



Design and Performance Evaluation of a Solar-Assisted Refrigeration System for Energy-Efficient Cooling

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Peer Review Information	Abstract
<i>Submission: 02 Jan 2020</i> <i>Revision: 17 Feb 2020</i> <i>Acceptance: 05 March 2020</i> Keywords <i>Solar refrigeration, Photovoltaic cooling, Vapor compression, Energy efficiency, Coefficient of performance</i>	This paper presents the design methodology and performance-evaluation framework for a solar-assisted vapor-compression refrigeration system intended to reduce grid electricity consumption while maintaining reliable cooling under variable solar conditions. The proposed configuration integrates a photovoltaic (PV) array, maximum-power-point-tracking (MPPT) controller, DC bus, variable-speed DC compressor, conventional condenser–expansion–evaporator loop, and grid backup for periods of insufficient solar power. The methodology combines component sizing, thermodynamic analysis, electrical-energy accounting, instrumentation, controlled test conditions, and uncertainty assessment. Performance is evaluated using refrigeration coefficient of performance (COP), solar fraction, PV utilization, cabinet pull-down time, temperature stability, and grid-energy saving. A model-based design evaluation is included to demonstrate the analysis procedure at irradiance levels from 400 to 1000 W/m². The calculated system COP rises from approximately 2.62 to 3.20 as solar availability and compressor matching improve, while the solar fraction increases from 55% to 100%. For an eight-hour representative cooling period, the proposed hybrid arrangement can reduce grid energy use by about 65–70% relative to a grid-only benchmark, depending on weather and load. The methodology is suitable for laboratory prototyping and can be extended to vaccine storage, food preservation, and small commercial cooling applications.

Introduction

Refrigeration and air-conditioning are essential for food preservation, thermal comfort, medical storage, and industrial processing, yet conventional vapor-compression equipment can impose substantial electrical demand, particularly in hot regions where cooling loads coincide with periods of high solar radiation. This coincidence makes solar energy especially attractive for refrigeration. Solar cooling can be implemented through solar-electric vapor compression, solar-thermal absorption or adsorption, ejector cycles, and thermo-mechanical combinations. Comparative reviews have shown that each route has different

requirements for collector temperature, storage, working fluids, system complexity, and capital cost [1–4].

For small and medium refrigeration capacities, photovoltaic-driven vapor-compression systems have become increasingly practical because PV modules can supply electricity directly to efficient DC compressors. Unlike thermally driven absorption systems, PV-assisted compression refrigeration uses mature refrigeration hardware and can reach conventional vapor-compression COP levels while displacing grid electricity. Direct-current configurations also avoid inverter losses and

high compressor starting surges when a variable-speed compressor is used. Opoku et al. [7] reported that a PV-powered DC refrigerator could achieve similar cabinet temperature to an AC unit while reducing system cost associated with inverter and surge requirements. More recent studies have emphasized direct coupling, variable-speed compressor control, and improved PV utilization [10,12].

However, solar refrigeration design remains challenging because solar irradiance, ambient temperature, refrigeration load, and compressor operating speed vary continuously. Poor matching between the PV array and compressor can cause cycling, unstable temperatures, low solar utilization, or unnecessary dependence on batteries. High ambient temperature also raises condensing pressure and reduces cooling capacity. Therefore, a useful methodology must evaluate the electrical and thermodynamic subsystems together rather than sizing the PV array and refrigeration unit independently. The present study proposes a hybrid solar-assisted architecture with grid backup instead of mandatory battery storage. The objective is to maximize direct solar utilization during daylight while preserving uninterrupted cooling when irradiance is low.

The specific objectives are: (i) to define the system configuration and component-sizing procedure; (ii) to establish a repeatable experimental test method under different irradiance and ambient-temperature conditions; (iii) to calculate COP, solar fraction, grid-energy saving, and temperature-control performance; and (iv) to identify design variables that most strongly influence energy-efficient operation. The paper focuses on methodology rather than claiming field-test data; the numerical results are model-based examples used to show how the proposed performance metrics are applied.

Literature Review

Kim and Infante Ferreira [1] compared solar-electric, solar-thermal, absorption, adsorption, desiccant, and emerging solar refrigeration routes, establishing that performance and cost depend strongly on application scale and source temperature. Abdulateef et al. [2] reviewed solar-driven ejector refrigeration and highlighted its simple construction and low mechanical power demand, but also noted its relatively low COP and sensitivity to operating conditions. Ullah et al. [3] summarized absorption and adsorption refrigeration using solar thermal energy, while Sarbu and Sebarchievici [4] reviewed practical solar refrigeration configurations and

emphasized the importance of working-pair selection, operating temperature, and hybridization.

Thermo-mechanical solar refrigeration is another pathway. Zeyghami et al. [5] reviewed solar Rankine and ejector cooling and showed that solar heat can be converted into mechanical work to operate refrigeration cycles, with potential benefits at off-design conditions. Experimental solar-thermal absorption systems have also demonstrated technically feasible cooling. Said et al. [6], for example, tested an ammonia–water absorption chiller supplied by evacuated-tube solar collectors and reported COP values that varied considerably with generator, condenser/absorber, and evaporator temperatures. This variation illustrates the strong coupling between ambient heat rejection and solar-source conditions.

For PV-powered compression refrigeration, direct-current systems reduce conversion stages. Opoku et al. [7] found that a converted DC refrigerator had lower surge-power requirements than an AC refrigerator and reduced the overall PV-system cost in their comparison. Bellos and Tzivanidis [8] used optimization to demonstrate how solar refrigeration performance changes across different evaporation and heat-rejection temperatures, reinforcing the need to evaluate systems over a range of operating conditions rather than at a single design point. Zheng et al. [9] investigated a solar Rankine-driven vapor-compression refrigerator and showed that working-fluid selection and heat-source temperature can significantly affect overall system efficiency.

More directly relevant to the proposed configuration, Salilih and Birhane [10] modeled a directly coupled PV vapor-compression system with a variable-speed compressor under real-weather conditions. Their work showed the value of matching the PV current–voltage behavior with compressor characteristics. Alrwashdeh and Ammari [11] compared life-cycle costs of PV vapor-compression and solar-thermal absorption refrigeration and found the PV compression route economically favorable in their case study. Su et al. [12] subsequently developed and experimentally validated a variable-speed PV DC refrigerator without battery or inverter and reported markedly improved PV utilization compared with fixed-speed operation. Together, these studies support a methodology centered on direct PV use, variable-speed compression, and hybrid backup rather than battery-dominated operation.

Table 1. Proposed design parameters and experimental measurement plan

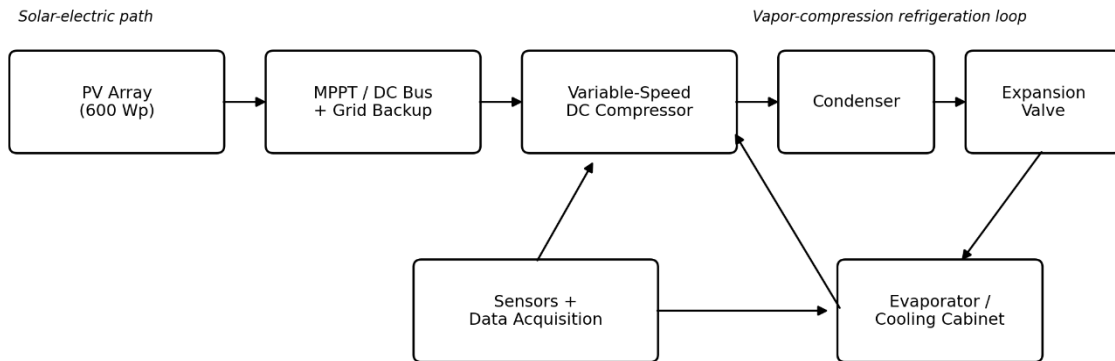
Item	Nominal specification	Measured / controlled variable	Instrument / method
PV source	600 Wp monocrystalline array	Irradiance, PV voltage, PV current	Pyranometer; DC voltage/current sensors
Power interface	MPPT controller + DC bus + grid backup	PV power, grid power, DC-bus voltage	Power analyzer / data logger
Refrigeration unit	Variable-speed DC VCR, 0.5–0.8 kW cooling	Compressor speed and input power	Tachometer/controller signal; wattmeter
Thermal loop	Condenser, expansion valve, evaporator	Suction/discharge pressure; component temperatures	Pressure transducers; T-type thermocouples
Cooling cabinet	Insulated chamber 100–150 L	Air/product-simulator temperature	Calibrated temperature sensors

Methodology

1. System configuration and design basis

The proposed solar-assisted refrigeration system is shown in Figure 1. A 600 Wp PV array feeds an MPPT controller connected to a regulated DC bus. The DC bus supplies the variable-speed compressor and low-power auxiliaries. Grid backup is connected through a suitable DC power supply or hybrid converter so that the refrigeration unit continues operating whenever

PV power falls below the instantaneous electrical demand. The system does not require a large electrochemical battery; instead, the insulated cabinet and stored thermal mass provide short-term thermal buffering. The vapor-compression loop consists of compressor, air-cooled condenser, expansion device, and evaporator. A low-GWP refrigerant appropriate for the selected compressor should be used according to applicable safety standards.

**Figure 1.** Functional arrangement of the proposed solar-assisted vapor-compression refrigeration system.

2. Component sizing and energy balance

The refrigeration unit is first sized from the design cooling load, including cabinet transmission, product load, air infiltration, and internal loads. A design cooling capacity of approximately 0.6 kW is adopted for the methodology demonstration. The required compressor electrical power is estimated from the target refrigeration COP. The PV array is then selected so that its maximum-power output during typical high-irradiance hours can cover the compressor and auxiliary demand with an allowance for temperature and wiring losses. The

PV-side power is calculated as $P_{PV} = V_{PV} \times I_{PV}$, while the instantaneous refrigeration COP is calculated as $COP = Q_e / P_{sys}$, where Q_e is evaporator cooling rate and P_{sys} is compressor plus auxiliary electrical input.

For an instrumented test rig, evaporator cooling rate can be determined by a calibrated secondary-fluid energy balance, $Q_e = \dot{m} c_p (T_{in} - T_{out})$, or by a refrigerant enthalpy method when mass-flow instrumentation is available. The solar fraction is defined as $SF = E_{PV,used} / E_{total}$, where E_{total} is the electrical energy consumed by the refrigeration system

during the evaluation period. Grid-energy saving relative to a conventional benchmark is calculated as $\text{Saving} = (E_{\text{grid,baseline}} - E_{\text{grid,solar}}) / E_{\text{grid,baseline}} \times 100\%$. These metrics separate thermodynamic efficiency from renewable-energy contribution: a high solar fraction does not automatically imply a high refrigeration COP, and both should therefore be reported.

3. Experimental procedure

Testing is conducted after checking refrigerant charge, sensor calibration, electrical protection, and data-acquisition synchronization. The cooling cabinet is loaded with a repeatable thermal mass (for example water containers) so that each test begins from approximately the same initial condition. Measurements are logged at 30–60 s intervals. Tests are performed across representative irradiance bands of about 400, 550, 700, 850, and 1000 W/m², with ambient temperature recorded simultaneously. Where outdoor irradiance cannot be controlled, data are grouped into irradiance bins after testing. The controller is set to vary compressor speed within the safe manufacturer range to follow available solar power while maintaining the target cabinet temperature.

Each test includes four stages: stabilization, pull-down, steady cooling, and low-irradiance transition. During stabilization, pressures and temperatures are checked at low compressor speed. During pull-down, the cabinet temperature is reduced from the initial condition to the target range. During steady cooling, COP, electrical power, and solar fraction are averaged for a defined period after temperatures become quasi-steady. During the transition stage, shading or naturally declining irradiance is used to verify that grid backup enters smoothly without loss of temperature control. At least

three repeat runs are recommended for each operating band.

4. Performance indicators and uncertainty

The main dependent variables are COP, cooling capacity, cabinet temperature, pull-down time, solar fraction, PV utilization ratio, compressor duty/speed, and grid-energy consumption. Independent variables include solar irradiance, ambient temperature, refrigeration load, and compressor control mode. Sensor uncertainties should be propagated using the root-sum-square method. For a calculated quantity $R = f(x_1, x_2, \dots, x_n)$, the combined uncertainty is estimated from the square root of the sum of squared sensitivity terms $(\partial R / \partial x_i \cdot u_{xi})^2$. A practical target is temperature uncertainty within ± 0.3 °C, electrical power within ± 1 – 2% , irradiance within $\pm 3\%$, and pressure within $\pm 1\%$ of full scale. Reporting uncertainty is important because solar-refrigeration performance can change by only a few percent between adjacent operating points.

Results

To demonstrate the proposed analysis workflow, a model-based design evaluation was performed for five irradiance levels. These values are illustrative design-study results, not claimed laboratory measurements. The model assumes a variable-speed compressor, an ambient temperature near 30–33 °C, adequate condenser airflow, and grid backup only when available PV power is insufficient. Table 2 shows the resulting trends. As irradiance rises, the controller increases compressor speed and a larger portion of the electrical demand is met directly by the PV source. The calculated system COP increases from 2.62 at 400 W/m² to 3.20 at 1000 W/m², while solar fraction increases from 55% to 100%.

Table 2. Model-based performance evaluation of the proposed system

Irradiance (W/m ²)	PV used (W)	Grid input (W)	Cooling capacity (W)	System COP	Solar fraction (%)	Cabinet temp. (°C)
400	115	94	548	2.62	55	5.8
550	145	68	592	2.78	68	4.7
700	176	44	651	2.96	80	3.8
850	205	20	700	3.11	91	3.2
1000	230	0	736	3.2	100	2.9

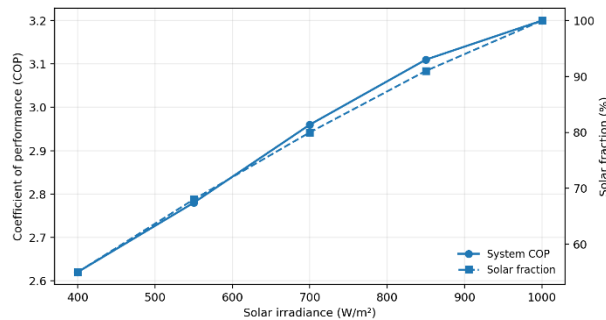


Figure 2. Model-based variation of COP and solar fraction with solar irradiance.

The trend is consistent with prior research on variable-speed PV refrigeration, where closer matching between available PV power and compressor speed improves solar-energy utilization [10,12]. At low irradiance, grid backup supports the DC bus and prevents repeated compressor shutdown. At high irradiance, direct solar power covers the complete electrical demand. For an eight-hour representative cooling period with varying irradiance, the model gives approximately 1.35 kWh of directly used PV energy and 0.65 kWh of grid energy, compared with about 2.0 kWh for the grid-only benchmark. This corresponds to a grid-energy saving of roughly 67.5%. The result is not a universal efficiency value; it depends on location, load profile, PV size, cabinet insulation, control settings, and ambient temperature.

Conclusion and Discussion

The proposed methodology provides a practical framework for designing and evaluating a solar-assisted refrigeration system that combines direct PV utilization with the reliability of grid backup. The configuration is intentionally simpler than battery-dominated stand-alone systems: the PV array and MPPT controller supply a variable-speed DC compressor whenever solar power is available, and backup electricity is introduced only for the shortfall. This arrangement reduces conversion stages, avoids oversized inverter starting capacity, and can reduce battery cost and maintenance. The design is supported by earlier evidence that DC refrigeration can lower PV-system cost [7], directly coupled PV compression systems benefit from compressor–PV matching [10], and variable-speed PV refrigeration improves utilization of available solar energy [12]. The model-based evaluation indicates that the system should be assessed using both thermodynamic and electrical indicators. COP describes how effectively electrical input is converted to cooling, while solar fraction

describes how much of that electrical input is supplied by renewable energy. In the illustrative calculation, COP improved from 2.62 to 3.20 across the irradiance range, and direct solar contribution reached 100% at the highest irradiance. A representative grid-energy reduction of about two-thirds is feasible when the PV array is appropriately sized for the daytime load. This is compatible with the broader literature showing that solar refrigeration performance is strongly influenced by heat-rejection temperature, source availability, working-fluid selection, and control strategy [5,6,8,9]. The methodology also highlights several practical limitations. First, outdoor solar irradiance is transient, so short steady-state tests should be supplemented by full-day experiments. Second, PV output decreases as module temperature rises, while refrigeration demand commonly increases with ambient temperature; therefore, hot-weather testing is essential. Third, a hybrid grid connection improves reliability but changes the economic comparison with stand-alone systems. Finally, refrigerant choice must consider safety, global-warming potential, compressor compatibility, and local regulation. Future work should build the proposed test rig, validate the model with measured pressure–enthalpy data, compare fixed-speed and variable-speed control, investigate thermal storage or phase-change material in the cabinet, and perform seasonal life-cycle cost and carbon-emission analysis. Within these boundaries, the proposed system offers a technically credible route to energy-efficient cooling in solar-rich regions.

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