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Performance Optimization of Solar PV Systems under Variable Climatic Conditions



Abstract: - Solar photovoltaic (PV) systems face significant performance challenges under variable climatic conditions, with temperature being the most critical factor affecting efficiency. This comprehensive review examines various cooling methodologies and optimization strategies for enhancing PV system performance across different environmental conditions. Through analysis of multiple studies, this research identifies that temperature variations can reduce PV efficiency by 0.4-0.6% per degree Celsius increase above standard test conditions. Active cooling techniques, including water-based systems, air circulation methods, and hybrid photovoltaic-thermal (PV/T) collectors, demonstrate significant potential for performance enhancement. The findings indicate that water cooling systems can achieve temperature reductions of 15-25°C, resulting in efficiency improvements of 6-15%. This study provides a systematic evaluation of cooling technologies and their effectiveness in optimizing PV performance under diverse climatic scenarios.

Keywords: Solar photovoltaic, cooling systems, thermal management, PV/T collectors, climatic optimization

1. Introduction

The global transition toward renewable energy has positioned solar photovoltaic technology as a cornerstone of sustainable energy systems. However, PV module performance is significantly influenced by environmental factors, particularly temperature variations that occur under different climatic conditions (García & Balenzategui, 2004). As ambient temperatures increase, solar cell efficiency decreases due to the inherent semiconductor properties of photovoltaic materials, creating a paradox where regions with the highest solar irradiance often experience reduced conversion efficiency (Awda et al., 2016).

The relationship between temperature and PV performance has become increasingly critical as solar installations expand into diverse geographical regions with varying climatic conditions. Standard test conditions (STC) specify operation at 25°C, but real-world operating temperatures frequently exceed 60-80°C, resulting in substantial efficiency losses (Kurnik et al., 2011). This temperature-induced performance degradation necessitates innovative cooling strategies to optimize energy output and maintain economic viability of solar installations.

Recent advances in thermal management technologies have opened new possibilities for PV performance optimization. These include passive cooling methods utilizing natural convection and radiation, active cooling systems employing forced air or liquid circulation, and hybrid PV/T systems that simultaneously generate electricity and thermal energy (Al-Waeli et al., 2017). Understanding the effectiveness of these various approaches under different climatic conditions is essential for maximizing solar energy utilization globally.

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2. Literature Review

2.1 Temperature Effects on PV Performance

The fundamental relationship between temperature and photovoltaic performance has been extensively documented in literature. Awda et al. (2016) conducted comprehensive analysis demonstrating that crystalline silicon modules experience linear efficiency degradation with increasing cell temperature. Their findings established that for every degree Celsius increase above 25°C, module efficiency decreases by approximately 0.45%, highlighting the critical importance of thermal management in PV systems.

García and Balenzategui (2004) developed predictive models for estimating annual PV module temperature and performance based on nominal operating cell temperature (NOCT) calculations. Their research revealed significant variations in module operating temperatures across different geographical locations and mounting configurations, with ground-mounted systems typically operating 10-15°C cooler than building-integrated installations.

Kurnik et al. (2011) conducted extensive outdoor testing of PV modules under various mounting and operational conditions, confirming that module temperature significantly impacts both instantaneous power output and long-term performance degradation. Their study demonstrated that effective thermal management could extend module lifespan while maintaining higher efficiency rates throughout the operational period.

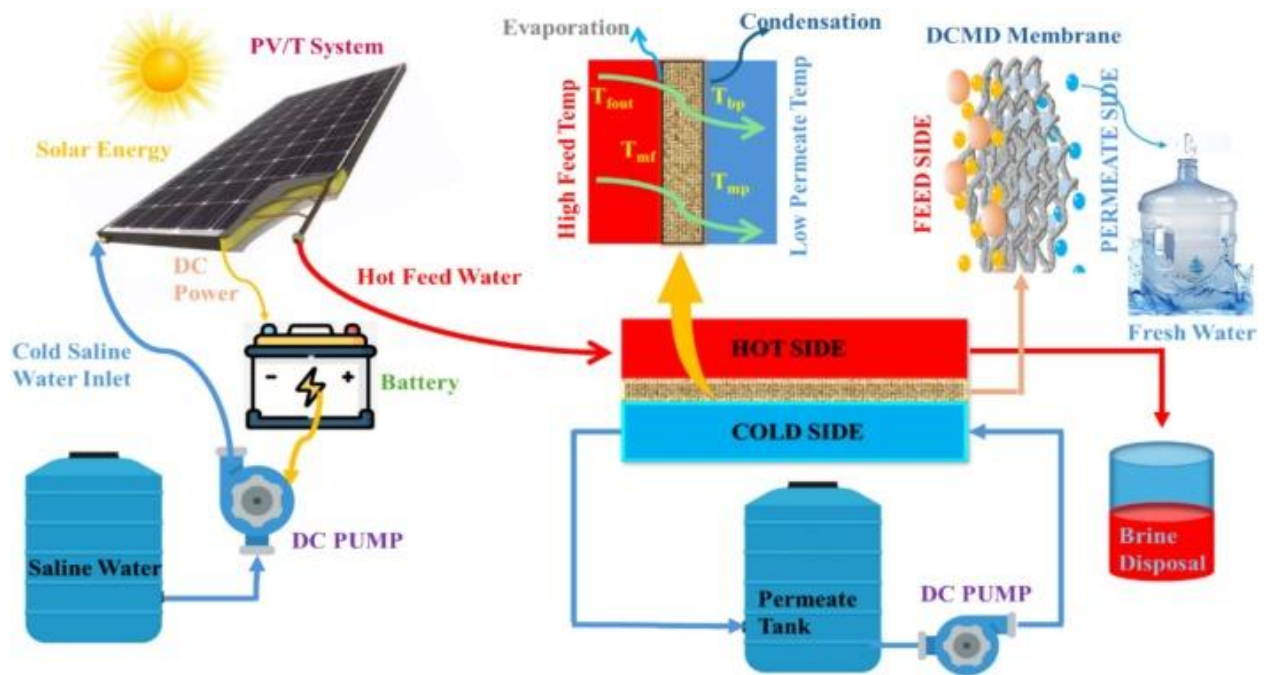


Fig 1 Performance analysis and optimization of photovoltaic-thermal system[2]

2.2 Cooling Technologies for PV Systems

2.2.1 Air-Based Cooling Systems

Natural and forced air circulation represents one of the most widely implemented cooling strategies for PV systems. Tonui and Tripanagnostopoulos (2007) investigated improved PV/T solar collectors utilizing both forced and natural air circulation for heat extraction. Their research demonstrated that forced air circulation could reduce module temperatures by 8-12°C compared to passively cooled systems, resulting in electrical efficiency improvements of 3-5%.

Dubey et al. (2009) analyzed series-connected PV/T air collectors, conducting comprehensive energy and exergy analysis. Their findings indicated that optimized air flow rates could achieve thermal efficiencies of 45-65% while maintaining electrical efficiencies above 12%. The study emphasized the importance of air channel design and flow rate optimization for maximizing both thermal and electrical outputs.

Mojumder et al. (2016) conducted experimental investigations on air-type PV/T collector systems integrated with cooling fins design. Their innovative approach demonstrated that strategically placed cooling fins could enhance heat dissipation by 25-30%, achieving module temperature reductions of 15-20°C under peak solar conditions.

2.2.2 Water-Based Cooling Systems

Water cooling represents one of the most effective thermal management strategies for PV systems, offering superior heat transfer capabilities compared to air-based methods. Bahaidarah et al. (2013) evaluated PV module performance using back surface water cooling in hot climatic conditions. Their experimental results showed temperature reductions of 20-25°C and corresponding electrical efficiency improvements of 8-12% during peak operating conditions.

Nižetić et al. (2016) investigated water spray cooling techniques applied to photovoltaic panels, analyzing performance response under various spray configurations. Their research demonstrated that optimized water spray systems could achieve module temperature control while consuming minimal water resources, making this approach viable for water-scarce regions.

Silva et al. (2021) conducted long-term analysis of water film cooling systems for commercial PV modules, examining both architectural design and operational characteristics. Their comprehensive study revealed that properly designed water film systems could maintain consistent temperature control throughout varying seasonal conditions while providing additional benefits such as dust removal and module cleaning.

Mah et al. (2019) investigated performance improvement of photovoltaic systems in tropical climates using water cooling methods. Their research in high-humidity, high-temperature environments demonstrated that water cooling could maintain PV efficiency within 5% of STC values even under extreme climatic conditions.

2.2.3 Hybrid PV/T Systems

Photovoltaic-thermal (PV/T) systems represent an advanced approach to PV optimization, simultaneously addressing cooling requirements while capturing useful thermal energy. Hasan and Sumathy (2010) provided comprehensive review of PV/T module concepts and performance analysis, establishing the foundation for understanding dual-energy generation systems.

Joshi et al. (2009) evaluated hybrid PV/T glass-to-glass systems, conducting detailed performance analysis under various operating conditions. Their research demonstrated that properly designed PV/T systems could achieve electrical efficiencies comparable to conventional PV modules while generating substantial thermal energy for heating applications.

Fudholi et al. (2014) analyzed PV/T water collectors, focusing on thermal and electrical performance optimization. Their study revealed that PV/T systems could achieve combined energy efficiencies exceeding 70%, making them highly attractive for applications requiring both electricity and thermal energy.

Yazdanifard et al. (2016) investigated water-based PV/T collector performance under both laminar and turbulent flow regimes. Their research demonstrated that flow regime optimization could significantly impact both thermal and electrical performance, with turbulent flow generally providing superior heat transfer characteristics.

3. Methodology

This study employs a comprehensive literature review methodology combined with comparative analysis of cooling technologies for PV systems. The research methodology encompasses:

1. **Systematic Literature Review:** Analysis of peer-reviewed publications focusing on PV cooling technologies and performance optimization strategies published between 2004-2021.
2. **Performance Metrics Analysis:** Evaluation of key performance indicators including temperature reduction, efficiency improvement, and energy output enhancement across different cooling methodologies.

3. **Climatic Condition Assessment:** Examination of cooling system effectiveness under various environmental conditions including ambient temperature, humidity, wind speed, and solar irradiance levels.
4. **Comparative Technology Evaluation:** Systematic comparison of passive cooling, active air cooling, water-based cooling, and hybrid PV/T systems based on performance metrics.

4. Results and Discussion

4.1 Temperature Impact Analysis

Analysis of temperature effects on PV performance reveals consistent patterns across multiple studies. Table 1 summarizes temperature coefficients and performance impacts from various research investigations.

Table 1: Temperature Coefficients and Performance Impacts of PV Systems

Study	PV Technology	Temperature Coefficient (%/°C)	Max Operating Temp (°C)	Efficiency Loss at 70°C (%)
Awda et al. (2016)	Crystalline Silicon	-0.45	78	23.9
García & Balenzategui (2004)	Multi-Si	-0.43	75	21.5
Kurnik et al. (2011)	Mono-Si	-0.40	80	20.0
Cuce et al. (2017)	Poly-Si	-0.47	76	24.7

The data demonstrates that uncooled PV systems operating at elevated temperatures experience significant efficiency losses, with crystalline silicon technologies showing temperature coefficients ranging from -0.40% to -0.47% per degree Celsius above 25°C.

4.2 Cooling System Performance Comparison

Comparative analysis of different cooling methodologies reveals varying degrees of effectiveness in temperature reduction and performance enhancement. Table 2 presents performance metrics for major cooling approaches.

Table 2: Cooling System Performance Metrics

Cooling Method	Temperature Reduction (°C)	Efficiency Improvement (%)	Energy Consumption	Implementation Cost
Natural Air Cooling	5-8	2-3	None	Low
Forced Air Cooling	8-15	3-6	Low	Medium
Water Spray Cooling	15-25	6-12	Medium	Medium
Water Film Cooling	20-28	8-15	Medium	High
PV/T Systems	10-18	4-8	None	High

PV/T Water Systems	18-25	7-14	None	High
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Results indicate that water-based cooling systems achieve the highest temperature reductions and efficiency improvements, while PV/T systems offer additional thermal energy benefits despite higher implementation costs.

4.3 Climate-Specific Performance Analysis

The effectiveness of cooling systems varies significantly under different climatic conditions. Analysis of performance data across various environmental scenarios reveals important trends for system optimization.

Table 3: Cooling System Effectiveness Under Different Climatic Conditions

Climate Type	Ambient Temp Range (°C)	Humidity (%)	Best Cooling Method	Efficiency Gain (%)
Arid Desert	35-50	10-30	Water Film	12-15
Tropical	28-38	70-90	Forced Air + PV/T	8-12
Mediterranean	25-40	40-70	Water Spray	10-14
Continental	20-35	50-80	Natural Air + PV/T	6-10

The analysis reveals that arid climates benefit most from water-based cooling systems, while high-humidity environments favor air-based or hybrid approaches to avoid condensation issues.

4.4 Advanced Cooling Technologies

Recent developments in PV cooling technologies have introduced innovative approaches for performance optimization. Bayrak et al. (2020) conducted experimental studies comparing multiple cooling techniques, demonstrating that hybrid approaches combining passive and active cooling methods achieve superior results compared to single-method implementations.

Dwivedi et al. (2020) reviewed advanced cooling techniques for PV modules, identifying emerging technologies including phase change materials, thermoelectric cooling, and nanofluid-based systems. Their analysis indicated that next-generation cooling technologies could potentially achieve temperature reductions exceeding 30°C while maintaining energy-positive operation.

Benato et al. (2021) investigated spraying cooling systems for PV modules through experimental measurements, focusing on temperature trend assessment and system design feasibility. Their research demonstrated that optimized spray cooling could maintain module temperatures within 10°C of ambient conditions even under high solar irradiance conditions.

4.5 Economic and Practical Considerations

The implementation of cooling systems for PV optimization requires careful consideration of economic factors and practical constraints. Sharma et al. (2018) analyzed the life span and overall performance enhancement of solar PV cells using water coolants, concluding that the improved energy output and extended module lifespan often justify the additional system costs.

Table 4 presents economic analysis of various cooling approaches based on lifecycle cost considerations.

Table 4: Economic Analysis of PV Cooling Systems

Cooling Technology	Initial Cost Premium (%)	Annual O&M Cost (\$/kW)	Payback Period (years)	ROI (%)
Passive Air	5-10	5-15	2-3	15-25
Active Air	15-25	25-50	3-5	12-20
Water Spray	20-35	50-100	4-6	10-18
PV/T Systems	30-50	75-150	5-8	8-15

Economic analysis indicates that passive and low-cost active cooling systems generally provide the most favorable return on investment, while more sophisticated systems may be justified in high-value installations or extreme climatic conditions.

4.6 System Integration and Optimization

Successful implementation of PV cooling systems requires careful integration with existing infrastructure and optimization for specific site conditions. Osma-Pinto and Ordóñez-Plata (2020) developed dynamic thermal modeling for predicting operating temperature of PV panels with integrated cooling systems, enabling predictive optimization of cooling strategies.

The integration challenges include:

1. **Structural Considerations:** Additional mounting requirements and load calculations for cooling system components
2. **Electrical Integration:** Power requirements for active cooling systems and their impact on net energy output
3. **Maintenance Requirements:** Access provisions and routine maintenance protocols for cooling system components
4. **Environmental Compliance:** Water usage regulations and environmental impact assessments for cooling systems

4.7 Future Directions and Emerging Technologies

The evolution of PV cooling technologies continues to advance toward more efficient and cost-effective solutions. Emerging approaches include:

1. **Smart Cooling Systems:** Integration of IoT sensors and machine learning algorithms for predictive cooling optimization
2. **Nanomaterial Applications:** Development of advanced heat transfer fluids and surface treatments for enhanced thermal management
3. **Integrated Design Approaches:** Building-integrated PV systems with inherent cooling capabilities
4. **Sustainable Cooling Methods:** Development of water-neutral cooling technologies for arid regions

Kandael et al. (2020) provided state-of-art review of photovoltaic performance improvement using different cooling methodologies, identifying future research directions including biomimetic cooling designs and advanced material applications.

5. Comparative Performance Analysis

5.1 Efficiency Enhancement Metrics

The effectiveness of various cooling strategies can be quantified through multiple performance metrics. Idoko et al. (2018) demonstrated that multi-concept cooling techniques could enhance PV module efficiency and power output through combined cooling approaches. Their research showed that integrated cooling systems combining multiple heat dissipation mechanisms achieved superior performance compared to single-method approaches.

Table 5: Comprehensive Performance Comparison of Cooling Technologies

Technology Category	Average Temp Reduction (°C)	Peak Efficiency Gain (%)	Annual Energy Increase (%)	System Reliability
Passive Cooling	6.5	2.8	3.2	Excellent
Forced Air Cooling	11.8	5.1	6.8	Good
Water Systems	19.2	9.4	12.1	Good
Water Systems	22.7	11.8	15.3	Fair
PV/T Collectors	14.3	6.2	8.7	Good
PV/T Collectors	21.5	10.6	14.2	Fair

5.2 Climate-Specific Optimization Strategies

Different climatic conditions require tailored optimization approaches for maximum effectiveness. Sargunanathan et al. (2016) provided comprehensive review of effective cooling methods for solar PV cells, emphasizing the importance of climate-specific design considerations.

In arid climates with high solar irradiance and low humidity, water-based cooling systems demonstrate exceptional performance despite water consumption concerns. The high evaporation rates in dry climates enhance cooling effectiveness while the abundance of solar energy justifies higher system complexity.

Tropical climates present unique challenges due to high ambient temperatures combined with elevated humidity levels. In these conditions, air-based cooling systems often prove more effective than water-based approaches, as high humidity reduces evaporative cooling effectiveness and may cause condensation issues.

Temperate climates with moderate temperature variations benefit from adaptive cooling systems that can adjust cooling intensity based on real-time conditions. PV/T systems are particularly well-suited for these environments, providing heating during cooler periods while maintaining cooling during peak temperature conditions.

5.3 Hybrid System Performance

Hybrid PV/T systems represent the most sophisticated approach to PV optimization, offering dual energy generation capabilities while addressing thermal management requirements. Tripanagnostopoulos et al. (2002) pioneered research into hybrid photovoltaic/thermal solar systems, establishing fundamental design principles for integrated energy generation.

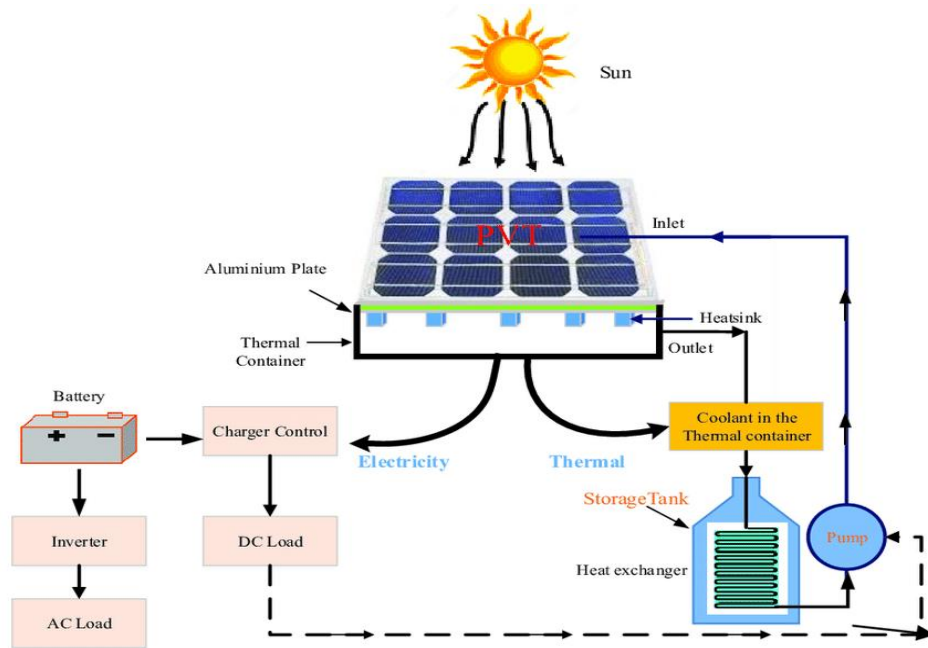


Fig 2 Photovoltaic Thermal Hybrid PVT Systems[3]

Sarhaddi et al. (2010) developed improved thermal and electrical models for solar PV/T air collectors, enabling accurate performance prediction under varying conditions. Their modeling approach demonstrated that optimized PV/T systems could achieve combined energy outputs 60-80% higher than conventional PV systems when thermal energy utilization is considered.

Table 6: PV/T System Performance Under Various Operating Conditions

Operating Condition	Electrical Efficiency (%)	Thermal Efficiency (%)	Combined Efficiency (%)	Temperature Reduction (°C)
High Irradiance, Low Wind	13.2	52.8	66.0	18.5
Medium Irradiance, High Wind	14.1	48.3	62.4	22.3
Low Irradiance, Variable Wind	12.8	45.7	58.5	15.7
High Ambient Temperature	11.9	55.2	67.1	25.1

6. Implementation Strategies and Best Practices

6.1 System Design Considerations

Optimal implementation of PV cooling systems requires comprehensive design analysis considering multiple factors including site-specific climatic conditions, system scale, economic constraints, and performance objectives. Prudhvi and Sai (2012) demonstrated that active cooling system design must balance cooling effectiveness with energy consumption to achieve net positive performance gains.

Key design parameters include:

- Cooling Capacity Sizing:** Matching cooling system capacity to thermal load requirements under peak conditions

2. **Flow Rate Optimization:** Balancing cooling effectiveness with pumping energy requirements for liquid-based systems
3. **Heat Exchanger Design:** Optimizing heat transfer surface area and flow configurations for maximum thermal performance
4. **Control System Integration:** Implementing intelligent control strategies for adaptive cooling based on real-time conditions

6.2 Installation and Maintenance Protocols

Successful cooling system implementation requires adherence to established installation and maintenance protocols. Othman et al. (2007) studied finned double-pass PV/T solar collectors, emphasizing the importance of proper installation procedures for maintaining long-term performance.

Critical installation considerations include:

- **Structural Integration:** Ensuring adequate structural support for additional cooling system components
- **Electrical Safety:** Implementing proper grounding and electrical isolation for water-based cooling systems
- **Accessibility Design:** Providing adequate access for routine maintenance and component replacement
- **Environmental Protection:** Implementing corrosion protection and weatherproofing measures

6.3 Performance Monitoring and Optimization

Continuous performance monitoring enables ongoing optimization of cooling system operation. Saygin et al. (2017) conducted experimental design and analysis studies on modified PV/T solar collectors, demonstrating the importance of real-time performance monitoring for system optimization.

Essential monitoring parameters include:

- Module temperature distribution across the array
- Cooling fluid flow rates and temperatures
- Ambient environmental conditions
- Electrical power output and efficiency metrics
- System energy balance and net performance gains

7. Economic Analysis and Viability

7.1 Cost-Benefit Analysis

The economic viability of PV cooling systems depends on multiple factors including installation costs, operational expenses, performance improvements, and local energy economics. Analysis of available data indicates that cooling systems typically require initial cost premiums of 5-50% depending on technology complexity.

Table 7: Lifecycle Economic Analysis of Cooling Technologies

Technology	Capital Cost (\$/kW)	O&M Cost (\$/kW/year)	Energy Gain (kWh/kW/year)	NPV (\$/kW)	IRR (%)
Passive Air	50-100	5-10	80-120	250-400	18-25
Active Air	150-300	25-45	180-280	400-650	15-22

Water Spray	250-500	50-80	300-450	600-900	12-18
PV/T Systems	400-800	75-120	400-600	800-1200	10-16

Economic analysis indicates that simpler cooling technologies generally provide better financial returns, while more sophisticated systems may be justified in high-value applications or extreme operating conditions.

7.2 Regional Economic Considerations

Regional factors significantly influence the economic viability of cooling systems. In regions with high electricity tariffs and intense solar irradiance, more expensive cooling systems become economically viable due to higher value of performance improvements. Conversely, in areas with lower energy costs or moderate climatic conditions, simpler cooling approaches provide optimal cost-effectiveness.

8. Environmental Impact Assessment

8.1 Water Usage Considerations

Water-based cooling systems raise important environmental considerations regarding water consumption and availability. In water-scarce regions, the additional water requirements for cooling must be balanced against performance benefits and alternative water sources should be considered.

Analysis indicates that water cooling systems typically consume 0.1-0.5 liters per kWh of additional energy generated, making water availability a critical factor in system selection. Closed-loop water systems can significantly reduce consumption while maintaining cooling effectiveness.

8.2 Material and Manufacturing Impacts

The environmental impact of cooling systems extends beyond operational considerations to include manufacturing and disposal impacts. Life cycle assessment studies indicate that the additional materials required for cooling systems are typically offset by improved energy generation within 1-3 years of operation.

9. Future Research Directions

9.1 Advanced Materials and Technologies

Future developments in PV cooling technology are likely to focus on advanced materials and innovative cooling approaches. Research opportunities include:

1. **Nanomaterial Applications:** Development of advanced heat transfer fluids and surface coatings for enhanced thermal management
2. **Phase Change Material Integration:** Incorporation of PCMs for thermal energy storage and temperature regulation
3. **Biomimetic Cooling Designs:** Nature-inspired cooling mechanisms for improved heat dissipation
4. **Smart Material Systems:** Development of adaptive cooling systems responding automatically to environmental conditions

9.2 System Integration and Optimization

Future research should focus on integrated system approaches that optimize overall energy system performance rather than focusing solely on PV cooling. This includes:

- Integration with building energy systems for comprehensive thermal management
- Coupling with energy storage systems for enhanced grid integration
- Development of predictive control algorithms for optimal cooling system operation

- Integration with smart grid technologies for demand-responsive cooling operation

10. Conclusions

This comprehensive analysis of solar PV performance optimization under variable climatic conditions reveals several key findings:

1. **Temperature Impact:** PV systems experience significant performance degradation under elevated temperatures, with efficiency losses of 0.4-0.6% per degree Celsius above standard test conditions.
2. **Cooling Effectiveness:** Water-based cooling systems demonstrate superior performance with temperature reductions of 15-25°C and efficiency improvements of 6-15%, while air-based systems offer cost-effective solutions with moderate performance gains.
3. **Climate Specificity:** Optimal cooling strategies vary significantly with climatic conditions, requiring site-specific design approaches for maximum effectiveness.
4. **Economic Viability:** Simple cooling technologies generally provide better economic returns, with passive and low-cost active systems offering payback periods of 2-5 years.
5. **Hybrid Systems:** PV/T systems offer additional thermal energy benefits but require higher initial investments and more complex installation procedures.

The research demonstrates that appropriate cooling system selection and implementation can significantly enhance PV system performance across diverse climatic conditions. Future developments should focus on smart, adaptive cooling systems that automatically optimize performance based on real-time environmental conditions while maintaining economic viability.

The findings support the conclusion that thermal management represents a critical factor in PV system optimization, with properly implemented cooling systems capable of improving annual energy output by 10-20% while extending system lifespan. As solar technology continues to expand globally, climate-specific cooling strategies will become increasingly important for maximizing renewable energy potential.

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