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# INTEGRATED PV/T-MD SYSTEM WITH NANOFLUID COOLING, MEMBRANE DISTILLATION, AND ADAPTIVE PV PANEL CLEANING

**Annaev Axmed**

Researcher

**Toshmamatov Bobir**

e-mail: bobir.toshmamatov@kstu.uz

PhD, Ass.Prof. Karshi State Technical University, Kasrhi, Uzbekistan

***Abstract***

*In arid regions, the increasing operating temperature of photovoltaic (PV) modules and the accumulation of dust on their surfaces significantly contribute to the reduction in the efficiency of photovoltaic power plants. Furthermore, the limited availability of high-quality freshwater resources for regular PV module cleaning in such regions leads to increased operational costs. This study develops an integrated method and technological configurations based on nanofluid-assisted PV module cooling, the utilization of low-grade thermal energy recovered from the photovoltaic–thermal (PV/T) circuit in the membrane distillation (MD) process, and the use of the produced distillate water for adaptive PV module cleaning. The proposed PV/T-MD system enables a reduction in PV module operating temperature, improvement in electrical conversion efficiency, recovery and utilization of waste heat, and production of clean technical water. The application of the produced distillate in an adaptive panel cleaning system can reduce dependence on external freshwater resources and mitigate optical losses associated with dust accumulation. The proposed system integrates electricity generation, useful heat recovery, and distillate water production within a unified energy and technological framework.*

***Keywords***

*photovoltaic power plant, PV/T system, nanofluid, membrane distillation, distillate water, adaptive panel cleaning, PV module cooling, energy efficiency.*

***Аннотация.*** *В засушливых регионах повышение рабочей температуры фотоэлектрических модулей (PV) и накопление пыли на их поверхности*

*оказывают существенное влияние на снижение эффективности фотоэлектрических станций (ФЭС). Кроме того, ограниченность ресурсов качественной пресной воды, необходимой для регулярной очистки PV-модулей в таких регионах, приводит к увеличению эксплуатационных затрат. В данной работе разработаны интегрированный метод и технологические схемы, основанные на охлаждении PV-модулей с использованием наножидкости, применении низкопотенциальной тепловой энергии, отводимой из контура фотоэлектрической тепловой системы (PV/T), в процессе мембранной дистилляции (MD), а также использовании полученного дистиллята для адаптивной очистки PV-модулей. Предлагаемая система PV/T-MD позволяет снизить рабочую температуру PV-модулей, повысить эффективность преобразования солнечной энергии в электрическую, обеспечить утилизацию и полезное использование отводимой теплоты, а также получение чистой технической воды. Использование полученного дистиллята в системе адаптивной очистки панелей позволяет снизить потребность во внешних ресурсах пресной воды и уменьшить оптические потери, связанные с накоплением пыли. В предлагаемой системе процессы выработки электрической энергии, утилизации полезной теплоты и получения дистиллированной воды объединены в единую энергетическую и технологическую схему.*

***Ключевые слова:*** *фотоэлектрическая станция, система PV/T, наножидкость, мембранная дистилляция, дистиллированная вода, адаптивная очистка панелей, охлаждение PV-модулей, энергоэффективность.*

## Introduction

In recent years, the growing need to mitigate environmental problems arising from the extensive use of conventional fuel and energy resources and to minimize their adverse impacts on the environment has accelerated scientific and applied research aimed at the rational utilization of energy resources and the development of green technologies. At the same time, particular attention has been devoted to developing innovative solutions based on renewable energy sources (RES) to reduce dependence on conventional energy sources. Among various renewable energy sources, solar energy is

regarded as one of the most promising energy resources worldwide due to its widespread availability, high technical and economic potential, and relatively low environmental impact [1-4].

Solar photovoltaic (PV) panels enable the direct conversion of solar radiation into electrical energy. However, a substantial proportion of the solar energy absorbed by PV modules is converted into thermal energy rather than electricity. Consequently, the temperature of photovoltaic cells increases, resulting in a reduction in their electrical conversion efficiency. Furthermore, temperature-induced efficiency losses remain a significant operational limitation affecting the performance of conventional PV systems. To address these challenges, increasing research attention has been focused on the development of photovoltaic–thermal (PV/T) collectors, which integrate electricity generation and the recovery of excess thermal energy within a single system. Accordingly, research and technological advancements in PV/T systems have intensified considerably in recent years [2,5,6].

**Method and materials**

In the proposed method, excess heat generated by the photovoltaic (PV) module is extracted through a circulating nanofluid cooling loop, thereby reducing the operating temperature of the panel and improving its electrical conversion efficiency. The thermal energy recovered from the photovoltaic–thermal (PV/T) system is subsequently utilized in a membrane distillation process to desalinate saline groundwater or artesian water. The resulting distillate is then employed for the adaptive removal of dust and other contaminants accumulated on the surfaces of PV panels [2,4,7].

The cleaning process is controlled based on key operational parameters, including the degree of surface soiling, reduction in electrical power output, panel surface temperature, and incident solar irradiance. The proposed approach integrates PV module cooling, enhanced electrical conversion efficiency, thermal energy recovery, freshwater production, and autonomous water-based panel cleaning into a unified system. Consequently, an integrated method has been developed to improve the overall energy performance, water-use efficiency, and operational sustainability of PV/T systems

through the combined application of nanofluid-based cooling, membrane distillation, and adaptive surface cleaning.

The produced water is intended to be reused for washing and removing dust from the surfaces of PV modules. In this approach, the cleaning process is not performed according to a fixed periodic schedule but is adaptively controlled based on parameters such as the degree of panel soiling, reduction in electrical power output, panel surface temperature, solar irradiance, and available water reserves. This approach enables a reduction in water consumption for cleaning, prevents unnecessary washing cycles, and ensures that the cleaning process is activated only when it is energetically justified.

The scientific novelty of the proposed scientific and technical solution lies in integrating nanofluid-based cooling of PV modules, the utilization of low-grade thermal energy recovered from the PV/T system for water production through membrane distillation, and the use of the produced water for adaptive cleaning of panel surfaces within a unified energy and control system. In this configuration, thermal energy, electrical energy, and water flows are interconnected and automatically controlled.

Furthermore, the application of the proposed system under the hot and dusty climatic conditions of the Kashkadarya region is expected to reduce PV module operating temperatures, minimize optical losses caused by dust accumulation, promote the efficient utilization of water resources, and improve the overall energy efficiency of photovoltaic power plants. Consequently, electricity generation, waste heat recovery, water production, and PV module cleaning can be integrated into a single technological system.

## Results and discussions

The study synthesized the performance characteristics of photovoltaic–thermal (PV/T) systems under various configurations and climatic conditions and conducted a comparative analysis of experimental, analytical, and numerical research findings. By evaluating the key energy performance indicators, technological development trends, and existing limitations of PV/T systems, promising research directions were identified to enhance their efficiency and practical applicability. In line with these research directions, the technological configuration and operating principles of the proposed

photovoltaic–thermal and membrane distillation (PV/T–MD) system are illustrated in Figures 1-3.

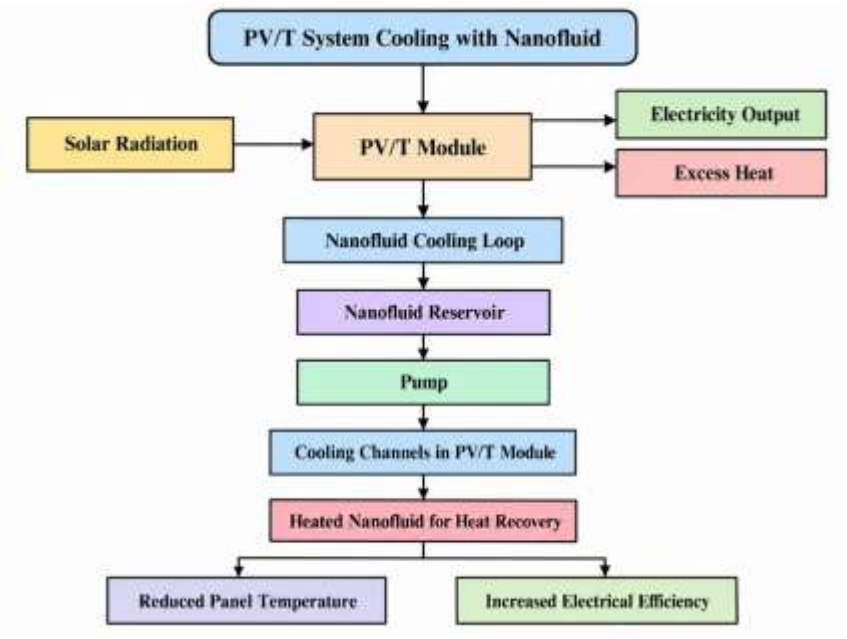


**Fig.1. Nanofluid-Based Cooling of a Photovoltaic-Thermal (PV/T) Module.**

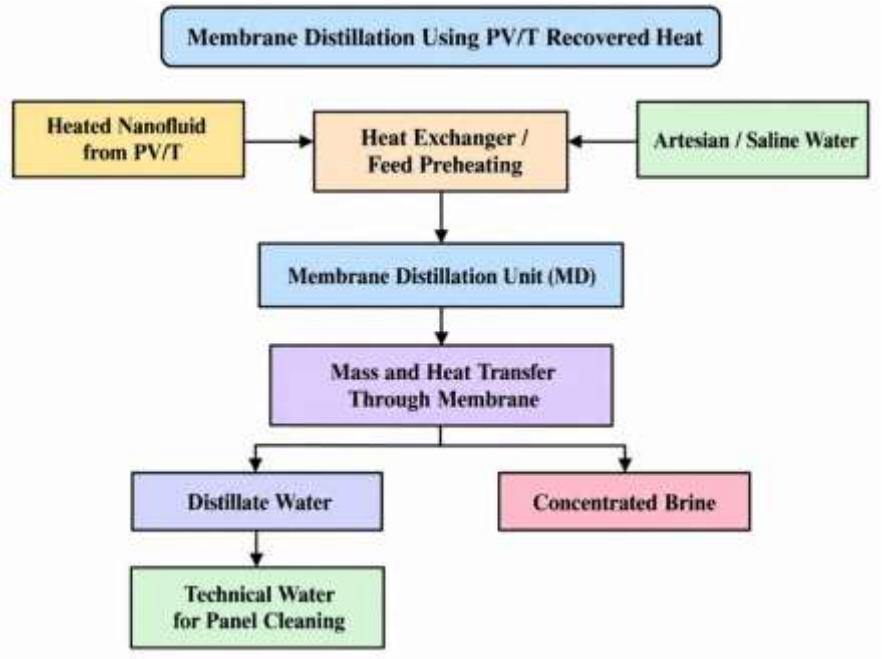


**Fig.2. Membrane Distillation of Saline and Artesian Water Using Heat Recovered from a PV/T System.**

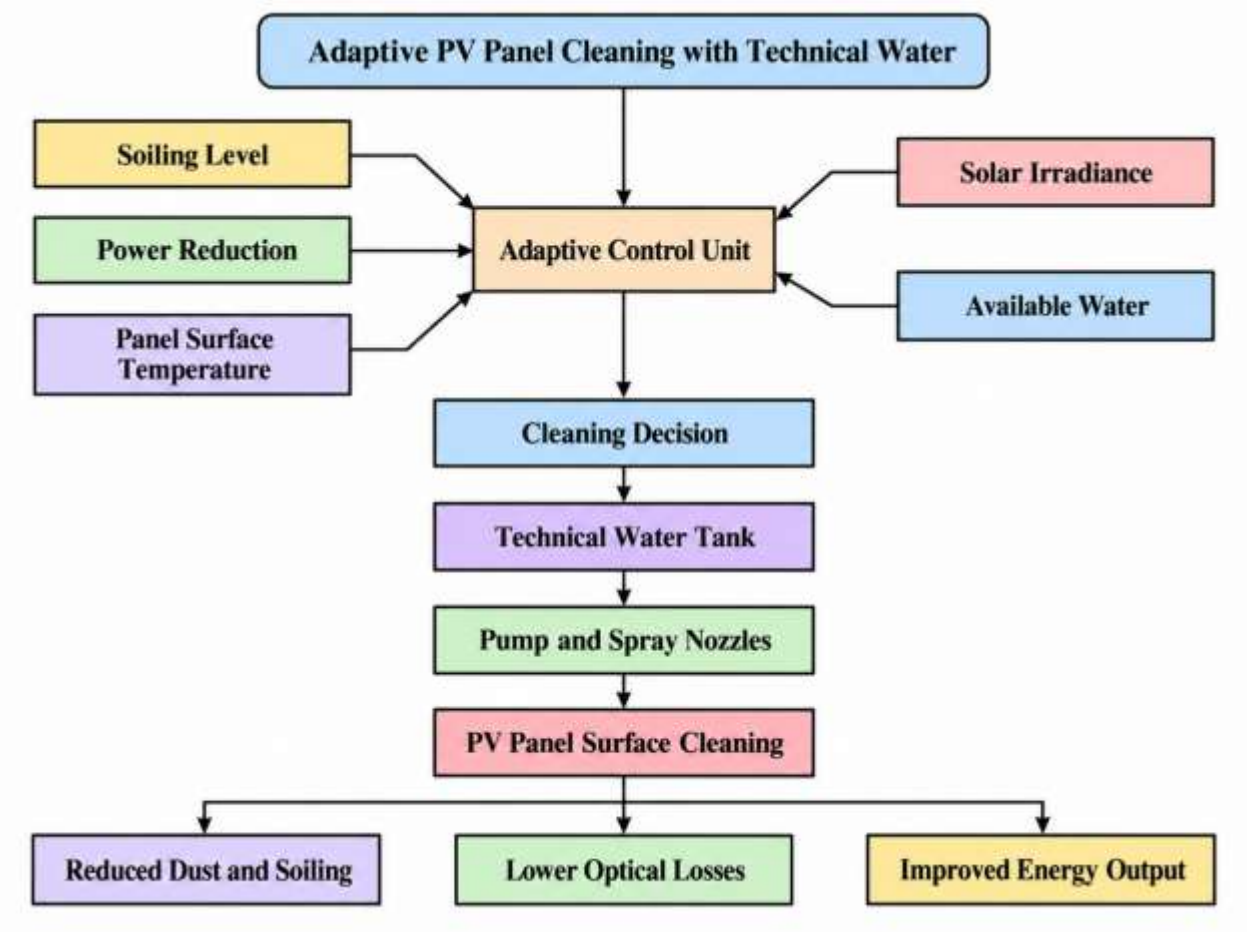


**Fig. 3. Adaptive Cleaning of PV Panels Using Distillate Water Produced by Membrane Distillation.**

## Conclusions

The technological schemes presented in Figures 1-3 demonstrate the integration of nanofluid-based PV/T module cooling, membrane distillation of saline and artesian water using recovered thermal energy, and adaptive PV panel cleaning into a unified energy and water management system. In the proposed configuration, the nanofluid absorbs excess heat from the PV/T module, thereby reducing its operating temperature and potentially improving electrical conversion efficiency. The recovered thermal energy is subsequently transferred to saline or artesian water through a heat exchanger to drive the membrane distillation process, while the cooled nanofluid is recirculated to the PV/T cooling loop. The produced distillate is utilized for adaptive panel cleaning based on surface soiling, electrical power reduction, panel temperature, solar irradiance, and water availability. This integrated approach is expected to reduce thermal and optical losses, minimize water consumption for panel maintenance, and enhance the overall

energy and resource efficiency of PV/T systems, particularly under the hot and dusty climatic conditions of the Kashkadarya region.

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