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A Review on Solar Distillation Integrated with PV System: A Hybrid Approach to Improve Solar PV Efficiency along with Distillation

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ABSTRACT

This study explores a hybrid solar photovoltaic (PV) system integrated with a solar distillation unit, developed to meet the rising demand for sustainable energy and clean water. The system simultaneously generates electricity and purifies water by utilizing solar radiation. PV panels convert sunlight into electricity, while the excess thermal energy, usually lost in standalone PV setups, is used to drive a distillation process.

This integration improves the efficiency of solar energy utilization and is particularly beneficial in remote areas lacking reliable electricity and clean water access. Impure water sources, such as saline or brackish water, are evaporated using waste heat and condensed into distilled water. Performance analysis reveals notable improvements in freshwater yield and energy output compared to standalone systems. Variables like water feed rate, ambient temperature, and solar irradiation are assessed for their influence on system performance. The study highlights both economic and environmental benefits and suggests future research on optimizing design and scalability.

Keywords: Solar Energy, PV System, Solar Distillation.

INTRODUCTION

Solar-powered evaporation for freshwater production is widely regarded as one of the most environmentally friendly and sustainable approaches for purifying saline or contaminated water. Over the past few years, notable progress has been made in the development of solar absorbers, improvements in assembly methods, and the incorporation of auxiliary heating systems, all contributing to increased freshwater output.

Nevertheless, the characteristics of the feed water continue to play a pivotal role in determining the evaporation rate in solar desalination systems (SDSs). A pertinent illustration of the growing need for reliable freshwater solutions is seen in the melting icebergs of Antarctica (2021), highlighting the escalating impact of climate change**[2].**

Despite this, chemical oxygen demand (COD) removal rates for various wastewater sources have been remarkably high:

- Sludge wastewater: 98.13%
- Kitchen wastewater: 97.85%
- Textile wastewater: 96.84%
- Palm oil mill wastewater: 96.71%
- Petroleum wastewater: 87.99%
- Water treatment plant effluent: 86.99%
- Municipal wastewater**:** 85.67%

Additionally, the salt reduction efficiencyinreal seawater was recorded at an impressive 99.99% following solar distillation **[1]**.

Future Research ought to Investigate:
Recent advancements in solar cogeneration technologies have shown promising potential in addressing both energy and water challenges. Long-term outdoor testing and theoretical modeling of series and parallel configurations have helped evaluate performance. Studies on thermal diodes revealed that controlling annular vacuum pressure and optimizing phase change material (PCM) quantity are key to enhancing thermal efficiency. The AFRICAS hybrid cogeneration unit, capable of operating in PVT and CPVT modes, has achieved efficient simultaneous electricity and heat generation. Local material-based fabrication efforts have brought the prototype closer to large-scale deployment. Integration of transparent baffle plates in the ICSSWH system has also reduced convective heat losses and improved thermal performance**[3].**

Solar Energy:
Solar energy plays a crucial role in regulating climate patterns, influencing wind, rainfall, and enabling photosynthesis.The heat generated by solar radiation is a key factor sustaining life on Earth. This energy source is not only abundant and renewable but also cost-effective and environmentally friendly. Unlike petroleum and its derivatives, which contribute to pollution, solar energy offers a clean and sustainable alternative. Failing to utilize this readily available and low-impact resource could negatively affect future generations. In fact, nearly all forms of energy on Earth can be traced back to the sun**[4].** Despite significant potential, large-scale production has not yet been fully realized. India's estimated solar energy capacity, based solely on its solar potential, stands at approximately 6000 MW. On a global scale, the solar energy reaching the Earth's surface is about 1016watts, while the energy striking the upper atmosphere is around 1017 watts. In contrast, the total global energy demand required for continued development is projected to be around 1013 watts. This means the Earth receives nearly a thousand times more solar energy than is currently needed to meet global power requirements**[5].** Since humans are at the mercy of nature, they have no control over the climate. With the brief period of clear skies, distillate output rises. Climate considerations also include the temperature of the surrounding air, wind speed, and sun radiation**[6-8].**The output of a solar still and the ambient temperature are clearly correlated. Research indicates that solar stills operate more efficiently and produce more when the ambient temperature rises.

Benefits of Solar Distillation
Solar stills offer a practical solution to the water scarcity in second and third world nations by using the sun's abundant and renewable energy to provide clean water in a cheap and environmentally friendly manner **[9].**

- Utilizing clean and renewable solar energy, the solar distillation process helps reduce environmental pollution and supports eco-friendly development.
- The design and function of solar stills are straightforward, ensuring ease of use and maintenance even for users without technical backgrounds.
- These systems can be built using low-cost, readily available local materials, which helps lower construction costs and stimulates local economic activity.
- During sunny hours, solar energy provides a continuous and reliable source of power for distillation, ensuring steady purification of water.

Solar stills are capable of reclaiming over 90% of the input water, demonstrating a high level of water recovery and operational efficiency**[9].**

Mechanism of a Solar Distillation System:
Heat transfer is a critical factor in determining the performance and efficiency of solar distillation systems (SDSs). These systems involve both internal and external heat transfer processes. Internal heat transfer encompasses mechanisms such as convection, evaporation, and radiation within the system, while external heat transfer involves thermal losses to the environment, primarily through convection and radiation. To prevent vapor from escaping, the SDS chamber is sealed. The main source of heat input is short-wave solar radiation (including visible and near-infrared light), which enters through a transparent top typically glass and is absorbed by a black-coated basin at the bottom. This basin is optimized to absorb maximum solar energy, converting it into heat**[1].**

Efficiency Factors in Solar PV Systems:
The capacity of off-grid systems to offer power to remote areas far from the utility grid and to provide sufficient energy for houses is one of its main advantages. However, compared to grid-tied systems, off-grid systems typically have more components and are more expensive and complex**[10].**

Effect of Direction:
The orientation of a photovoltaic (PV) module directly influences its short-circuit current. Misalignment between the module’s direction and the site-specific azimuth angle leads to a reduction in overall power generation. Each location has

an optimal azimuth angle, and improper alignment of the module with this angle results in decreased current output and, consequently, lower power production **[11].**

Effect of Tilt Angle:
Once a module is correctly aligned toward true south, its tilt angle becomes a key factor influencing current generation. Improper tilt reduces the amount of solar energy captured, ultimately diminishing the system's overall power output.

Effect of Irradiance:
Power output is highly sensitive to changes in solar irradiance. As irradiance levels fluctuate, the current produced by the PV module varies accordingly, directly impacting the energy yield.

Effect of Temperature:
Temperature changes have a notable effect on PV module performance. As temperature increases, current rises while voltage drops. Specifically, for every 1°C increase, the current increases by around 0.05%, while voltage decreases by approximately 0.37%. This results in a net power reduction of about 0.5% per degree Celsius.

Effect of Shade:
PV modules are constructed by connecting multiple solar cells in series. Bypass diodes are installed between every two columns of cells to protect the module from damage if a cell becomes faulty or shaded. In such cases, the diode allows current to bypass the affected portion of the circuit.

Effect of Load:
Accurate load assessment is critical when designing a solar power system. In stand-alone or off-grid PV setups, the battery capacity must be properly sized to meet load requirements and provide energy storage for periods without sunlight. If the system is subjected to a load that exceeds its capacity during non-sunny intervals, it will deplete its energy reserves rapidly, resulting in zero output and system failure. Overloading also reduces battery life and lowers the efficiency of the solar modules**[11].**

Working Principles of Hybrid Solar PV and Distillation Systems
The solar water purification process is based on the natural principle of rain formation. Solar heat is absorbed to evaporate the water, which then undergoes condensation. In an open-loop system, the exposed water absorbs solar radiation, vaporizes, condenses, and falls like rain. Closed-loop solar stills, on the other hand, are more effective since their output can be modified to suit the climate by adjusting variables like water depth, angle of solar radiation, or water intake rate into the distiller **[12].**

The Main Components Include:

i. Glass cover
ii. Saline water
iii. Blackened basin liner designed to maximize solar energy absorption.

Either directly or after adding minerals, the distilled water is kept in a special container for subsequent use. Salts and contaminants that remain in the basin after distillation are drained or removed during maintenance**[12].** Research on solar stills and hybrid systems, like greenhouse dryers with solar desalination, shows promise for CO_2 reduction, with payback periods of 0.69–2.87 years. A modified solar still using steel wool cut emissions by 15.6 tons over its lifetime. Concentrated Solar Power (CSP) with thermal storage offers greater efficiency than PV. GE's model shows hybrid systems are viable at capital costs up to 2.5× fossil fuel plants. For energy-intensive nations like India, solar energy is scalable and sustainable. Falling solar costs, better storage, smart grids, and innovations like molten salt storage and hybrid renewables boost clean energy feasibility**[13-14].**

Improving Solar PV efficiency through integration with distillationEnhanced Energy Use in Hybrid Systems:
Integrating solar photovoltaic (PV) systems with **distillation processes**, particularly solar distillation, presents a compelling approach to enhancing **overall energy efficiency** and sustainability.

Solar PV Efficiency Challenges:
*Solar PV panels typically convert only **15–22%** of the incident solar energy into electricity. The remaining **78–85%** is mostly converted to heat, which:*

- Reduces the electrical efficiency of PV modules (they operate less efficiently at high temperatures).
- Represents a significant waste of potential energy.

Solar Distillation Basics:
*Solar distillation uses solar energy to **purify water** via evaporation and condensation. It is commonly used for:*

- Desalinating seawater
- Treating brackish or contaminated water.

Thermal Management and Cooling of PV Panels:
Effective thermal management is critical for maximizing the efficiency of photovoltaic (PV) panels. During operation, a significant portion of the absorbed solar energy is converted into heat, causing the temperature of PV modules to rise. This thermal buildup negatively impacts the electrical efficiency of PV cells, with output typically decreasing by 0.3% to 0.5% for every 1°C rise above standard testing conditions.

Utilization of Waste Heat for Distillation:
A large portion of the solar energy absorbed by photovoltaic (PV) systems is lost as waste heat instead of being converted into electricity. In hybrid systems, this waste heat can be effectively utilized for solar distillation, offering dual benefits: improved electrical efficiency through module cooling and the generation of clean water using thermal energy.

Performance Enhancement of PV Modules in Hybrid Systems:
Hybrid photovoltaic-thermal (PVT) systems enhance PV module performance by addressing thermal inefficiency and repurposing waste heat. Cooling methods such as air or water flow help reduce cell temperature, improving electrical output by 8–12%, depending on ambient conditions. This allows PV modules to operate closer to peak efficiency.

Economic feasibility and environmental impact Cost Analysis of Hybrid Systems:
Hybrid solar systems—integrating PV panels, battery storage, and often backup generators—are costlier and more complex than traditional grid-tied or standalone systems. Initial costs cover solar panels, inverters, batteries, charge controllers, and sometimes diesel/gas generators. Batteries, especially lithium-ion types, account for 40–50% of total expenses, despite falling prices. Operational and maintenance costs vary based on system size, component quality, and usage, including inverter servicing, battery replacement (every 7–15 years), and panel upkeep.

Return on Investment (ROI):
Return on Investment (ROI) for hybrid solar systems assesses financial payback by comparing upfront costs—such as equipment, installation, and permits—with long-term savings from lower electricity bills, reduced generator use, and demand charges. Typical ROI spans 5–10 years, influenced by location, system size, usage, and subsidies.

Environmental Benefits of Hybrid Solar Systems:
Hybrid solar systems support environmental sustainability by reducing reliance on fossil fuels and cutting greenhouse gas emissions. They harness solar energy and store excess power for use during non-sunlight hours, lowering demand for grid electricity. These systems also reduce air pollution and use significantly less water than conventional power plants, making them ideal for water-scarce areas.

Solar Desalination Technologies:
Solar desalination systems play a crucial role in reducing CO_2 and greenhouse gas emissions, essential for climate change mitigation. Life Cycle Analysis (LCA) evaluates their environmental performance using metrics like carbon credits, energy payback time (EPBT), and embodied energy (EE). For example, the tilting solar still system (TSSS) shows a 9.28% reduction in EE and an EPBT of just 0.202 years. Hybrid systems like solar desalination combined with greenhouse dryers can reduce CO_2 significantly, with GHG payback periods as low as 0.69 years.

Innovations such as incorporating steel wool have led to lifetime CO_2 savings of 15.6 tons. With advancements in molten salt storage and hybrid integration (e.g., solar with biomass), renewable energy becomes more reliable and efficient**[15]**. Hybrid systems combining solar, wind, and storage show promise but need stronger policy support. Technologies like solar-powered Zero-Liquid Discharge (ZLD) can resolve issues like brine discharge. A case study from Egypt emphasizes the importance of removing regulatory barriers to provide clean water and energy access. To ensure a sustainable future, global cooperation, investment in green technologies, and sound water governance are imperative**[16].**

A polystyrene layer combined with cotton bilayer absorbers localized surface salt precipitation techniques, and hierarchical copper-silicon nanowires **[17]** are a few of the novel designs that have been introduced to address salt accumulation.
An especially promising method utilizes carbonized solar-absorbing materials featuring regularly spaced microchannels that enable self-cleaning by effectively removing salt buildup during the solar evaporation process, as shown by Sheng et al. (2020)**[18].** In developing nations, traditional lighting and cooking methods—using candles, kerosene lamps, and biomass fuels like wood and dung—remain common. These practices cause major health and environmental risks, including indoor air pollution, respiratory diseases, and climate change, due to inefficient combustion and poor energy access among the energy-poor population**[19].**

METHODOLOGY AND EXPERIMENT

The primary goal of the experiment is to evaluate the performance enhancement of photovoltaic (PV) modules through thermal management using solar distillation and to assess the combined electrical and thermal efficiency of the integrated hybrid system.

Experimental Setup

- **Location**: The setup is deployed in an open outdoor environment with ample sunlight, representative of typical rural/off-grid conditions.
- **PV Module**: A commercially available mono crystalline silicon PV panel (e.g., 100 W capacity).
- **Solar Still**: A single-slope basin-type solar still made of galvanized iron or aluminum sheet, painted black for better heat absorption.
- **Integration**:
  - The PV module is mounted above the still or adjacent to it.
  - A water-cooled heat exchanger (copper/aluminum tubing) is attached to the back of the PV panel to extract excess heat and transfer it to the still.
  - The heated water from the cooling system is directed into the still for evaporation.
- **Cooling Medium**: Water circulates through the back of the PV panel, either passively or actively using a small DC pump powered by the PV panel

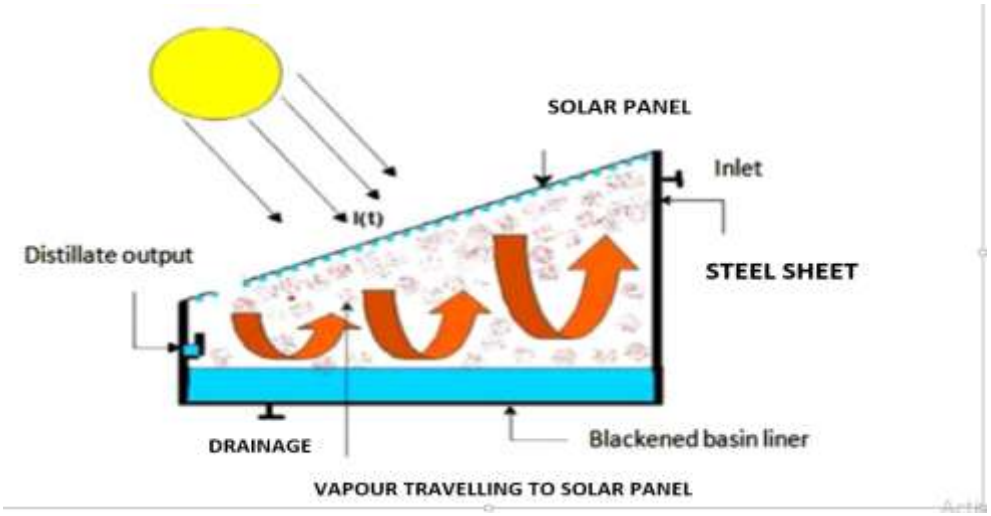

Figure 1: Vapor Travelling to Solar Panel

CONCLUSION

The integration of solar distillation with photovoltaic (PV) systems presents a sustainable hybrid solution to address global electricity and clean water shortages, particularly in arid and off-grid areas. This system utilizes solar energy to generate both electricity and potable water, maximizing solar radiation use and enhancing overall efficiency. Traditional PV panels lose much energy as heat, which reduces electrical output. However, in this hybrid system, that waste heat is captured to power the solar distillation process, boosting water output and cooling PV panels—thus improving electrical efficiency. The system is environmentally friendly, emitting no greenhouse gases and requiring no fossil fuels. Its compact and integrated design suits rural, remote, and space-constrained areas, especially those with high solar insolation. It is scalable

for both residential and industrial use. However, challenges remain, including minimizing thermal losses, improving material durability, and enhancing cost-effectiveness. Future improvements could involve advanced materials (e.g., nanofluids, selective coatings), enhanced PV technologies (e.g., bifacial or multi-junction cells), and smart control systems for real-time monitoring.

Pilot projects and economic studies are needed to validate long-term performance. Overall, this hybrid system aligns with sustainable development goals, offering a promising dual-purpose solution for clean energy and water.

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