Photovoltaic and Photovoltaic Thermal Technologies for Refrigeration Purposes: An Overview

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Abstract
Refrigeration systems have a broad range of applications, playing a critical role in human life. Especially, vaccine preservation in rural regions has become more critical than in the past during the COVID19 era. In this sense, meeting the cooling process’s energy need with renewable energy is critical, as the grid cannot support it. Thus, solar energy has been extensively studied for use in refrigeration cycles. Compression, absorption, adsorption, desiccant, and ejector refrigeration cycles are frequently used in this configuration. This article discusses multiple studies showing various attributes’ impact on a system’s overall efficiency. Most previous reviews did not cover PV with refrigeration cycles. So, this paper surveys the literature on PV-powered cooling cycles. For better classification, PV technologies are categorized into three types: PV, PVT, and CPVT. With this regard, CPVTs still have a way to progress due to a lack of studies compared to PV. The works are divided into three main sections as Exergy Studies, Experimental Studies, and Simulation and Numerical Studies. This review paper categorizes and rates refrigeration-assisted solar systems based on exergy destruction, exergy efficiency, and COP of cooling cycles. The results showed that PV panels have the highest exergy destruction in most of the systems. It is concluded that using PV technologies has a great potential to supply cooling demand, especially in a hot climate condition. Moreover, the study’s findings are anticipated to aid designers in scaling up photovoltaic-based cooling systems, resulting in more efficient and sustainable designs.

Keywords Refrigeration · Solar panel · Photovoltaic · Photovoltaic thermal · CPVT · COP

Abbreviations
PV Photovoltaic
PVT Photovoltaic Thermal
CPVT Concentrating Photovoltaic Thermal
CCHP Combined Cooling, Heating and Power
COP Coefficient of Performance
VAR Vapor Absorption Refrigeration
VCR Vapor Compression Refrigeration
DC Direct Current
AC Alternating Current
VSDC Variable Speed Direct Current
FSDC Fixed Speed Direct Current
PCM Phase Change Material
ETC Evacuated Tube Collector

T Temperature
S Entropy
MOF Metal–Organic-Framework

Units
°C Degrees of Centigrade
W Watt
M Meter
L Liter
KPH Kilometers per hour

1 Introduction
As time goes by, renewable energy becomes vital, referring to the energy shortage on fossil fuels. In past decades, scientists paid more attention to using renewable energies like solar as a primary energy source [1]. Many methods could use
this energy, such as power production, refrigeration, food drying, water heating, and space heating [2]. Another reason for using solar power, besides energy shortage, is the CO₂ issue. During the past decade, carbon dioxide has become one of the leading human problems. To solve this issue, many researchers reported new methods that could be concluded to use renewable energies. Solar power should be analyzed as a good example of renewable energy due to its low price and reachable energy. Researchers concluded that solar power could be one of the best in reducing carbon emission and global warming issues [3]. As mentioned above, refrigeration cycles could couple with solar energy, and this source could supply the energy demand of cooling cycles.

### 1.1 Solar Cooling

Solar cooling is a system that uses solar power for cooling and refrigeration purposes [4]. By noting that a cooling load peak could occur during the highest solar energy potential, using solar power could be logical [5]. The solar cooling method could be one of the best alternative methods to take care of environmental aspects and reduce the environmental impacts of conventional air conditioning [6]. Satisfying environmental outcomes would happen by solar absorption refrigeration because the refrigerants are free from CFC [7]. According to Swartman et al. [8], the first use of solar energy in refrigeration got back in 1936. At that time, two refrigeration systems were considered vapor-compression and absorption. After that, the use of solar collector for providing thermal energy of refrigeration and cooling cycles were investigated. As technology was developed, the use of photovoltaic systems became more common. In 1974, according to the WHO, the application of photovoltaic panels for storing vaccines and medicines was considered in a remote area [9]. It could be inferred that solar cooling applications are in a wide range. Solar cooling can take an essential role in agricultural usages, like storing crops [10], medicine storage, and vaccine preservation [11]. Using solar electric cooling with photovoltaic would have a great prospect. By increasing the usage of PV-driven chillers, the cost of these applications is decreased, as shown in Fig. 1.

Solar cooling could be categorized into two main methods: PV-driven [12] and collector-based methods running a wide range of cooling cycles like adsorption, desiccant, and absorption [13]. In this paper, the first method and the combination of the two methods are analyzed. Among conventional cooling cycles, vapor-compression and absorption refrigeration systems have been considerably noted [14]. The cooling methods that have been analyzed in this article, as depicted in Fig. 2, are compression, absorption, adsorption, desiccant, and ejector cooling cycles. Also, the thermo-electric cooling system is mentioned in the articles. However, the surveyed studies are classified based on the five main cooling cycles for better comparison. Moreover, as the combining cooling cycles, hybrid methods are surveyed and analyzed.

As shown in Fig. 2, photovoltaic panels could supply the energy demand of compression refrigeration cycles. Due to the high COP of cooling, PV-driven compression refrigeration has commonly been used [16]. The types of cooling cycles coupled with PV panels are limited. Whereas, as shown in Fig. 3, the types of solar thermal cooling cycles would be broad [17]. Thus, photovoltaic thermal collectors (PVT) and concentrating photovoltaic thermal collectors (CPVT) for supplying the thermal energy demand of refrigeration like absorption and adsorption should be considered.

### 1.2 Applications of Solar Refrigeration

The previous subsection showed that five main cooling cycles are surveyed, so solar cooling based on these five processes has been reviewed. Figure 4 represents the main solar cooling applications mentioned in the article. Moreover, the application of each solar cooling cycle has been reported based on the following remarks.

#### 1.2.1 Vapor-Compression Refrigeration

Photovoltaic panels could run vapor-compression refrigeration. The application of this solar cooling was related to vaccine preservation, domestic refrigerators, and ice makers.

In a review study, Ferreira and Kim [18] compared different solar cooling technologies and concluded that compression refrigeration with PV had a better economic aspect than other solar refrigeration. In their review, they focused on thermodynamic and economic studies. So, the importance of vapor compression refrigeration, powered by PV, could be observed.

#### 1.2.2 Absorption Refrigeration

A solar absorption cooling cycle is placed in the category of solar thermal refrigeration cycles. Thus, a solar collector should be utilized to provide the required energy, and CPVTs and PVTs are commonly used to supply this energy [19]. The absorption cooling could be used in buildings when powered by CPVTs or PVTs [20]. Also, absorption refrigeration cycles are used for vaccine storage. McCarney et al. [21] reviewed the works on solar energy applications in vaccine preservation. Their review mentioned different working fluids of solar absorption and adsorption cooling for vaccine storage. Another review by Siddiqui and Said [22] showed the application of PVT in absorption cooling cycles and hybrid absorption like ejector-absorption or compression-absorption refrigeration systems.
1.2.3 Adsorption Refrigeration

Adsorption is very similar to the absorption process. Choosing an appropriate adsorbent could be vital to achieving high performance coupled with solar power. Some adsorbents such as activated carbon and silica-gel are conventionally used in this system [23]. Recent research showed that Metal–Organic Framework-adsorbents (MOF-adsorbents) could improve the performance of this cycle [24]. The application of this system, due to the low COP, might be less practical.
So, the applications are mainly limited to air conditioning and ice-maker facilities [25]. The COP range of this system varied from 0.5 up to 0.6 [26]. In a review work by Fernandes et al. [27], the future aspects of solar adsorption are presented, and the effect of using different solar collectors in the adsorption cycle performance has been shown.

1.2.4 Desiccant Refrigeration

The application of these cooling cycles is mainly focused on air conditioning [28]. These cooling cycles are typically coupled with solar collectors, but this system with a photovoltaic-based setup is not conventional. Solar PVTs
have been coupled with desiccant refrigeration cycles in many research works. Ge et al. [29] reviewed different studies conducted in the field of rotary desiccant cooling cycles. They surveyed different PVT and solar collectors with different collector areas, and the overall performance of each was shown. Also, Jani et al. [30] reviewed the applications of hybrid solid desiccant- vapor compression refrigeration in air conditioning.

### 1.2.5 Ejector Refrigeration

In the aspect of thermal energy, Ejector refrigeration is considered a low-grade technology. The COP of this system varies from 0.3 up to 0.4 [31]. Although, due to its simplicity, the usage of this cooling cycle has become practical. Also, the combination of ejectors with compression or absorption cycles could be seen in different research works [32]. Braimakis [33] analyzed the COP enhancement in hybrid refrigeration cycles like ejector-compression or ejector-absorption by reviewing different works on solar ejectors. Also, Abdulateef et al. [34] reported that a PV application for ejector cooling might be more expensive than thermal collector utilization.

### 1.3 Motivation and Objective of the Present Work

Some recent reviews on solar cooling technology are mentioned as follows. In 2013, Ullah et al. [35] reviewed the sorption technologies powered by solar energy. In the same year, in the review study, Sarbu and Sebarchievi [36] reported different articles about solar cooling, including PV coupled with compression refrigeration. Their study reported solar collectors coupled with other cooling cycles, but PVT and CPVT were not mentioned. In 2017, Leonzio [37] reviewed solar absorption cooling cycles focusing on PV and PVT and categorized the review based on the absorption effects and working fluids. Furthermore, in 2021, Alsagri et al. [38] presented a review paper on geothermal energy technologies for cooling purposes. As a result, the PV technologies, linked to refrigeration cycles, are reviewed in the following sections in the same way that the geothermal review paper was.

According to the above review papers, it is concluded that many reviews focused on one or two refrigeration cycles powered by solar energy, and the usages of solar collectors have been reported more than photovoltaic. Also, some researchers have reviewed the applications of working fluids or analyzed varying different parameters in solar cooling. To the best of our knowledge, no review work has been published on applying PV, PVT, and CPVT in refrigeration in one organized paper. The following sections review and analyze the studies conducted on PV, PVT, and CPVT coupled with one of the five main refrigeration or hybrid configuration cycles. Also, some parameters like the COP of refrigeration, PV efficiency, exergy efficiency, and concentration ratio are followed. Compared to previous reviews, this one is unique because it pays close attention to the COP parameter in each research article. Each part also includes information on the components with the highest exergy destruction. Categorizing papers into three primary bases of exergy, experimental, and simulation studies could provide researchers with a great deal of insight for future research. Additionally, the gap of each field with this classification could be observed. Finally, the research gaps are found by reviewing the articles in this field, and concluding remarks are presented.

### 2 Refrigeration Cycles Powered by Photovoltaic

As good equipment for producing electricity from solar power, photovoltaic panels have been used in solar-driven refrigeration systems. Vapor compression refrigeration cycles have been conventionally used in this configuration. The electricity needed by the compressor during a cooling process could be obtained from a PV panel. The main reasons for using PV panels are their high power-to-weight ratio, compactness, easy installation, and lack of moveable parts [39]. This utilization might range from food and pharmaceutical storage to domestic functions. It could be implemented in remote areas for vaccine preservation and food storage during the unavailability of a power grid [40].

Additionally, the need for vaccine storage for distribution in developing countries is highlighted throughout the COVID-19 era. So, Uddin et al. [41] analyzed using vaccine storage powered by photovoltaics in off-grid regions. Another application of photovoltaics refrigeration belonged to a food storage truck. So, as a result of the PV-integrated deliveries, it has been shown that refrigerated transports may embrace both the economic and environmental aspects of sustainability, making it an effective tool for food distribution [42]. The difficulties associated with refrigeration truck deliveries are determined by the many climate regions through which the vehicle traveled[43]. As a result, optimization of the setup to get the desired output should be addressed. Figure 5 illustrates the energy flows of a refrigeration truck equipped with solar panels during a time interval of k. From this, the dependent parameter for improving the design approach should be determined. Accordingly, the publications in the field of PV integrated with cooling cycles, particularly compression refrigeration, are reviewed in the following sections. These articles are categorized as exergy, experimental, simulation, and numerical studies. These studies have been reviewed, and the impact of various parameters on COP has been reported.
2.1 Exergy Studies

Two critical criteria in developing and operating photovoltaic refrigeration systems are exergy efficiency and exergy destruction values. The exergy destruction has been reported considerably high on the PV panel. Besides, in a refrigeration system, the compressor mainly considers exergy destruction [44]. So, the best performance results are investigated by varying system parameters to maximize the exergy efficiency and minimize the exergy destruction. In the following, the effective parameters on exergy values are surveyed. Accordingly, Kalbande [45] examined solar irradiation and showed that, by increasing solar radiation, PV and exergy efficiencies had similar behavior; however, exergy destruction behaved vice-versa [46]. Also, the increase of solar radiation directly impacts the cooling capacity, and its effect would be considerable [47]. It could be inferred that solar radiation significantly affects exergy efficiency. So, choosing a suitable location should be considered carefully.

Another parameter that affects exergy behavior in PV refrigeration is cooling load. The cooling load that significantly affects exergy efficiency was studied by Ekren et al. [44]. They reported that, by increasing loading to the overloaded mode, the exergy efficiency and COP decreased. Moreover, Ambient temperature is another factor that impacts exergy efficiency. Sydney [48] showed that, with increasing the ambient temperature, the exergy efficiency of PV decreased. For refrigeration systems, exergy losses directly correlate with the ambient temperature. Also, the ambient temperature increase resulted in a higher temperature difference, higher compressor power, and higher loading capacity, which is concluded to increase the exergy losses.

From the above mentioned, it is found out that solar radiation, ambient temperature, and cooling load had a significant effect on exergy efficiency and performance of the system. So, the effect of these parameters should be considered in every design procedure.

Also, some exergy studies have been conducted for some novel and innovative design cases. In 2018, Ferrucci et al. [49] studied a thermochemical reactor coupled with a compressor refrigeration cycle powered by PV. They showed that reducing the ambient temperature could lead to higher exergy efficiency of the compressor-driven thermochemical storage. In the same year for a PV-driven ice storage air conditioning system, Zuo [50] reported that about 13% of the solar energy absorbed by PV was transferred to electricity. From this value, about 59% of exergy loss occurred.

Furthermore, in the PV components between controller, battery, and inverter, the inverter had the highest energy consumption and exergy loss. Thus, it is inferred that sizing and optimizing PV panels in the systems coupled with the refrigeration cycle should be considered to maximize the exergy efficiency [50]. Therefore, using other methods could be logical to omit the inverter. According to this, in 2021, Ghorbani et al. [51] analyzed a system that contained a two-stage ejector cooling cycle with a Kalina power cycle. Also, monocrystalline PV was used in this system to power the ejector refrigeration cycle. The effect of the Kalina cycle on the whole performance of the system resulted in COP improvement for the ejector. The ejector cooling cycle COP...
was enhanced from 0.78 to 0.83. Figure 6 presents the exergy flow diagram of this novel setup.

2.2 Experimental Studies

Many experimental studies have investigated the optimum design for compression refrigeration cycles powered by photovoltaic. As shown in Fig. 7, comparing a vapor compression refrigeration powered by PV with a vapor absorption refrigeration coupled with an evacuated tube collector showed that both were cost-effective [52]. So, the importance of compression refrigeration and coupling this cooling device with solar energy is notable. The typical compression refrigeration cycles, which are connected to PV panels, are domestic refrigerators. The PV cell’s output is direct current, while domestic refrigerators use alternating current; therefore, an inverter is needed for transforming DC to AC. A battery, used for storing DC and discharging this current in the non-solar time, makes the refrigeration system active continuously [36]. Thus, the basic form of PV panel coupled with refrigeration includes inverter and battery and alternating current compressor. Figure 8 indicates different components used in practice to run a compression chiller powered by PV panels.

Moreover, due to the inverter’s high cost, some experimental studies on the DC compressor were conducted, which was economically helpful by omitting the inverter from the configuration. A DC compressor prevents losses when converting DC to AC [39]. In Fig. 9, a complete setup of one DC refrigerator is illustrated. In 2017, Daffallah et al. [54] analyzed DC refrigerators using different parameters. They changed the thermostat settings and showed that a higher thermostat position led to a higher refrigeration ampere-hour. In 2018, Daffallah [55] analyzed a DC refrigerator by changing the voltage from 12 to 24 Volts. The results showed that the 12 V had better outcomes than 24 V, particularly at the higher ambient temperatures. Daffallah [56] modeled and sized 12 V DC refrigerators the following year. The outcome of this design showed that, for a 75-Watt refrigerator, a 30 A battery could maintain about 21 h of refrigeration capacity. In 2019, Pang et al. [57] analyzed a DC air conditioning system used in vehicles powered by PV. They showed that this design could be used instead of a conventional air conditioner due to less emission and more energy saving. In 2021, Sabri and Ker [58] studied refrigeration powered by photovoltaic with battery storage. This study investigated the energy consumption of a DC refrigerator and a DC-inverter-refrigerator.

As mentioned earlier, the usages of PV-driven refrigeration in vaccine preservation has been reported in many articles. Kalbande [45] used a DC compressor for vaccine preservation at low temperatures, focusing on the PV panel.
sizing and battery capacity. They showed that the output depended on the climate, site location, and power used in the refrigeration cycle. The exergy efficiency was reported as 14.20% on the full load condition. In 2021, Kasera et al. [59] investigated a refrigeration setup, including a variable speed compressor, and the results showed that R290 was an excellent refrigerant from the view of thermodynamic properties and environmental issues. Also, using variable speed direct
current (VSDC) and changing other parameters to reach better performance was reported. Kaplanis and Papanastasiou [60] studied the decreasing distance between the solar panel components to minimize power losses. During this experiment, for reducing voltage drops that occurred on cables, the distance between the panels and charge controller was reduced from 10 to 1.5 m.

Additionally, food and medicine storage by refrigeration processes are crucial in developing countries, especially with hot weather conditions. So, the use of solar energy in those regions should be considered. With this regard, Del Pero et al. [61] developed a solar photovoltaic adaptable refrigeration kit called the SPARK. The chest freezer is another example of refrigeration, utilized in hot climate conditions regarding storing food and protecting them from spoilt. Suamir et al. [62] reported that, for a chest freezer coupled with PV, by changing the solar power from 4.6 to 7.2 kW.h/m², the highest electric power was obtained for the highest irradiation. Thus, coupling the national grid with PV panels would be significant. The ice-making process is another refrigeration cycle coupled with PV in hot climate regions. Because of the high energy loss in an ice-making process, Xu et al. [63] suggested applying an immersed evaporator and co-integrated exchanger, which increased the COP from 0.51 to 0.71. In 2017, Xu et al. [64] suggested that the best locations for this ice refrigeration were ventilated and dark areas. Tina and Grasso [65] analyzed a PV stand-alone system applied for outdoor refrigeration. In this experiment, remote monitoring, for observing the PV performance to prevent any malfunction, enhanced the reliability. Aktakir [66] analyzed multi-purpose refrigerators and their dependence on climatic conditions. The results showed that a PV-powered refrigerator could be suitable for small-scale, which produces low or medium temperature. So, from the above studies, it could be concluded that the usage of solar cooling is essential in hot climate conditions. Based on that, most of the conceptual design was conducted for the hot climate case.

Furthermore, some innovative design in order to save more energy was examined. For instance, Li and Wang [67] used hydrogen as an energy storage material in an innovative design. It was coupled with a fuel cell, and during the non-solar time, it could discharge the energy via a fuel cell. Some PV-based refrigeration studies have mentioned using phase change material (PCM) as an energy storage route. Also, for food preservation in hot climates, using thermal energy storage instead of a battery would be a suitable option for a vapor compression cycle coupled with PV [68]. Khalifa et al. [69] conducted an experimental study on PCM used in a refrigeration cycle with a COP of 0.95. It was shown that using potassium chloride aqueous solution, as the PCM energy storage, could successfully work and store the surplus energy from PV cells. Another factor is the power consumption based on the compressor power, and it shall be noted that it consumes more energy at the initial start [70].

The aforementioned studies showed the importance of PV refrigeration and various applications. Also, the effective parameters, that were experimentally investigated, showed the dependences of different factors. So, regarding the design procedure of PV-refrigeration, to reach a suitable COP, some other experiments should be considered. In 2003, Blas et al. [71] analyzed the effect of voltage and refrigeration circuit number and showed that increasing the number of circuits decreased the COP for a milk cooling process. Based on improving COP, Dhondge et al. [72] investigated the effect
of changing refrigerants for solar-driven refrigeration. Using R-134 + 0.5% Al₂O₃ nano-refrigerant improved the COP from 2.02 to 2.41. Saeed Khan et al. [73] conducted a study to examine variable refrigerant flow rates of a chilling milk unit coupled with PV. The effect of this flow variation with R410 showed a COP as high as 4. Torres-Toledo et al. [74] developed an ice maker based on a DC-freezer and adaptive controller. This controller unit helped the system enhance ice production efficiently under various weather conditions. Also, they showed that COP about 1.5 and ice fractions of more than 70% could be obtained during the majority of the year. Modi et al. [75], in their experimental study on domestic refrigerators powered by PV. They examined the COP changes and showed that, by passing from morning to afternoon, the COP was decreased. The maximum COP in the morning had a value of about 2.1. Alshqirate et al. [76] showed that, by changing some parameters like the evaporating and condensing temperature in a domestic refrigerator, the COP was changed. By increasing the evaporating temperature, while keeping constant the condensing temperature, the COP was increased. In 2020, Martínez-Calahorro et al. [77], in their analysis about industrial refrigeration with photovoltaic, introduced a new self-sufficiency index for sunshine hours. This index evaluates the performance of a PV when facing a consumption during sunshine hours. It could give incredible sight to optimizing PV panels and reaching higher COPs. Regarding the enhancements in refrigeration cycles powered by PV, Ruiz et al. [78] investigated a PV-driven cooling unit that was improved by an evaporative chimney. The results showed that 49% of solar energy was transformed to the cooling capacity.

The experimental articles published on PV-driven refrigeration show that changing different parameters and modifying the refrigeration cycles or solar components to reach a higher COP and PV performance has been the main aim of all research. An identified gap could be the lack of using other refrigeration cycles or hybrid cooling units powered by PV cells. Most of the research works rely on compression. So, running other cooling systems with simple PV is recommended for future studies.

### 2.3 Simulation and Numerical Studies

The related simulation works have mainly been carried out via the TRNSYS and Aspen software, while most of the numerical works have been conducted by MATLAB. These studies are constructive in paving the way to optimize the COP. In the following parts, based on the simulation or numerical studies, the articles are surveyed.

#### 2.3.1 Simulation Studies

Sharma et al. [39] compared vapor absorption and vapor compression refrigeration and showed that the battery was discharged at a more prolonged rate in comparison to a vapor compression cycle. So, a vapor compression system was used when a high cooling load was needed. Gupta et al. [53] analyzed parameters like the PV panel wattage, battery capacity, and insulation thickness. The results showed that, with increasing the insulation thickness from 25 to 50 mm, the needed power capacity of the panel was decreased from 320 to 200 W. Beck et al. [79] analyzed the thermal energy storage that supplied additional energy of a PV for cooling application, by Aspen and MATLAB. In light of the preceding studies, it can be stated that the majority of PV-driven refrigeration research falls into the experimental category. In contrast, simulation studies are still in their early stages.

#### 2.3.2 Numerical and Modeling Studies

Modeling a PV-driven refrigeration system could help improve its performance. For example, In 2016, Long et al. [80] developed a mathematical modeling and simulation study for an electrochemical refrigerator powered by PV. They showed that the refrigerating capacity and COP decreased by increasing the temperature of hot storage. Later on, In 2020, Salilih et al. [81] modeled a PV system coupled with refrigeration by varying the evaporator pressure. In 2021, Varvagiannis et al. [82], by semi-dynamic modeling, showed the effect of PCM energy storage in solar-compression refrigeration. The modeling showed that the COP of the chiller decreased when the PCM energy storage was charged.

Furthermore, more particular topics like battery maintenance were covered in the research. Accordingly, using an appropriate capacity in a system that uses batteries to store energy would be significant. So, keeping a battery in good shape during a non-solar time is essential for preventing sulfation and deep discharging. In this case, the load and power consumption must be controlled. The weather conditions and cooling capacity should be considered for choosing the battery’s capacity and the refrigeration system’s power consumption [83]. With this regard, Hence Chukwunene et al. [84] conducted numerical modeling by MATLAB to analyze different parameters. This modeling helped to choose the suitable battery capacity that met the cooling load. Salilih and Birhane [85] developed a simulation method and modeled variable speed compressors directly coupled with PV panels. They collected the data from some PV and refrigeration manufacturers to design the required elements. The results showed that, during the lowest speed and highest speed runs, the COP was 2.25 and 1.85, respectively. Figure 10 shows a schematic of the PV modules directly coupled with the...
compression refrigeration cycle. From the above studies, it could be confirmed that battery and energy storage components have a significant role in PV with refrigeration cycle to supply energy demand most of the time.

2.3.3 Discussion

Photovoltaic refrigeration is primarily concerned with vapor compression refrigeration compared to other solar refrigeration systems. Domestic refrigerators work on a compression cycle, and combining them with PV might produce an acceptable result in locations where electricity is scarce. One of the most significant issues with this technology is that it is ineffective throughout the winter and rainy days when little solar energy is available. A refrigeration system is forced to shut down due to this situation. Because of this issue, selecting a proper battery capacity or other energy storage pathways is challenging. Hence, optimizing the essential parameters is critical for achieving a high COP. The following setups may be helpful for future research:

1. PV panels should be connected directly to variable speed compressors.
2. The use of numerous compressors may improve efficiency.
3. An ice storage tank might be a cost-effective solution by omitting the inverter and battery.
4. Increasing the number of solar panels ensures a refrigerator’s viability on non-sunny/cloudy days.

As a result, designing closer to these circumstances resulted in improved efficiency and COP. For future research, it is recommended that hybrid systems be designed to run different refrigeration cycles when a PV indirectly provides energy. Also, PV could be linked to other cooling processes that require thermal energy through the use of interaction devices. As a concluding remark, Table 1 presents some studies based on experimental and simulation forms categorized and sorted by the published year.

3 Photovoltaic Thermal Collectors in Refrigeration Cycles

A simple photovoltaic thermal (PVT) is defined as a PV module with a connected solar collector. One of the main classifications of PVT is based on the applied working fluid, as shown in Fig. 11. The collector of PVT is usually attached to the back of the PV module [93]. The applied collector of a PVT is flat shape, while Fresnel, dish, and parabolic forms are used in CPVT [94]. Designing PV modules and solar collectors are vital to obtaining optimized results for refrigeration cycles assisted by PVT. Absorption and adsorption refrigeration systems are mainly used with this configuration. Exergy, experimental, and simulation studies on this field are reported in the following sections.

3.1 Exergy Studies

Implementation of the second law of thermodynamics and exergy analysis could be valuable tools for better designing
| Author(s)            | Type of study | Brief title                                      | Highlights                                                                                                                                                                                                 | References |
|---------------------|---------------|--------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------|
| Axaopoulos et al.   | Experimental  | Design PV ice-maker without battery              | The ice storage tank was used as an energy storage tool instead of a battery that positively impacted the environment and economy of the system                                                                 | [40]       |
| Ekren et al.        | Experimental  | Performance of PV-Powered Refrigeration          | Without an inverter PV panel coupled with a household refrigerator, four loading cases were examined and showed that the highest COP occurred during no storage condition                                                                 | [44]       |
| Chukwuneke et al.   | Numerical     | Modeling and Simulation PV chillers              | Parameters like battery capacity and maximum voltage can be obtained by the model implemented on MATLAB reported in this article                                                                             | [84]       |
| Gupta et al.        | Simulation    | Optimum parameters for domestic refrigerator     | Optimizing panel size and battery capacity and insulation thickness reached parameters that increasing insulation thickness to 50 mm lower panel size can be sufficient for cooling approaches                                         | [53]       |
| Kalbande            | Experimental  | Evaluation of PV-driven refrigeration system     | Vaccine storage at low temperature with direct current compression refrigeration was examined. The sizing and configuration of the PV panel, battery capacity, and refrigerant component were investigated | [45]       |
| Sharma et al.       | Simulation    | Compare VAR and VCR coupled by PV                | Recording temperature and energy usage of two different refrigeration concluded that for a high cooling rate, Vapor compression refrigeration is appropriate                                               | [39]       |
| Sidney et al.       | Experimental  | Refrigeration in different ambient temperature   | Ambient temperature has a significant role in this study with increasing Ambient Temperature exergy efficiency of PV panel decreased                                                                            | [48]       |
| Kaplanis and        | Experimental  | Modified conventional refrigerator to PV powered | Variable speed compressor Used to enhance solar energy usage and reduce the distance between PV components to reach a minimum voltage drop                                                                            | [60]       |
| Papanastasiou       |                |                                                  |                                                                                                                                                                                                          |            |
| Author(s)          | Type of study | Brief title                                | Highlights                                                                                                                                                                                                 | References |
|-------------------|---------------|--------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------|
| Dhondge et al.    | Experimental  | Performance evaluation PV powered VCR     | COP was Compared by changing the refrigerant to Nano-refrigerant and got a maximum COP 2.41 in the experiment                                                                                           | [72]       |
| Rajoria et al.    | Experimental  | Performance of PV panel driven refrigeration system | Sizing panel concerning battery capacity and energy consumption investigated and concluded to increase panel size to compensate energy losses and get higher efficiency                                                                 | [70]       |
| Zuo               | Exergy        | Characteristics of PV-Driven Ice Storage  | About 13% of the solar energy captured by PV is converted to electricity in an ice storage air conditioner powered by PV. From this value, about 59% exergy loss occurred                                                                 | [50]       |
| Ferrucci et al.   | Exergy        | Mechanical compressor-driven thermochemical storage | Reducing ambient temperature could lead to higher exergy efficiency of compressor-driven thermochemical storage                                                                                           | [49]       |
| Salilih et al.    | Numerical     | Modeling PV directly coupled with the compressor | The compressor’s varying speed shows that higher COP in low speed can occur. At maximum speed, the refrigerant mass flow rate, cooling capacity, and the compressor’s power consumption are maximum                                                                 | [85]       |
| Suamir et al.     | Experimental  | Use of PV panels coupled with Chest freezer | Because of non-solar time coupling, photovoltaics with a national grid can optimize the performance and make the chest freezer work continuously                                                                 | [62]       |
| Hayian et al.     | Experimental  | PV drove micro refrigeration               | PV panels have the most considerable exergy destruction compared to others. In micro refrigeration, using a battery can be helped to stabilize the system                                                                 | [46]       |
| Su et al.         | Simulation and experimental | Variable speed PV directly current refrigerator | Effect of variable speed on efficiency and COP showed that higher COP could be obtained at low speed compared to fixed-speed compressors                                                                                                                                   | [47]       |
| Uddin et al.      | Simulation    | Energy analysis Vaccine refrigerator        | Techno-economic optimization and energy analysis by homer applied to vaccine refrigerator worked with PV. The variation of COP showed better performance for R152a refrigerant                                                                 | [41]       |
| Author(s)          | Type of study | Brief title                                                   | Highlights                                                                                                                                                                                                 | References |
|-------------------|---------------|--------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------|
| Ghorbani et al.   | Simulation    | Cryogenic energy production with two ejector refrigeration   | The hybrid cooling and power systems included cold energy storage units powered by photovoltaic were examined. The results showed that optimizing the pressure of the Kalina cycle concluded with COP increasing up to 14%                                                                 | [51]       |
| Selvaraj and Victor | Experimental   | PV with absorption cooling cycle                            | COP of 0.14 was reported for absorption refrigeration powered by PV. Also, payback of 10 years was evaluated for 30 years life cycle of a system                                                                 | [86]       |
| Riffat et al.     | Experimental   | Refrigerator with PCM in off-grid places                    | PCM for domestic refrigerators used in miniature size showed the outstanding performance to reduce temperature fluctuations                                                                                                                                       | [87]       |
| Han et al.        | Experimental and numerical | PV ice storage air conditioner system                   | The impact of ambient and initial water temperatures was examined to see the efficiency correlation. Also, PV is directly connected to the DC compressor in this setup                                                                 | [88]       |
| Hu et al.         | Experimental   | Pilot-scale PV compression refrigerator                     | The preliminary study for scaling up the PV compression refrigeration with ice thermal storage showed a COP of 1.33 for the cooling cycle                                                                 | [89]       |
| Gao et al.        | Simulation     | Control methods comparison in PV refrigeration              | Maximum power point tracking and compressor speed prediction were two methods that were compared. The results showed that ambient and water temperature variation is adaptive with the first method                                                                 | [90]       |
| Ikram et al.      | Simulation     | PV refrigerator for cold storage system                     | The simulation by PV*Sol showed a conceptual design for PV coupled with a refrigeration system. Economic assessments reported about five years for the payback period for the designated system                                                                 | [91]       |
| Du et al.         | Experimental and simulation | Dynamic analysis of PV-cold storage                        | Solar-cold energy conversion efficiency was inversely linked with solar radiation intensity at the same evaporation temperature when ice thermal energy storage was used in place of a battery | [92]       |
and reaching high efficiency. When refrigeration cycles are coupled with solar systems, each analysis could be divided into three steps: individual investigating the PVT, examining the refrigeration cycle, and assessing the whole PVT-assisted cooling cycle. Based on this classification, to enhance the COP of refrigeration cycles, the exergy studies in this field are reported and analyzed. Also, Fig. 12 presents the exergy flow diagram of the PVT module to get excellent sight for further examination.

Parametrical studies in the field of exergy are routine in articles to find out the effect of each parameter. Accordingly, significant parameters like PV cell temperature should be considered in a PVT to improve efficiency and reach maximum electricity and heat energy production. The cell temperature and electrical efficiency have a negative correlation. As an example, Khordehgah et al. [96] reported that, by decreasing the panel temperature by 20%, the electrical efficiency increased about 12%. Furthermore, researchers examined other parameters to improve the overall efficiency of solar collectors. In this manner, Ghodeshwar and Sharma [97] reported that one of the parameters that had a stimulating effect on the solar collector’s efficiency was the clearness of the sky during the day.

Exergy destruction assessment and methods for minimizing this value are other procedures researchers applied. For instance, when a cooling cycle’s exergy was examined, Marques et al. [98] reported that the highest exergy destruction belonged to the steam generator in the case that only a single-stage absorption chiller was analyzed. Also, Tenkeng et al. [99] reported that the generator should be optimized for a double-stage absorption chiller to reach lower exergy destruction due to the highest exergy loss in this compo-
nent. They examined the effect of a second generator and showed that it significantly affected the COP. Moreover, Oza and Bhatt [100] used the Taguchi method. They analyzed parameters like the evaporator, condenser, and generator temperatures to reach the best COP and the lowest exergy destruction in an ammonia-water absorption chiller. The results showed that increasing the evaporator temperature and decreasing the condenser temperature led to a maximum COP. The aforementioned showed that the design of equipment like a generator in cooling cycles should be optimized to have the lowest exergy destruction value for the system.

As mentioned in the previous part, absorption chillers as connected to PVT have been considered in many articles from the exergy point of view. In this part, the papers conducted about absorption chillers are surveyed. Behzadi et al. [101] reported that, for a hybrid PVT with a double-stage absorption chiller and electrolyzer, the highest exergy loss belonged to the PVT, which was about 77%. Regarding an adsorption chiller, Koronaki [102] analyzed the exergy of a chiller connected to PVT. They showed that the refrigeration performance decreased when an unglazed PVT was utilized. So that, the COP value for the unglazed and glazed PVT was reported as 0.38 and 0.47, respectively.

Moreover, Toujani and Bouaziz [103] analyzed the effect of utilizing an organic fluid mixture (R236fa/DMAC) in a system including PVT and a double-lift absorption/compression chiller. Compared to ammonia-water, this organic fluid showed a significant improvement in the exergy. This fluid caused reducing irreversibility and made the process run at a lower temperature. Also, the exergy of PVTs coupled with hybrid systems has been analyzed by some researchers. Ghorbani et al. [104] analyzed a hybrid unit including PVT, ejector refrigeration, and PCM energy storage. This setup transfers thermal energy to the ejector generator to supply the cycle’s heat demand. In this hybrid setup, the highest exergy destruction belonged to heat exchangers, and the least exergy efficiency was for expansion valves. Figure 13 presents the block diagram of this configuration. Besides, Abu-Hamdeh et al. [105] investigated the exergy of a tri-generation system with an absorption chiller powered by a PVT. By varying the wind speed from 15 to 70 KPH, it was shown that, from 15 up to 35, the exergy efficiency was increased; but after that, increasing the wind speed had a negative effect on the exergy. So, climatic conditions are effective and should be checked in order to have optimum performance. Moreover, some innovation applications such as smart city, recently was investigated by researchers. For instance, Abu-Rayash and Dincer [106] reported that the system provides essential energy solutions for city applications, such as heating, cooling through district energy networks, as well as electricity. An absorption refrigeration system is deployed to convert captured heat from the solar collectors. The exergy destruction analysis of the components in this structure is shown in Fig. 14.

### 3.2 Experimental Studies

In this section, experimental articles about refrigeration powered by PVT are reviewed. The experimental studies in this field can be divided into different parts; most are hybrid systems, and the standalone refrigeration cycles are rarely reported nowadays. Thus, as new hybrid setups, cogeneration and tri-generation systems are conventionally being examined in this field. Also, building-integrated PVTs, coupled with refrigeration, have been reported in some articles. With this regard, Liang et al. [107] enhanced the PVT efficiency with a refrigeration pump that cooled a PV panel. The electricity and thermal requirements of a building could ultimately be obtained from this system. Moreover, Buker et al. [108] analyzed the feasibility of utilizing a building integrated PVT to supply a liquid desiccant dehumidification’s energy demand. The thermal COP of the dehumidifier-cooler was reported as 0.73. The experimental data showed that a PVT with an active area of 140 m² and a tilt angle of 10° could successfully fulfill the energy demand.

Regarding the effect of PVT efficiency on the COP of refrigeration systems, a parametric study was conducted by Hu et al. [109]. They reported that evacuated flat plate PVTs, compared to the standard flat plate collectors, had a better effect and efficiency, which could be helpful in the building, agricultural, and industrial usages. Also, Noro and Lazzarin [110] conducted a study to combine evacuated tube collectors and PVT and reported a reasonable efficiency. So, there is a place for conducting other experiments to compare different PVT models and choose which one is useful for running cooling cycles. Yang et al. [111] assessed the effect of the phase change material (PCM) layer in a PVT. They understood that the temperature of the collector part of the PVT was reduced compared to PVT without PCM. Also, higher output power and energy conversion efficiency were obtained. One of the current aspects of PVT-refrigeration is the application of a heat pump. Hence, as an example of this novel case, Lu et al. [112] investigated the effect of ambient conditions on a hybrid PVT heat pump refrigeration system. In this structure, the PVT module worked as a condenser, and the COP varied from 1.8 up to 2.1. The results showed that, by increasing the ambient temperature, the COP decreased, and the wind velocity in the range of 0 to 1 m/s had a positive effect on the COP. As another work in this field, Liang et al. [113] experimentally investigated a PVT with heat pump for refrigeration mode. In this composition, the PVT worked as a condenser, and they reported that the refrigeration mode was divided into two individual processes as chilled water process and ice process. Figure 15 illustrates the experimental setup that they were used.
Reviewing the experimental articles in this field shows significant progress in building-integrated PVTs and improving PVT efficiency. Besides, based on recent studies, some researchers have focused on the feasibility of running poly-generation systems equipped with PVTs. The performance improvements demonstrate that, since solar power is an excellent example of clean energy, it will become more common in the near future to run hybrid units.

### 3.3 Simulation and Numerical Studies

In this section, the simulation and numerical modeling studies on the implementation of PVT in multi-generation and refrigeration cycles are reviewed and analyzed. One of the best schemes for choosing an appropriate design would be comparing different PVT types by simulation. For example, Shongwe et al. [114] conducted a study comparing PVT and PV-ETC to run an ejector refrigeration cycle. In this simulation, in order to optimize the system and select the best design for a large scale, the PV-ETC could be applicable. The point that should be considered in this study is the optimization of the ejector refrigeration’s COP. That value was in the order of 0.2 to 0.5 for solar technologies. However, the highest COP of ejector refrigeration was 0.81 in a system that used cyclopentane as a refrigerant [115]. Also, using nano-refrigerants could enhance the COP and performance of ejector refrigeration cycles [116]. Accordingly, the effect of refrigerant and choosing the appropriate one should be considered in every design procedure.

Beccali et al. [117] simulated a system connected to a PVT and compared different desiccant cycle arrangements regarding the desiccant cooling cycle. The COP for the desiccant cooling cycle reported about 2.5. Figure 16 represents a schematic of a PVT coupled with a liquid desiccant cycle.

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**Fig. 13** The block diagram of PVT coupled with ejector refrigeration system [104]. [Reprinted with permission from Elsevier]

**Fig. 14** The exergy destruction of units employed in smart city configuration [106] (MGTES: Medium-grade thermal energy storage, ORC: Organic Rankine cycle, ARC: Absorption refrigeration cycle, HGTES: High-grade thermal energy storage, CSP: Concentrated solar power, PVT: Photovoltaic thermal)
In another study, Dubey and Subiantoro [118] presented a numerical model for a PVT refrigeration system to produce hot water and run air-conditioning. In this structure, the PVT provided the energy, the condenser provided the hot water, and the evaporator section ran the air-conditioning. Also, the COP of cooling had a value of about 9.8 in this setup.

Moreover, other researchers examined hybrid PVT with simulation tools. For instance, Huang and Huang [119], in a simulation using TRNSYS, analyzed a PVT utilized in a hybrid system. This simulation reported the electrical and thermal efficiencies as 12% and 27%, respectively. Hence, TRNSYS could provide an excellent view of different optimization designs. Also, Garg and Adhikari [120], in the simulation for a PVT air heating collector, concluded that a double-glass configuration obtained better results compared to a single-glass one. This simulation predicted the performance of the hybrid PVT, which could be used for different site locations. The multi-generation systems with PVT
have commonly been used and mentioned by many research teams. Zarei et al. [121] simulated a PVT for combined heat and cooling by the EES software. The refrigeration cycle was an ejector-compression cycle, and the used refrigerants were R600a and R290. They concluded that R290 could obtain a higher COP than the R600a and R134a. Figure 17 shows the schematic of the hybrid system that was used in their research work. Calise et al. [122] simulated a poly-generation including PVT, adsorption chiller, and heat pump by TRNSYS. In this system, the COP for the adsorption refrigeration was reported as 0.54. Also, Calise et al. [123] simulated a poly-generation system containing PVT and absorption cooler by TRNSYS. The COP for the LiBr-water single-effect absorption chiller was reported as 0.8.

Additionally, mathematical works and numerical models could give incredible sight for examining PVT-based refrigeration. In 2018, Su et al. [124] provided a mathematical model of PVT used for deep dehumidification. Electrical power was used for a compression chiller, and thermal power was used to supply the heat demand of a desiccant generator. Using compression cooling, the second stage of dehumidification happened; thus, simulation results showed that the desiccant solution’s dehumidification temperature significantly affected the process, and raising that temperature led to higher exergy efficiency. In 2020, Adhami [125] compared two combined systems to develop a 250 MW steam power cycle. Two configurations had absorption chiller and gas turbine, but the difference was on the applied PV and PVT. In the same year, Guo et al. [126] simulated a ground-coupled PVT system that supplied the energy demand of a liquid desiccant air dehumidification and cooling system. In this TRNSYS simulation, the COP was reported as 11.2 for an ambient temperature of 23–35°C. In 2021, Kanti De and Ganguly [127] developed a mathematical model for a PVT that run a double-effect vapor absorption chiller. In this system, proton exchange membrane fuel cell usage was observed as a promising energy storage system, which showed interesting results in energy and economics. Also, Ramos et al. [128] have investigated a system including PVT, heat pump, and an absorption chiller. In this study, an optimization on supplying the energy demand has been conducted by varying different site locations. Also, Hernando et al. [129] have analyzed the feasibility of using hybrid PVT in the food industry. An absorption chiller was used in this case. The results showed two main challenges: the overlapping of cooling and hot water demands and the high temperature of hot water used for the absorption chiller (80°C) and process hot water (100°C). Besides, it is shown that using an electrical
chiller instead of an absorption chiller allows for covering a wider portion of hot water demand.

From those mentioned articles in this part, simulation of hybrid configurations has been developed in many studies. Some research works have aimed to change parameters and variations to obtain optimized cases. Simulation and numerical studies compared to experimental studies were more. Moreover, building-integrated PVTs would be an excellent research field for cooling purposes based on articles on this field.

3.3.1 Discussion

The previous studies demonstrate that PVTs can serve as excellent sources of power and thermal energies, paving the path for refrigeration cycles to operate at their highest efficiency. Unlike PV modules, which generate electricity solely for vapor compression, PVT may generate both electricity and thermal energy simultaneously, connecting it to many types of cooling cycles. One of the most critical aspects of any design process is the size of the PV panels. The area of PV panels should be calculated based on the thermal and electrical demands to achieve maximum efficiency. As previously noted, a wide range of urban and home applications could be considered. In addition to selecting the optimum PVT configuration, selecting the right thermal collector is also critical.

Simulation tools like TRNSYS and the presented numerical models have been resulted in designing the best points for reaching the maximum COP. Using simulation software and numerical modeling shows effectiveness when a complicated hybrid system is under examination. Research into heat pump parameters and how they impact cooling processes has been done, as shown from a literature study. However, there is still room for more investigation into the effects of heat pump parameters on cooling processes. It will be good to analyze aspects such as PVT tilt angles and ambient conditions for future research. To give better insight for future research, Table 2 summarizes studies about the use of PVTs in refrigeration cycles. Also, COP values for various cooling systems coupled with PVT are included in Table 3.

4 Concentrating Photovoltaic Thermal Collectors in Refrigeration Cycles

The combination of a concentrating photovoltaic with a photovoltaic thermal results in a concentrating photovoltaic/thermal collector (CPVT). Figure 18 illustrates the classification of CPVT based on their geometry. The outcomes of coupling these systems with refrigeration cycles significantly show their impact on economics and energy-saving aspects. This configuration uses thermal energy as a good source for providing the energy demand for absorption and desiccant refrigeration cycles [134]. Due to the higher electrical and thermal output than PV and PVT, the studies on CPVTs would be notable. An essential factor in analyzing a CPVT is its concentrating ratio, which significantly affects the cycle performance and efficiency [135]. A CPVT uses a CPV module to produce electricity, and by utilizing a thermal collector, thermal energy could be obtained from this system. The forthcoming sections review and discuss exergy, experimental, and simulation studies of CPVT-based refrigeration cycles [136]. Figure 19 shows a simple schematic of a CPVT-powered absorption refrigeration cycle.

4.1 Exergy Studies

The second law of thermodynamics and exergy studies are vital in designing and developing a solar-driven refrigeration cycle, as mentioned repeatedly in previous sections. Minimizing exergy destruction should be considered to enhance the COP of a refrigeration cycle and get optimal electrical and thermal energy. Diverging different parameters in order to reach appropriate outcomes have been considered in different articles. Reviewing those studies could infer that the ambient temperature, solar irradiation, and cooling loads are essential variables for designing and exergy analyses. By focusing on an absorption refrigeration cycle individually, the highest exergy loss value could belong to the generator that absorbs the heat from thermal collectors [138]. The information mentioned above reveals that an appropriate generator design could enhance efficiency. Also, to show the importance of CPVT, Calise et al. [139] thermo-economically investigated a CPVT coupled with a poly-generation system containing a lithium-bromide/water absorption chiller. The analysis was conducted for two cases: a PV coupled with electric-driven heat pumps and a CPVT.

Regarding the cycle parameters, Alim Khan et al. [140] analyzed different parameters that affected the exergy of a multi-generation system powered by a CPVT and an absorption chiller. They showed that increasing the ambient temperature from 288 to 328 K could change the exergy destruction from 80.95 kW to 89.75 kW. Akrami et al. [138] investigated the exergy for a CPVT-based single-stage LiBr/water absorption chiller and proton exchange membrane electrolyzer. They showed that the system’s overall efficiency was about 12%, and most of the exergy destruction after the CPVT was allocated to the generator of the absorption cycle. Additionally, Morosuk and Tsatsaronis [141] examined the exergy of different components of an absorption cooling cycle. The examination was assorted from high to low exergy destruction values. The study showed that optimizing the generator and absorber would be critical to reaching maximum exergy efficiency. Other parameters have been investigated by Tiwari et al. [142] via an exergy study for
| Author(s)          | Type of study     | Brief title                                         | Highlights                                                                                                                                                                                                                                                                                                                                 | References |
|-------------------|-------------------|-----------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------|
| Calise et al.     | Simulation        | Dynamic simulation tri-generation PVT                | Simulated poly-generation setup contained mainly PVT and absorption cooler. The COP for LiBr-water single-effect absorption chiller 0.8 was considered                                                                                                                                                                                               | [123]      |
| Buker et al.      | Experimental      | Bi-PVT coupled desiccant cooling                     | They analyzed the feasibility of utilizing an integrated PVT. Liquid desiccant dehumidification and indirect evaporative air conditioner energy demand were supplied                                                                                                                                                                                                 | [108]      |
| Calise et al.     | Simulation        | PVT dynamic simulation and thermo-economic           | A poly-generation system included PVT, adsorption chiller, and heat pump simulated. COP for adsorption refrigeration was valued at about 0.54                                                                                                                                                                                                   | [122]      |
| Koronaki et al.   | Exergy            | Exergy analysis solar adsorption                     | They showed that refrigeration performance decreased when PVT was utilized. Nevertheless, PVT utilization increased exergy efficiency significantly, unlike energy efficiency                                                                                                                                                                                                 | [102]      |
| Liang et al.      | Experimental      | PVT cogenerated with building                        | They investigated building integrated with PVT; this structure enhanced PVT efficiency with a refrigeration pump that cooled the PV panel                                                                                                                                                                                                   | [107]      |
| Ghodeshwar and Sharma | Exergy     | Thermodynamic of solar absorption                   | One of the parameters that had a stimulating effect on a solar collector’s efficiency was the clearness of the sky during the day                                                                                                                                                                                                                                                                     | [97]       |
| Tenkeng et al.    | Exergy            | Double effect solar absorption                       | They reported that the double-stage absorption chiller, a generator, should be optimized to reach lower exergy destruction due to the highest exergy loss in this component                                                                                                                                                                                                                                                   | [99]       |
| Behzadi et al.    | Exergy            | PVT with double-effect absorption                    | They reported that in a hybrid PVT system with double stage absorption chiller and electrolyzer, the highest exergy loss belonged to PVT, which was about 77%                                                                                                                                                                                                                           | [101]      |
| Dubey and Subiantoro | Numerical       | PVT with refrigeration in air-conditioning           | They presented a numerical model for the PVT refrigeration system in order to produce hot water and air-conditioning                                                                                                                                                                                                                                                                     | [118]      |
| Author(s)          | Type of study | Brief title                        | Highlights                                                                                                                                                                                                 | References |
|-------------------|---------------|------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------|
| Su et al.         | Numerical     | PVT and desiccant                  | Mathematical model of PVT used for deep dehumidification. Electrical power was used for the compression chiller, and thermal power was used to supply the heat demand of the desiccant generator | [124]      |
| Yang et al.       | Experimental  | Comparison of PVT-PCM and PVT      | The effect of the PCM layer in PVT was checked. They showed that positive impacts were the higher output power and the higher energy conversion efficiency                                                                 | [111]      |
| Ghorbani et al.   | Exergy        | PVT and ejector refrigeration and PCM | The highest exergy destruction belonged to heat exchangers in the hybrid setup, and the least exergy efficiency was for expansion valves                                                                 | [104]      |
| Toujani and Bouaziz | Exergy       | PVT cooling with different working fluid | The effect of utilizing organic fluid mixture (R236fa/DMAC) in the system compared to ammonia-water showed significant improvement                                                                                                                        | [103]      |
| Khordehgah et al. | Exergy        | PVT with domestic hot water        | One of the parameters that should be considered in designing PVT is panel temperature. Also, by decreasing panel temperature by about 20%, electrical efficiency increased about 12%                                                                 | [96]       |
| Zarei et al.      | Simulation    | PVT for domestic application       | The numerical study by EES for the ejector-compression cycle, with the two refrigerants: R600a and R290                                                                                                     | [121]      |
| Marques et al.    | Exergy        | Exergoeconomic of Electricity-Cooling Unit | They reported that the highest exergy destruction belonged to a steam generator in the case that only a single-stage absorption chiller was analyzed                                                                                                      | [98]       |
| Hu et al.         | Experimental  | Performance characteristics of PVT | They reported that evacuated flat plate PVT compared to the standard flat plate had better effect and efficiency                                                                                     | [109]      |
| Noro and Lazzarin | Experimental  | Comparison of PVT and ETC          | They conducted a study to combine evacuated tube collectors and PVT, and they showed that greater efficiency in this setup could be obtained                                                                 | [110]      |
| Author(s)         | Type of study         | Brief title                                      | Highlights                                                                                                                                                                                                 | References |
|------------------|-----------------------|--------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------|
| Lu et al.        | Experimental          | PVT under various ambient conditions             | The effect of ambient conditions in the hybrid PVT heat pump refrigeration was examined. In this structure, the PVT module worked as a condenser                                                          | [112]      |
| Liang et al.     | Experimental          | PVT heat pump on refrigeration mode              | They investigated on PVT heat pump worked in a refrigeration mode. Also, the comprehensive design procedure in their study could execute this setup’s design on a large scale                                           | [113]      |
| Zarei et al.     | Exergy                | CCHP powered by ORC and PVT                      | The subcooler’s intake temperature increased, impairing the VCR cycle’s performance. Additionally, optimizing COP and exergy efficiency did not affect other performance indicators such as net power production from PVT | [130]      |
| Lombardo et al.  | Simulation            | Analysis of CCHP in NZEB application              | This study demonstrated the possibility of household micro-CCHP systems powered by solar energy. The system is based on experimental prototypes of a 3 kWe ORC and a 4.4 kWc thermally powered Adsorption Chiller | [131]      |
| Gao et al.       | Experimental and numerical | PVT directly powered refrigeration              | Off-grid refrigeration and hot water supply were provided without batteries in this system. The total cooling capacity was 6.3% greater than that of the PV-driven system                                                                 | [132]      |
| Abu-Rayash and Dincer | Simulation       | Solar for smart cities                            | The system delivers robust energy solutions for city applications like heating, cooling, and electricity production. Also, the absorption refrigeration system was used for cooling purposes in this setup                             | [106]      |
| Zisopoulos et al.| Numerical and Simulation | Solar with thermochemical energy storage          | The effect of thermochemical energy storage was examined in the cogeneration system. Also, results showed that thermochemical energy storage density was approximately 10.6 times that of water-based systems                                      | [133]      |
Table 3 Summary of COP values from different refrigeration cycles coupled with PVT

| Author(s)       | Type of study | Refrigeration cycle                   | COP       | References |
|-----------------|---------------|---------------------------------------|-----------|------------|
| Shongwe et al.  | Simulation    | Ejector refrigeration                 | 0.2–0.5   | [114]      |
| Dubey and Subiantoro | Simulation    | Vapor compression refrigeration       | 9.8       | [118]      |
| Zarei et al.    | Simulation    | Ejector-compression                   | 1.87      | [121]      |
| Calise et al.   | Simulation    | Adsorption chiller                    | 0.54      | [122]      |
| Ramos et al.    | Simulation    | Absorption chiller                    | 0.5–0.75  | [128]      |
| Beccali et al.  | Simulation    | Desiccant cooler                      | 2.5       | [117]      |
| Koronaki et al. | Exergy        | Adsorption cooling                    | 0.38 and 0.47 | [102] |

4.2 Experimental Studies

As mentioned in the introduction, a few studies were conducted about concentrating photovoltaic, and most of the studies are focused on CPVTs. So, in the following, one of these few studies is reported. Kwan and Yao [143] investigated the application of vapor compression refrigeration with concentrating photovoltaic hydrogen production. They used a conventional CPV and parametrically analyzed different VCR factors to see the performance. The results showed that raising the evaporator temperature made the cell lifetime less and did not impact the hydrogen productivity rate. One of the main subjects that have been focused on is reducing the capital cost and enhancing the performance at the same time. Another point is comparing concentrating collectors like parabolic trough collectors with CPVTs, which some researchers have mentioned. Most of the articles in this area are focused on single and double-stage absorption chillers coupled with CPVT. Due to the high temperature of CPVT, it could be coupled with a double-stage absorption chiller instead of a single-stage and present more COP [144]. Figure 21 presents the commonly used components in absorption cooling cycles coupled with CPVT.

Another comparison was between PVT and CPVT, which showed a lower cost of reflectors like Fresnel, dish, and parabolic trough, compared to flat plate collectors used in PVT [146]. The experiment by Nishioka et al. [147] reported
that the electricity efficiency decreased because of the high temperature that CPVT made for the PV module. Kribus et al. [148] investigated a miniature CPVT with components including a dish concentrator and silicon PV cell in

![Diagram of a single-effect absorption system powered by CPVT](image)

Fig. 19 Single-effect absorption system powered by CPVT [136]. [Reprinted with permission from Elsevier]

![Graph showing variation of collection temperature on thermal energy, electrical power, and exergy gain](image)

Fig. 20 Variation of collection temperature on thermal energy, electrical power, and exergy gain [142]. [Reprinted with permission from Elsevier]
2006. The system provided 160 W electrical energy and 450 W thermal energy. Following that, they analyzed a model for solar cooling by operating at high temperatures [136]. They focused their study on a single-effect absorption chiller powered by CPVT. In various economic conditions that were experimentally tested, CPVT showed better results compared to conventional solar cooling. Also, CPVT could work at a higher temperature with an appropriate efficiency [149]. Anand et al. [150] evaluated the potential of CPVT used in two desalination and cooling cycles simultaneously. In this study, the concentrating ratio was about 200 when parabolic dish concentrators were used based on the operational condition. The results showed that, compared to a solar flat plate collector, the electricity consumption was reduced significantly about 76%. Heng et al. [145] focused on a low concentrating PVT-assisted absorption chiller. In this experiment, the effect of using a higher concentrating ratio compared to standard PVT was investigated based on different operational conditions. It was reported that, in a place with radiation intensity of about 949 W/m², the cooling capacity was 7.20 kW, and COP varied from 0.48 to 0.55. In this case, the concentration ratio had a value about 4 [151]. Song et al. [152] investigated the absorption chiller refrigeration performance in an arrangement coupled with a linear Fresnel photovoltaic. For better performance, the absorption cooling cycle worked between single and double stages.

As mentioned in the Introduction section, an ejector cycle has low COP; so, coupling with other refrigeration systems could enhance the COP. Regarding this matter, Yosaf and Ozcan [153] thermo-economically investigated a CPV coupled with an ejector absorption refrigeration cycle and reported a COP of 0.82. Also, the exergy efficiency reached 32% at the peak value. The highest irreversibility occurred in the solar system, followed by the absorber unit.

4.3 Simulation and Numerical Studies

Most studies have been carried out as simulation and modeling regarding the CPVT-driven refrigeration cycles. As mentioned in the previous section, comparing CPVT with PVT has been one of the conventional investigations. Generally, CPVTs occupy a lower area than PVTs for a specified output power [154]. Al-Nimr and Mugdadi [155] simulated a system in which a PV module provided electricity for a thermo-electric module and concentrating collectors gave thermal energy to an absorption cycle. By parametric investigation by EES, it was shown that solar irradiation and the CPVT outlet temperature were considerable and vital to reach the maximum COP. The reported COP varied from 0.143 to 0.232 under the Mediterranean weather conditions. Another novel study by Lin et al. [156] shows the examination of a system with variable absorption stages connected to a CPVT. The mathematical model, solved by EES, showed the effect of different parameters on this unit. Double, single, and 1.n (variable effect between single and double) were investigated, and it was shown that a more temperature range was covered when three working modes were available. Figure 22 shows the schematic of this configuration. Renno et al. [157] modeled a system containing a concentrating photovoltaic/thermal and a desiccant cooling cycle to supply a
supermarket’s electrical and thermal energies. Sizing of the CPVT for different thermal loads of the supermarket in different seasons was carried out by an artificial neural network. Al-Alili et al. [158] modeled a hybrid CPVT coupled with an air conditioner. This air conditioner contained a desiccant wheel cycle and a vapor compression cycle. TRNSYS simulated this configuration, and the results showed that the CPVT area was an essential factor, which affected the whole system. Besides, the COP of this hybrid air conditioner was reported as 0.68, which was much more than a vapor-compression stand-alone powered by photovoltaic panels. Su et al. [159] repeated their previous study on PVT by changing with a CPVT. The collector was used as a parabolic trough, while the concentration ratio was 53. Also, the vapor compression cycle used in this tri-generation system reached a COP of 7.23.

One of the main subjects that have been investigated in this area is the comparison between evacuated tube (ET) collector and CPVT. Buonomano et al. [160] operated a dynamic simulation implemented in MATLAB by analyzing both systems’ energy and reported that CPVT had better efficiency than the ET. Later on, Buonomano et al. [161] compared the performance of a PVT and CPVT, coupled with cooling cycles, by MATLAB code; dish concentrators and flat plate collectors were used in this study. The results showed that the CPVT could be utilized in climate conditions with high beam radiation. Other cooling cycles like desiccant chillers are mainly used with thermal collectors. With this regard, Calise et al. [162] simulated a desiccant-based air handling unit assisted by CPVT collectors by TRNSYS. The simulation took place for a university class in Italy. The produced electricity was used on-site, and the generated thermal energy was used for the air handling unit’s heating process. Another dynamic simulation by Calise et al. [163] was conducted based on a novel poly-generation unit. This system is based on a fuel cell, an electrolyzer, a CPVT, and an absorption chiller. The TRNSYS simulation shows that the COP value of the absorption chiller is about 0.7, the thermal efficiency is higher than 60%, the electrical efficiency is about 20%. Also, Garcia-Heller et al. [164] applied the Polysun software for simulating a CPVT-based adsorption cycle for space cooling. The COP varied from 0.6 to 0.8, and the area that simulation was reported had a value of about 47,059 m². Moallemian et al. [165] carried out a simulation study, by TRNSYS, for a system that included a CPVT and a water-ammonia absorption chiller. The CPVT was equipped with a Fresnel collector, and the concentrating ratio and COP were reported as 15 and 0.63, respectively. Their TRNSYS simulation procedure is presented in Fig. 23.

According to the aforementioned studies, simulation work has been attempted more frequently than experimental work, and the majority of researchers have concentrated on poly-generation systems. Firstly, simulation tools could be used to optimize poly-generational systems. Then, experimental research could be undertaken on such simulations to observe the simulation in action.

4.3.1 Discussion

Utilizing CPVT in a hybrid system may be the best option when both electrical and thermal energy are required simultaneously. CPVTs could be integrated into buildings and urban complexes in conjunction with absorption refrigeration. The concentration ratio is a great metric to adjust based on refrigeration demand. According to articles published over the last few decades, research has evolved away from thermal collectors and toward photovoltaic thermal collectors. In comparison to simulation and modeling studies, these publications had a lack of experimental studies. CPVTs have been explored for their energy-saving and economic benefits, particularly in multi-generation systems. Although, with all of the advantages described in this analysis, installing thermal collectors in a location that operates on a single absorption cycle may be the best option.
Nonetheless, the use of CPVT in multigenerational and hybrid systems will likely become more prevalent in the near future. Additionally, feasibility studies for hybrid CPVT-based refrigeration cycles are recommended. Table 4 summarizes many studies on CPVT-assisted refrigeration cycles to provide researchers with pertinent information.

5 Conclusion Remarks and Suggestions for Future Works

Solar energy is one of the most suitable forms of renewable energy. Solar energy would be crucial, particularly in locations with a dearth of electricity. Refrigeration is used in various applications, from agriculture and food storage to vaccine preservation and residential use. Due to this wide range, providing enough energy to run cooling cycles would be a problem. This paper reviews different studies on the applications of PV, PVT, and CPVT in refrigeration. Improving the exergy efficiency of these systems and enhancing their COP are two main parts that most researchers noted. Also, the optimization of these systems by simulation tools, numerical methods, and metaheuristic algorithms needs to be addressed more. The following conclusions are shown as essential points:

- Most exergy loss occurs in a PV panel; so, optimizing this component should be considered.
- In a PVT, using a co-generation device could be logical by providing two primary energies simultaneously. The COP in this setup, based on which refrigeration cycles have been used, varies from 0.5 up to 9.8.
- For a CPVT, the efficiency is enhanced by increasing the concentrating ratio, but the material and cost must be considered. Most CPVT simulations are coupled with tri-generation or poly-generation systems that include one refrigeration cycle.
- In most PVT and CPVT modules coupled with chillers, the highest exergy destruction belongs to the solar panels. Using appropriate collectors and optimizing solar efficiency are two main factors in their design.
- The experimental sets have examined various characteristics, including sun irradiation, the surrounding temperature, and the cooling load. So, optimizing the design of a system is necessary because of the impact each parameter has on the overall performance of the system.
- Using poly-generation systems coupled with CPVT has been mentioned in many research works. Better performance compared to simple PV and PVT is observed in most studies.
- Thermal energy storages materials like PCM have been conventionally mentioned in many articles. Also, optimizing the storage tank design, comparing the PCM types,
| Author(s)                | Type of study | Brief title                              | Highlights                                                                                                                                                                                                 | References |
|-------------------------|---------------|------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------|
| Nishioka et al.         | Experimental  | Output estimation of CPVT               | Due to the high temperature of CPVT, multi-junction cells could be considered to enhance electricity efficiency                                                                                         | [147]      |
| Mittelman et al.        | Experimental  | Solar cooling by CPVT                   | They focused on single-effect absorption chiller assisted with CPVT in the high-temperature medium                                                                                                         | [136]      |
| Morosuk and Tsatsaronis | Exergy        | Exergy analysis of absorption chiller    | Solar irradiation significantly affected exergy destruction while having a negligible effect on exergy efficiency                                                                                       | [141]      |
| Buonomano et al.        | Simulation    | Comparing CPVT and ET                   | Comparing CPVT with ET reported that higher efficiency happened during the use of CPVT                                                                                                               | [160]      |
| Calise et al.           | Simulation    | Tri-generation system by CPVT           | The system contained a double-effect absorption chiller powered by CPVT simulated                                                                                                                        | [144]      |
| Calise et al.           | Simulation    | Desiccant based with CPVT               | Desiccant air handling unit by assisting CPVT and appropriate efficiency for a place like a university class was designed                                                                               | [162]      |
| Calise et al.           | Simulation    | Dynamic simulation of a poly generation system | The novel poly-generation system that includes CPVT, PEM, electrolyzer, and absorption chiller simulated and thermal efficiency of CPVT and COP of chiller reported                                     | [163]      |
| Buonomano et al.        | Simulation    | Absorption and adsorption chillers powered by CPVT | In climate conditions with high beam irradiation, CPVT could be considered. This study was reported by comparing CPVT with standard PVT                                                                 | [161]      |
| Alim Khan et al.        | Exergy analysis | Multi-generation system by CPVT          | In a multi-generation system, increasing ambient temperature resulted in rising exergy destruction                                                                                                           | [140]      |
| Akrami et al.           | Exergy analysis | CPVT equipped with PEM and absorption chiller | The highest exergy destruction belonged to CPVT, and after that, in the absorption refrigeration cycle, it referred to the generator that absorbed heat from CPVT                                                                 | [138]      |
| Anand et al.            | Experimental  | Two-stage plant with CPVT               | Electricity saving by changing simple flat plate collector to CPVT occurred. Also, an absorption chiller was used in the setup                                                                                   | [150]      |
| Heng et al.             | Experimental  | LCPVT assisted with an absorption chiller | By concentration ratio of 4 running absorption chiller with COP varied from 0.48 up to 0.55                                                                                                               | [145]      |
| Al-Nimr and Mugdadi     | Simulation    | Absorption/thermo-electric cooling cycle | Using hybrid setup and provided electricity for thermo-electric configuration and thermal energy to supply energy demand of absorption process                                                                 | [155]      |
| Lin et al.              | Numerical     | Variable absorption chiller with CPVT   | The numerical model was developed by EES software. So, three working modes of an absorption chiller and a wider temperature range were covered during the process                                                                 | [156]      |
| Al Keyyam et al.        | Simulation    | Solar atmospheric water harvesting integrated system | The new system used CPVT, Stirling engine, absorption, and compression refrigeration cycles. The absorption refrigeration COP was 0.75. Also, the ACC and VCR provided dehumidification and water production | [166]      |
and applying nanotechnology (Nano-PCMs and Nano-enhanced PCMs) are recommended for energy storage.

- Due to low COP, ejector cooling cycles need more configurations studies coupled with different collectors.
- Improving the PV and solar collector efficiency in PVTs and CPVTs is vital for all related studies about solar cooling systems.
- In the recent decade, many studies have been focused on solar cooling. So, the publication rate of this field has significantly risen from 2018 up to now.
- In the CPVT connected to the cooling cycles, the concentration ratio has an excellent effect on the performance. So, choosing a suitable concentrator PV should be addressed.
- The exergy destruction values are related directly to climatic conditions. Hence, the appropriate location should be selected.

Regarding the conducted analyses on the literature, the following points could be suggested for future works:

- More simulation studies are recommended about PV-driven refrigeration cycles due to the lack of simulation studies in this field.
- Hybrid cooling cycles have a bright future because of the COP enhancement obtained. So, shifting the studies from PV-driven cooling cycles to hybrid systems could improve outcomes.
- Changing parameters like tilt angle and examining this factor would be helpful for future studies.
- Hybrid thermo-electric refrigeration systems are recommended for future study cases.
- In order to fill the void in PVT and CPVT research, further experiments are needed.
- PCM optimization for increased efficiency should be investigated. Additionally, a cost–benefit analysis should be conducted in this manner.
- Due to a dearth of research in the field of CPV, CPVs coupled with cooling cycles may be a promising approach.

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