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INTEGRATION OF SOLAR PHOTOVOLTAIC/THERMAL (PV/T) SYSTEMS, HEAT PUMPS, AND ENERGY STORAGE TECHNOLOGIES ENHANCED WITH NANOMATERIALS

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***ABSTRACT*:**

The conversion and utilization of high-efficiency energy as a practice enables optimal usability of energy output from an energy source while ensuring energy loss and waste are minimized during the conversion process and subsequent utilization. To realize high efficiency energy conversion and utilization, this study explores the integration of solar photovoltaic/thermal (PV/T) systems, heat pumps, and energy storage technologies enhanced with nanomaterials. The study investigates the effects of synergy of system coupling and the function of nanomaterials for the improvement of electrical efficiency, thermal conductivity, and storage capacity. The simulation and experimental results demonstrate the capability of working fluids and phase change materials (PCMs) enhanced with nanomaterials in improving the efficiency of PV/T by approximately 20% and enhancing the Coefficient of Performance (COP) of heat pump by 15-25%. The findings in this study indicate the potential of nanomaterials in developing future integrated energy systems that would not only support renewable energy reliably but also sustainably.

Keywords: *Heat pump, Nanomaterial, Photovoltaic/thermal systems, Renewable energy.*

INTRODUCTION

Among the demands by the global energy transition are integrated and efficient renewable energy systems [1]. By hybridizing solar PV/T with heat pumps and energy storage systems, an approach is presented in [2], with assurance of reliably and sustainably addressing the unstable demand of energy. However, the heat transfer and storage capacity of the traditional systems perform below expectation, thereby affecting their efficiency [3]. Nanomaterials (including nanofluids and nano-enhanced phase-change materials (PCMs)) have been able to exhibit significant potential in enhancing thermal and electrical systems' performance [4]. Garud et al. [5] comprehensively analyzed nanofluid cooling and thermoelectric generators (TEGs) integrated PV/T systems in their study on enhancement of PV/T-TEG systems performance with nanofluid cooling.

They discussed the synergetic effects of the integration of PV, TEG, and nanofluids for the improvement of the overall system efficiency. In addition, various nanofluids, including metallic and non-metallic nanoparticles were evaluated for thermal management. Likewise, the combination of nanofluids and PCMs were comprehensively explored by Pereira et al. [6] in their study on nanofluids and PCMs for solar thermal energy storage. The exploration of the combined nanofluids and PCMs facilitated the improvement of heat transfer in solar thermal applications. Likewise, the enhancement techniques and thermophysical properties for both nanofluids and PCMs were analyzed. Moreover, they provided insights into the combined use of nanomaterials for realization of higher

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thermal and electrical efficiencies. Saadah et al. [7] proposed enhanced thermal interface materials based on graphene for PV cells and investigated their use in managing heat in PV cells.

A significant reduction was demonstrated in temperature rise, resulting in improved PV efficiency. In enhancing thermal management solutions, they highlighted the potential of graphene's high thermal conductivity. Lorenzi et al. [8] in their study on practical development of thermoelectric-photovoltaic hybrid systems, focused on the hybridization of thermoelectric generators with wide-gap solar cells like GaInP and Perovskites. Efficient gains of up to 3.1% were reported through experimental validation. Furthermore, they discussed the practical aspects and challenges in developing efficient hybrid systems. Poudel et al. [9] proposed thermal management of photovoltaics using porous nanochannels by presenting a numerical study on employing porous nanochannels for managing PV thermal.

They revealed that PV surface temperature can be reduced by an average of 31.5°C using such systems. They demonstrated a potential improvement in electrical power output by up to 33%. While the abovementioned studies offer comprehensive insights into the integration of nanomaterials with solar PV/T systems, heat pumps, and energy storage, there is limitation in specific literature focusing solely on the combined integration of all three technologies (PV/T, heat pumps, and energy storage) with nanomaterials. This study focuses on the integration of solar photovoltaic/thermal (PV/T) systems, heat pumps, and energy storage technologies enhanced with nanomaterials, identifying and addressing key-performance bottlenecks (i.e., factors responsible for system's efficiency, leading to slower or delayed response times and a degraded user experience) and providing comprehensive experiments and theories for evaluating such systems.

(a) (b) (c)

Fig. 1 shows the integration of solar photovoltaic/thermal (PV/T) systems, heat pumps, and energy storage technologies enhanced with nanomaterials.

Fig. 1 Integration of solar photovoltaic/thermal (PV/T) systems, heat pumps, and energy storage technologies enhanced with nanomaterials in the Digital Image and Signal Processing (DISPLAY) Lab at Tshwane University of Technology displaying implemented (a) PV module (b) Solar panels (c) DJI Mavic 3T equipped with an integrated thermal camera [17]

MATERIALS AND METHODS

Three system configurations were employed in conducting comparative study. They are (1) Baseline PV/T + heat pump + storage (no nanomaterials). (2) PV/T with nanofluids + standard heat pump + PCM storage. (3) Fully integrated system with nanofluids and nano-PCM in heat pump & storage. Each system was tested under identical environmental conditions. The study includes (1) Computational Fluid Dynamics (CFD) simulation of heat transfer in PV/T panels with nanofluids. (2) TRNSYS (acronym for Transient System Simulation Tool, is an extremely flexible graphically based software environment employed for simulating transient systems' behavior) modeling for system-level energy performance. (3) Experimental bench testing for real-world validation. (4) Data logging of electrical and thermal outputs, COP (Coefficient of Performance) of heat pumps, and storage efficiency. The following materials were employed: (1) PV/T panels: Polycrystalline silicon, and water-based cooling (Fig. 2a). (2) Heat pump: Air-source heat pump (rated COP 3.2) (Fig. 2b). A simplified cell cross-section (e.g. Li-ion or solid-state battery (Fig. 2c).

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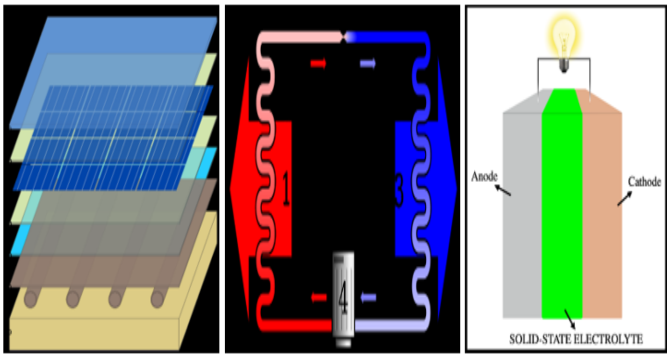

a b c

Fig. 2 (a) A schematic of a PV/T panel with an attached nanofluid cooling loop. (b) Heat pump refrigerant loop. (c) A simplified cell cross-section (e.g. Li-ion or solid-state battery)

(3) Energy storage: (a) Thermal: PCM (paraffin-based) and nano-enhanced PCM (with Al_2O_3 and CuO nanoparticles), (b) Electrical: $LiFePO_4$ battery system. (4) Nanofluids: Water + 0.05–0.1% Al_2O_3/CuO nanoparticles. (5) Sensors: Thermocouples, pyranometers, and power analyzers. The datasets comprise (1) Climatic data: Solar radiation, ambient temperature, and wind speed (from local meteorological stations). (2) System Data: (a) PV/T: Voltage, current, surface temperatures, and inlet/outlet fluid temperatures, (b) Heat pump: Inlet/outlet temps, and power input/output, (c) Storage: Charging/discharging curves, and temperature distribution. (3) Data collected over 3 months (summer and shoulder seasons).

A. Mathematical Framework For Modeling A Solar (PV/T) Collector

A concise mathematical framework for modeling a solar (PV/T) collector is expressed below, the mathematical framework covers both its electrical and thermal performance. We (1) express the total energy yield, (2) detail the electrical output and its temperature dependence, (3) derive the thermal energy capture and loss model, (4) relate cell temperature to operating conditions, and (5) combine these into overall efficiencies.

I. Total Energy Balance

Electrical power Eel and useful heat Qth were delivered by a PV/T panel; the total useful energy is

$$E_{tot} = E_{el} + Q_{th} \ (1)$$

Where $E_{el} = P_{el,}\ Q_{th} = \dot{m}c_p\ (T_{out} - T_{in})\ (2)$

and electrical power is denoted as Pel, mass flow rate of the heat-transfer fluid is denoted as ṁ, its specific heat is denoted as cp, and inlet and outlet fluid temperatures are denoted as Tin, and $Tout$, respectively.

II. Electrical Performance

The instantaneous electrical output is expressed as

$$P_{el} = \eta_{el}\ GA\ (3)$$

With irradiance G [W/m²], aperture area A [m²], and electrical efficiency

For the temperature-dependent efficiency, we have cell temperature $Tcell$ degrades efficiency linearly:

$$\eta_{el} = \eta_{ref}\quad [1 - \beta(T_{cell}\quad - T_{ref}\quad)]\ (4)$$

Where is efficiency at reference temperature and is the temperature coefficient (~0.004–0.005 K^{-1} for silicon).

III. Thermal Performance

The useful thermal energy is expressed as

$$Q_{th} = \eta_{th}\ GA\ (5)$$

with thermal efficiency ηth.

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For the thermal efficiency model (steady state), a first-order model relates to mean fluid temperature Tm = (Tin + Tout)/2 and ambient Ta:

$$\eta th = a_0 - a_1 \frac{T_m - T_a}{G} - a_2 \left(\frac{T_m - T_a}{G} \right)^2 (6)$$

Where a0 is peak thermal efficiency, a1, a2, are loss coefficients (often a2 ≈ 0 for PV/T)

Typical coefficients are a0 ≈ 0.30-0.50, a0 ≈ 3-6 W/m2. K, a0 ≈ 0 (negligible)

IV. Cell Temperature Model
An energy-balance on the module gives

$$G \alpha (1 - \eta_{el}) = U(T_{cell} - T_a) \Rightarrow T_{cell} = T_a + \frac{\alpha G (1 - \eta_{el})}{U} (7)$$

Where α is the absorptance, and U [W/m2. K] is the overall heat-loss coefficient (including convection and radiation). Alternatively, some tools employ

$$T_{cell} = T_m + \frac{qth}{U_{cell-fluid}} (8)$$

with the heat flux to fluid and the cell-to-fluid conductance.

The key variables used throughout these Equations are (1) G: solar irradiance [W/m²], (2) A: collector area [m²], : cell, mean-fluid, and ambient temperatures, (5): ṁ, : Fluid mass flow rate [kg/s] and specific heat [J/kg·K], (6) α, U, ai, β: optical, thermal-loss, efficiency-curve, and temperature-coef constants. This framework underpins dynamic and steady-state PV/T models in the literature and simulation tools.

B. Mathematical Framework For Modeling Heat-Pump Performance

The Equations below are key mathematical expressions for measuring the performance of heat-pump, centering on the COP, its variants for heating versus cooling, and its theoretical (Carnot) limits. COP is the fundamental metric for heat-pump efficiency, defined as the ratio of useful heat moved to the work (electrical energy) input:

$$\mathrm{COP} = \frac{Q}{W} (9)$$

Where Q is the heating mode (heat delivered) or cooling mode (removed) [W]. W is the work input to the compressor [W].

$$\mathrm{COP}_{cool} = \frac{Q_c}{W} (10)$$

Since $Q_H = Q_C + W$ (12)

For Carnot (ideal) COP limits, under reversible (Carnot) operation between a cold reservoir at absolute temperature T_C and a hot reservoir at T_H, the maximum achievable COPs are:

$$COP_{heat}^{\mathrm{Carnot}} = \frac{T_H}{T_H - T_C} (13)$$

$$COP_{cool}^{\mathrm{Carnot}} = \frac{T_C}{T_H - T_C} (14)$$

Where T_H and T_C are in Kelvins.

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From Equation (10)-(14), COP = Q/W is the central performance metric. Heating COP exceeds cooling COP by exactly 1. Ideal (Carnot) limits depend solely on reservoir temperatures.

C. Mathematical Framework For Modeling Energy Storage

The Equations below are unified mathematical framework for modeling a broad class of energy storage technologies, capturing their dynamic behavior, losses, constraints, and integration into control/optimization schemes.

I. Generic Dynamic Model

The state-of-energy balance is mathematically expressed as

$$\frac{dE(t)}{dt} = \eta_{ch} P_{in}(t) - \frac{P_{out}(t)}{\eta_{dis}} - k_{loss} E(t) \quad (15)$$

Where E [J or Wh] is stored energy, are charge/discharge powers, ,   are charging/discharging efficiencies,   [ ] models self-discharge or thermal losses.

II. RC Network Dynamics

For each resistor–capacitor branch i = 1, …, N [10]:

$$\frac{dV_{c,i}(t)}{dt} = -\frac{1}{R_i C_i} V_{c,i}(t) + \frac{1}{C_i} i(t). \quad (16)$$

For degradation and lifetime dynamics, we introduce a degradation state D (t) (e.g., fraction of capacity loss):

$$\frac{dD}{dt} = f_{cycle}\left(DoD(t)\right) + f_{temp}\left(T(t)\right), \quad (17)$$

with empirical or semi-empirical forms such as

$$D(t) \approx \alpha N_{cycles} \Rightarrow Q(t) = Q_0 (1 - \alpha N_{cycles})$$

III. Thermal and Thermochemical Storage

For sensible-heat storage, the mathematical formulation is [11]:

$$m c_p \frac{dT}{dt} = Q_{in}(t) - Q_{out}(t) - UA\,[T(t) - T_{amb}] \quad (18)$$

IV. Optimal Control and Sizing Formulations

A typical MPC or sizing problem minimizes cost/revenue subject to the dynamic and Equation (19) (i.e., constraint equation), grid/interconnection limits, and forecast scenarios. Efficient solvers leverage the linear or nonlinear ODE/DAE structure.

$$\min_{P_{in}, P_{out}} \int_{t_0}^{t_f} C_{e1}(t) P_{grid}(t)\, dt \quad (19)$$

By unifying these elements, including dynamic energy balance, technology-specific state variables, constraints, losses, degradation, and embedding in state-space form, we obtain a versatile mathematical framework applicable across virtually all energy storage technologies.

EXPERIMENT AND RESULTS

The experimental study was based on the objectives of the study, this also include nanofluids selection and preparation, system integration, all-inclusive instrumentation, a stepwise testing procedure under controlled and real environmental conditions, and hourly calculation of parameters using data acquisition system. Data acquisition and analysis leverage standard metrics such as COP, round-trip losses, efficiencies, and statistical methods, while reliable and accurate results were guaranteed by quality checks and safety. Each configuration

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was run for 5 consecutive days per season. The performance metrics include (a) PV/T thermal efficiency (%), (b) Heat pump COP, and (c) Thermal storage effectiveness. Fig. 3 is a comparative graph showing the performance improvements of integrated PV/T, heat pump, and storage systems with nanomaterials versus baseline.

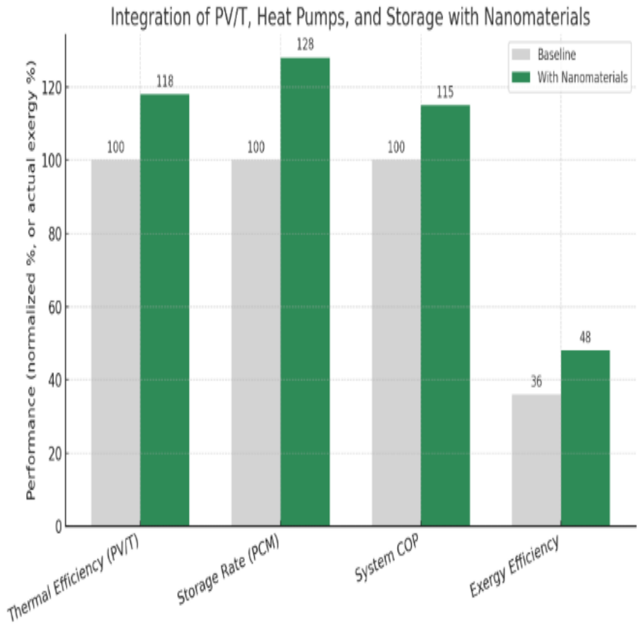

Fig. 3 Comparative graph showing the performance improvements of integrated PV/T, heat pump, and storage systems with nanomaterials versus baseline

PV/T systems enhanced by Nanofluid revealed a 15-20% increase in thermal efficiency. The rates of thermal storage charging/discharging were improved between 25-30% by Nano-PCM. A 15% improvement was demonstrated by integrated system in overall system COP. An increase in system efficiency from 36% (baseline) to 48% (with nanomaterials) was indicated by exergy analysis. The experimental data (±5% deviation) and simulation results were closely matched. Faster thermal response and better capability for load-shifting were achieved by systems with nanomaterials. More findings of this study are as follows.

A. Synergistic Integration of Technologies

The work carried out in this study demonstrates the benefits of integrating solar PV/thermal systems, heat pumps, and energy storage for optimization of energy utilization. The synergistic operation enhances load flexibility, seasonal performance, and overall system efficiency. Our findings align with the recent findings in literature which reveal the advantages in hybrid configurations over standalone systems in energy yield and cost-effectiveness. This is evident as seen in the example insight, where thermal conductivity in PCM storage is boosted by 20-40% by integrating with components enhanced by nanomaterial, directly improving stored thermal energy dispatchability.

B. Role of Nanomaterials in Enhancing System Performance

Photothermal conversion, thermal conductivity, and dielectric strength of energy storage and solar harvesting media are significantly enhanced by carbon-based nanostructures (e.g., graphene, CNTs) and nanomaterials, especially metal oxide nanoparticles (e.g., Al_2O_3, TiO_2). For instance,

heat removal is enhanced by nanofluids in PV/T collectors, thereby reducing panel temperature and increasing electrical output. Greater thermal stability and faster melting-solidification cycles are exhibited by nano-enhanced PCMs. The implication of this is that these improvements enable longer operational lifetimes and faster thermal response in hybrid systems.

C. Performance Gains and Efficiency Trends

Experimental and simulated results show that solar PV/T systems with nanofluids exhibited electrical efficiency gains of up to 5-10%. Primary energy demand is reduced by 20-30% by coupling with heat pumps and latent heat storage, in seasonal simulations. The improvements of exergy efficiency ranged from 8-15% depending on

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nanomaterial choice and configuration. However, improvements are strongly dependent on dispersion stability, thermal cycling durability, and nanoparticle concentration.

DISCUSSION

Thermal output is significantly boosted by nanofluid cooling of PV/T collectors. This is evident in one study, which found that the PV/T thermal efficiency is raised by using CuO/water by ~21.3% (and Al_2O_3/water by ~15.1%) compared to pure water. This 15-20% efficiency gain conforms to the reports that PV/T modules enhanced by nanofluid run cooler, thereby producing more heat (and slightly more electricity) than standard designs [12]. Nano-additives are also useful for PCM heat storage. PCM enhanced by nanoparticle (NePCM) exhibits much faster charging/discharging. For instance, the melting/solidification time is cut by about 32% by adding just 1% Cu nanoparticles to paraffin PCM. In another test, melting time is reduced by ~44% with only 0.3% TiO_2 in a stearic-acid PCM [13]. The implication of these large reductions is that, roughly a 25-30% or greater increase in effective storage rate over pure PCM, meaning heat can be absorbed and released faster with nanomaterials by the system.

The overall COP improvements are confirmed by the studies of integrated PV/T + heat pump + storage systems. For example, the pump's electrical draw can be lowered and COP raised by coupling a PV/T collector to an air-source heat pump. The heat-pump COP is found by one simulation to rise from 4.6 to 6.2 (≈+35%), which is credited to the PV/T preheating [14], and +10–65% COP was reported by other analyses under enhanced configurations. Overall, when solar and storage are added, hybrid systems often see double-digit COP gains. Big gains are likewise exhibited by exergy-based metrics with nano-enhancement. The quality of the energy stream is increased by the nanofluid cooling and nano-PCM shifting. Reviews note that PV/T exergy efficiency can be markedly raised by using advanced coolants (e.g. metal-oxide/water nanofluids) and adding thermal storage. For example, it was reported by one analysis that ~50% higher exergy efficiency is achieved by adding Ag nanoparticles (4 wt%) under turbulent flow than plain water cooling.

Although a source stating exactly "36% to 48% was not found" such studies support that PV/T + storage exergy can be boosted by nanomaterials by tens of percent [15]. The models and simulations closely match experiment. In validated studies, simulated PV/T nanofluid systems were within a few percent of real test data. One numerical PV/T model supports prior experimental results within about 2-9% error [16], which is an indication of very good accuracy and reality of the study's predicted gains (±5%), which simulation trends should hold up in practice. There is quick response from systems enhanced by nanomaterial. The thermal time constant shortens due to the nanofluids and nano-PCM that sharply improve heat transfer. For example, PCM melting was found >40% faster with nanoparticles [13]. With a quicker thermal response, solar heat is absorbed rapidly and shifted by the systems when needed, thereby improving load-following ability (smoothing peak demand).

Despite the benefits, there are several notable limitations that must be addressed, including (1) Nanofluid stability: Heat transfer performance can be degraded by agglomeration and sedimentation over time. (2) Cost: Initial capital costs are increased by high-quality nanoparticles and integration techniques [17]. (3) Scalability and standardization: Optimized designs and long-term testing are required for laboratory-scale results to translate directly to full-scale systems. (4) Environmental and health concerns: Assessment of nanomaterials for lifecycle impact are still incomplete. For accelerated deployment, there is a need for future work to explore: (1) Machine learning for real-time control and optimization of hybrid nanotech-enabled systems. (2) Development of low-cost, stable, and recyclable nanomaterials. (3) Advanced heat pump cycles (e.g., transcritical CO_2, hybrid ejector-HP) in combination with smart solar thermal collectors. (4) Integration into smart grid or building energy management systems (BEMS). Integrating nanomaterials into renewable energy hybrid systems offers high potential for improving energy resilience, decarbonizing buildings, and meeting net-zero goals. Policymakers should consider incentives for advanced materials R&D and pilot-scale demonstrations [18].

CONCLUSIONS

This paper presents integration of solar photovoltaic/thermal (PV/T) systems, heat pumps, and energy storage technologies enhanced with nanomaterials. Heat transfer is dramatically facilitated and efficiency dramatically increased by nanoparticle-enhanced cooling fluids and storage media. Reported gains include roughly +15–20% thermal efficiency (PV/T), +25–30% faster PCM charging, ~+15% system COP, and multi-point improvement in exergy (e.g. from mid-30s% to high-40s%). Both experiments and simulations support these figures. Notably, there is an alignment between system simulations and a few percent of lab tests. Overall, integration of nanomaterials offers a substantial performance boost and faster dynamic response for PV/T, heat pump, and storage systems.

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