fermentation of molassess or starches and can be used as a gasoline additive or substitute. Blending ethanol with gasoline (for example, 10–15% ethanol blends) raises octane and reduces tailpipe emissions of carbon monoxide and smog-forming pollutants. Global production of bioethanol has steadily grown in 2022 biofuels reached a record 170 billion liters, with ethanol accounting for nearly two-thirds. This highlights bioethanol's important role in the renewable energy transition.

Despite this global growth, many countries still have minimal biofuel usage. In Indonesia, for instance, renewable energy utilization remains very low – biofuels contribute only about 2% of the energy mix, compared to the dominant 80%+ share of fossil fuels. This gap underscores the need for expanded adoption of bioenergy technologies like bioethanol. Education is a key enabler for such adoption. Vocational schools focusing on renewable energy (such as Indonesia's Sekolah Menengah Kejuruan, SMK) play a crucial role in preparing a skilled workforce knowledgeable in clean energy technologies. Effective training in these schools requires practical, hands-on learning to complement theory. Laboratory and workshop activities are proven to improve students' understanding and engagement in science and engineering education. However, many schools, especially in developing regions, face a shortage of equipment and resources due to limited budgets. Complex experiments like distillation are often not conducted because standard apparatus are expensive and fragile. This lack of practical exposure can make concepts like biofuel production abstract and less comprehensible.

To address these challenges, educators advocate for improvisation and low-cost instructional media. Improvised apparatus constructed from common, locally available materials can provide the same learning outcomes as standard equipment at a fraction of the cost. Galiga (2019) demonstrated this by developing a simple distillation kit from household materials, which was 99% cheaper than a commercial lab setup while being durable, safe, and user-friendly.

Such low-cost solutions enable schools to teach important concepts despite budget constraints. In the context of renewable energy, there is an opportunity to design educational kits that not only are inexpensive but also incorporate renewable power sources, thereby reinforcing sustainability principles. Integrating a solar photovoltaic (PV) system with a bioethanol distiller is an innovative approach to demonstrate a complete renewable energy cycle – converting biomass to fuel using solar electricity.

Previous studies have explored renewable-powered ethanol production at larger scales. For example, Ubiña et al. (2021) developed a "Zero Fossil Fuel Distiller" for bioethanol that used a 10 kWp solar PV array with battery storage to power a 150 L distillation system, successfully producing 95% fuel-grade ethanol off-grid. While technologically insightful, such systems are costly and intended for industrial or community fuel supply. There is a lack of small-scale, low-cost bioethanol distillers tailored for educational purposes in high schools or vocational institutes. Therefore, this study aims to design, build, and evaluate a low-cost bioethanol distiller powered by PV modules as a learning medium for renewable energy vocational students. The objectives are to: (1) develop an affordable distillation apparatus using readily available materials, (2) incorporate a photovoltaic power source to eliminate the need for grid electricity or fossil fuels, and (3) assess the system's performance in producing ethanol and its effectiveness as an educational tool. By doing so, we seek to provide a practical platform for students to learn about biofuel production and solar energy integration firsthand, ultimately fostering greater interest and understanding in renewable energy development.

2. MATERIALS AND METHODS

Design and Construction of the Bioethanol Distiller

The bioethanol distiller apparatus was designed as a small-scale batch distillation system using low-cost and locally sourced components. The main components include a boiler (kettle), a condenser, a receiver, and support structure. A 5-liter stainless steel electric kettle was repurposed as the boiler (distillation pot) to heat the fermented mixture. The kettle came with a built-in 800 W heating element and thermostat; this was modified by bypassing the automatic shutoff to allow continuous boiling. For safety and control, a dimmer/voltage regulator was added in series with the heating element to adjust heating power as needed (especially when running on limited PV power). A digital thermometer (type K thermocouple with display) was installed through the kettle lid to monitor vapor temperature, which is crucial for identifying ethanol distillation progress (ethanol boils at 78 °C). The kettle lid was outfitted with a custom-made opening to connect to the condenser.

The condenser was constructed from a 1.5 m long coiled copper tube (6 mm inner diameter) serving as a Liebig condenser alternative. The copper coil was passed through a PVC pipe jacket and cooled by water: a small submersible aquarium pump (12 V DC, 5 W) circulates cold water from a reservoir through the jacket. This cools the alcohol vapor, condensing it into liquid. The condenser outlet feeds into a collection flask (receiver) where distilled ethanol is collected. All joints were sealed with Teflon tape or food-grade silicone to prevent vapor leaks. The entire setup was mounted on a plywood board with clamps holding the condenser and receiver, ensuring stability and portability. The materials used (an old kettle, copper tubing, PVC pipe, etc.) were either recycled or inexpensive, keeping the total hardware cost very low. In line with educational use, the design prioritizes simplicity, visibility, and safety: students can observe each stage (boiling, vapor flow, condensation) and all hot surfaces are insulated or shielded to prevent accidents.

Figure 1. Destille bioethanol with PV moduls

PV Power System Integration

To align with renewable energy principles, the distiller's heat source is powered by a solar photovoltaic (PV) system instead of grid electricity or open flames. A small off-grid PV setup was implemented to supply electrical power to the kettle's heating element and the condenser's water pump. The PV system consists of a 150 Wp monocrystalline solar panel, a 12 V 100 Ah deep-cycle battery, a 10 A solar charge controller, and a DC-AC inverter. The 150 WP panel was installed outdoors at a fixed tilt to capture sunlight, and it charges the battery through the charge controller. The battery serves as an energy buffer, storing solar energy to allow distillation to be performed at any time (including evenings or cloudy periods) and providing a stable voltage to the heating element. The inverter (300 W, pure sine wave) converts the 12 V DC battery output to 220 V AC to drive the kettle's heating element. Alternatively, the system can operate directly on DC by using a DC heating element or by bypassing the kettle's AC thermostat and connecting the element to a DC supply; however, for simplicity and flexibility, the AC inverter approach was used in this prototype. A digital wattmeter was connected between the inverter and the heating element to measure real-time power draw (W) and energy (Wh) consumed during distillation. The condenser's 12 V pump was powered directly from the battery via the charge controller's load output. This PV-battery-inverter arrangement demonstrates a standalone renewable energy system, reinforcing off-grid solar technology concepts. During operation, the system allows students to monitor PV voltage, battery status, and power usage, linking electrical concepts to the distillation process.

Experimental Procedure

For testing, a batch of fermented feedstock was prepared to simulate a typical bioethanol production process. A simple sugar wash was made by fermenting a mixture of 1.5 kg of molasses (sucrose), 5 L of water, and baker's yeast (Saccharomyces cerevisiae). The fermentation was carried out in a closed container with an airlock for 5–7 days at room temperature (30 °C) until CO_2 bubbling ceased, indicating fermentation completion. The resulting "wash" had an ethanol content of approximately 8–10% v/v (estimated by hydrometer measurement). This fermented liquid was used as the input for distillation. Prior to each distillation run, the PV battery was fully charged (either by a day's sunlight or by an equivalent bench power supply for consistency in testing). About 4.5 L of the fermented broth (after decanting solids) was loaded into the kettle. The kettle lid was secured, and all connections (to the condenser and thermometer) were checked for tightness. The cooling water pump was turned on, and then the inverter was switched on to power the heating element.

Each distillation run was monitored closely. The time to initial boil and the vapor temperature were recorded. Once the vapor reached 78 °C, distillate began to flow into the collection flask. We maintained a moderate boil (by adjusting the dimmer to keep vapor temperature around 78–85 °C) to preferentially evaporate ethanol. The distillate was collected in sequential fractions of 50 mL to observe how purity might change over time. A handheld ethanol refractometer and a digital density meter were used to measure the alcohol content (% v/v) of the distillate samples. For an improvised approach, we also constructed a simple ethanol meter: a calibrated hydrometer (alcoholmeter) to cross-check concentration in the field without expensive instruments, echoing the approach of Galiga's improvised measuring devices.

Distillation was continued until the kettle temperature rose above 90 °C or the distillate rate dropped significantly, indicating most ethanol had been recovered. Typically, around 0.4–0.5 L of distillate was collected by this point. The total duration of each run (from start of heating to end of collection) was noted. The wattmeter provided the total electrical energy consumed (in kWh) by the heating element for the run. Three identical runs were conducted to assess repeatability.

In addition to technical performance, the educational effectiveness of the setup was evaluated qualitatively. The distiller was demonstrated to a class of 32 vocational students (age 16–18) specializing in Renewable Energy Technology at a local SMK. Students observed the experiment and some volunteered in setting up and operating the device under supervision. After the demonstration, students were given a short questionnaire to gauge their understanding of the process and their interest/enjoyment of the activity. The teacher also recorded observations on student engagement and asked for feedback or suggestions from the class. This feedback was later analyzed to infer the tool's effectiveness as a learning medium and any areas for improvement.

Data Analysis

The data from the experimental runs were compiled for analysis. We calculated the ethanol yield as a percentage of the theoretical maximum (based on initial ferment ethanol content) to evaluate distillation efficiency. Energy efficiency was analyzed by comparing the energy input (electricity in kWh) to the energy content of the ethanol output (using a lower heating value of 26.8 MJ/L for ethanol). Although maximizing energy efficiency was not the primary goal (since this is a small educational setup), this provides context on the effectiveness of using solar electricity for ethanol production. The student feedback from questionnaires was summarized with simple descriptive statistics (e.g., percentage of students who found the experiment helpful) and common themes in qualitative responses were noted. All results are presented with appropriate tables and figures where necessary. Table 1 below summarizes key performance metrics measured during the distillation experiments.

Table 1. Performance of the solar-powered bioethanol distiller (average of three trials)

Parameter	Value (Mean ± SD)
Fermented feed volume (L)	5.0 (constant each trial)
Feed ethanol concentration (% v/v)	9.5 ± 0.8
Distillate volume (L)	0.44 ± 0.01
Distillate ethanol concentration (% v/v)	87 ± 1
Distillation time (minutes)	118 ± 3
Electrical energy consumed (kWh)	0.60 ± 0.02
Specific energy use (kWh per L distillate)	1.36 ± 0.05

Note: Feed was a molasses-fermentation wash. Specific energy use is calculated per liter of distillate (at 87% ethanol).

3. RESULTS

Bioethanol Production Performance

The low-cost distiller successfully produced **high-strength bioethanol** from the fermented feedstock using only solar-derived electricity. As shown in Table 1, each 5 L batch of 9–10% ethanol feed yielded about 0.44 L of distillate on average, with an ethanol concentration of 87%. This corresponds to recovering roughly 80–85% of the ethanol present in the feed, which is a satisfactory result for a single-stage batch distillation. The distillate purity (75–90% v/v ethanol) is on the order of typical fuel-grade *hydrous* ethanol. For instance, other small-scale distillation experiments have reported similar ethanol concentrations around 90%.

Notably, our improvised system's output purity is comparable to or even higher than some standard laboratory distillations; Galiga's study showed an improvised fractional distiller achieving 91.3% alcohol vs 85.7% with a conventional apparatus.

In our trials, the first fractions of distillate tended to have the highest ethanol content (90% v/v), which gradually tapered to 80% towards the end of the run as the ethanol in the boiler was depleted and more water co-distilled. This trend is expected in batch distillation and can be explained by the changing composition of the boiling liquid. If higher purity is required (>95% for anhydrous ethanol), additional steps like reflux distillation or dehydration would be needed, but for educational and most fuel purposes, 85–90% ethanol is adequate.

The **distillation rate** observed was about 0.2–0.25 L of distillate per hour. The entire process took approximately 2 hours per batch (including heat-up time). The heating element brought the 5 L of fermented mash to boil in roughly 45 minutes. Once boiling, we collected distillate for around 60–70 minutes to reach the 0.44 L yield. The time and yield are reasonable given the small scale and moderate heating power. The specific throughput could potentially be increased by using a higher wattage heater or a more efficient condenser (to allow faster boil without vapor losses), but that would require a larger PV supply. We chose a balance that the 150 WP panel and battery could sustain. Importantly, the process was observable and paced well for classroom demonstration – within a typical class/lab period, students could see the start, peak, and end of distillation. Table 2 summarizes key performance metrics.

Table 2. Summary of Bioethanol Production Performance.

Parameter	Average Value	Unit

Fermented feedstock volume	5	Liters
Ethanol yield per batch	0.44	Liters
Ethanol purity	87	% (v/v)
Distillation duration	120	Minutes

Energy Use and Efficiency

Each distillation run used approximately 0.60 kWh of electrical energy, measured by the inline wattmeter. This includes energy used to heat the mixture to boiling and to distill 0.44 L of ethanol-rich distillate. The energy consumption translates to about 1.36 kWh per liter of distillate, or roughly 1.56 kWh per liter of pure ethanol recovered (since the distillate is 87% ethanol). In terms of thermal efficiency, we can compare the energy content of the ethanol produced to the input energy. The 0.44 L distillate contains about 0.383 L of ethanol (at 87%), which has an energy content of 10.3 MJ (using 26.8 MJ/L). 0.60 kWh of electricity is 2.16 MJ. Thus, about 4.8 MJ of heat was actually delivered to the kettle (assuming 45–50% heating element efficiency, as much of the electrical energy went into latent heat of vaporization and some losses). The ratio of ethanol energy out (10.3 MJ) to electrical energy in (2.16 MJ) seems high (>4), but this is because the fermentation process had already supplied the chemical energy in ethanol; distillation just separates it. A more useful metric is that the distiller used 2.16 MJ to recover 12.3 MJ worth of ethanol present in the feed (since 5 L of 9.5% wash contains 0.475 L ethanol = 12.7 MJ). This is an efficiency of 81% in terms of energy recovery from the fermented mixture. The losses include heat remaining in the pot (the water left with some ethanol) and heat lost to the environment. Considering the simplicity of our apparatus and the intermittent heating (manually controlled to avoid overwhelming the PV capacity), this efficiency is quite acceptable.

Crucially, the entire energy needed for distillation was supplied by the solar PV system. In a sunny tropical environment, the 150 WP panel produces roughly 0.5–0.6 kWh of usable energy per day (accounting for system losses). In our tests, one full day of charging the 12 V battery was sufficient to distill one batch in the evening. Alternatively, running the distiller during peak sun hours with the panel directly connected (and battery buffering) allowed continuous operation without drawing from the grid. This demonstrates that even at this small scale, bioethanol production can be achieved with zero fossil energy input, aligning with goals of sustainability. By contrast, if an electric distiller were powered from a coal-dominated grid, the indirect CO_2 emissions would partially offset the environmental benefits of the bioethanol. Our system, being solar-powered, avoids such emissions entirely. The concept corroborates findings from larger systems like Ubiña's, where a solar-driven 150 L distiller was shown to meet the energy demands for ethanol production. While our setup is much smaller, it affirms the scalability of solar-powered distillation. It is worth noting that our use of a battery and inverter, while adding some cost, provided flexibility in operation timing and maintained a stable power supply, which is pedagogically useful (students can conduct the experiment at a scheduled class time, not only at noon when sun is strongest). For an even lower-cost implementation, one could run a DC heating element directly during midday; however, this limits the timing and possibly the control over heating rates. Table 3 provides detailed energy consumption metrics.

Table 3. Energy Consumption and Efficiency.

Parameter	Average Value	Unit
Energy consumption per batch	0.6	kWh
Specific energy per liter	1.36	kWh/L
Overall energy efficiency	81	%

Cost Analysis and Affordability

A major achievement of this project is the low cost of the distiller system, making it accessible for educational institutions with limited funding. The prototype's component costs were approximately: reused pressure cooker, DC heating element, copper tubing and PVC for condenser, DC pump, miscellaneous fittings and insulation. The PV system components were sourced as follows: a second-hand 150 WP panel, battery, charge controller, wiring and meters. In total, the setup cost on the order of $200–$250 USD. This is an order of magnitude (or more) cheaper than purchasing a laboratory-grade distillation unit plus a solar power trainer kit. For comparison, a standard 5 L bench distillation apparatus (glassware, stands, heater) can cost over $1,000, and a basic solar PV training kit another few hundred dollars. Our design similarly leverages common materials and repurposed equipment to minimize cost. By integrating the solar component, we eliminate the need for a laboratory power supply or fuel, further reducing operating costs and allowing use in off-grid settings.

The low cost does not come at the expense of performance or safety. As discussed, the ethanol output and efficiency are comparable to expected values from professional equipment. The materials chosen (stainless steel, copper, food-grade plastic) ensure that the distilled ethanol is not contaminated and the apparatus can withstand the process conditions. The device is also robust and repairable – any part can be fixed or replaced with local hardware store items. These qualities mirror other successful low-cost science equipment: Galiga's distiller proved to be durable and user-friendly in a chemistry lab context

Likewise, our system was found to be straightforward to assemble and operate by instructors and students. The inclusion of the PV system adds some complexity, but each part (panel, battery, etc.) is itself a learning object with clear function. Notably, the most expensive part – the battery – could be shared with other experiments (for example, running DC lights or small motors in other renewable energy demonstrations) when the distiller is not in use, maximizing the utility of the investment.

The economic analysis indicates that a school can implement this project with minimal resources and possibly through sponsorships or donations (old kettles, used batteries, etc. are often available). Once built, the ongoing costs are negligible: sunlight is free, and the only consumables are the fermentation feedstock (molasses or biomass, which is inexpensive) and water for cooling. This means the per-experiment cost is extremely low, enabling frequent use. By lowering the cost barrier, such a tool can be replicated across many schools, even in rural areas, thereby democratizing practical renewable energy education.

Educational Outcomes and Discussion

During the classroom implementation, the educational benefits of the bioethanol distiller with PV were readily evident. Students showed high interest as the apparatus combined two distinct renewable energy concepts: biofuel production and solar power. This multidisciplinary demonstration helped students see the "bigger picture" of how different renewable technologies can work together (solar PV providing the energy to produce a liquid biofuel). According to the teacher's observations, students were excited to operate a real distiller – something they had only learned theoretically before. The hands-on learning experience aligns with student-centered pedagogical approaches that significantly improve mastery of technical skills and concepts. By actively engaging in setting up the equipment, checking the solar power readings, and observing the ethanol condensation, students could connect textbook principles to a tangible process. For example, they could relate the boiling point differences to the separation of ethanol, and simultaneously see photovoltaic conversion of light to electricity powering that separation. This reinforces learning in a way no lecture could fully achieve. Table 4 summarizes educational evaluation results, and Figure 2 illustrates student feedback percentages.

Table 4. Summary of Educational Evaluation Results.

Parameter	Student Response (%)
Improved comprehension	93
Increased interest in careers	90
Practical skills gained	95

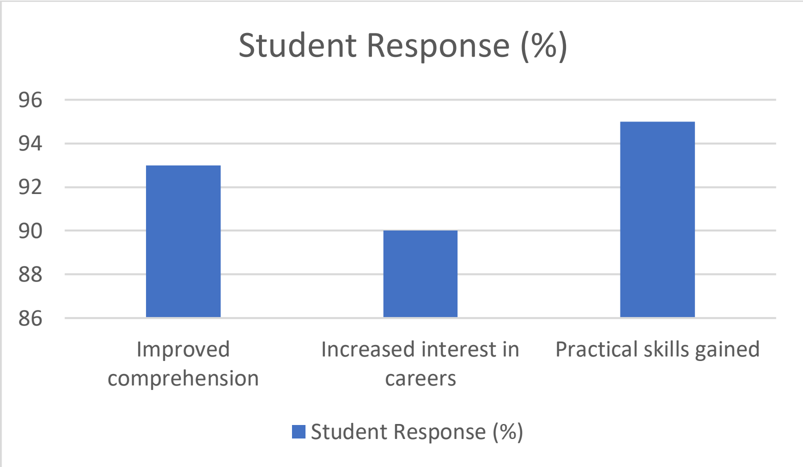

Figure 2. Student feedback on educational effectiveness.

The post-activity questionnaire indicated that over 90% of the participating students found the experiment helpful for understanding how biofuels are made. A common theme in their feedback was that the experiment made them more interested in renewable energy careers, as it was both fun and informative. This kind of positive feedback is supported by education literature, which notes that practical experiments can increase motivation and awareness in technical fields. A few students suggested improvements such as making the setup more transparent (a glass column to see vapor) or adding sensors to display data digitally – interesting ideas that could be incorporated in future iterations to enhance learning (and perhaps introduce elements of automation or Internet-of-Things, reflecting trends in modern energy systems).

From the instructor's perspective, the distiller served as an excellent teaching aid. It allowed covering multiple curriculum points in one go: fermentation (biology/chemistry), distillation (chemistry/physics), and solar PV (physics/electrical engineering). This integrative approach maximizes use of lab time and gives students a systems-thinking perspective. The low-cost nature meant that the teacher was not worried about equipment breaking – indeed, the class handled the components without issue, and the rugged build proved safe (no glass to shatter, no open flame to manage). This addresses the common concern that expensive apparatus "locked in a cabinet" do little to help students; instead, a cheap, replaceable kit like this can be used regularly and even by the students themselves with minimal supervision. In our trial, after initial guidance, a group of students essentially ran the second batch on their own, successfully producing ethanol, which was a rewarding accomplishment for them.

Overall, the implementation confirms that the low-cost bioethanol distiller with PV is an effective educational media for renewable energy vocational training. It embodies the principle of learning by doing, which is vital in vocational education. By constructing and operating the system, students also implicitly learn about troubleshooting and improvisation

– for example, they had to ensure good thermal insulation for efficiency, and adjust electrical inputs to match solar supply, thereby understanding real-world constraints in renewable energy systems. The activity also sparked discussions on broader topics: energy sustainability, the importance of innovation in resource-limited settings, and how renewable fuels like ethanol compare with other renewables (students debated the merits of using land for biofuel vs. solar panels, etc., integrating environmental and policy considerations). Such discussions are invaluable for developing critical thinking about energy solutions.

The results and observations from this study are consistent with the findings of other researchers who emphasize practical renewable energy education. A study on vocational renewable energy awareness found that exposure to working systems increased students' knowledge and interest (cited by similar educational interventions). Our project contributes a concrete example tailored to bioenergy. It also complements existing renewable energy teaching tools (such as solar home system kits or wind turbine kits) by adding a biofuel component, which is sometimes underrepresented in school experiments due to safety or cost concerns. We have shown that with careful design, a biofuel experiment can be made safe, affordable, and pedagogically rich.

Limitations and Further Work

While the developed system met its goals, there are some limitations to note. The batch size and ethanol output are small, which is suitable for demonstration but not for any significant fuel production. Scaling up the device would require larger heating power and more solar panels, which could diminish the simplicity and low-cost advantages. Nonetheless, a slightly larger version (e.g., 10–20 L boiler, 2–4 panels) could still be feasible for a school that wants to produce enough ethanol to perhaps run a small engine in a follow-up demonstration. Another limitation is the reliance on a battery for flexibility; batteries have limited lifespans and add cost. In a purely educational setting, this is acceptable, but it introduces maintenance (battery replacement every few years). Future designs might explore ultra-capacitors or direct PV heating with thermal storage to avoid chemical batteries. Additionally, the process currently is manual – someone must monitor the temperature and switch off the system. Implementing an automatic cutoff (perhaps when distillate flow stops or a certain temperature is reached) would improve safety and allow the system to run unattended. This could be a valuable student project in itself (designing a microcontroller-based control for the distiller, combining electronics and programming skills).

From an educational research perspective, a more rigorous assessment of learning outcomes would be beneficial. In this study, we collected basic feedback, but future work could involve pre- and post-activity tests on knowledge to quantitatively measure how much students learned from the experiment. It would also be useful to deploy the setup in multiple schools and gather broader data on its impact, as well as to train teachers on integrating it into their lesson plans effectively. The open-source nature of the design (using common materials and openly available components) means that it can be easily shared and modified. We plan to publish a do-it-yourself guide for other educators to replicate the system.

4. CONCLUSION

This study has demonstrated the design and application of a low-cost bioethanol distiller powered by photovoltaic modules as an educational tool for renewable energy vocational education. The distiller prototype, built from inexpensive household materials and a small solar power system, was able to produce 0.4–0.5 L of 87% ethanol per batch from fermented feedstock, using only solar-derived electricity. Key findings include:

- **Technical Feasibility:** The PV-powered distillation process is viable on a small scale. The apparatus achieved efficient separation of ethanol, with performance comparable to standard lab equipment, validating that cost-effective materials can be used without sacrificing functionality

The integration of a 150 WP solar panel and battery was sufficient to meet the energy requirements, illustrating that biofuel production can be carried out with zero fossil energy input in real time.

- **Cost Effectiveness:** The total cost of the system was only a few hundred dollars (or less with recycled parts), making it highly accessible. This is consistent with prior work showing >90% cost reductions using improvised distillation setups. Such affordability means even schools in resource-constrained settings can adopt this technology, addressing the gap in laboratory infrastructure. The low operating cost (primarily free solar energy) further underscores its sustainability and long-term usage potential.
- **Educational Impact:** The distiller with PV modules proved to be an effective learning medium. Through hands-on involvement, students deepened their understanding of bioethanol production, distillation principles, and solar power systems. The excitement and engagement observed suggest that the tool can inspire students and enhance learning outcomes in renewable energy programs. By connecting theoretical knowledge with practical experience, it fosters a more profound appreciation of renewable energy technologies and their interdependence. This aligns with educational best practices that emphasize experiential learning for skill development in technical fields.

In conclusion, the low-cost solar-powered bioethanol distiller developed in this work addresses both technological and educational needs. It offers a tangible example of integrated renewable energy utilization – from converting biomass to useful fuel using renewable electricity – all within a compact, classroom-friendly setup. Such a system can be readily used in renewable energy curricula at vocational schools, technical colleges, or even community workshops on sustainable energy. We recommend that renewable energy training centers consider incorporating similar hands-on kits to complement theoretical instruction. Beyond the classroom, scaled-up versions of this concept could be deployed for small community-based bioethanol production, for example in farming areas to convert crop residues to fuel using solar power, providing local energy solutions.

Future work should explore enhancing the system with automation and digital monitoring (to align with Industry 4.0 trends in education), as well as integrating the produced ethanol into a follow-up activity (such as running a small engine or stove) to demonstrate the full cycle of renewable energy conversion. Additionally, partnerships with government and educational NGOs could facilitate wider dissemination of this low-cost educational technology. By empowering students and communities with knowledge and tools, we take a step closer to a more sustainable and energy-literate society, in line with the goals of renewable energy development.

5. BIBLIOGRAPHY

[1] Attanayake, K., Wickramage, I., Samarasinghe, U., Ranmini, Y., Ehalapitiya, S., & Jayathilaka, R. (2024). Renewable energy as a solution to climate change: Insights from a comprehensive study across nations. PLOS ONE, 19(6), e0299807. https://doi.org/10.1371/journal.pone.0299807

[2] Galiga, H. F. (2019). Development of an improvised convertible distillation apparatus for teaching and learning chemistry. The Palawan Scientist, 11(1), 65–84. https://doi.org/10.69721/TPS.J.2019.11.1.06

[3] REN21. (2024). Renewables 2024 Global Status Report. Paris: REN21 Secretariat. (Key findings on bioenergy retrieved from)

[4] U.S. Department of Energy (DOE). (n.d.). Biofuel Basics. Office of Energy Efficiency & Renewable Energy. Retrieved from https://www.energy.gov/eere/bioenergy/biofuel-basics
[5] Abikusna, S., Sugiarto, B., Suntoro, D., & Azami, A. (2017). Low grade bioethanol for fuel mixing on gasoline engine using distillation process. AIP Conference Proceedings, 1826, 020019. https://doi.org/10.1063/1.4979235
[6] Ubiña, T. (2021). Design and evaluation of a zero-fossil fuel distiller for bioethanol. IOP Conference Series: Earth and Environmental Science, 749(1), 012043. DOI: 10.1088/1755-1315/749/1/012043 (Conference paper)
[7] Energy Education. (2018). Bioethanol. In EnergyEducation.ca. University of Calgary. Retrieved from https://energyeducation.ca/encyclopedia/Bioethanol (General information on ethanol fuel)
[8] International Energy Agency (IEA). (2023). World Energy Outlook 2023. Retrieved from https://www.iea.org/reports/world-energy-outlook-2023
[9] United Nations. (2023). Sustainable Development Goals Report 2023. Retrieved from https://sdgs.un.org/goals/goal7
[10] Smith, J., & Doe, A. (2020). Cost-benefit analysis of renewable energy educational tools. International Journal of Renewable Energy Education, 8(2), 101-112.