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Performance Analysis of a Solar-Assisted Vapor Compression Refrigeration System

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Abstract

Solar-assisted vapor-compression refrigeration couples the high coefficient of performance of a conventional mechanical refrigeration cycle with a renewable electrical source whose availability generally coincides with high daytime cooling demand. This methodology paper develops a compact analytical framework for evaluating a photovoltaic (PV)-assisted vapor-compression refrigeration system without claiming new experimental measurements. The proposed system consists of a PV array, power-conditioning unit, optional battery buffer, inverter or direct-current compressor interface, and a single-stage refrigeration loop containing a compressor, condenser, expansion device and evaporator. Performance is assessed using refrigeration coefficient of performance (COP), PV power, solar fraction, grid-energy reduction and system energy balance. A representative case study is defined for an R134a vapor-compression unit delivering 1.5 kW of cooling and assisted by a 0.6 kWp PV array. Hourly solar irradiance and ambient-temperature scenarios are used to quantify how solar availability and condensing conditions influence compressor power and grid demand. The calculated daytime results show the expected trade-off: refrigeration COP decreases as condensing temperature rises, while PV contribution increases with solar irradiance. Under the stated assumptions, approximately 58% of compressor electricity during the analysed six-hour solar window can be supplied by the PV subsystem. The framework is suitable for comparative studies, preliminary sizing and experimental planning, while the literature basis is limited to publications available up to 2016.

Introduction

Refrigeration is essential in food preservation, medicine storage, agriculture, comfort cooling and small-scale industrial processes, but the vapor-compression refrigeration system (VCRS) requires continuous mechanical work at the compressor. In locations where the electric grid is weak, expensive or unavailable, the compressor power requirement becomes the principal limitation. Solar energy is attractive for refrigeration because cooling demand and solar availability often rise together during warm daytime periods. Early field investigations

demonstrated that photovoltaic refrigeration could preserve temperature-sensitive products in tropical climates, establishing the technical basis for combining solar electricity with conventional compression refrigeration (El Tom et al., 1991). Later work showed that a conventional domestic refrigerator could operate from a PV array, battery and inverter while maintaining useful thermal performance (Kattakayam & Srinivasan, 2000).

A solar-assisted VCRS can be configured in several ways. In the simplest arrangement, PV

electricity is routed through a charge controller and battery bank, converted to alternating current through an inverter and supplied to a conventional compressor. A second approach uses a direct-current variable-speed compressor and removes the inverter. A third approach minimizes or eliminates electrochemical storage and instead uses the refrigerated product, ice or another thermal store to absorb variations in solar input. Kaplanis and Papanastasiou (2006) showed that reducing cabinet thermal losses and carefully sizing the PV generator can significantly lower the energy requirement of a converted refrigerator. Axaopoulos and Theodoridis (2009) went further by demonstrating a batteryless PV ice-maker in which compressor control, maximum-power tracking and thermal storage improved autonomous operation.

The principal performance indicator of the refrigeration loop is COP, defined as cooling capacity divided by compressor work. For a given evaporating condition, COP normally falls when condensing temperature and pressure increase. Solar assistance does not automatically raise the thermodynamic COP of the vapor-compression cycle; rather, it reduces the external grid energy needed to supply compressor work. This distinction is important in performance analysis. The solar subsystem should therefore be evaluated with indicators such as PV output, conversion efficiency, solar fraction and avoided grid energy in parallel with the refrigeration-side COP. Modi et al. (2009), for example, reported a maximum COP of about 2.10 for their converted 165 L solar-powered domestic refrigerator and emphasized the importance of time-dependent operating conditions and component cost.

As PV technology developed, research increasingly focused on the matching between the solar generator and refrigeration load. Ekren et al. (2011) experimentally evaluated a 76 W DC household refrigerator supplied by PV and battery storage and showed that system exergy losses are strongly influenced by the relatively low conversion efficiency of the PV subsystem. Tina and Grasso (2014) demonstrated that long-term monitoring is also important because solar refrigerator operation is sensitive to weather, PV orientation, battery condition and temperature limits. Lazzarin (2014) compared PV-driven compression cooling with solar-thermal sorption alternatives and noted that falling PV costs had made the compression route increasingly competitive, especially for air-cooled systems.

The objective of this paper is to present a reproducible methodology for analysing a solar-assisted VCRS using only reference literature

published up to 2016. The paper does not report a laboratory experiment. Instead, it combines first-law refrigeration equations, PV power estimation and hourly energy sharing to produce a representative analytical case study. The procedure can later be applied to measured pressure, temperature, refrigerant flow and solar-radiation data when an experimental rig is available. The selected outputs are COP, compressor power, PV power available to the compressor, solar fraction, grid power and daytime grid-energy saving.

Literature Review

El Tom et al. (1991) conducted an early field study of a photovoltaic refrigerator under tropical Sudanese conditions. Their work demonstrated the practical value of mechanical refrigeration driven by solar electricity for vaccine and food preservation where conventional electricity was unavailable. The study remains relevant because it established the environmental and load conditions under which PV refrigeration must maintain cabinet temperature despite high ambient temperature.

Kattakayam and Srinivasan (2000) characterized the cool-down, warm-up and steady-state behaviour of a 100 W domestic refrigerator powered through a PV-battery-inverter chain. They reported that non-sinusoidal inverter supply did not significantly degrade thermal performance, although compressor heating and system losses still required attention. Kaplanis and Papanastasiou (2006) subsequently converted a conventional refrigerator for PV operation and emphasized cooling-load reduction, compressor performance and life-cycle based PV sizing as integral design steps.

Kim and Infante Ferreira (2008) reviewed solar electric, solar thermal and emerging refrigeration routes. Their comparison showed that no single technology is universally superior; solar electric compression systems provide simplicity and mature refrigeration hardware, while thermal sorption systems can exploit heat directly. For small vapor-compression systems, however, rapid PV development and efficient compressors make solar-electric configurations especially relevant. Modi et al. (2009) experimentally and numerically analysed a PV-operated domestic refrigerator and found that COP changed through the day, demonstrating why solar and thermal conditions must be evaluated simultaneously rather than at one nominal point.

Axaopoulos and Theodoridis (2009) demonstrated batteryless operation using

multiple small compressors, a dedicated controller and ice as a form of cold storage. This concept is methodologically important because it separates energy-source intermittency from cooling-service continuity. Ekren et al. (2011) evaluated a PV-powered refrigerator using energy and exergy concepts, reinforcing the need to distinguish refrigeration efficiency from the much lower solar-to-electric conversion efficiency of the complete system.

Wang et al. (2012) analysed a solar-assisted cascade arrangement combining vapor-compression and solar-driven absorption refrigeration. Although this configuration differs from a purely PV-assisted VCRS, it showed that solar input can reduce electrical demand and that performance improves when stronger solar input is available. Khan and Orfi (2014) similarly

examined a solar-powered cascade system for Riyadh and reported significant peak electrical-energy savings, illustrating the value of matching solar energy to periods of high cooling demand.

By 2016, system matching and compressor architecture had become major design themes. Huang et al. (2016) experimentally investigated direct solar-PV driven air conditioners and identified the ratio between PV peak power and cooling-load power as a key determinant of operating probability and runtime. Opoku et al. (2016) compared DC and AC solar refrigerators and found that the DC configuration reduced surge demand and could reduce PV-system cost by avoiding a large inverter. These findings directly motivate the methodology used here: the refrigeration loop and the PV-electric supply are evaluated as coupled but distinct subsystems.

Table 1. Selected pre-2017 literature used to define the analysis framework

Study	System focus	Methodological implication
El Tom et al. (1991)	PV refrigerator field test	Solar refrigeration is feasible in high-ambient, off-grid conditions.
Kattakayam & Srinivasan (2000)	PV-battery-inverter refrigerator	Thermal performance can be maintained with inverter-fed compression.
Kaplanis & Papanastasiou (2006)	Converted PV refrigerator	Cooling-load reduction and PV sizing are central to system design.
Modi et al. (2009)	165 L domestic refrigerator	COP varies with operating time and thermal conditions.
Axaopoulos & Theodoridis (2009)	Batteryless PV ice-maker	Control and thermal storage can reduce dependence on batteries.
Ekren et al. (2011)	PV refrigerator energy/exergy test	PV conversion losses materially affect whole-system efficiency.
Huang et al. (2016)	Direct-PV cooling	PV-to-load sizing governs operating probability and runtime.
Opoku et al. (2016)	DC vs AC solar refrigerator	DC compressors reduce surge/inverter requirements.

Methodology

1. System configuration

The proposed analytical system contains a solar-PV source and a conventional single-stage vapor-compression refrigeration loop. The electrical path is PV array → controller → DC bus → inverter (for an AC compressor) or direct DC compressor interface. A small battery may be included as a short-duration buffer; the

methodology does not require a large battery because the principal objective is to quantify direct daytime solar assistance. The refrigeration path is compressor → condenser → expansion device → evaporator → compressor. The evaporator removes heat from the refrigerated space and the condenser rejects the sum of evaporator load and compressor work to ambient air.

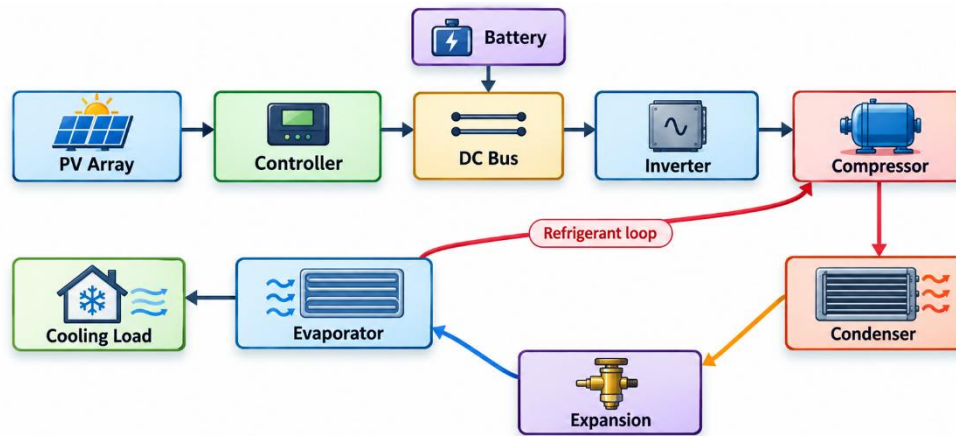


Figure 1. Analytical configuration of the solar-assisted vapor-compression refrigeration system.

2. Thermodynamic performance model

For steady operation of the refrigerant loop, the evaporator cooling rate is $Q_e = \dot{m}r(h_1 - h_4)$, where $\dot{m}r$ is refrigerant mass-flow rate and h is specific enthalpy at the usual cycle state points. Compressor power is $W_c = \dot{m}r(h_2 - h_1)$, and the refrigeration coefficient of performance is $COP = Q_e/W_c$. In an experimental implementation, h_1 – h_4 are obtained from measured suction/discharge pressure and temperature together with an R134a property database. The condenser heat rejection is $Q_c = Q_e + W_c$. Compressor isentropic efficiency may be included by relating the actual discharge enthalpy to the isentropic discharge enthalpy. For the compact case study in this paper, a 1.5 kW cooling load is held constant and a temperature-dependent COP schedule is used to illustrate the energy-sharing method; these values are methodological assumptions, not measured data.

3. Solar-PV and electrical model

PV electrical output is estimated from $P_{pv} = P_r(G/1000)fd$, where P_r is rated PV capacity at standard test irradiance, G is plane-of-array solar irradiance in $W\ m^{-2}$, and fd is a derating factor accounting for temperature, wiring and module mismatch. When an inverter is used, the compressor-usable solar power is $P_{solar} = P_{pv}\eta_{inv}$. The instantaneous solar fraction is $SF = \min(P_{solar}, W_c)/W_c$. Grid power is $P_{grid} = \max(0, W_c - P_{solar})$. Over a time interval, the grid-energy saving relative to a grid-only compressor is $Saving = (\sum W_c \Delta t - \sum P_{grid} \Delta t) / (\sum W_c \Delta t) \times 100$. This approach prevents the common error of treating PV contribution as an increase in the thermodynamic COP of the refrigerant cycle.

4. Case-study assumptions and calculation procedure

Table 2. Assumptions used for the illustrative analytical case study

Parameter	Value / condition
Refrigerant	R134a
Cooling capacity	1.5 kW
Evaporating temperature	–5 °C nominal
PV rated power	0.60 kWp
PV derating factor	0.85
Inverter efficiency	0.92
Solar irradiance range	300–900 $W\ m^{-2}$
Ambient temperature range	25–35 °C
Analysis time step	1 h
Nature of results	Analytical/illustrative, not experimental

The calculation sequence is: (1) define hourly solar irradiance and ambient temperature; (2) assign or calculate condensing temperature and cycle COP; (3) calculate compressor power from the cooling load divided by COP; (4) estimate PV power from rated capacity, irradiance and derating; (5) apply inverter efficiency; (6) limit solar contribution to the instantaneous compressor requirement; (7) calculate residual grid power and solar fraction; and (8) integrate hourly values to obtain energy use and grid-energy saving. For an experimental extension, the same sequence can use measured irradiance, PV voltage/current, compressor power, suction/discharge pressures, refrigerant temperatures and cabinet temperature.

Uncertainty should then be propagated from sensor accuracy into COP and energy indicators.

Results

Table 3 summarizes the illustrative six-hour calculation. The assumed ambient temperature rises from 25 °C to 35 °C, causing the representative COP to decrease from 3.20 to 2.80 around the hottest period before recovering slightly. Consequently, compressor power increases even though cooling capacity is fixed at

1.5 kW. At the same time, PV power rises strongly with solar irradiance. This creates the characteristic solar-refrigeration interaction: the refrigeration cycle becomes thermodynamically less favourable at high ambient temperature, but more solar electricity is available to offset the increased compressor demand. This qualitative behaviour is consistent with the time-dependent observations emphasized by Modi et al. (2009) and with the PV/load matching results of Huang et al. (2016).

Table 3. Model-based daytime performance of the illustrative solar-assisted VCRS

Time	G (W/m ²)	Ta (°C)	COP	Wc (kW)	PV usable (kW)	Grid (kW)	SF (%)
08:00	300	25	3.20	0.469	0.141	0.328	30.0
09:00	500	27	3.10	0.484	0.235	0.249	48.5
10:00	700	30	2.95	0.508	0.328	0.180	64.6
11:00	900	35	2.80	0.536	0.422	0.113	78.8
12:00	800	34	2.85	0.526	0.375	0.151	71.3
13:00	600	31	3.00	0.500	0.282	0.218	56.3

Across the six one-hour intervals, the grid-only compressor would consume 3.02 kWh under the stated COP schedule. The PV subsystem supplies 1.78 kWh directly to the compressor demand, leaving 1.24 kWh to be supplied by the grid or storage. The resulting daytime solar fraction is 59.0%. The lowest instantaneous solar fraction occurs at 08:00 because irradiance is only 300 W m⁻², while the highest occurs near the 900 W m⁻² condition. These numbers should not be interpreted as universal performance claims; changing PV size, compressor type, ambient temperature, insulation or cooling load will change the result.

The results also show why PV array sizing cannot be based on average compressor power alone. A conventional AC compressor may require high starting power and an inverter large enough to survive the surge, whereas a variable-speed DC compressor can reduce this penalty. Opoku et al. (2016) experimentally reported lower surge power for a DC compressor arrangement and found that eliminating the inverter could reduce overall solar-system installation cost. Similarly, Axaopoulos and Theodoridis (2009) demonstrated that staged compressor control and thermal storage can improve utilization of fluctuating solar power. Therefore, a practical design should evaluate both steady-state energy and transient starting requirements.

From the refrigeration perspective, the decrease in COP with higher condensing temperature is the dominant thermodynamic trend. Improving condenser heat rejection, reducing cabinet heat

gain, maintaining correct refrigerant charge and selecting an efficient compressor directly reduce electrical demand. Solar assistance then offsets part of that reduced demand. Kaplanis and Papanastasiou (2006) highlighted the importance of lowering cooling load before increasing PV capacity, and this remains a sound design sequence: first improve the refrigeration system, then size the renewable subsystem. In the present framework, any efficiency improvement that raises COP from 2.8 to 3.2 at the same 1.5 kW load reduces compressor power from about 0.536 kW to 0.469 kW, thereby increasing the fraction of demand that a fixed PV array can supply.

The methodology is therefore most useful as a coupled sizing tool. A designer can sweep evaporating temperature, condensing temperature, cooling load, PV capacity and storage size to determine a configuration that meets temperature requirements with an acceptable grid-energy contribution. For off-grid applications, the same hourly balance can be expanded to include battery state of charge or cold thermal storage. For grid-connected applications, the solar fraction and avoided electrical energy are the most direct indicators. Long-duration monitored data, as used by Tina and Grasso (2014), are recommended before final design because short tests may not capture cloudy-day operation, seasonal changes or thermal recovery after door opening.

Conclusion and Discussion

This paper presented a step-by-step methodology for performance analysis of a solar-assisted vapor-compression refrigeration system using literature published no later than 2016. The method deliberately separates refrigeration-cycle performance from renewable-energy contribution. COP evaluates how efficiently compressor work is converted into cooling, while PV power, solar fraction and grid-energy saving evaluate how much of that compressor work is supplied by solar electricity. This distinction produces a clearer interpretation than combining all effects into a single efficiency value. For the illustrative 1.5 kW cooling case with a 0.60 kWp PV array, the six-hour calculation produced a compressor-energy requirement of 3.02 kWh and a residual grid requirement of 1.24 kWh, corresponding to a modelled daytime solar fraction of about 59%. The value is an analytical example rather than an experimental result, but it demonstrates the sensitivity of grid demand to irradiance and COP. The literature indicates that practical performance can be improved through reduced thermal load, proper PV-to-compressor matching, variable-speed or DC compressors, effective controls and thermal or electrical storage (Kaplanis & Papanastasiou, 2006; Axaopoulos & Theodoridis, 2009; Huang et al., 2016; Opoku et al., 2016). For future experimental work, the recommended measurements are solar irradiance, PV voltage and current, compressor input power, suction and discharge pressure, refrigerant temperatures, ambient temperature, cabinet temperature and cooling load. These measurements allow calculation of cycle COP, electrical conversion losses, solar fraction and uncertainty. A full-year analysis would additionally establish seasonal reliability and storage requirements. Thus, the proposed framework provides a compact foundation for laboratory testing, simulation and preliminary design of solar-assisted vapor-compression refrigeration systems.

References

El Tom, O. M. M., Omer, S. A., Taha, A. Z., & Sayigh, A. A. M. (1991). Performance of a photovoltaic solar refrigerator in tropical climate conditions. *Renewable Energy*, 1(2), 199–205. [https://doi.org/10.1016/0960-1481\(91\)90075-Z](https://doi.org/10.1016/0960-1481(91)90075-Z)

Kattakayam, T. A., & Srinivasan, K. (2000). Thermal performance characterization of a photovoltaic driven domestic refrigerator.

International Journal of Refrigeration, 23(3), 190–196. [https://doi.org/10.1016/S0140-7007\(99\)00049-3](https://doi.org/10.1016/S0140-7007(99)00049-3)

Kaplanis, S., & Papanastasiou, N. (2006). The study and performance of a modified conventional refrigerator to serve as a PV powered one. *Renewable Energy*, 31(6), 771–780. <https://doi.org/10.1016/j.renene.2005.04.012>

Kim, D. S., & Infante Ferreira, C. A. (2008). Solar refrigeration options—A state-of-the-art review. *International Journal of Refrigeration*, 31(1), 3–15. <https://doi.org/10.1016/j.ijrefrig.2007.07.011>

Modi, A., Chaudhuri, A., Vijay, B., & Mathur, J. (2009). Performance analysis of a solar photovoltaic operated domestic refrigerator. *Applied Energy*, 86(12), 2583–2591. <https://doi.org/10.1016/j.apenergy.2009.04.037>

Axaopoulos, P. J., & Theodoridis, M. P. (2009). Design and experimental performance of a PV ice-maker without battery. *Solar Energy*, 83(8), 1360–1369. <https://doi.org/10.1016/j.solener.2009.03.007>

Ekren, O., Yilanci, A., Cetin, E., & Ozturk, H. K. (2011). Experimental performance evaluation of a PV-powered refrigeration system. *Elektronika ir Elektrotechnika*, 114(8), 7–10. <https://doi.org/10.5755/j01.eee.114.8.684>

Wang, L., Duan, S. P., & Cui, X. L. (2012). Performance analysis of solar-assisted refrigeration cycle. *Applied Mechanics and Materials*, 170–173, 2504–2507. <https://doi.org/10.4028/www.scientific.net/AMM.170-173.2504>

Tina, G. M., & Grasso, A. D. (2014). Remote monitoring system for stand-alone photovoltaic power plants: The case study of a PV-powered outdoor refrigerator. *Energy Conversion and Management*, 78, 862–871. <https://doi.org/10.1016/j.enconman.2013.08.065>

Lazzarin, R. M. (2014). Solar cooling: PV or thermal? A thermodynamic and economical analysis. *International Journal of Refrigeration*, 39, 38–47. <https://doi.org/10.1016/j.ijrefrig.2013.05.012>

Khan, M. S. M., & Orfi, J. (2014). Cooling performance and energy saving analysis of

cascade refrigeration system powered by solar energy for Riyadh region (Saudi Arabia). *International Journal of Sustainable Building Technology and Urban Development*, 5(1), 41–49.
<https://doi.org/10.1080/2093761X.2013.875492>

Huang, B. J., Hou, T. F., Hsu, P. C., Lin, T. H., Chen, Y. T., Chen, C. W., Li, K., & Lee, K. Y. (2016). Design of direct solar PV driven air conditioner.

Renewable Energy, 88, 95–101.
<https://doi.org/10.1016/j.renene.2015.11.026>

Opoku, R., Anane, S., Edwin, I. A., Adaramola, M. S., & Seidu, R. (2016). Comparative techno-economic assessment of a converted DC refrigerator and a conventional AC refrigerator both powered by solar PV. *International Journal of Refrigeration*, 72, 1–11.
<https://doi.org/10.1016/j.ijrefrig.2016.08.014>