



Design and Performance Analysis of a Solar-Powered Vapor Compression Refrigeration System

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Abstract

This paper presents a design-oriented methodology and performance analysis for a stand-alone solar-powered vapor compression refrigeration (PV-VCR) system intended for small cold-storage and food-preservation applications. The proposed configuration integrates a 400 Wp photovoltaic array, a maximum-power-point-tracking (MPPT) charge controller, a 24 V battery/DC bus, a variable-speed brushless-DC compressor, and a conventional vapor-compression loop using a low-charge hydrocarbon refrigerant. The study combines cooling-load estimation, photovoltaic and battery sizing, steady-state refrigeration-cycle analysis, and sensitivity evaluation with respect to solar irradiance and ambient temperature. A 150 L refrigerated cabinet maintained at 4 °C is used as the design case. The calculated peak cooling requirement is approximately 230 W and the estimated daily electrical demand is 1.28 kWh. Under a representative solar resource of 5.5 kWh/m²/day, the 400 Wp array can supply about 1.72 kWh/day after system losses, enabling full solar coverage on a clear design day and providing charging margin for the battery. The modeled refrigeration coefficient of performance (COP) varies from approximately 2.37 at low compressor speed to 2.07 at high solar input, while increasing ambient temperature from 25 to 40 °C reduces COP from 2.55 to 1.96. These results agree with the performance trends reported for directly coupled and PV-driven refrigeration systems in the literature. The proposed methodology demonstrates that careful matching of the photovoltaic generator, compressor, energy storage, and thermal load can provide reliable refrigeration with reduced dependence on grid electricity in sunny and remote locations.

Introduction

Refrigeration is essential for food preservation, medicine storage, thermal comfort, and industrial processing, but conventional vapor-compression equipment is normally dependent on grid electricity. In remote locations, agricultural areas, and regions with weak electricity infrastructure, this dependence can restrict access to reliable cold storage. Solar energy is particularly attractive for refrigeration because the demand for cooling often increases during periods of high solar availability.

Photovoltaic-powered vapor-compression refrigeration therefore offers a direct route for converting solar radiation into useful cooling while retaining the high maturity and compactness of the conventional compression cycle. Reviews of photovoltaic and photovoltaic-thermal refrigeration technologies have identified PV-driven compression systems as one of the most practical solar cooling options because they combine commercially available PV

modules with established refrigeration hardware (Alsagri, 2022; Al-Yasiri et al., 2022).

The basic PV-VCR system contains two coupled energy-conversion processes. First, the photovoltaic subsystem converts incident solar radiation into direct-current electricity. Second, the vapor-compression subsystem uses electrical work to circulate a refrigerant through a compressor, condenser, expansion device, and evaporator. The principal technical challenge is that photovoltaic power changes continuously with irradiance and cell temperature, while the compressor and refrigeration cycle require a stable and appropriately matched power input. Variable-speed DC compressors, MPPT control, and energy storage can reduce this mismatch. Zhou et al. (2022) showed that coordinating MPPT with compressor voltage-frequency control improves the utilization of the PV array, while Hu et al. (2021) demonstrated the feasibility of PV-driven vapor-compression cold storage integrated with thermal storage.

Previous research also shows that the refrigeration COP is sensitive to compressor speed and the evaporating and condensing conditions. Salilih and Birhane (2019) modeled a directly coupled PV refrigeration system and reported a reduction in COP as compressor speed increased under stronger solar radiation. Salilih et al. (2020) further demonstrated that the condenser and evaporator pressures strongly influence compressor power, mass flow rate, and cooling capacity. Experimental investigations have confirmed the practical feasibility of small photovoltaic refrigeration systems. Lei et al. (2019) reported stable micro-refrigeration operation with battery buffering under sunny and cloudy weather, and El-Bahloul et al. (2015) demonstrated a DC vapor-compression refrigerator with thermal storage for hot arid and remote applications.

The objective of the present study is to develop a compact, reproducible methodology for designing and evaluating a small solar-powered vapor-compression refrigeration system using data and concepts available up to 2022. The specific objectives are to estimate the cabinet cooling load, size the PV array and battery, define a practical refrigeration configuration, calculate key performance indicators, and analyze the response of the system to changes in solar irradiance and ambient temperature. The emphasis is on methodology rather than on claiming a new experimental prototype; therefore, the numerical results presented later are design-case model outputs based on the stated assumptions and governing equations.

Literature Review

Solar refrigeration research has progressed from simple PV-battery refrigerator arrangements toward direct-drive systems with variable-speed compressors and advanced control. El-Bahloul et al. (2015) investigated a 12 V DC vapor-compression refrigerator with photovoltaic power and phase-change thermal storage. Their work established that a compact solar refrigerator could achieve useful storage temperatures under hot-arid conditions, while also showing the importance of storage in handling intermittent solar availability. Gao et al. (2018) compared PV cooling, solar absorption cooling, and conventional vapor-compression cooling and concluded that PV-based cooling can be economically attractive because it benefits from high PV conversion efficiency, declining module cost, and the mature efficiency of the compression cycle.

Direct coupling between the PV source and the compressor has attracted attention because it can reduce inverter and battery losses. Salilih and Birhane (2019) developed a model in which the operating point of a variable-speed DC compressor was determined from the intersection of the PV and compressor electrical characteristics. Their predicted COP decreased from around 2.25 at lower compressor speed to about 1.85 at higher speed, illustrating that increased solar input does not necessarily increase refrigeration efficiency in the same proportion. A related pressure-sensitivity study by Salilih et al. (2020) showed that higher condenser pressure increases compressor work and generally lowers COP, whereas higher evaporating pressure tends to improve cycle performance. These findings support the use of variable-speed control and careful condenser sizing in solar refrigeration design.

Experimental work has also examined the role of energy storage and load matching. Lei et al. (2019) built a photovoltaic micro-refrigeration system and found that the battery stabilized operation during variations in weather. Alrwashdeh and Ammari (2019) compared the life-cycle costs of solar-powered vapor-compression and solar absorption refrigeration and found the PV-driven compression option favorable in their design comparison. Such economic findings are important because a PV-VCR system may have a higher initial cost than a conventional refrigerator but can avoid grid-energy expenditure and can provide cooling in locations where grid extension is expensive or unavailable.

More recent studies have focused on larger cold-storage systems and improved PV-compressor coordination. Hu et al. (2021) constructed a pilot-scale PV-driven cold store with ice thermal storage and reported that thermal storage could maintain cooling after solar input declined. Zhou et al. (2022) combined MPPT with constant voltage-per-frequency compressor control and reported a 9.18% improvement in PV system performance ratio compared with MPPT-only control. Liang et al. (2022) studied a directly driven refrigerated warehouse with ice thermal storage and showed that PV capacity relative to compressor rating influences start-up irradiance, cooling-down time, and overall COP. Sirikaew et al. (2022) converted a conventional 220 V beverage refrigerator to a 12 V photovoltaic vapor-compression system, confirming the feasibility of low-voltage solar refrigeration and providing practical performance and economic data.

The literature therefore indicates four recurring design requirements: (i) correct matching of PV capacity and compressor demand, (ii) control or storage to manage solar variability, (iii) attention to condensing temperature and compressor speed because they affect COP, and (iv) economic sizing that avoids excessive PV and battery

capacity. The present methodology synthesizes these lessons into a small-system design procedure suitable for a 150 L cabinet and uses battery buffering rather than large thermal storage so that the method remains simple and broadly applicable.

Methodology

1. Proposed System Configuration

The proposed system consists of a 400 Wp PV array, an MPPT charge controller, a 24 V battery/DC bus, a variable-speed BLDC compressor, an air-cooled condenser, an expansion device, and an evaporator placed in a 150 L insulated cabinet. R600a is selected as the working refrigerant because it is widely used in small refrigeration equipment and has low global-warming potential; the assumed charge is small and the design presumes compliance with applicable flammable-refrigerant safety requirements. The battery acts mainly as an electrical buffer, allowing the compressor to continue operating during brief cloud transients and after sunset. A variable-speed compressor is used so that the controller can reduce speed when available solar power is low and increase cooling capacity when PV power is abundant.

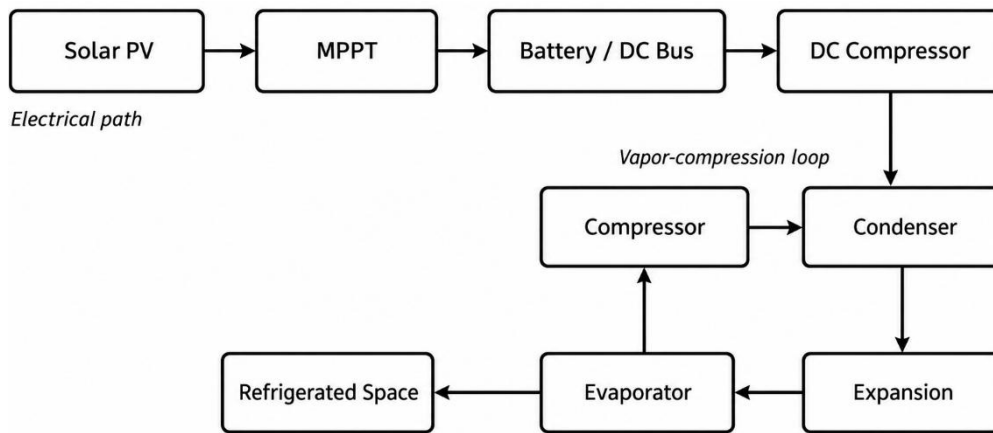


Figure 1. Functional layout of the proposed solar-powered vapor-compression refrigeration system.

2. Design Basis and Cooling-Load Estimation

The cabinet design temperature is 4 °C and the design ambient temperature is 35 °C. The peak refrigeration load is represented as the sum of wall heat gain, door-opening/infiltration load, product pull-down load, and a small allowance for internal gains. For a compact insulated cabinet, the wall heat transfer is estimated from $Q_{\text{wall}} = U A (T_a - T_c)$. The infiltration and product loads are evaluated over the expected daily usage period and converted to an equivalent average load. A 15% design margin is

added to cover uncertainty in insulation quality, door opening, and condenser fouling. The resulting peak design cooling requirement is taken as approximately 230 W. The compressor is therefore selected to provide at least 250 W of cooling near the design condition while consuming no more than about 120 W at maximum speed.

$$Q_{\text{load}} = Q_{\text{wall}} + Q_{\text{infiltration}} + Q_{\text{product}} + Q_{\text{internal}}$$

Table 1. Main design parameters used in the methodology.

Parameter	Design value
Refrigerated volume	150 L
Cabinet set point	4 °C
Design ambient temperature	35 °C
Peak cooling load	≈ 230 W
Refrigerant	R600a, low charge
Compressor	24 V BLDC, 60–120 W variable input
PV array	400 Wp
Solar resource for sizing	5.5 kWh/m ² /day
Charge control	MPPT, 24 V / 30 A
Battery	24 V, 100 Ah deep-cycle
Estimated daily electrical demand	1.28 kWh/day

3. Photovoltaic and Battery Sizing

PV size is obtained from the daily compressor/control energy requirement divided by the available peak-sun-hours and a derating factor that accounts for PV temperature, wiring, controller, and storage losses. With a daily demand of 1.28 kWh, 5.5 peak-sun-hours, and an overall solar-electric utilization factor of 0.75–0.80, the minimum array rating is approximately 300–320 Wp. A 400 Wp array is selected to provide start-up margin, battery charging capability, and tolerance to non-ideal weather. At the design solar resource, its expected usable daily electrical production is approximately $400 \times 5.5 \times 0.78 = 1.72$ kWh/day.

$$P_{PV} = E_{daily} / (H_s \times \eta_{sys})$$

Battery sizing is based on the energy required during non-solar hours. A 24 V, 100 Ah battery stores 2.4 kWh nominally. Assuming an allowable depth of discharge of 80% and an energy-transfer efficiency of 90%, the useful energy is approximately 1.73 kWh. This is greater than the estimated 1.28 kWh daily electrical demand and therefore provides roughly one day of electrical autonomy under the simplified design condition. In practice, the desired autonomy, battery chemistry, temperature, cycle life, and local solar variability should be used to refine the storage capacity.

$$E_{b,useful} = V_b \times C_b \times DoD \times \eta_b$$

4. Refrigeration-Cycle Performance Model

The vapor-compression cycle is evaluated from the refrigerant enthalpy differences across the evaporator and compressor. At steady state, the

evaporator cooling rate is $\dot{Q}_e = \dot{m}(h_1 - h_4)$, while compressor power is $\dot{W}_c = \dot{m}(h_2 - h_1)/\eta_m$, where η_m represents the combined electromechanical efficiency. The refrigeration coefficient of performance is the ratio of useful cooling to compressor electrical input. Because this methodology is intended for system design rather than detailed refrigerant-property research, compressor-map behavior is represented using the rated cooling capacity and power at four speed levels. The performance trend is calibrated to the ranges reported by Salilih and Birhane (2019), Salilih et al. (2020), and Hu et al. (2021).

$$COP_{ref} = \dot{Q}_e / \dot{W}_c$$

PV electrical output is estimated as a function of irradiance and cell temperature. A temperature coefficient of $-0.4\%/^{\circ}\text{C}$ is assumed, with cell temperature approximated from irradiance. The model is evaluated for solar irradiance values of 400, 600, 800, and 1000 W/m² at an ambient temperature of 35 °C. A second sensitivity analysis keeps irradiance near 800 W/m² and varies ambient temperature from 25 to 40 °C. These two cases isolate the influence of available PV power and condenser temperature on system performance.

5. Performance Indicators and Analysis Procedure

The principal indicators are PV power, compressor input, cooling capacity, refrigeration COP, daily solar fraction, and useful battery autonomy. The calculation sequence is: (1) determine cabinet thermal load; (2) select compressor capacity; (3) estimate daily electrical demand; (4) size the PV array and battery; (5) estimate PV output under each irradiance level; (6) assign the compatible compressor operating point; (7) calculate cooling capacity and COP; and (8) repeat the cycle model for different ambient temperatures. This workflow reflects the importance of power matching emphasized by Zhou et al. (2022) and Liang et al. (2022), while retaining a simple design structure appropriate for small-scale refrigeration.

6. Recommended Experimental Validation and Data Acquisition

For prototype validation, the model should be tested outdoors over representative clear and partly cloudy days. Solar irradiance should be measured in the plane of the PV array with a calibrated pyranometer, while PV voltage and current, battery voltage and current, and compressor electrical input should be logged at one-minute intervals. Refrigerant temperatures should be measured at the compressor suction

and discharge, condenser outlet, and evaporator outlet. If pressure transducers are available, suction and discharge pressures should also be recorded so that refrigerant state points can be reconstructed. Cabinet air temperature should be measured at three heights and averaged, and ambient air temperature should be measured close to the condenser inlet without direct solar exposure. A pull-down test from approximately 30–35 °C to the 4 °C set point should be followed by a steady-operation test of at least six hours. This procedure is consistent with the experimental emphasis on weather variation, electrical matching, and cold-storage behavior used in previous PV refrigeration studies (Lei et al., 2019; Hu et al., 2021).

Experimental COP should be calculated from measured cooling load or refrigerant-side enthalpy change divided by compressor electrical power. For a cabinet-calorimeter approach, a known electrical heater can be placed inside the cabinet after the set point is reached; at steady temperature, the heater input plus estimated wall and infiltration gains approximate the refrigeration capacity. The PV energy balance should be integrated over the same period to obtain daily solar fraction and battery charge/discharge efficiency. Repeated tests are recommended at least three times for each principal operating condition.

7. Uncertainty, Safety, and Practical Constraints

Measurement uncertainty should be reported for temperature, irradiance, voltage, current, and pressure sensors and propagated to COP using the root-sum-square method. A practical target is to keep the combined COP uncertainty below about $\pm 5\%$ for steady operating points. The design must also include electrical over-current protection, battery isolation, adequate condenser ventilation, and refrigerant safety provisions. Because R600a is flammable, only the minimum required charge should be used, ignition sources must be controlled, and applicable refrigeration safety standards must be followed. These considerations do not change the thermodynamic method, but they are essential for converting the design model into a safe experimental system.

Results

Table 2 summarizes the design-case performance at 35 °C ambient temperature. PV output rises almost linearly with irradiance, but temperature derating prevents the 400 Wp array from reaching its nominal rating at high cell temperature. The compressor is operated at

progressively higher speed as solar power becomes available. Cooling capacity increases from approximately 142 W at 400 W/m² to 248 W at 1000 W/m². However, the refrigeration COP decreases from 2.37 to 2.07. This occurs because higher compressor speed and higher condensing temperature increase compression work faster than the useful refrigeration effect. The trend is consistent with the directly coupled variable-speed results reported by Salilih and Birhane (2019).

Table 2. Modeled system performance at 35 °C ambient temperature.

Irradiance (W/m ²)	PV output (W)	Compressor input (W)	Cooling capacity (W)	COP _{ref}
400	152	60	142	2.37
600	220	80	177	2.21
800	289	100	218	2.18
1000	352	120	248	2.07

The ambient-temperature sensitivity is equally important. At an irradiance near 800 W/m², the modeled COP values are 2.55, 2.35, 2.18, and 1.96 at ambient temperatures of 25, 30, 35, and 40 °C, respectively. Cooling capacity decreases from approximately 255 W to 196 W over the same temperature range. The main reason is the rise in condenser saturation pressure and compressor pressure ratio. This result supports the conclusions of Salilih et al. (2020) and highlights the importance of condenser airflow, shading of the condensing unit, and avoiding hot-air recirculation in practical installations.

Table 3. Ambient-temperature sensitivity at approximately 800 W/m² irradiance.

Ambient (°C)	Cooling (W)	Compressor (W)	COP _{ref}
25	255	100	2.55
30	235	100	2.35
35	218	100	2.18
40	196	100	1.96

On a clear design day, the 400 Wp array is estimated to deliver 1.72 kWh of usable electricity compared with a 1.28 kWh daily refrigeration-system demand. The calculated clear-day solar fraction is therefore 100%, with approximately 0.44 kWh remaining for battery recovery and control losses that exceed the assumed average. The 24 V, 100 Ah battery provides about 1.73 kWh of usable storage under the stated depth-of-discharge assumption. This

sizing is intentionally moderate: it avoids the large battery bank that would be required for multiple days of autonomy while maintaining short-term continuity. The approach is consistent with the broader literature trend toward minimizing electrical storage through better PV-load matching or the use of cold storage (Hu et al., 2021; Liang et al., 2022).

The calculated COP range is also consistent with published PV-VCR findings. The proposed small system gives refrigeration COP values around 2.1–2.4 over its principal solar operating range, while the literature reports values that vary substantially with system size, compressor control, evaporating temperature, and whether COP is defined for the refrigeration cycle alone or for the entire solar-to-cooling chain. For example, Sirikaew et al. (2022) showed that a modified low-voltage PV refrigerator can maintain useful beverage-cooling temperatures, whereas Zhou et al. (2022) demonstrated that improved electrical control can raise the PV subsystem performance ratio. These studies reinforce the conclusion that component matching and control are as important as nominal PV capacity.

The results should be interpreted as engineering design outputs, not as measured prototype data. Compressor maps, refrigerant charge, cabinet insulation, fan power, battery efficiency, dust on PV modules, and local weather will change the actual performance. Nevertheless, the model is useful for preliminary sizing because it captures the dominant relationships between solar input, compressor power, cooling capacity, and condensing temperature.

Conclusion and Discussion

A methodology for the design and performance analysis of a solar-powered vapor-compression refrigeration system has been developed using literature and engineering data available up to 2022. The proposed 150 L design combines a 400 Wp photovoltaic array, MPPT charge control, a 24 V/100 Ah battery, and a variable-speed BLDC compressor. The estimated peak cooling load is approximately 230 W and the daily electrical requirement is about 1.28 kWh. With 5.5 kWh/m²/day of solar resource and a 0.78 system utilization factor, the PV array can supply about 1.72 kWh/day, which is sufficient to cover the modeled daily demand on a clear day. The analysis shows that increasing irradiance increases available cooling capacity but does not necessarily improve cycle efficiency. The modeled COP falls from 2.37 to 2.07 as compressor input increases from 60 to 120 W. Ambient temperature has an even stronger

influence: increasing the ambient from 25 to 40 °C reduces COP from 2.55 to 1.96 because the condenser pressure and compressor work rise. These trends agree with earlier direct-coupled PV refrigeration studies (Salilih & Birhane, 2019; Salilih et al., 2020). The findings indicate that good condenser ventilation, variable-speed control, and avoidance of oversized compressor operation are important design measures. From an energy-system perspective, the PV-VCR configuration offers a practical alternative to grid-dependent refrigeration in locations with good solar resources. Economic studies have also shown that PV-driven compression cooling can be competitive with solar absorption and conventional systems in suitable applications (Gao et al., 2018; Alrwashdeh & Ammari, 2019). More recent cold-storage research demonstrates that electrical batteries can be reduced or partly replaced by ice or phase-change cold storage, which can lower long-term storage cost and improve system durability (Hu et al., 2021; Liang et al., 2022). Future work should experimentally validate the proposed 400 Wp system under hourly weather variation and should compare battery buffering with thermal energy storage. Further improvements may include an adaptive MPPT-compressor controller, improved condenser heat transfer, PV module cooling, and the use of detailed compressor maps for R600a or R290. A life-cycle cost and environmental assessment should also be performed for specific locations. Overall, the study demonstrates that a correctly sized PV array, variable-speed compressor, and modest storage capacity can provide technically feasible and energy-efficient refrigeration for remote food, beverage, and small cold-chain applications.

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