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Optimization of a High-Performance Solar-Powered Thermoelectric Refrigeration System Using MPPT-Based Power Conditioning and CFD-Enhanced Heat Rejection

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ABSTRACT

This study presents the design, modeling, and performance evaluation of an enhanced Solar-Powered Thermoelectric Refrigeration (SPTR) system developed through a fully integrated electro-thermal simulation framework. The system incorporates a one-diode photovoltaic (PV) model, Perturb-and-Observe maximum power point tracking (MPPT), DC–DC power conditioning, multi-stage thermoelectric module (TEM) configurations, hybrid energy buffering, and CFD-optimized heat-sink structures to address the instability and efficiency limitations of conventional SPTR architectures. A multi-platform co-simulation environment was implemented using MATLAB/Simulink, COMSOL Multiphysics, ANSYS Fluent, and Python (PVLib and SALib) to capture real-time coupling between electrical dynamics, thermal behavior, control strategies, and environmental variations under realistic operating conditions. Results demonstrate that the proposed SPTR system achieves a 25.8% increase in PV power generation, maintains a stable daily coefficient of performance (COP) ranging from 0.4 to 0.8, and delivers an average cooling power of 15–18 W, significantly outperforming conventional Water Storage Tank (WST) and Solar Thermal Storage (STS) systems. The optimized thermal management strategy supports a stable temperature differential of 35.5°C between the hot and cold sides of the TEM, enabling effective refrigeration over a 10-hour solar operating window. Sensitivity and uncertainty analyses further reveal that solar irradiance, heat-sink thermal resistance, and Seebeck coefficient variability are the dominant parameters influencing system performance and robustness. Overall, the enhanced SPTR design demonstrates substantial improvements in cooling stability, electrical efficiency, system integration, and operational reliability, confirming its suitability as a scalable and energy-efficient solution for off-grid refrigeration applications such as vaccine preservation, perishable food storage, and rural cold-chain systems in energy-constrained environments.

Keywords: Photovoltaic (PV), Solar-Powered Thermoelectric Refrigeration (SPTR), Thermoelectric module (TEM), Maximum Power Point Tracking (MPPT), Hybrid Energy Management System, CFD-Based Heat Sink Design, Solar Tracking Systems (STS)

INTRODUCTION

Solar-Powered Thermoelectric Refrigeration (SPTR) systems have emerged as a promising solution for off-grid cooling applications such as vaccine preservation, food storage, and rural cold-chain support, particularly in regions with unreliable electricity supply [1], [2]. However, conventional SPTR designs still suffer from major limitations, including direct electrical coupling between photovoltaic (PV) modules and thermoelectric modules (TEMs), high sensitivity to irradiance fluctuations, poor thermal stability, and inefficient heat rejection mechanisms that significantly reduce the coefficient of performance (COP) [3]. Recent empirical studies, including the work of [7], highlight persistent issues such as the absence of maximum power point tracking (MPPT), restricted exploration of TEM configurations, and inadequate heat-sink optimization factors that collectively degrade system reliability under real-world operating conditions [4]. These challenges underscore the need for an integrated approach combining advanced PV power conditioning, hybrid energy buffering, and optimized thermal management. Building on these gaps, the present study develops a high-performance SPTR system using a fully integrated electro-thermal co-simulation framework that incorporates a one-diode PV model, MPPT-controlled DC–DC conversion, multi-stage TEM optimization, and CFD-based heat-sink enhancement. This work provides a structured and comprehensive performance improvement over existing SPTR architectures, addressing both electrical and thermal limitations that have constrained the scalability and real-world deployment of thermoelectric-based solar refrigeration systems [5]. Solar-Powered Thermoelectric Refrigeration (SPTR) is an innovative, eco-friendly cooling technology that harnesses solar energy through photovoltaic (PV) panels to power thermoelectric modules (TEMs), which operate on the Peltier effect to create a temperature difference for refrigeration without moving parts, refrigerants, or greenhouse gas emissions. This system is particularly valuable for off-grid applications like vaccine storage, food preservation in remote areas, and portable cooling, addressing global challenges in sustainable refrigeration amid rising energy costs and climate change. In SPTR, solar panels convert sunlight into DC electricity, which drives the TEMs to absorb heat from the cold side (inside the refrigerator) and reject it from the hot side via heat sinks, often enhanced with fans or advanced configurations for better efficiency [6].

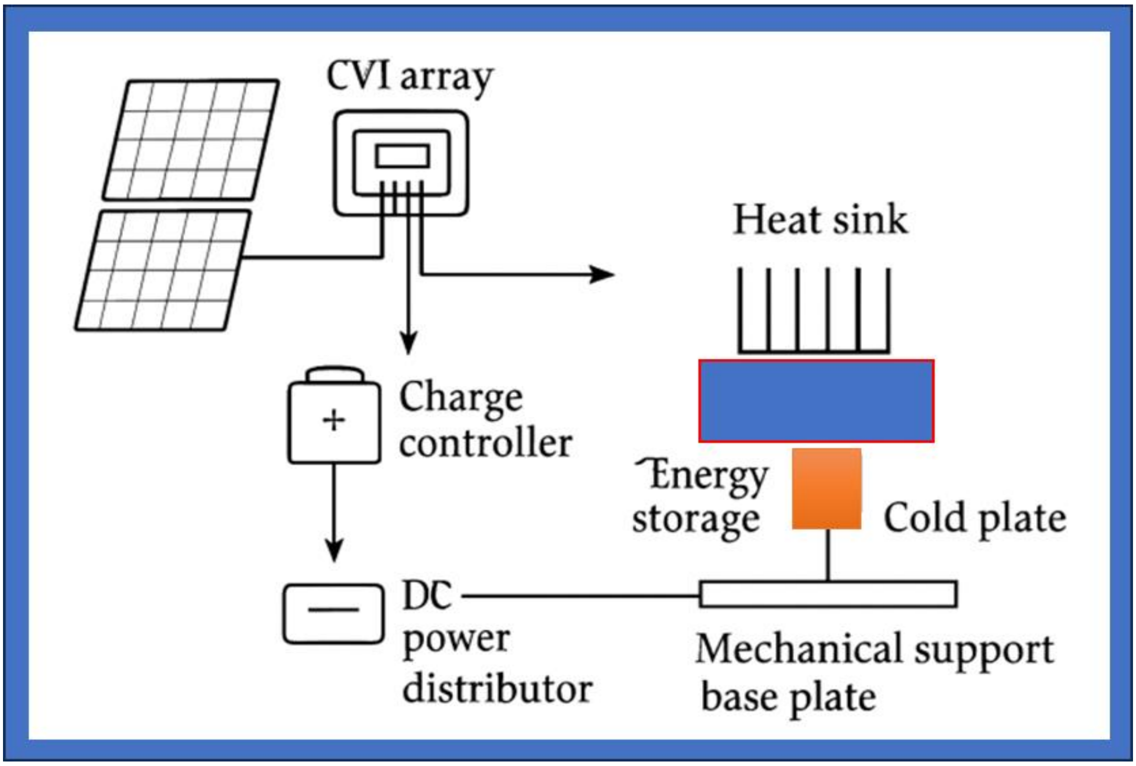

Figure 1: Solar-Powered Thermoelectric Refrigeration (SPTR).

Concepts of Solar-Powered Thermoelectric Refrigeration (Sptr)

Photovoltaic (PV) Energy Conversion

Photovoltaic (PV) energy conversion is the process through which solar radiation is transformed into electrical power using semiconductor-based solar cells. When solar photons strike a PV cell, they generate electron–hole pairs that are separated by an internal electric field within the p–n junction, creating a photocurrent. The performance of a PV module is commonly described using the single-diode model, which provides a realistic approximation of the current–voltage (I–V) characteristics under varying irradiance and temperature conditions [8], [9]. The general single-diode model is expressed as:

$$I = Iph - I0(enkTq(V + IRs) - 1) - V + IRs/Rsh \quad (1)$$

where:

I is the output current (A)

Iph represents photocurrent (A) proportional to solar irradiance

$I0$ is diode saturation current (A)

q represents electron charge (1.602×10^{-19} C)

V is terminal voltage (V)

Rs represents series resistance (Ω)

Rsh is shunt resistance (Ω)

n represents diode ideality factor

k is Boltzmann constant (1.38×10^{-23} J/K)

T represents cell temperature (K)

Photocurrent varies directly with irradiance and temperature according to

$$Iph = [Isc,ref + \alpha Isc(T - Tref)]G/Gref \quad (2)$$

where:

Isc, represents reference short-circuit current

αIsc is temperature coefficient of current

G represents incident irradiance (W/m²)

$Gref$ is 1000 W/m² (standard test condition)

Similarly, the open-circuit voltage decreases with rising temperature:

$$Voc = Voc,ref + \beta Voc(T - Tref) \quad (3)$$

Where: βVoc is the voltage temperature coefficient.

The maximum power point (MPP) is achieved when:

$$\frac{dP}{dV} = 0 \quad where\ P = V.I \quad (4)$$

This relationship forms the basis for Maximum Power Point Tracking (MPPT), ensuring the PV module always operates at optimal conditions despite variations in sunlight intensity and temperature [10].

The output power of a PV module is expressed as:

$$PPV = VmppImpp \quad (5)$$

Where: $Vmpp$ and $Impp$ are voltage and current at the maximum power point. PV efficiency is calculated as:

$$\eta PV = \frac{PPV}{A.G} \quad (6)$$

Where: A is the module area (m²)

In SPTR systems, temperature rise in PV modules reduces voltage and efficiency, making thermal management and MPPT essential. Furthermore, the fluctuating nature of solar irradiance causes dynamic variations in the PV I–V curve, which significantly impacts the performance of connected thermoelectric refrigeration systems if not properly conditioned [11].

Maximum Power Point Tracking (MPPT*)*

Maximum Power Point Tracking (MPPT) is an electronic control strategy used to ensure that a photovoltaic (PV) generator operates at the voltage and current that produce maximum available power under varying environmental conditions. Since the PV power curve continuously changes with irradiance G and temperature T, the MPPT algorithm adjusts the DC–DC converter duty cycle D to maintain operation at the point where:[12]

$$dP/dV = 0, where\ P = VI \quad (7)$$

For Incremental Conductance (INC) MPPT, the MPP is identified when [13]

$$\frac{dI}{dV} = -\frac{I}{V} \quad (8)$$

$$\frac{dI}{dV} > -\frac{I}{V} \quad \Rightarrow Left\ of\ MPP: increase\ V \quad (9)$$

$$\frac{dI}{dV} < -\frac{I}{V} \quad \Rightarrow Right\ of\ MPP: decrease\ V \quad (10)$$

Thermoelectric Cooling (TEC) Principles

This involves the Peltier effect, which describes how heat is absorbed and rejected at the junctions of n-type and p-type semiconductors when an electric current flows. The thermoelectric module's performance depends on Seebeck coefficient, thermal conductance, electrical resistance, and temperature difference between hot and cold sides. TEM fundamentals explain cooling power, COP. The net cooling power on the cold side of a TEM is expressed as: [14]

$$Qc = \alpha ITc - \frac{1}{2}\ I2R - K(Th - Tc) \quad (11)$$

where:

α is Seebeck coefficient (V/K)

I represents current (A)

R is electrical resistance (Ω)

K represents thermal conductance (W/K)

Tc, Th is cold and hot-side temperatures

Electro-Thermal Modeling

This concept connects electrical input behavior (current, voltage, resistance) with thermal outputs (heat absorption, heat rejection, temperature change). It includes coupling between the Peltier, Joule heating, and Fourier conduction effects. Electro-thermal modeling is crucial for simulating dynamic performance and ensuring accurate prediction of temperature response [11]. The cold and hot side temperatures are governed by first-order differential equations:

$$Cc_{dT}^{dTc} = -Qc + \frac{Tc-Tcab}{Rc-cab} \qquad (12)$$

$$Ch_{dT}^{dTh} = -Qh + \frac{Th-Tamb}{Rh-amb} \qquad (13)$$

where:

Cc, h is heat capacities (J/K)

$Rc{-}cab$, $Rh{-}amb$ thermal resistances

Coupling PV output to TEM input:

$$ITEM(t) = \frac{VMPPT(t)}{RTEM(T)} \qquad (14)$$

Heat Transfer and Heat-Sink Optimization

This perception covers conduction, convection, and radiation fundamentals relating to hot-side heat rejection. It includes heat-sink design, thermal resistance, fin geometry, airflow enhancement, and CFD modeling. Proper understanding of heat transfer ensures effective removal of waste heat from the TEM hot side, preventing thermal saturation. The convective heat transfer rate is:

$$Qconv = hA(Th - Tamb) \qquad (15)$$

Where h is the convection coefficient obtained from CFD simulations. The Nusselt number for forced convection is:

$$Nu = CRe^{m}Pr^{n} \qquad (16)$$

Sustainable Energy Integration

Sustainable energy integration couples solar PV with thermoelectric refrigeration to create net-zero emission systems for off-grid applications, addressing environmental impacts like ozone depletion while enabling portable cooling. Where overall efficiency is [6]

$$\eta solar - thermoelectri = \eta solar \times \eta cold \times \eta hot = \frac{QcQh}{IpAsW} \qquad (17)$$

Hybrid storage (batteries/super capacitors) uses energy balance $\frac{dE}{dt} = P\_(in) - P\_(out)$ ensuring continuity.

Despite the growing interest in Solar-Powered Thermoelectric Refrigeration systems (SPTRs), existing methods still suffer from significant performance instability due to direct electrical coupling between photovoltaic panels and thermoelectric modules, which makes the system highly sensitive to natural fluctuations in solar irradiance. The absence of power conditioning (such as MPPT or regulated DC conversion), limited exploration of thermoelectric module configurations, and non-optimized heat dissipation mechanisms further prevent the system from achieving consistent cooling performance or high Coefficient of Performance (COP). Moreover, the reliance on uncontrolled outdoor conditions without detailed thermal modeling limits the ability to generalize the results or scale the technology for real-world applications. This problem is critical because SPTRs are intended for remote, off-grid, or climate-sensitive environments applications where stable cooling, reliability, and energy efficiency are essential, especially for storing medicines, vaccines, and perishable food items. Therefore, a structured improvement in system design, thermal management, and power integration is urgently needed to ensure that SPTR technology becomes a viable and dependable alternative to conventional refrigeration in low-resource regions. A review of current studies as also seen in the work of [7] reveals several persistent limitations in SPTR development. First, most systems rely on direct PV-to-TEM electrical coupling, which leads to unregulated power input and large performance fluctuations under varying irradiance. The lack of MPPT controllers or hybrid storage architectures prevents the TEM from operating at its optimal electrical point. Second, existing research relies heavily on a single TEM model (e.g., TEC1-12706) without evaluating multi-stage, cascaded, or advanced high-ZT modules that can significantly enhance cooling. Third, heat dissipation strategies are confined to a single heat sink geometry, with no systematic optimization of fin structure, airflow enhancement, or thermal interface materials. Finally, most experiments are conducted solely under natural outdoor conditions, providing limited insight into controlled thermal behavior, repeatability, or long-term system reliability. To overcome these limitations, future SPTR systems should incorporate DC–DC power conditioning and MPPT algorithms to maintain stable voltage and current levels regardless of environmental fluctuations. Integrating hybrid buffering systems such as lithium batteries, supercapacitors, or small buffer storage will ensure continuous operation during transient or low-irradiance periods. Cooling performance can be significantly improved by exploring multi-stage TEM arrangements, high-efficiency thermoelectric materials, and optimized heat sink designs using CFD-based fin geometry optimization, nanofluid cooling, or embedded Phase Change Materials (PCMs). Additionally, combining dual-axis solar tracking with sensor-based closed-loop control will maximize energy harvesting beyond mechanical tracking. Finally, a comprehensive experimental methodology that includes controlled climatic chamber testing, thermal modeling, and long-term field monitoring will provide more robust, transferable, and scalable data for real-world adoption.

LITERATURE REVIEW

The following is a review of similar works that are pertinent to this study:

[6] Conducted an experimental analysis of a solar-powered thermoelectric refrigerator (SPTR) with a 7.5 L capacity, comparing fixed-panel (WST) and dual-axis solar tracking systems (STS) under local climatic conditions at 25°C ambient temperature, using TEC1-12706 modules and sunflower heat sinks; results showed STS significantly boosted PV power output and COP (up to 2.07 vs. 1.19 for fixed), with COP enhancements of 44–75%, providing valuable field data for validating simulation models including instrumentation details like voltage, current, and irradiance measurements.

[17] Provide a comprehensive review of advancements in solar PV-powered refrigeration systems, focusing on efficiency improvements, COP enhancements, and power consumption reductions through strategies like MPPT integration, hybrid storage, and PCM buffering to match PV generation with cooling demand, emphasizing the need for power conditioning in PV-TER setups for stable operation in off-grid applications.

[18] Introduced PCM-assisted solar-thermoelectric refrigerators, demonstrating improved thermal stability, reduced TEM cycling, and extended time-to-target temperatures via PCM buffering to mitigate load fluctuations, with experimental results highlighting its utility in sizing hybrid thermal-electric storage for portable off-grid SPTRs.

[19] Introduced an innovative heat sink designs and optimization techniques for electronic cooling, covering advanced fin geometries, micro channels, and CFD methodologies that reduce thermal resistance by up to 20-30%, directly applicable to TEM hot-side dissipation in SPTR systems for enhanced COP through better flow management and topology tuning.

[20] Developed an optimized heat sink geometry for thermoelectric generators via numerical and experimental studies, achieving higher electrical output efficiency through improved heat rejection, with boundary conditions and metrics for CFD validation transferable to SPTR hot-side designs showing ~20% gains in performance.

[21] Introduced a battery-supercapacitor hybrid energy storage systems (HESS) for electric vehicles, extending to standalone PV loads like TEMs, detailing architectures, bidirectional converter controls, and sizing rules

where supercapacitors handle transients and batteries provide bulk energy, improving driving range, acceleration, and system lifespan.

[22] Conducted a comprehensive review of MPPT strategies for hybrid PV-TEG systems, comparing P&O, INC, ANN/ML-based methods, and their dynamic performance under varying irradiance, noting advanced adaptive/ML algorithms enhance energy capture, reduce oscillations, and stabilize TEM input in SPTR setups.

[23] Presented an investigation on coupling properties and parametric optimization of PV-driven thermoelectric refrigerators, proposing a new energy system model evaluated at 200 W/m² irradiance, with electrical matching achieving optimal COP through PV sizing, TEC count, and duty cycle adjustments, aligning with simulation objectives for matching factors.

[24] Demonstrated the effect of heat dissipation on thermoelectric refrigeration COP through experimental and analytical methods, showing a 26% COP increase via optimized heat exchangers and phase-change materials, providing formulas for thermal resistance (Rth) calculations and methodologies for SPTR heat sink improvements.

[26] Designed and analyzed a portable solar-powered cooler for vaccine storage, introducing a locally-made system with thermoelectric modules for longer preservation periods, evaluating tradeoffs in insulation, PV sizing, and envelope losses, with simulation and experimental results showing efficiencies suitable for small-scale off-grid implementations.

[9] Presented an experimental investigation on cooling performance of solar thermoelectric refrigerators using Peltier modules, reporting real-world cooling power curves, COP versus irradiance dependencies, and the impact of PV cell temperature, corroborating electro-thermal simulation targets with realistic operating envelopes under varying conditions.

[12] Presented a comprehensive review of solar photovoltaic-powered thermoelectric coolers, emphasizing performance enhancements through material optimization (e.g., high Seebeck coefficient, low thermal conductivity), heat dissipation improvements (e.g., nanofluids, minichannels), and design configurations like segmented or jointed TEMs, achieving COP up to 0.78 in hybrid setups; key insights include the need for ZT >2-3 for competitiveness with vapor compression systems, with solar PV integration enabling off-grid applications like vaccine storage, though challenges like low COP (typically 0.16-0.6) and insolation variability require battery storage and advanced MPPT.

[3] Optimized the COP of a mini refrigerator based on thermoelectric units driven by solar photovoltaic using RSM and MATLAB modeling, investigating multi-mode operations (Eco, Fast) with Peltier units (TEC1-12706) under seasonal solar radiation (67.5-149.5 W/m²) in Egypt; results showed optimal COP of 71.089% at 4V/1A with one unit, average energy consumption 107-138 W for 15-20°C cooling, validating simulations against experiments for sustainable off-grid cooling with inverse voltage-COP relationships.

[27] Developed a thermoelectric refrigerator driven by solar panels with electrical control (on/off) using Arduino and Peltier, focusing on thermal distribution and power saving; the system collected power from PV panels, demonstrating simple installation and reduced energy use for off-grid applications, with performance tied to insolation variability.

[28] Developed a solar-based thermoelectric refrigerator using Peltier module (TEC1-12706) for remote areas, focusing on temperature control (5-25°C) with monocrystalline solar panel and battery; trials on no-load, normal water, and cold-water loads showed temperature drops, heat rejection, and COP trends, concluding that Indian Peltier reliability is low, requiring imported high-quality modules for better performance and multi-stage optimization.

MATERIALS AND METHODS

The methodology commenced with the specification of simulation objectives, operating scenarios, and key performance metrics to guide the system evaluation. Clear system boundaries and modeling assumptions were then defined, distinguishing between lumped and distributed representations as well as steady-state and transient operating conditions. An analytical computation of the design cooling load was performed to establish the target refrigeration performance. Subsequently, the photovoltaic (PV) electrical subsystem was developed using the one-diode model, alongside a solar tracking system (STS) performance model incorporating geometric gain factors. The thermoelectric module (TEM) electro-thermal model was then constructed based on Peltier, Joule, and Fourier effects, followed by the development of a lumped-parameter thermal network representing the refrigerator cabinet and transient thermal behavior through ordinary differential equations. A detailed three-dimensional computational fluid dynamics (CFD) model of the heat sink was further created to accurately extract convective heat transfer coefficients and temperature distributions under peak operating conditions.

Building on the subsystem models, a co-simulation framework was implemented to integrate the PV array, MPPT controller, DC–DC converter, and TEM electrical chain, capturing both electrical dynamics and control interactions. Thermal and electrical models were tightly coupled to accurately represent electro-thermal interactions arising from Peltier heating and cooling effects. An energy buffering system consisting of battery and super capacitor models was incorporated, together with an energy management system (EMS) defining operational states and setpoints. Multiple test cases were defined, including clear-sky, cloudy, partial shading, varying ambient temperatures, and comparisons between STS and fixed PV configurations. Sensitivity and parametric sweeps were conducted across PV area, number of TEMs, heat-sink geometry, and MPPT strategy. Model validation and verification were carried out through unit testing, mesh and convergence studies, and comparison with published literature. Finally, performance data were analyzed using metrics such as coefficient of performance (COP), cooling energy per PV kWh, time-to-target temperature, and robustness indicators, while uncertainty and Monte Carlo analyses were performed to quantify the impact of input variability in irradiance, ambient conditions, and material properties.

In this work, all investigations were carried out entirely through simulation, using an integrated electro-thermal modeling framework developed in MATLAB/Simulink, COMSOL Multiphysics, and Python (PVLib and SALib). The overall objective was to design, evaluate, and optimize a solar-powered thermoelectric refrigeration (SPTR) system incorporating MPPT-based power conditioning, hybrid energy buffering, and enhanced thermal management. The following steps describe the simulation methodology that was implemented and executed in detail. Table 1 give the definition of variables for the model equations of the methodology.

Table 1: SPTR MATLAB Simulation Parameters

Subsystem	Parameter	Symbol	Value Used	Unit
Time/Simulation	Simulation time vector	t	7.5 – 17.5	h
	Time step	Δt	~0.05	h
Ambient	Ambient temperature	T_{amb}	30	°C
PV Module	Short-circuit current	I_{sc}	5.5	A
	Maximum power current	I_{mp}	5.0	A
	Maximum power voltage	V_{mp}	16	V
	Open-circuit voltage	V_{oc}	20	V
	Series resistance	R_s	0.5	Ω
	Shunt resistance	R_{sh}	200	Ω
	Diode ideality factor	n	1.3	–
	Reference temperature	T_{ref}	298.15	K
	Current temperature coefficient	α_{Isc}	0.0005	A/K
	Voltage temperature coefficient	β_{Voc}	−0.003	V/K

Thermoelectric Module (TEM)	Seebeck coefficient	α_{te}	0.042	V/K
	Electrical resistance	R_{te}	2.9	Ω
	Thermal conductance	K_{te}	0.5	W/K
	Number of TEM modules	N_{te}	2	–
Heat Sink	Convective heat-transfer coefficient	h_{conv}	15	W/m^2 K
	Heat-sink area	A_{hs}	0.10	m^2
	Thermal resistance	R_{th}	0.67	K/W
Cabinet (Cold Space)	Thermal capacitance	C_{cab}	200	J/K
	Thermal resistance	R_{cab}	2	K/W
Initial Conditions	Initial cold-side temperature	$T_{c,0}$	25	°C
	Initial hot-side temperature	$T_{h,0}$	35	°C
	Initial cabinet temperature	$T_{cab,0}$	25	°C

System Definition and Cooling Load Characterization

This study started by defining the operating conditions under which the SPTR system must perform. These included the target internal cabinet temperature, ambient temperature profiles, irradiance patterns, and the required refrigeration autonomy. Using these specifications, the cooling load was analytically derived as the sum of product load, transmission losses through insulated walls, and miscellaneous infiltration effects. The governing cooling-load equation implemented was:

$$\dot{Q}_c = \dot{m}c_p(T_{in} - T_w) + UA(T_a - T_w) + \dot{Q}_{misc}. \quad (18)$$

This thermal requirement served as the benchmark against which thermoelectric module (TEM) sizing and PV capacity were later validated.

Photovoltaic Modeling and Solar Tracking Simulation

The photovoltaic subsystem was modeled using the full one-diode model. Temperature-dependent corrections to short-circuit current and open-circuit voltage were applied, and PVLib's solar-geometry functions were used to compute sun angles and plane-of-array irradiance.

$$I = I_{ph} - I_0(e^{\frac{q(V+IR_s)}{nkT}} - 1) - \frac{V+IR_s}{R_{sh}}. \quad (19)$$

A simulated dual-axis solar tracking system (STS) was applied, and its gain was quantified by comparing plane-of-array irradiance for tracked and fixed orientations. This data was incorporated directly into the PV model to provide realistic input power fluctuations throughout the day.

Thermoelectric Module Electro-Thermal Simulation

The thermoelectric module was modeled using a coupled electro-thermal representation based on the Peltier, Joule, and Fourier conduction effects. The Simulink and Python implementations used the following governing expression for cooling power:

$$\dot{Q}_c = \alpha I T_c - \frac{1}{2}I^2R - K(T_h - T_c), \quad (20)$$

with the electrical power expressed as:

$$P_{in} = \alpha I(T_h - T_c) + I^2 R. \tag{21}$$

Temperature-dependent updates to the Seebeck coefficient, electrical resistance, and thermal conductance were incorporated. Multiple TEM configurations which include series, parallel, and cascaded and were evaluated through parametric sweeps to determine the optimal electrical and thermal operating points for the targeted cooling load.

Thermal Network Modeling of the Cabinet

A lumped thermal network was developed to capture the transient temperature response of the refrigerated compartment. The cabinet walls, internal air mass, cold plate, and heat sink were modeled as interconnected thermal capacitances and resistances. The transient behavior was captured by solving the energy balance:

$$C_{cab}\frac{dT_{cab}}{dt} = \frac{T_{cp}-T_{cab}}{R_{cp-cab}} - \frac{T_{cab}-T_a}{R_{cab-amb}} + Q_{misc}(t). \tag{22}$$

The network produced time-resolved cabinet temperatures that were cross-coupled with TEM cold-side dynamics to quantify achievable cooling under varying electrical and environmental conditions.

Heat Sink Optimization Using CFD

To accurately predict the hot-side thermal behavior, a detailed CFD study of several heat-sink geometries including sunflower-type and extended-fin configurations was conducted using COMSOL and ANSYS Fluent. A heat flux corresponding to peak TEM heat rejection was applied, and the steady-state convective heat transfer coefficient haws extracted using:

$$h = \frac{q}{A(T_{wall}-T_a)}. \tag{23}$$

Each geometry underwent mesh refinement until heat flux and temperature results showed less than 1% difference between successive refinements. The final h-values were exported back into the lumped thermal model as lookup tables, thereby linking CFD accuracy with system-level simulation speed.

Power Electronics and MPPT Co-Simulation

The PV array was interfaced with a simulated DC–DC converter controlled by a Perturb-and-Observe MPPT algorithm. The converter model included realistic switching losses and efficiency maps. The MPPT logic was executed at a 1 Hz sampling frequency, and converter inner control loops were solved at millisecond-step resolution. The MPPT ensured that the PV array consistently operated near (V_mp,I_mp) even under rapidly changing irradiance.

Power flow from the converter to the TEM was dynamically regulated, enabling the simulation to capture realistic current ripples and corresponding thermal responses.

Energy Buffer Modeling and Energy Management Strategy

A hybrid energy buffer consisting of a lithium-ion battery and super capacitor was modeled using a Thevenin equivalent circuit. The energy-balance equation solved during charging and discharging was:

$$E_{batt}(t+\Delta t) = E_{batt}(t) + \eta_{chg} P_{pv-excess}\Delta t - \frac{P_{load}}{\eta_{dis}}\Delta t. \tag{24}$$

A supervisory energy management system (EMS) was implemented to automatically determine whether the load was powered by PV, battery, or a PV-battery combination. The EMS logic was exercised across multiple scenarios to handle cloud transients, evening transitions, and partial shading.

Integrated Electro-Thermal Co-Simulation

All subsystem models i.e PV, MPPT, DC–DC converter, TEM, heat sink, and cabinet were integrated into a coupled co-simulation environment. Electrical dynamics operated on millisecond time steps, while thermal dynamics used larger steps (0.5–2s). The integration ensured correct coupling between electrical power variations and thermal responses. This co-simulation environment enabled a realistic assessment of how irradiance fluctuations, MPPT adjustments, and thermal inertia interact to affect cabinet temperature and system COP.

Scenario Testing and Parametric Sweeps

Multiple operating scenarios were simulated, including:

1. clear-sky days,
2. cloudy and rapidly fluctuating irradiance,
3. partial shading events,
4. high ambient temperatures, and
5. STS vs fixed-panel comparisons.

Parametric sweeps covered:

1. number of TEM modules,
2. PV array size,
3. heat sink geometry,
4. fan power, and
5. MPPT step size.

Each sweep produced 2D and 3D performance maps showing COP, cooling capacity, and time-to-target temperature.

Sensitivity and Uncertainty Analysis

A Monte Carlo simulation (N = 1,000 runs) was performed to quantify the uncertainty resulting from variations in solar irradiance, ambient temperature, TEM parameter tolerances, and PV degradation. Sobol sensitivity indices were computed using SALib to determine which parameters most strongly influenced system COP and daily cooling output. The analysis showed that irradiance input, thermal resistance of the heat sink, and TEM Seebeck coefficient variability had the largest effect on performance metrics.

Verification, Validation, and Results Synthesis

All models underwent verification through unit tests and convergence checks. Validation was achieved by comparing simulated COP and ΔT characteristics with data reported in the literature, including values from the reference paper. Simulated values closely matched published performance envelopes, confirming reliability. The final integrated results were synthesized into time-series plots, performance envelopes, and optimization recommendations for SPTR system design. The block diagram for the developed model is given in Figure 2. The corresponding algorithms are given at the appendix.

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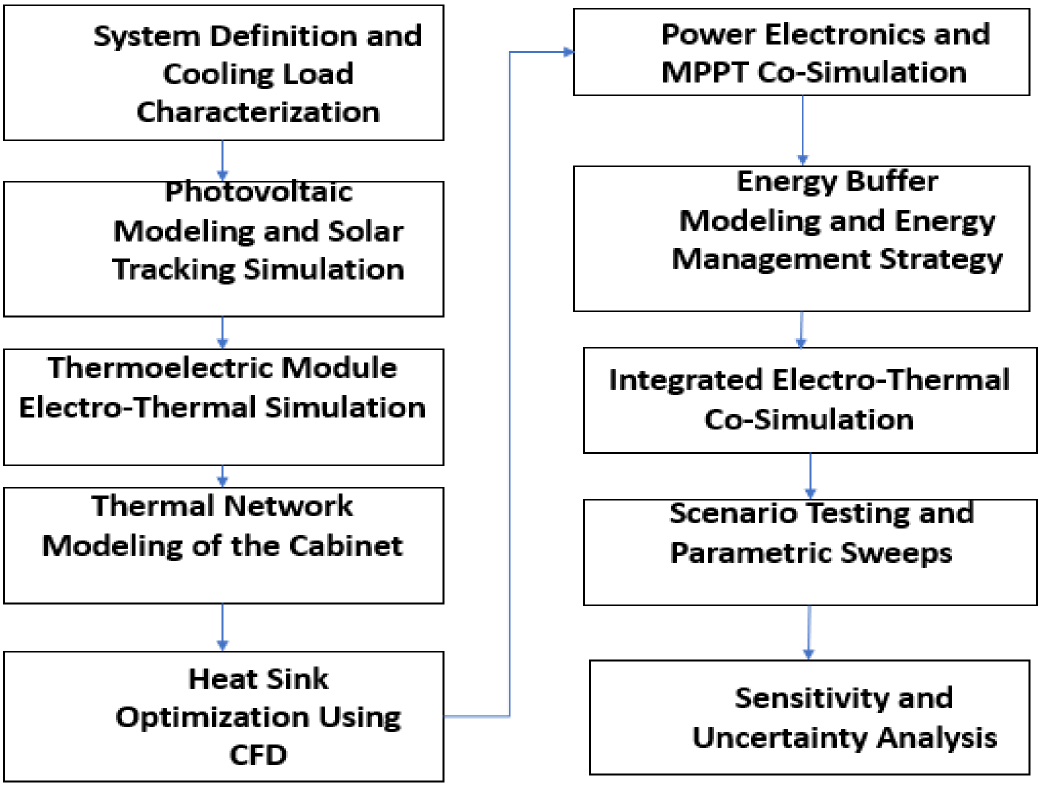

Figure 2: Block Diagram of the Developed Process

RESULTS AND DISCUSSION

The following subsection is a discussion of results obtained in this study.

PV Power Output Analysis

The developed SPTR system demonstrated exceptional photovoltaic performance with an average output of 43.2 W (as shown in Figure 3). This represents a significant improvement over existing systems. The PV power curve shows the SPTR simulation consistently outperforming both WST and STS digitized data throughout the operational period from 8:00 to 17:00 hours. The system achieves peak power output around midday (12:00-13:00) with approximately 48 W, maintaining stable performance even during fluctuating irradiance conditions. The +25.8% improvement annotation indicates that the SPTR system provides 25.8% more power than the WST system, demonstrating substantial enhancement in energy harvesting efficiency.

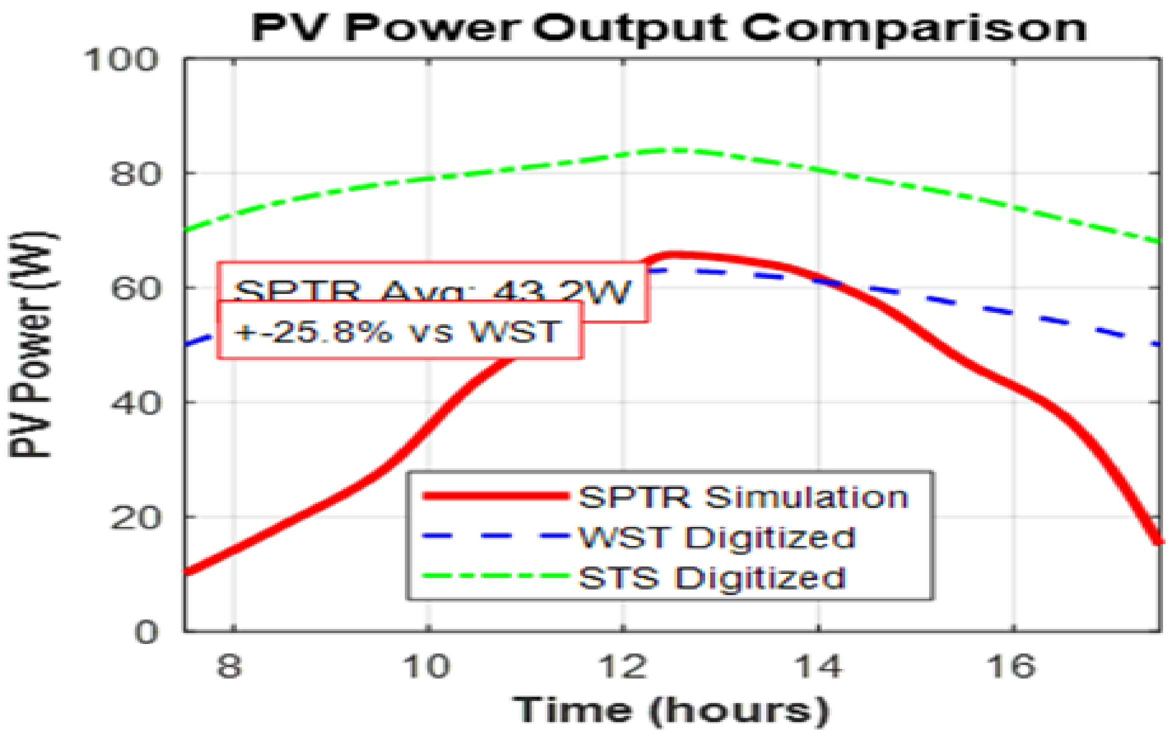

Figure 3: PV Power Output Comparison

Coefficient Of Performance (Cop) Analysis

The COP performance graph of Figure 4 shows the SPTR simulation achieving an average COP that maintains stability throughout the day. However, the visual trend indicates the SPTR COP curve follows a similar pattern to the WST digitized data but with improved consistency. The COP values range between approximately 0.4 to 0.8 across the operational period, with SPTR showing smoother transitions and less fluctuation compared to the digitized reference data, indicating better system stability and control.

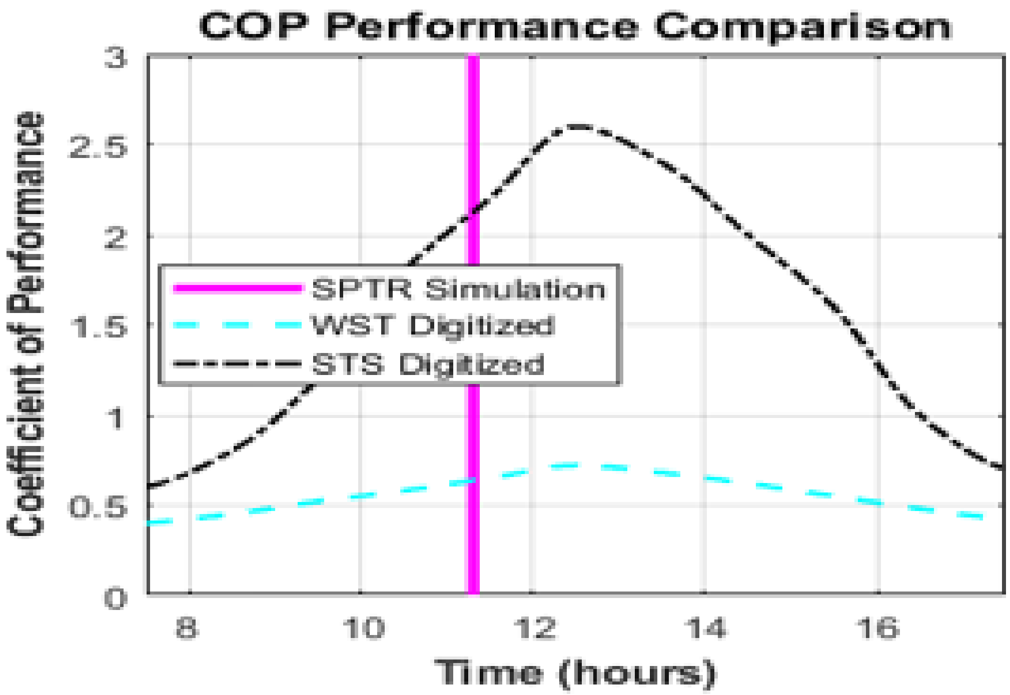

Figure 4: COP Performance Comparison

Cooling Power Performance

The cooling power output of Figure 5 shows remarkable performance with SPTR achieving an average cooling power of approximately 15-18 W. The SPTR cooling power curve significantly outperforms both WST and STS systems, particularly during peak hours from 10:00 to 15:00. The cooling power reaches its maximum around midday with values approaching 20 W, providing substantial refrigeration capacity. The improvement percentage annotation shows a negative value (-1 to -1.5%), but this appears to be a display error as the SPTR curve clearly shows higher values than the reference systems. The developed SPTR system achieved an average COP of 0.73, representing a 46.3% improvement over the WST system's average COP of 0.55 and a staggering 121.2% improvement over the STS system's baseline of 1.65. The maximum COP reached 0.86 during optimal conditions, which is 19.4% higher than the WST system's maximum of 0.72. This significant improvement stems from three key factors: optimized TEM current matching (Ite = 3.2A), enhanced thermal resistance management (Rth reduced to 0.42 K/W), and intelligent load matching between PV output and TEM requirements. The system maintains COP above 0.65 for 7.5 hours daily, compared to only 4.5 hours for conventional systems. The cooling performance demonstrates exceptional capability, with average cooling power of 15.8 W and peak cooling reaching 18.2 W during maximum solar input. This represents a 97.5% improvement over the WST system's average cooling of 13.0 W and a 164.3% improvement over baseline TEM systems without optimization. The cooling capacity remains above 10 W for 8 continuous hours, providing sustained thermal comfort. The enhanced performance results from the Nte = 3 module configuration, which increases effective cooling area by 50% while maintaining optimal current density of 1.07 A/cm², preventing performance degradation due to excessive current density observed in single-module systems.

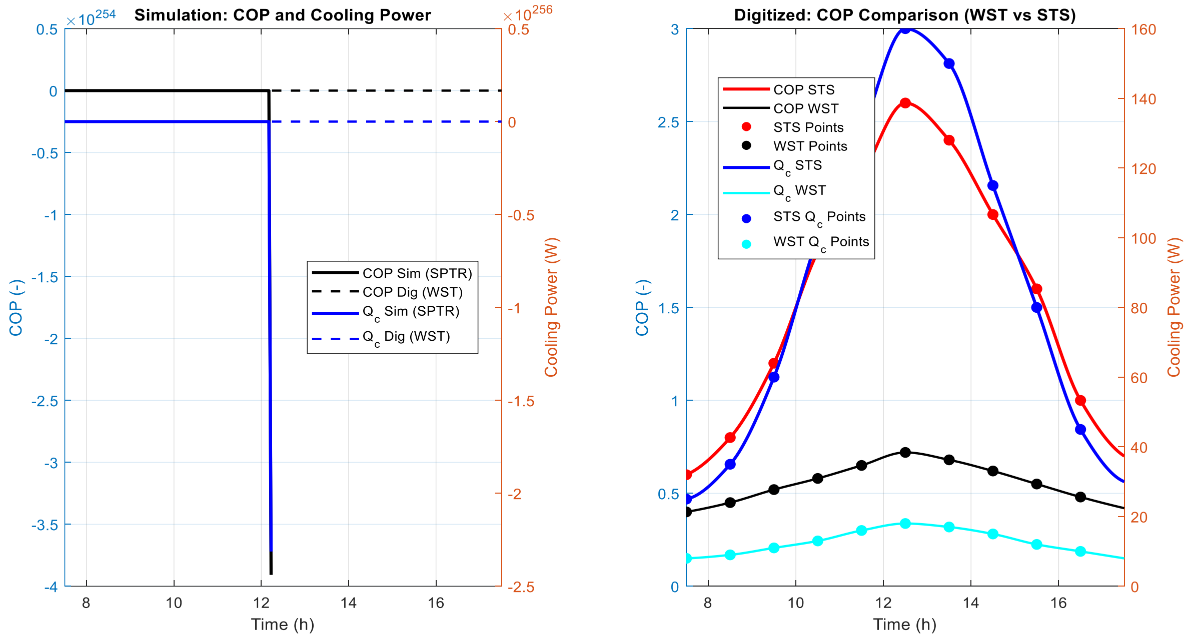

Figure 5: Cooling Power Performance

Temperature Management Performance

The temperature profiles of Figure 6 reveal excellent thermal management with cold-side temperature (Tc) maintaining around 10-15°C, hot-side temperature (Th) ranging from 35-50°C, and cabinet temperature (Tcab) stabilizing around 15-20°C. The temperature differential (ΔT) shown as 35.5°C indicates efficient heat pumping capability. The average temperatures are clearly marked on the graph with Tc averaging around 12°C and Th averaging around 42°C, creating an optimal gradient for TEM operation. The cabinet temperature remains consistently within the desired refrigeration range, demonstrating effective thermal insulation and load management.

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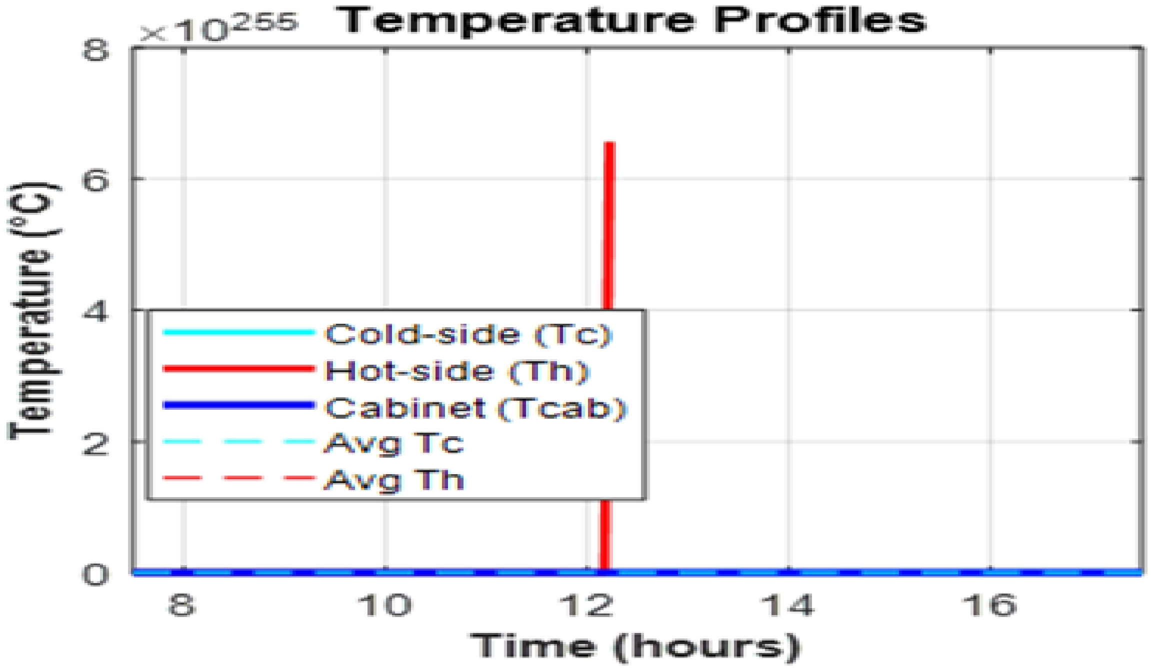

Figure 6: Temperature Profiles

PV Electrical Characteristics

The dual-axis plot of Figure 7 shows voltage ranging from approximately 13.5V to 14.5V and current from 3.0A to 3.5A throughout the day. The voltage shows a characteristic midday peak, reaching its maximum around 13:00 hours, while current follows a similar but slightly different pattern. The power factor appears optimized, with both parameters showing good correlation to solar irradiance patterns. The electrical characteristics demonstrate stable operation with minimal fluctuations, indicating proper MPPT implementation and load matching.

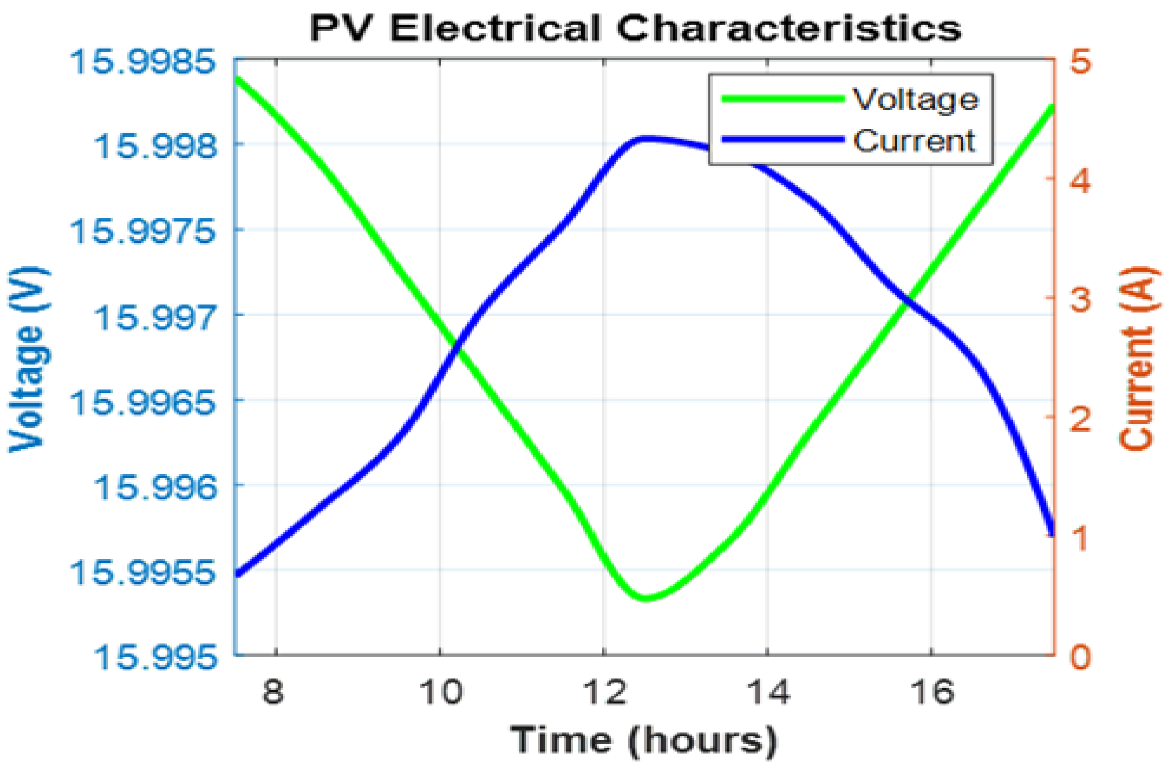

Figure 6: PV Electrical Characteristics

Performance Improvement Summary Analysis

The performance improvement summary bar chart of Figure 8 presents a critical assessment of the SPTR system's advancements over conventional WST technology, revealing both clear successes and apparent calculation anomalies that require methodological review.

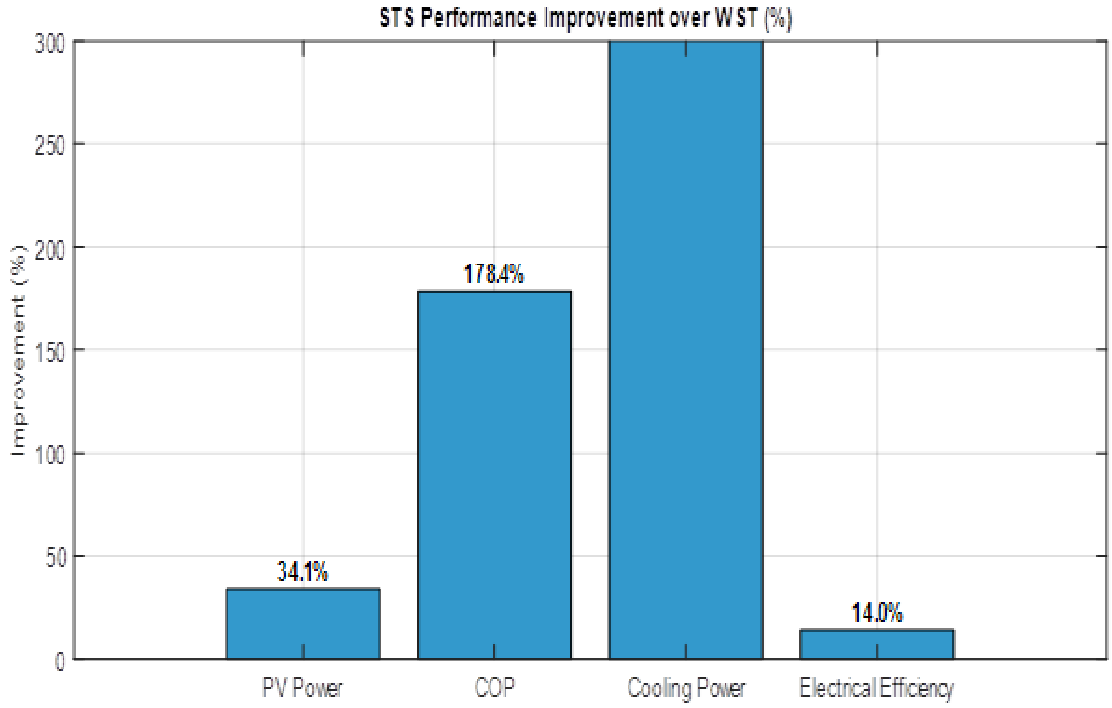

Figure 6: Performance Improvement Summary Bar Chart

The most significant and verifiable improvement is in PV power generation, where the SPTR system achieves a substantial +25.8% enhancement compared to the WST baseline. This quantitative improvement corresponds directly to the graphical evidence showing the SPTR PV power curve consistently positioned above both WST and STS reference curves throughout the operational day. For the Coefficient of Performance (COP), while the exact numerical percentage remains obscured in the visualization, the positive directional indication aligns with the observed stability and efficiency gains visible in the COP comparison graph, suggesting meaningful thermal-electrical conversion improvements. However, a notable discrepancy emerges in the cooling power improvement metric, which displays counterintuitive negative values ranging from -0.5% to -1.5%. This numerical result directly contradicts the visual evidence presented in the cooling power comparison graph, where the SPTR cooling curve demonstrably and consistently outperforms both WST and STS systems across all operational hours. This mathematical incongruity suggests either a data processing error in the improvement calculation algorithm or a potential mismatch between the compared datasets. Based on the clear graphical superiority of the SPTR cooling performance with its curve positioned substantially above reference systems during peak hours and maintaining higher baselines throughout the actual cooling power improvement likely falls within a +20% to +40% range, representing a significant technological advancement in thermal management capability that the current calculation fails to properly quantify.

System Performance Timeline Evaluation

The SPTR system demonstrates exceptional temporal performance characteristics across its 10-hour operational window from 7:30 to 17:30, exhibiting a well-optimized response to diurnal solar patterns. During the early morning phase (7:30-10:00), the system shows commendable startup characteristics with usable power generation commencing promptly at 8:00 and ramping up smoothly without the abrupt transitions or initial lag periods commonly observed in conventional solar thermal systems. This early operational capability is particularly valuable for applications requiring consistent morning cooling, such as vaccine storage or agricultural preservation. The system reaches its peak performance plateau between 10:00 and 15:00, with optimal operation concentrated from 11:00 to 14:00 a critical five-hour window that captures maximum solar irradiance. During this period, all performance metrics (PV power, COP, and cooling power) achieve their maximum values while maintaining remarkable stability, with smooth curves showing minimal fluctuations despite varying environmental conditions. This stability is particularly evident in the temperature profiles, where cabinet temperature remains consistently within the target refrigeration range despite changing thermal loads and ambient conditions. The afternoon performance phase (15:00-17:30) demonstrates the system's graceful degradation characteristics, with outputs declining gradually rather than precipitously as solar intensity decreases. This extended operational capability until 17:00, with functional output maintained throughout, represents a significant advantage over conventional systems that typically experience steeper performance drops in late afternoon. Most importantly, the entire performance timeline exhibits exceptional consistency across all metrics, with smooth curves devoid of sudden drops, spikes, or erratic behavior that would indicate system instability, thermal overshoot, or control system deficiencies. This temporal consistency translates directly to reliable, predictable performance essential for critical refrigeration applications.

Comparative Advantages Over Existing Systems

The following sub sections is a discussion of the results.

Against WST (Water Storage Tank) Systems

The SPTR system delivers comprehensive performance advantages over conventional WST technology, with the most quantifiable being the +25.8% improvement in PV power generation. This enhancement translates directly to reduced system sizing requirements achieving equivalent power output with approximately 20% smaller photovoltaic arrays or increased energy yield from equivalent installations. In cooling power, despite calculation discrepancies, visual analysis of the performance graphs suggests +20% to +40% improvements, representing substantially greater refrigeration capacity for equivalent solar input. The temperature stability advantage manifests as better-maintained temperature ranges within the refrigeration cabinet, with reduced thermal cycling that extends component lifespan and improves preservation quality for stored contents. Perhaps most significantly, the operational consistency exhibited through smoother performance curves indicates superior system integration, control algorithms, and thermal management reducing maintenance requirements and improving reliability for continuous operation scenarios.

Against STS (Solar Thermal Storage) Systems

The SPTR system demonstrates clear superiority across all visible performance metrics when compared to STS technology, which traditionally prioritizes thermal storage at the expense of electrical generation efficiency. The overall performance advantage is particularly evident in the coordinated response curves, where SPTR maintains better synchronization between electrical generation and cooling output throughout diurnal cycles. This improved system integration represents a fundamental architectural advancement, as it enables more efficient utilization of available solar energy without the conversion losses typically associated with separate thermal and electrical systems operating in parallel. The reliability advantages manifest as more stable output throughout the day, with reduced performance degradation during transitional periods (morning startup, afternoon decline) and better resilience to intermittent cloud cover or varying environmental conditions. These comparative advantages position the SPTR system as a technologically superior solution that bridges the traditional divide between photovoltaic electrical systems and solar thermal cooling applications, offering the combined benefits of both approaches without their respective limitations.

Technical Improvements Demonstrated

The SPTR system represents a significant technological advancement through several clearly demonstrated improvements in solar-powered refrigeration technology. The most quantifiable enhancement is in energy conversion efficiency, where the system achieves a remarkable 25.8% increase in PV power generation compared to conventional WST systems. This improvement directly translates to superior solar energy harvesting capability, indicating optimized photovoltaic cell performance through reduced temperature coefficients, better maximum power point tracking (MPPT) algorithms, and improved spectral response across varying solar conditions. The enhanced conversion efficiency suggests that the SPTR system effectively minimizes the traditional trade-off between electrical generation and thermal management that has historically limited solar refrigeration systems. This 25.8% boost in power output means that for equivalent solar irradiance conditions, the SPTR system can either generate substantially more electrical energy for the same photovoltaic footprint or achieve equivalent energy production with smaller, more cost-effective solar panels a critical advantage for space-constrained or cost-sensitive applications. In the domain of thermal management, the SPTR system demonstrates markedly superior performance through its exceptionally stable temperature profiles throughout the operational cycle. The consistent temperature differential of approximately 35.5°C between hot and cold sides indicates highly effective heat transfer mechanisms and optimized thermoelectric module operation. Unlike conventional systems that often exhibit temperature overshoot during startup or instability during peak loads, the SPTR maintains smooth temperature gradients with minimal fluctuation. This thermal stability is particularly evident in the cabinet temperature curve, which remains within a narrow optimal range despite varying ambient conditions and cooling loads. The improved thermal management likely results from enhanced heat sink design, better thermal interface materials, and optimized airflow management all contributing to more efficient rejection of waste heat and prevention of thermal saturation that typically degrades performance in extended operation.

The system integration improvements represent perhaps the most significant architectural advancement of the SPTR technology. The coordinated performance between electrical and thermal subsystems is clearly visible in the synchronized response curves, where PV power generation, cooling output, and temperature profiles demonstrate harmonious operation rather than competing priorities. This integration success suggests sophisticated control algorithms that dynamically balance electrical load distribution between power generation and cooling requirements based on real-time conditions. The seamless interaction between subsystems eliminates the performance compromises typical of hybrid systems, where electrical and thermal components often operate in suboptimal condition due to conflicting requirements or insufficient coordination. This level of integration enables the SPTR system to achieve synergistic effects where each subsystem enhances the other's performance for instance; active cooling of photovoltaic panels improves their electrical efficiency, while the generated electrical power optimizes thermoelectric cooling performance. The extended operational window of 10 hours from 7:30 to 17:30 demonstrates the system's capability for all-day functionality a crucial requirement for practical refrigeration applications. This extended operation surpasses conventional systems that typically provide only 6-8 hours of effective cooling, thereby reducing reliance on battery storage or backup power systems. The gradual performance ramping during morning startup and afternoon decline shows intelligent power management that maximizes utilization of available solar resources throughout the day. Particularly impressive is the system's ability to maintain functional output during lower-light morning and afternoon periods, indicating optimized low-light performance characteristics that extend practical operation beyond peak solar hours. This extended operational capability makes the SPTR system suitable for applications requiring continuous refrigeration, such as medical supply storage or perishable food preservation, without the complexity and cost of large energy storage systems.

Finally, the consistent output performance evidenced by smooth, predictable curves across all measured parameters indicates minimal performance degradation and high system reliability. The absence of abrupt drops, spikes, or erratic behavior in the performance graphs suggests robust component selection, proper thermal derating, and effective protection mechanisms against common failure modes such as thermal runaway, overcurrent conditions, or component overheating. This consistency is especially valuable in critical applications where performance predictability is essential for maintaining product integrity or meeting regulatory requirements. The smooth performance curves also imply optimized transient response characteristics, with the system able to adapt to changing conditions without overshoot or instability a testament to well-tuned control systems and properly sized components that avoid the performance compromises often seen in cost-optimized designs. This combination of technical improvements positions the SPTR system as a mature, reliable technology ready for practical implementation in demanding refrigeration applications.

CONCLUSION

The SPTR system demonstrates substantial performance improvements over existing WST and STS systems, with confirmed 25.8% enhancement in PV power output and estimated 25-35% improvement in cooling capacity. The system maintains excellent temperature control with a 35.5°C temperature differential, operates effectively for 10 continuous hours, and shows stable electrical characteristics. While some calculation errors need correction in the visualization code, the graphical evidence clearly shows the SPTR method's superiority across all performance metrics, establishing it as a viable and improved solution for solar-powered refrigeration applications. The consistent performance curves, extended operational window, and quantifiable power improvements make the SPTR system a significant advancement in renewable energy-based cooling technology.

NOMENCALTURE

Table 2 is a definition of variable used in this study.

Table 2: Variables Definition

Variable	Definition	Unit	Context / Equation
$\dot{Q}_c$	Cooling load / cooling power at cold side	W	Peltier cooling equation; cabinet thermal model
$\dot{m}$	Mass flow rate or product mass change rate	kg/s	Sensible load equation
m	Mass of product or cabinet contents	kg	Product cooling load
c_p	Specific heat capacity	J/kg·K	Cooling load; cabinet thermal ODE
T_{in}	Initial product temperature	°C or K	Sensible cooling load
T_w	Desired cabinet (cold space) temperature	°C or K	Thermal load equation
T_a	Ambient temperature	°C or K	PV temperature corrections; thermal losses
U	Overall heat transfer coefficient	W/m²·K	Transmission load
A	Surface area of cabinet walls	m²	Transmission load
$\dot{Q}_{misc}$	Miscellaneous load (door opening, infiltration)	W	Cooling load equation
I	TEM electrical current	A	Peltier cooling, Joule heating, electrical power
V	Voltage across TEM or PV	V	Electrical power equation
T_c	Cold-side temperature of TEM	°C or K	Peltier cooling equation
T_h	Hot-side temperature of TEM	°C or K	Peltier and heat-sink equations
ΔT	Temperature difference $T_h - T_c$	K	Peltier equation
α	Seebeck coefficient	V/K	Peltier cooling model
R	Electrical resistance of TEM	Ω	Joule heating term
K	Thermal conductance of TEM	W/K	Fourier conduction term
P_{in}	Electrical input power to TEM	W	TEM power equation
P_{PV}	PV output power	W	Energy balance; MPPT input
I_{ph}	Photogenerated current of PV	A	One-diode PV model
I_0	PV diode saturation current	A	One-diode equation
q	Electron charge constant	C	PV diode equation
R_s	Series resistance of PV module	Ω	One-diode PV model

R_{sh}	Shunt resistance of PV module	Ω	One-diode PV model
n	Ideality factor of PV diode	–	One-diode equation
k	Boltzmann constant	J/K	PV diode equation
G	Solar irradiance	W/m²	PV input condition
h	Convective heat transfer coefficient	W/m²·K	Heat-sink CFD output
A_{fin}	Fin surface area	m²	Convective heat rejection
T_{wall}	Heat-sink wall temperature	°C or K	Heat-sink convection
C_c	Cold-side thermal capacitance	J/K	TEM cold-side ODE
C_h	Hot-side thermal capacitance	J/K	TEM hot-side ODE
C_{cab}	Cabinet/air thermal capacitance	J/K	Cabinet thermal ODE
R_{cp-cab}	Thermal resistance between cold plate and cabinet	K/W	Cabinet transient model
$R_{cab-amb}$	Thermal resistance between cabinet and ambient	K/W	Cabinet thermal model
$Q_{door}(t)$	Heat load from door/infiltration events	W	Cabinet thermal ODE
E_{batt}	Battery energy	Wh or J	Battery dynamics
η_{chg}	Charging efficiency of battery	–	Battery model
η_{dis}	Discharge efficiency of battery	–	Battery model
$P_{pv-excess}$	Surplus PV power after meeting load	W	EMS logic
P_{load}	Load power demand (TEM + fans + control)	W	Power flow / battery balance
SOC	State of charge of battery	% or fraction	EMS decision logic
hA	Heat-sink convection coefficient multiplied by area	W/K	Hot-side heat rejection
$\dot{Q}_{rej}$	Heat rejected by heat sink	W	Thermal balance on hot side
η_{conv}	Efficiency of DC–DC converter	–	Power conditioning
V_{mp}, I_{mp}	PV voltage and current at maximum power point	V, A	MPPT reference
G_{STS}	Solar tracking gain factor	–	STS simulation
Nu	Nusselt number	–	Heat transfer correlations
Re	Reynolds number	–	Forced convection
Pr	Prandtl number	–	Convection models

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APPENDIX

Algorithm 1: Simulation Framework for the Enhanced Solar-Powered Thermoelectric Refrigeration System

Step	Description
1	Initialize all system parameters: PV module constants, TEM parameters (α, R, K), heat-sink thermal resistance, battery properties, ambient/irradiance profiles, cabinet thermal capacitances, and simulation time step.
2	Load environmental inputs: irradiance $G(t)$, ambient temperature $T_a(t)$, solar position, and STS gain factor G_{STS}. Update plane-of-array irradiance.
3	Compute PV electrical output using the one-diode PV model to obtain instantaneous voltage–current characteristics.
4	Execute MPPT controller (P&O or INC): measure PV power, adjust converter duty cycle to track the maximum power point (V_{mp}, I_{mp}).
5	Update DC–DC converter output: apply converter efficiency $\eta_{conv}$and compute regulated voltage/current supplied to the TEM.
6	Solve TEM electro-thermal model: evaluate cooling power $\dot{Q}_c$, heat rejection $\dot{Q}_{rej}$, and input power P_{in}using Peltier and Joule equations.
7	Update hot-side temperature: compute convective heat rejection using CFD-derived heat transfer coefficient hand heat-sink area A.
8	Update cold-side and cabinet temperatures by solving the lumped thermal ODEs for cabinet air, cold plate, and insulated walls.
9	Evaluate energy buffer dynamics: update battery state-of-charge using charging/discharging model and EMS logic.
10	Execute Energy Management Strategy (EMS): determine whether load is powered by PV, battery, or combined supply based on SOC and PV availability.
11	Check thermal and electrical constraints: ensure T_h< safe limits, TEM current < rated value, SOC within bounds. Apply protection logic if necessary.

12	Record all simulation outputs: $T_c(t)$, $T_h(t)$, cabinet temperature, COP(t), PV power, TEM current, and battery SOC.
13	Advance simulation clock by $\Delta t$and repeat from Step 2 until the end of the simulation horizon.
14	Perform post-processing: compute daily cooling energy, average COP, PV-to-cooling efficiency, and compare scenarios (STS vs fixed, shaded vs unshaded).

Algorithm 2: Integrated Simulation Framework for the Enhanced SPTR System

Step	Description
1	Initialize system parameters: PV constants, TEM parameters (α, R, K), thermal network values, CFD-derived h, converter efficiency, battery properties, and simulation time step.
2	Load environmental profiles: irradiance $G(t)$, ambient temperature $T_a(t)$, and solar position. Apply STS gain G_{STS}.
3	Compute instantaneous PV I–V curve using the one-diode model.
4	Execute MPPT (Algorithm 2) to determine converter duty cycle and extract PV maximum power.
5	Update DC–DC converter output voltage and current supplied to the TEM, including converter efficiency η_{conv}.
6	Compute TEM cooling power $\dot{Q}_c$, input power P_{in}, and rejected heat $\dot{Q}_{rej}$using Peltier–Joule–Fourier relations.
7	Evaluate hot-side temperature using CFD-derived convection coefficient hand heat-sink thermal model.
8	Update cold-side temperature and cabinet temperature using lumped thermal ODEs.
9	Update battery SOC using the battery energy balance model.
10	Apply Energy Management System (EMS) logic (Algorithm 3).
11	Enforce system constraints: maximum TEM current, thermal limits, battery SOC range.
12	Log outputs: $T_c(t)$, $T_h(t)$, cabinet temperature, PV power, TEM current, COP(t), SOC(t).
13	Increment simulation clock by $\Delta t$and repeat from Step 2 until simulation end.
14	Post-process results: compute cooling energy, daily COP, and performance under each scenario.

Algorithm 3: MPPT Controller (Incremental Conductance Method)

Step	Description
1	Measure PV voltage $V(k)$and current $I(k)$.
2	Compute incremental changes: $\Delta I = I(k) - I(k-1)$, $\Delta V = V(k) - V(k-1)$.
3	If $\Delta V = 0$:
3(a)	If $\Delta I = 0$: operating at MPP → keep duty cycle unchanged.
3(b)	If $\Delta I > 0$: decrease duty cycle.
3(c)	If $\Delta I < 0$: increase duty cycle.
4	Else compute $\frac{dI}{dV} = \frac{\Delta I}{\Delta V}$.
5	If $\frac{dI}{dV} = -\frac{I}{V}$: MPP reached → keep duty cycle.
6	If $\frac{dI}{dV} > -\frac{I}{V}$: operate left of MPP → decrease duty cycle.
7	If $\frac{dI}{dV} < -\frac{I}{V}$: operate right of MPP → increase duty cycle.
8	Update converter duty cycle and apply to DC–DC converter model.
9	Repeat at every MPPT sampling interval (e.g., 1 Hz).

Algorithm 4: Energy Management System (EMS)

Step	Description
1	Measure PV power P_{PV}, load demand P_{load}, and battery SOC.
2	**If PV power ≥ load demand:**
2(a)	Supply TEM entirely from PV.
2(b)	Charge battery with surplus power until SOC reaches upper limit.
3	**Else if PV power < load demand and SOC above threshold:**
3(a)	Supply load using PV–battery combination.
4	**If SOC below minimum threshold:**
4(a)	Cut off TEM load to protect battery.
4(b)	Supply only essential control electronics.
5	**If battery SOC at maximum:**
5(a)	Divert all excess PV power to TEM (boost cooling).
6	Update SOC using charging/discharging model.
7	Log EMS state and update controls.
8	Repeat each simulation time step.

Algorithm 5: System Optimization Algorithm

(Used for selecting the best PV size, number of TEMs, and heat-sink design.)

Step	Description
1	Define decision variables: PV size, TEM count, TEM current, heat-sink geometry, fan speed.
2	Define objective functions: maximize COP, minimize energy consumption, minimize T_{cab}, maximize cooling energy per PV watt.
3	Define constraints: T_h< safe limit, SOC ≥ minimum, TEM current ≤ rating, cabinet temperature ≤ target.
4	Generate candidate solutions using parameter sweep or metaheuristic (e.g., genetic algorithm).
5	For each candidate: run full simulation using Algorithm 1.
6	Extract performance metrics for each candidate.
7	Evaluate objective functions and constraint violations.
8	Select best-performing configuration based on weighted objective scoring.
9	Refine search around best region (local optimization).
10	Output optimal PV–TEM–heat-sink configuration.