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Current trends in thermoelectric technologies, prospects for thermal regulation

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This article provides an overview of current trends in thermoelectric technologies, covering various aspects of application and material development. In particular, it examines the potential integration of thermoelectric elements into solar panels to enhance energy conversion efficiency. Special attention is given to thermoelectric heat pumps, which show significant potential for use in low-temperature conditions. The study also analyzes thermal management systems for electric vehicle batteries, ensuring stable operation under various operating conditions. Additionally, modern materials for thermoelectric cooling systems are discussed, including nanostructured and composite materials. The prospects for the development of wearable thermoelectric elements are explored, offering efficient cooling and thermal regulation with minimal material use. The summarized findings highlight the importance of innovations in thermoelectrics for improving energy efficiency and comfort in modern technologies.

Keywords: Thermoelectric materials, energy efficiency, solar panels, heat pumps, thermal regulation, thermal management, electric vehicles, cooling systems.

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Content

Introduction

Thermoelectric technologies are playing an increasingly important role in the development of modern energy systems due to their ability to convert thermal energy into electricity and vice versa. This makes them indispensable in the context of the growing demand for energy-efficient solutions, especially in industries seeking to reduce carbon emissions and optimize energy use. Thermoelectric materials are used in a wide range of technologies, from solar panels to thermal management systems in electric vehicles. Solar panels integrated with thermoelectric cells can significantly increase the overall efficiency of energy harvesting by converting some of the waste heat into electricity. This opens up new opportunities for increasing the efficiency of renewable energy sources, especially in the context of global warming. Thermoelectric heat pumps are innovative systems that provide efficient thermal control in various areas, from domestic heating systems to industrial cooling. Current research is focused on improving materials and optimizing the design of such pumps to achieve maximum efficiency (COP). Particular attention should be paid to thermal management systems for electric vehicle batteries, as these systems are critical to ensuring safety and extending battery life. Thermoelectric modules in such systems allow for effective management of temperature fluctuations, which ensures stable battery performance.

I. Current State and Prospects of Hybridizing Solar Panels and Thermoelectric Technology

Modern thermoelectric materials and technologies continue to evolve, providing new opportunities to improve energy efficiency and create more sustainable energy systems. Solar photovoltaic (PV) systems are a crucial component of the transition to renewable energy sources. However, the efficiency of PV systems can significantly suffer from temperature increases. Various cooling methods have been developed to mitigate this issue, maintaining optimal operating conditions and improving the overall system performance. This review explores advancements in these methods, focusing on hybrid photovoltaic thermoelectric (PV-TE) systems, the use of nanofluids, and heat pipe technologies. Hybrid photovoltaic thermoelectric (PV-TE) systems combine photovoltaic elements (Fig. 1) with thermoelectric modules to utilize both solar and waste heat energy [1], [2]. This dual approach enhances overall energy conversion efficiency by using the Seebeck effect in thermoelectric materials to convert temperature differences into electrical voltage [3], [4]. Researchers in [2] evaluated the performance of the hybrid photovoltaic thermoelectric cogeneration system, demonstrating its potential to improve efficiency. The integration of thermoelectric (TE) modules with photovoltaic (PV) systems allows the efficient use of waste heat, leading to a higher overall energy output. Recent studies, such as those conducted by [3], focus on innovative designs like hybrid radiation cooling-thermoelectric-photovoltaic (RC-TE-PV) systems. These designs incorporate spectral splitting to optimize the absorption of different wavelengths, enhancing the performance of both PV and TE modules.

Nanofluids, which are engineered colloidal suspensions of nanoparticles in a base fluid, have proven to be promising for enhancing the thermal conductivity of

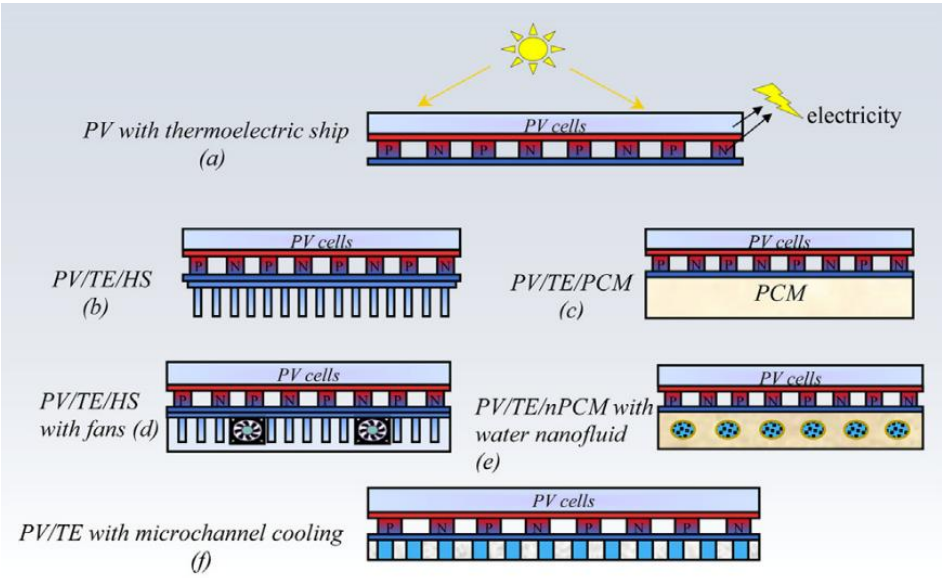

Fig. 1. Photovoltaic cells with thermoelectric casing (a) and different cooling methods: (b) with built-in heat sink, (c) with phase change materials, (d) with built-in heat sink and DC fans, (e) with water-nanofluid and phase change nanomaterials, and (f) with microchannel water co oling. [1].

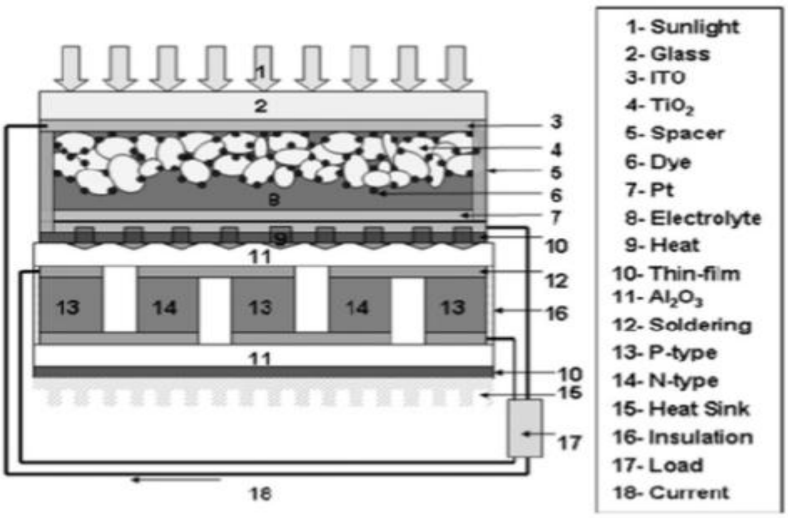

Fig. 2. Schematic diagram of a solar-thermal system [5].

cooling fluids used in PV systems [5], [6]. This section discusses their application and impact on system efficiency. In [5], researchers examined (Fig. 2) the use of nanofluids in solar energy systems, highlighting their excellent heat transfer properties.

By enhancing cooling efficiency, nanofluids help maintain a lower temperature of PV elements, thereby improving electrical output. Experimental studies conducted by various researchers, such as Elgendy [7], demonstrated (Fig. 3) and (Fig. 4) a significant improvement in the performance of solar desalination units using thermoelectric materials enhanced with nanofluids. Numerical simulations, such as those conducted by Maghrabi [14], provide insights into optimizing the composition of nanofluids for maximum thermal performance.

Heat pipes are heat management devices that transfer heat through the phase change of a working fluid [8], [9], [10]. They are particularly effective in maintaining an even temperature distribution in PV modules. Lashyn [8] analyzed the thermal performance of heat pipes for cooling concentrated photovoltaic (CPV) systems, demonstrating their effectiveness in heat dissipation and maintaining optimal operating temperatures. Innovations

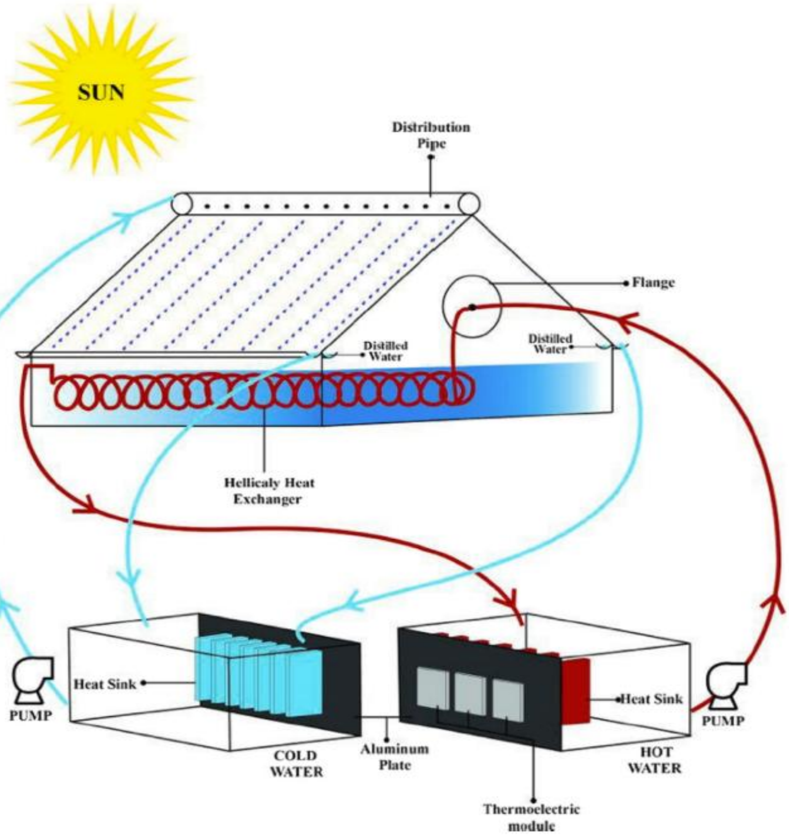

Fig. 3. Scheme of a modified solar collector on thermoelectric modules [7].

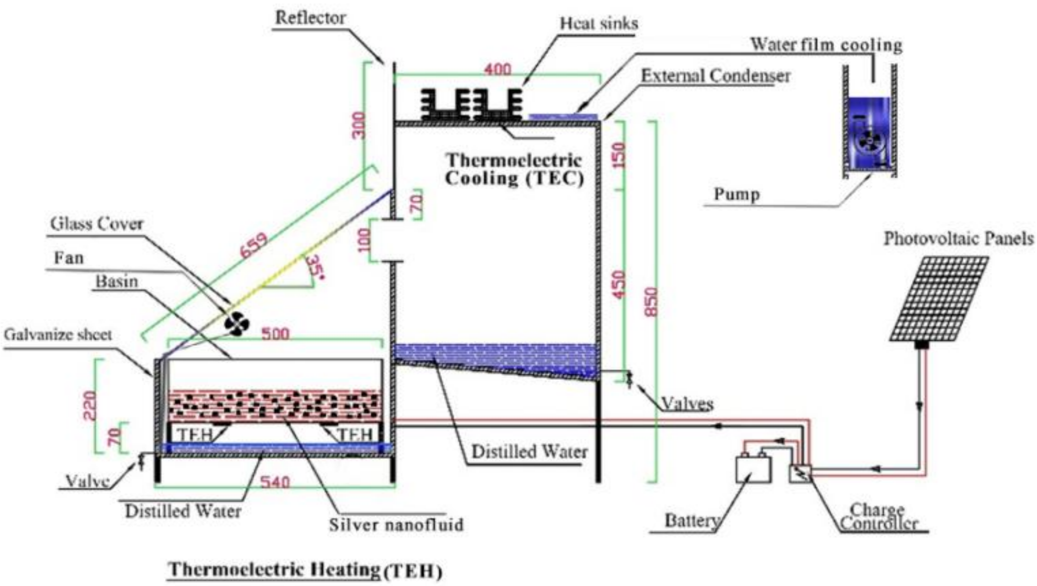

Fig. 4. Schematic of the experimental setup [7].

in heat pipe designs, such as those studied in [11], include the integration of self-cooling mechanisms (Fig. 5) with CPV-TE systems. These designs offer enhanced heat dissipation capabilities, which are critical for high-concentration solar energy applications.

Thermoelectric cooling utilizes the Peltier effect, where an electric current passing through the junction of two different materials creates a temperature gradient [12], [13], [14]. This principle is applied for effective cooling of PV modules. In [12], the properties of the junction and parametric optimization of thermoelectric-based refrigerator cooling systems (Fig. 6) were studied based on PV, demonstrating their potential for efficient thermal management in PV applications. Studies such as those conducted by Park et al. [13] focus on the development of lossless hybridization methods between PV and thermoelectric devices, aiming to minimize energy losses and maximize cooling efficiency.

The integration of PV and thermoelectric (TE) systems has led to the development of hybrid models that use the advantages of both technologies. Studies [15] and others have explored the feasibility and performance of these hybrid modules. Researchers in [16] discussed improving the efficiency of PV systems through optimal control of thermoelectric cooling. These techniques involve complex algorithms and control systems (Fig. 1) for dynamically adjusting cooling parameters for optimal performance. Future research, such as that conducted by Rejeb [17], focuses on innovative designs and integrated approaches to optimizing hybrid CPV-TE systems, considering both technical and economic aspects.

Various cooling methods for PV systems demonstrate significant potential for improving the efficiency and longevity of these systems (Table 1). Hybrid PV-TE systems, nanofluids, and heat pipes represent promising areas of development. Despite significant achievements, there are technical challenges, such as integration complexity and production costs. Further research is needed to address these issues and enhance the economic viability of these technologies. Future studies should focus on innovative designs, integrated approaches, and optimization of existing systems. Advances in materials, control algorithms, and interdisciplinary research are key to further progress. This review provides an analysis of

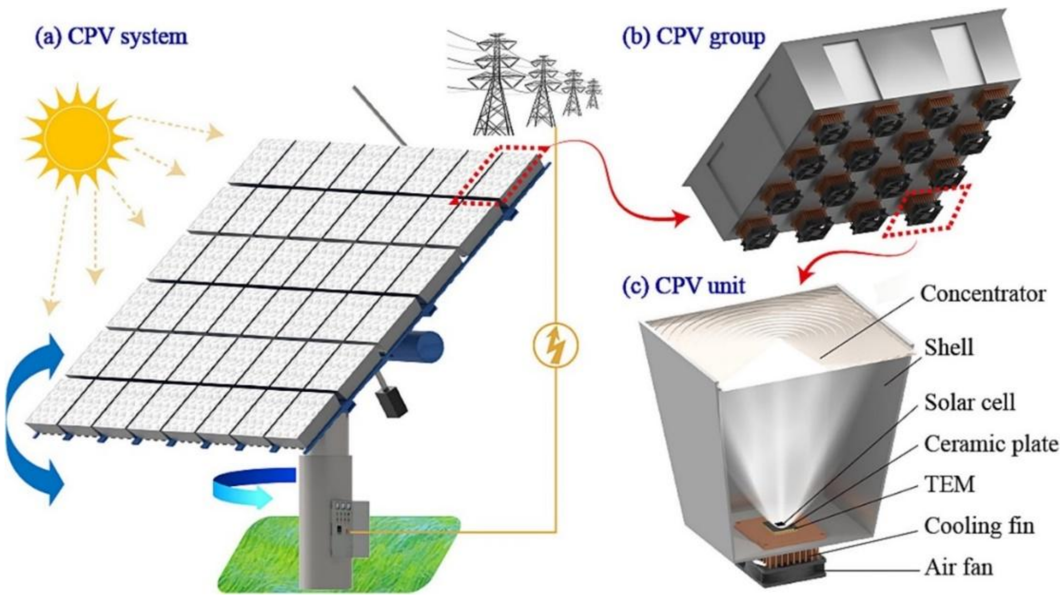

Fig. 5. Schematic diagram of a self-cooling photovoltaic system [11].

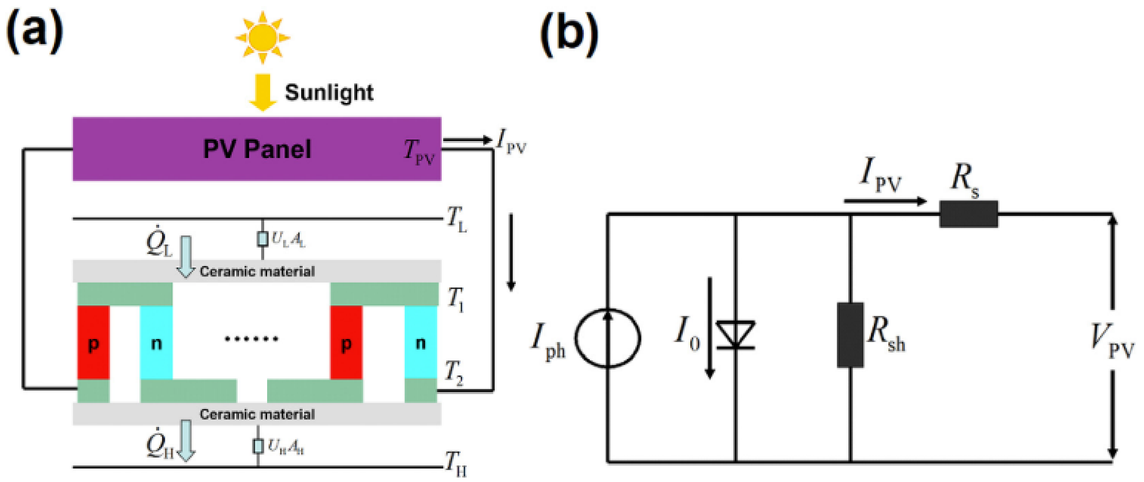

Fig. 6. (a) General scheme of a photo-thermoelectric refrigeration module system (b) Equivalent scheme of a photovoltaic panel. [12].

Table 1.

Comparative analysis of efficiency and performance characteristics of conventional and hybrid solar panels

Characteristic	Solar panels	Solar panels with thermoelectricity	References
Conversion efficiency	15-20%	20-25%	[1], [5], [6], [9], [18]
Installation cost (USD/kW)	1,000-1,500	1,200-1,800	[2], [10], [19], [20]
Service life (years)	20-25	20-30	[3], [21], [22], [23]
Temperature stability	Decreases with an increase in temperature	Improves due to thermoelectric cooling	[4], [7], [8], [16]
Impact on the environment	Low	Low	[12], [13], [14], [24]
The need for cooling	High	Low	[8], [15], [17], [24], [25]
Energy efficiency under high-temperature conditions	Decreases	Increases	[2], [6], [9], [12]
Additional functions	Absent	Generation of additional electricity from heat	[1], [3], [7], [16]
Voltage stability support	Limited	Is higher due to additional cooling	[4], [15], [18], [20]
Use in remote areas	Limited	Extended due to reduced maintenance requirements	[5], [13], [19], [21]

current advancements in cooling methods for solar photovoltaic systems, offering valuable insights for researchers and engineers interested in enhancing the efficiency of renewable energy sources.

II. Current state and development prospects of thermoelectric heat pumps

Thermoelectric heat pumps (TEHPs) are technologies that use thermoelectric effects to manage heat flow. The main components of such systems are thermoelectric generators (TEGs) or thermoelectric coolers (TECs), which operate based on the Peltier effect, allowing the conversion of electric current into temperature gradients. While the heat source works directly due to the Seebeck effect, the Peltier effect is used when the heat source operates in the reverse mode - when a voltage is applied to the device and it starts pumping heat. Thus, the same materials can work as both a generator (TEG) and a cooler (TEC), depending on the direction of energy interaction (heat → electricity or electricity → heat). These technologies demonstrate high potential efficiency in providing both heating and cooling [26], [27]. Key aspects include the improvement of thermoelectric materials that can ensure a high energy conversion efficiency coefficient. Recent studies, such as the work [26], show that the optimal selection of heat pump technologies for micro-heat pump systems can significantly improve energy efficiency. The upgrade of materials and thermoelectric elements continues to be an important direction for increasing their performance. Thermoelectric heat pumps use the Peltier effect to create temperature gradients, enabling heating or cooling. This principle is based on temperature changes resulting from the electric current passing through thermoelectric materials. The work [28] discusses the design of high-power thermoelectric coolers for railway transport (Fig. 7). The authors employed various optimization methods to develop a TEC system capable of operating efficiently at kilowatt levels, while ensuring temperature stability in the confined space of a railway carriage. Special attention was given to the selection of materials, thermal management, and the configuration of thermoelements to achieve the maximum coefficient of performance (COP). High-speed railway carriages require reliable and efficient cooling systems due to the intensive operating conditions and large volumes of passengers. The solutions proposed in the article can significantly improve cooling efficiency and reduce energy consumption of such systems, which is important considering the growing need for energy conservation and reduction of emissions.

This demonstrates how thermoelectric systems can be optimized for specific usage conditions. Experimental studies [27] focus on the use of thermoelectric technologies in "zero-energy" buildings, where the combination of various heat and cooling sources is critically important. These technologies can be effectively integrated with other systems, such as solar panels, to achieve high overall energy efficiency. Innovations in thermoelectric systems are focused on the development of new materials and the improvement of technological processes [65-67]. In articles [10], [29], a new type of thermoelectric heat pumps is presented, combining ventilation and heat recovery functions for residential applications. This system enhances the efficiency of thermoelectric technologies to improve comfort in living spaces. The work [12] discusses the optimization of parameters in thermoelectric cooling systems, leading to a significant increase in their performance. Such innovations allow for improved energy efficiency and reduced costs for the implementation and operation of thermoelectric systems. The integration of thermoelectric heat pumps with solar panels ensures efficient use of renewable energy sources. The work [30] demonstrates how the combination of thermoelectric and solar technologies can provide energy independence for buildings. This research highlights the importance of hybrid systems in reducing the consumption of traditional energy resources. Modern developments, such as the study

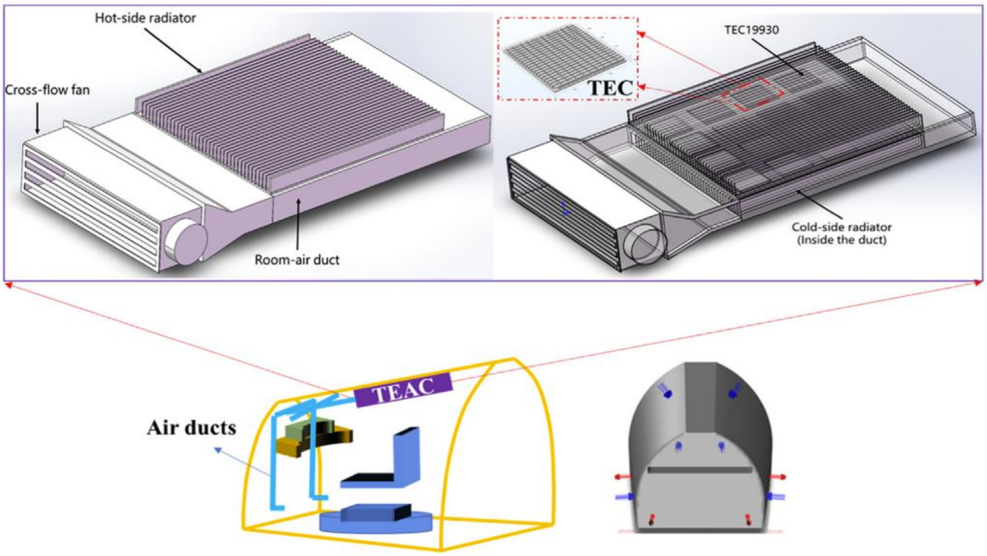

Fig. 7. Schematic of the TEAC system for a high-speed driver's car of a high-speed driver's car [28].

[23], focus on the development of hybrid systems that combine photovoltaic and thermoelectric elements. This allows more efficient use of solar energy and reduces energy resource costs.

Recent studies, such as the work [31], demonstrate the effectiveness of thermoelectric heat pumps for heating spaces and providing heat in low-temperature conditions (Fig. 8). This emphasizes the flexibility and universality of thermoelectric systems in various climatic conditions. Future trends in the development of thermoelectric heat pumps include further improvements in thermoelectric materials, particularly enhancing their thermoelectric efficiency. Recent studies, such as the work [6], show significant potential in the numerical modeling of new integrated systems that can improve the overall performance of thermoelectric technologies. Key aspects for future research include reducing the costs of implementing thermoelectric systems and enhancing their reliability and longevity. High material and technology costs remain a barrier to the widespread adoption of these systems in commercial and residential applications (Table 2). Recent research, such as the work [32], indicates that improving thermoelectric pumps and their integration with other technologies, such as heat storage systems, can significantly enhance their efficiency and reduce operational costs.

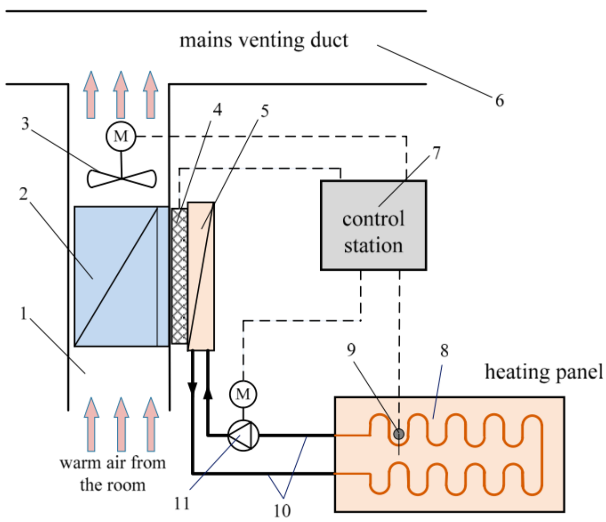

Fig. 8. Block diagram of a local underfloor heating system for piglets using the thermoelectric effect: 1-channel of the cold air circuit; 2-air heat exchanger on the cold side of the Peltier elements; 3-electric fan; 4- Peltier elements; 5-water heat exchanger on the hot side of the Peltier elements of the Peltier elements; 6-main ventilation duct; 7-control module; 8-wall heating panel; 9-temperature sensor; 10-air duct of the hot air circuit; 11-circulating heat pump [31].

Thermoelectric devices (TEDs) are increasingly being used in various industries due to their ability to efficiently convert heat into electrical energy and vice versa. This review examines recent research dedicated to thermoelectric coolers (TEC), thermoelectric heat pumps, and their practical applications.

Scientists in [44] conduct a practical study on the efficiency of thermoelectric coolers (TECs), examining their strengths and weaknesses. Authors [45] model the performance of a thermoelectric air conditioning system using high-power radiators that contribute to the utilization of waste heat. Mainil et al. [46] investigate the performance of a portable thermoelectric cooler based on input power and load. Tan et al. [47] explore a hybrid membrane distillation system with a thermoelectric heat pump for energy-efficient water purification and room cooling. Zhu et al. [48] propose strategies to enhance the efficiency of thermoelectric heat pumps that use water as a heat source. Erickson and Ungar [49] discuss the use of thermoelectric heat pumps in cascade distillation systems, highlighting their advantages and drawbacks. Chen et al. [50] examine recent research and challenges associated with nanostructured thermoelectric materials such as Bi_2Te_3. Trzaskowska and Mroz [51] investigate surface phonons in topological insulators based on Bi_2Te_3 using Brillouin light scattering. Zhang and Pei [52] study electrical transport manipulation in thermoelectrics, focusing on achievements and possible future directions. Hasan et al. [53] use numerical simulations in COMSOL Multiphysics to optimize the performance of thermoelectric coolers based on Bi_2Te_3. Scientists [54] propose a thermoelectric cooling system (Fig. 9) for thermal management of electric vehicle batteries.

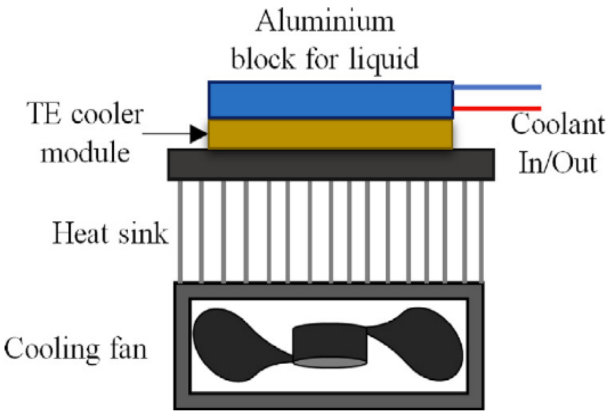

Fig. 9. Schematic illustration of a single TEC unit used for a battery thermal management system.

III. Systems of battery thermal management for electric vehicles

Ensuring proper thermal management of batteries is a crucial task for enhancing the efficiency and safety of electric vehicles (EVs). Recent research focuses on the development and optimization of thermoelectric cooling systems for batteries, as well as the exploration of various methods and materials that promote effective heat dissipation.

In [54], scientists investigate a thermoelectric cooling system for the thermal management of electric vehicle batteries, highlighting its effectiveness in maintaining stable battery temperatures. In another study, [55] they conducted experimental research on thermoelectric cooling for a new battery pack design, utilizing copper holders to improve heat transfer.

Scientists in [56], researchers analyze various battery heating methods at low temperatures (Fig. 10), which help maintain normal battery operation, extend their lifespan, and are particularly relevant for automotive applications. In [57], a thermal management system for batteries based on the thermoelectric effect is studied, highlighting the advantages of this approach for effective cooling. In [58], a predictive thermal management strategy for hybrid electric vehicles is proposed, which takes into account the uncertainty of thermoelectric device parameters. Zhang and others [59] develop a thermal management system that combines a heat pipe with a thermoelectric cooler, improving heat dissipation efficiency.

Ma et al. [60] investigate highly efficient electrocaloric (EC) cooling with an electrostatic flexible drive, which can be applied in battery thermal management systems as well as in a range of other useful applications. The authors developed and demonstrated a device (Fig. 11) based on the electrocaloric cooling effect, achieving a significant reduction in temperature by applying an electric field. Instead of using mechanical compression, the system is controlled by electrical signals, reducing the need for complex moving parts and lowering energy consumption. The electrocaloric effect occurs in materials that experience temperature changes when an applied electric field is altered. In this work, the authors used new materials and designs that significantly increase cooling efficiency. Specifically, the study demonstrated that electrostatic control can achieve substantial cooling with minimal energy expenditure. The developed technology can be applied in microelectronics, where there is a need for compact and efficient cooling systems.

Table 2.

Comparative characteristics of conventional heat pumps with TEHP

Characteristic	Heat pumps	Thermoelectric heat pumps	References
Coefficient of Performance (COP)	300-400%	150-250%	[28], [30], [33], [34]
Operating temperatures (°C)	-20 to +40	-10 to +30	[10], [18], [26], [31]
Working fluids	Refrigerants (e.g., R134a)	Semiconductor materials	[27], [35], [36], [37]
Installation cost (USD/kW)	800-1,200	1,000-1,500	[12], [29], [38], [39], [40]
Service life (years)	15-20	10-15	[17], [18], [30], [41]
Energy efficiency	High	Average	[29], [32], [33], [34], [42]
Impact on the environment	Low (with proper maintenance)	Very low	[26], [28], [36]
Size and weight	Average	Small	[27], [31], [35], [40], [41]
Noise level	Average	Low	[10], [30], [38]
Maintenance requirements	Regular	Minimal	[12], [18], [31], [40]
Advantages	High efficiency, ability to operate in various conditions	Compactness, low noise level, minimal maintenance requirements	[28], [29], [32], [34], [43]
Drawbacks	Need for regular maintenance, cost	Lower efficiency, high material cost	[27], [33], [36], [37], [39]

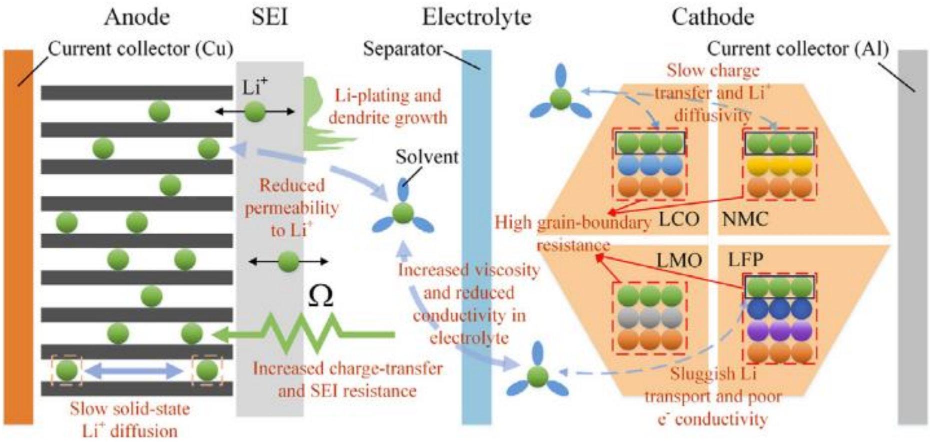

Fig. 10. Mechanisms of battery performance degradation at low temperatures from a material point of view.

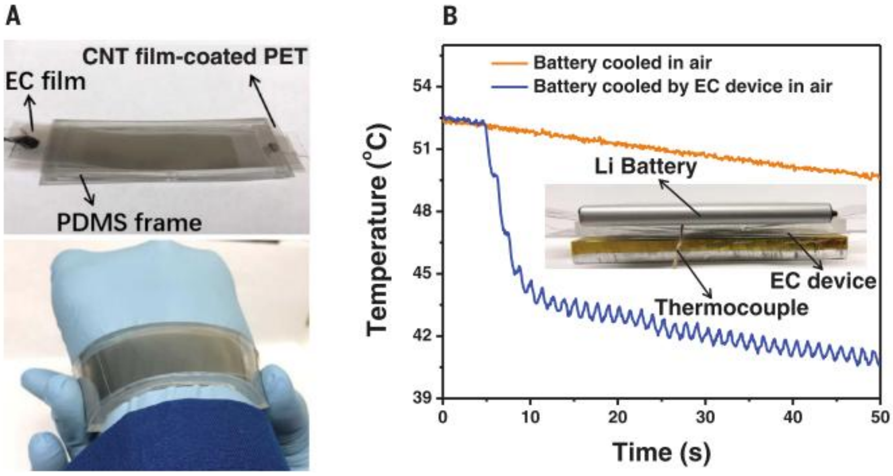

Fig. 11. The effectiveness of the flexible electro-caloric cooling device. (A) Photo of the flexible electro-caloric device. (B) Temperature change of an overheated smartphone battery with and without the EC cooling device. The inset shows the overheated battery at the top of the EC device [60].

Furthermore, it could be useful in household appliances, where eco-friendly and energy-saving solutions are becoming increasingly important.

In [61], scientists provide an overview of key external cooling technologies for lithium-ion batteries, highlighting their advantages and drawbacks. The article [62], in particular, focuses on the importance of effective heat management in batteries to improve their performance, safety, and longevity, especially in applications for electric vehicles. The paper discusses various types of thermal management systems, including air, liquid, and phase-change materials (PCM). The authors analyze the advantages and drawbacks of each approach, focusing on heat dissipation efficiency, design simplicity, energy efficiency, and the impact on the overall weight and cost of the system. Special attention is given to the use of modern technologies such as active cooling and integration with other components of the vehicle's power supply system. In addition, the authors explore the issues of modeling and optimizing BTMS systems, which can enhance their efficiency and reliability under real operating conditions. They also highlight future challenges in the development of BTMS, such as the need to create lighter, more efficient, and cost-effective systems capable of ensuring stable battery operation in various temperature ranges. They emphasize the importance of further research in this area to improve the efficiency of electric vehicles and other applications where high-performance batteries are used. Maiorino [63] and Hwang [64] conduct reviews of modern methods of thermal management for battery packs in electric vehicles, highlighting key trends and technological innovations.

The article [9] focuses on the use o f numerical models for analyzing and optimizing heat pipes in various applications, such as cooling electronic devices, thermal management in space technology, and even in renewable energy systems. Modeling allows the accurate prediction of the behavior of heat pipes, including their heat transfer capacity, thermal efficiency, and stability under different operating conditions. The authors of the article discuss several types of heat pipes, such as capillary-driven pipes and pipes with varying cross-sections, analyzing their performance in different scenarios. Special attention is given to comparing the results of numerical modeling with experimental data, which helps validate the models and draw conclusions about their accuracy. The results of the study demonstrate that numerical models can be effectively used to optimize heat pipe designs, particularly for achieving maximum thermal efficiency and reliability in various conditions.

Table 3.

Evaluation of advantages and disadvantages of thermal management systems for energy applications

System of thermal management	Advantages	Drawbacks	References
Thermoelectric cooling	High cooling efficiency, stable temperature, compactness	High cost, requires effective heat dissipation	[1], [4]
Methods of heating at low temperatures	Enhancing battery performance in cold conditions, preventing capacity degradation	Додаткова енергія для підігріву, складність інтеграції	[2]
Systems based on the thermoelectric effect	Enhanced thermal management efficiency, low weight	Need for high-quality materials, higher production cost	[3], [5]
Combined system with a heat pipe	Enhanced heat dissipation efficiency, adaptability to various conditions	Complex design, need for additional components	[6]
Electrocaloric cooling	High cooling efficiency, low energy consumption	Complex control, high cost	[7]
External cooling systems for lithium-ion batteries	High cooling efficiency, simple design	Large size, additional energy consumption	[8]
Integrated thermal management systems	Comprehensive solution for thermal management, efficiency	High cost, integration complexity	[9], [10], [11]
Heat pipes	Effective heat dissipation, simple design	Limited efficiency in extreme conditions, need for high-quality materials	[12]

Thermoelectric cooling is an effective method for maintaining the stable temperature of batteries in electric vehicles. The main advantages of this system include high cooling efficiency and compactness, which allows easy integration into the vehicle's design. However, the high cost and the need for effective heat dissipation can be significant limitations [54], [55].

Methods of heating at low temperatures help improve battery performance in cold conditions, preventing a decrease in their capacity. The main drawbacks include additional energy consumption for heating and the complexity of integration into existing systems [56]. Systems based on the thermoelectric effect are characterized by enhanced thermal management efficiency and low weight. The main disadvantages include the need for high-quality materials and higher production costs [59].

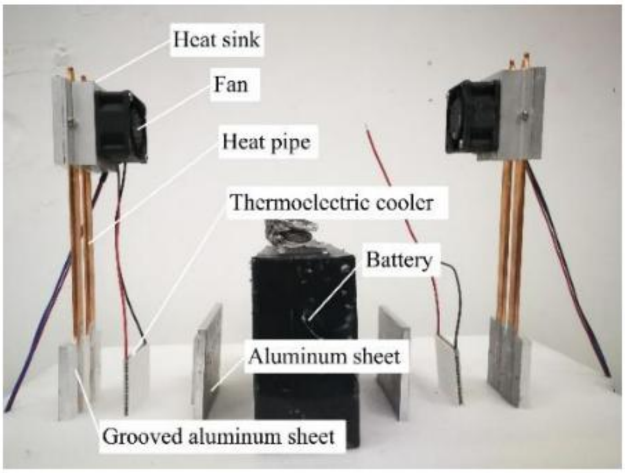

Fig. 12. Battery thermoregulation system based on a heat pump and a thermal power plant [59].

Combined systems with heat pipes provide enhanced heat dissipation efficiency and can be used in various conditions. The main drawbacks include the complexity of the design and the need for additional components [59].

Electrocaloric cooling is characterized by high efficiency and low energy consumption, but the complexity of control and high cost limit its widespread use [60]. External cooling systems are effective and have a simple design, but their large size and additional energy consumption can be significant drawbacks [61]. Integrated systems offer a comprehensive solution for thermal management, but the high cost and complexity of integration can be substantial limitations [62], [63], [64]. Heat pipes provide efficient heat dissipation and have a simple design, but limited effectiveness in extreme conditions, and the need for high-quality materials may limit their use [9].

The literature review shows that thermoelectric cooling systems and alternative thermal management methods have significant potential for improving the efficiency and safety of electric vehicles. Current research focuses on optimizing materials and technologies that contribute to effective heat dissipation and integrating cutting-edge technolog ies to ensure stable battery operation under various conditions.

Conclusion

The efficiency of modern heat pumps can be enhanced by using hybrid systems. Specifically, their coefficient of performance (COP) can exceed the values of traditional systems by 15-20%, making them more attractive for use in compact and mobile devices. The use of solar panels with thermoelectric modules can improve efficiency by 10-15% compared to traditional solar panels. This ensures more effective use of solar energy and helps reduce energy costs. In the field of electric vehicle battery cooling, it has been found that the use of thermoelectric systems can reduce battery temperature by 10-15°C, which increases their lifespan by 20-30% and reduces the risk of overheating. On the other hand, the lack of cooling leads to a significant decrease in battery efficiency and increases their wear. Thus, the use of thermoelectric technologies indicates a significant improvement in efficiency and reliability in future energy systems, making them promising for further research and implementation in various industrial sectors.

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Актуальні тенденції у термоелектричних технологіях, перспективи терморегуляції

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В цій статті представлено огляд сучасних тенденцій у термоелектричних технологіях, що охоплює різноманітні аспекти застосування та розвитку матеріалів. Зокрема, розглянуто можливості інтеграції термоелектричних елементів у сонячні панелі для підвищення ефективності перетворення енергії. Окрему увагу приділено термоелектричним тепловим насосам, які демонструють значний потенціал для використання в умовах низьких температур. Проаналізовано системи теплового менеджменту для батарей електричних транспортних засобів, що забезпечують стабільну роботу за різних умов експлуатації. Крім того, розглянуто сучасні матеріали для термоелектричних охолоджувальних систем, включаючи наноструктуровані та композитні матеріали. Нарешті, досліджено перспективи розвитку носимих термоелементів, які можуть забезпечити ефективне охолодження та терморегуляцію при мінімальному використанні матеріалів. Узагальнені дані підкреслюють важливість інновацій у термоелектриці для підвищення енергоефективності та комфорту в сучасних технологіях.

Ключові слова: Термоелектричні матеріали, енергоефективність, сонячні панелі, теплові насоси, терморегуляція, тепловий менеджмент, електричні транспортні засоби, охолоджувальні системи.