Low-grade thermal energy utilization: technologies and applications

Dongxu Ji[a], Guokun Liu[b], Alessandro Romagnoli[c], Srithar Rajoo[d], Christos N. Markides[e]

[a] School of Science and Engineering, The Chinese University of Hong Kong, Shenzhen, 518172, China

[b] Department of Engineering Science, University of Oxford, Oxford OX1 3PJ, UK

[c] School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore 639798, Singapore

[d] UTM Centre for Low Carbon Transport (LoCARtic), Universiti Teknologi Malaysia, Malaysia

[e] Clean Energy Processes (CEP) Laboratory and The Sargent Centre for Process Systems Engineering, Department of Chemical Engineering, Imperial College London, London SW7 2AZ, UK

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Abstract

Low-grade (i.e., temperature) thermal energy has been traditionally overlooked and wasted via rejection to the environment, leading to low overall energy efficiencies. However, recent years have seen a growing urgency for deep decarbonization and energy security, which have led to an increased interest in the utilization of low-grade thermal energy. Research has increasingly focused on a diverse range of technologies and applications for harnessing this energy resource. The Special Issue 'Low-grade thermal energy utilization: technologies and applications' served as a platform for presenting state-of-the-art research on the management and utilization of low-grade thermal energy. This editorial article reviews the articles featured in the Special Issue, and provides commentary on these contributions.

1. Introduction

While high-temperature heat sources have long been the primary focus of energy generation plants and industrial processes, the untapped potential of low-grade (temperature) thermal energy has been gaining increasing recognition in recent years. Low-grade thermal energy is typically generated as a by-product or waste of other industrial and everyday activities [1]. It possesses the potential to play a pivotal role in sustainable energy systems, revolutionizing our approach to energy generation and utilization. The field of low-grade thermal energy utilization has emerged as a promising frontier in energy research and technology development [2]. This field explores innovative technologies and applications that enable us to harvest, convert and leverage low-grade thermal energy for a wide range of purposes.

Significantly, there has been a surge of interest and in research focused on low-grade thermal energy utilization. A diverse array of solutions and technologies have been proposed and investigated, reflecting the multifaceted nature of this field. Prominent among these are innovative power cycles and heat pumps, thermoelectric generators (TEGs), and thermal energy storage solutions. These technologies are pushing the boundaries of what was previously considered possible, with each offering unique advantages and being suitable to specific applications [3,4]. The rapid development of these technologies in the diverse application areas underscores the growing recognition of the significance of low-grade thermal energy in meeting our energy needs while minimizing the associated environmental impact.

This Special Issue of *Applied Thermal Engineering* served as a vital platform to researchers across the globe for delving deeper into the multifaceted domain of low-grade thermal energy utilization. Through the compilation of research articles in this field, it aimed to shed light on the latest advancements, challenges, and opportunities within this growing and important area of study. This editorial article provides an overview of the collected research articles and introduces their contributions to the field.

2. Overview of the articles collected in the Special Issue

In this Special Issue, we received and published over 50 high-quality articles. According to the topic and research highlights in each case, these were mainly divided into the following categories: heat pumps, power cycles, TEGs, thermal storage, solar thermal energy utilization technologies, and other thermal energy technologies.

2.1 Heat pumps

Heat pumps are commonly used to 'upgrade', i.e., enhance the thermal quality of heat sources, primarily for heating but also (increasingly) for cooling applications. A significant recent trend in heat pump technology concerns their integration with various innovative heat sources and other subsystems. In this Special Issue, Ghaderi et al. [5] proposed the integration of a heat pump with seasonal heat storage to recover waste heat from the ventilation system of a greenhouse located in Saskatoon, Canada. They developed a climate model to generate input data and employed a clustering algorithm to reduce the data handling workload. This approach enables the generation of relatively reliable predictive results in cases where measured data and computational resources are limited. Through the optimization of dynamic pinch analysis, the results indicated that as much as 55% of the greenhouse's ventilation heat can be recovered through the integration of a heat pump and the greenhouse's ventilation system.

In the context of integration with solar thermal systems, Ma et al. [6,7] made significant contributions to this Special Issue through two articles focusing on solar-assisted air source heat pumps for domestic hot water production. They conducted a thorough investigation into the compatibility between the heat pump and the solar collector and identified an optimal ratio of 78 W m^{-2} for heat pump input power to collector area [6]. Their comprehensive findings were derived from advanced system modelling, simulations, and validation through experimental work. The noteworthy aspect of their articles lies in the wealth of data provided for energetic, economic, and environmental evaluations, which serve as valuable references for guiding practical system design and operation.

Another article, included in this Special Issue, delves into solar-assisted heat pumps and is authored by Sazon and Nikpey [8]. This study centres on the use of an environmentally-friendly working fluid, CO_2, and examines a ground-coupled heat pump system for space and water heating. Through modelling and simulation, they conducted sensitivity analysis, parametric evaluations, and a long-term performance assessment. Their results yielded a seasonal performance factor of 3.5 for the system and a levelized heating cost of 0.18 USD per kWh, demonstrating comparable performance to heat pump systems using conventional working fluids. Furthermore, their long-term simulations revealed that increasing the spacing of borehole heat exchangers or incorporating solar collectors could be more effective strategies for extending the system's lifetime, thus promoting economic performance.

In addition to the previously mentioned articles on heating systems, Zhang et al. [9] introduced and investigated a cascade absorption-compression refrigeration system for multi-temperature cooling, powered by waste heat. A key feature of their work is the innovative system design featuring a two-stage compression with complete intercooling, which was shown to deliver superior performance in terms of both energy efficiency and cost-effectiveness when compared to using multiple compressors. Through simulation and parametric analysis, they determined an optimal cascade condenser middle temperature of 11 °C. Their results also indicated an optimal exergy efficiency of 0.34 and an average annual cost of 246,300 USD, which represented significant improvements over the basic system.

2.2 Power cycles

Many power generation systems have been proposed and studied for heat-to-power conversion, such as ones based on the organic Rankine cycle (ORC), Kalina cycle (KC), Stirling cycle and various CO_2 cycles. Among these, the ORC is the most commonly considered and utilized for low-grade heat sources, and this Special Issue includes over 10 articles dedicated to the use of low-grade heat with ORC systems.

The selection of working fluid can substantially impact the cycle performance under varying conditions, making its selection a critical factor in system optimization. In this Special Issue, Su et al. [10] have developed an artificial neural network model for calculating the pseudocritical temperature of working fluids. They used a dataset consisting of 30,670 data points encompassing 93 different working fluids. This model allows for precise and swift prediction of the performance of transcritical ORC with any working fluid, thus enhancing the efficiency of fluid selection. Sahana et al. [11] introduced an ejector to replace the steam flashing device in the conventional combined flash binary geothermal cycle. To exploit the advantages of temperature glide, they compared various R245fa-isopentane mixtures as the secondary working fluid. The working fluid with a 0.7 mole fraction of isopentane was identified as optimal, exhibiting the highest second law efficiencies.

To fully harness the thermodynamic potential of working fluids in ORC, it is essential to examine and optimize heat transfer performance. In this context, Luo et al. [12] made a valuable contribution to the current Special Issue by experimentally investigating the flow boiling heat transfer characteristics of R245fa under various conditions, including mass flux, heat flux, and evaporating temperature. They compared the measured heat transfer coefficients with predicted results based on several correlations and identified the most accurate correlation, enabling the optimization of heat transfer performance. Furthermore, Wang et al. [13] utilized a backpropagation artificial neural network to predict the supercritical heat transfer performance of R134a. Their findings indicated that this method yielded more precise predictions of the Nusselt number, a crucial parameter in heat transfer analysis. This research provides a valuable reference for predicting heat transfer and designing fluid heaters in the ORC system. By improving our understanding of heat transfer characteristics and optimizing performance, we can enhance the efficiency and effectiveness of low-grade thermal energy utilization in ORC applications. Wang et al. [14] focused on the heat exchanger design for the binary flashing cycle. They developed detailed models for plate heat exchangers to analyse thermodynamic, hydraulic, and thermal aspects. In addition to the heat transfer process, Ogrodniczak et al. [15] focused on the wet-to-dry expansion of siloxane MM in a covering-diverging nozzle and conducted non-equilibrium numerical simulations. Compared with the single-phase ORC, the studied wet-to-dry ORC has the potential to improve power outputs by 30%.

To address the challenges posed by variable temperature waste heat sources, Ping et al. [16] introduced a synergistic multi-objective optimization approach within the context of dynamic driving cycles. By combining nonlinear dynamic modelling, they reduced the number of decision variables and construction time, ultimately enhancing the efficiency and reducing uncertainty and hysteresis in ORC operation. In another paper published by Ping et al. [17], an integrated online dynamic modelling scheme was proposed, aiming to enhance prediction accuracy, anti-interference ability, and adaptability of the ORC data-driven model in a changing environment. The approach leads to a 42.2% improvement in mean absolute error, a 79.56% reduction in construction time, providing a novel modelling approach for the entire ORC data-driven model design process. Liu et al. [18] investigated the ORC system's performance under different heat source temperatures in Harbin, China. The findings suggest that optimizing heat source conditions, particularly through increased mass flow rates, can effectively enhance the efficiency of ORC systems driven by low-grade thermal energies. To efficiently and accurately select system parameters under different waste heat source conditions, Zhang et al. [19] proposed a method for constructing system selection maps. Xu et al. [20] focused on waste heat recovery in marine hybrid propulsion systems and proposed the utilization of both TEG and ORC to recover waste heat from various sources. Employing a multi-objective optimization algorithm, they developed an energy management strategy that considered multiple energetic performance factors, resulting in reported energy savings of up to 14% for the propulsion systems. Liu et al. [21] put forward and evaluated the use of high-temperature fuel waste gas to enhance the temperature of conventional geothermal ORC. Their study explored a combined ORC system that simultaneously recovered waste heat from geothermal sources and high-temperature waste gas, leading to a 23% improvement in cycle output power. Meanwhile, ambient conditions have been recognized as another crucial factor affecting ORC performance. Wang et al. [22] investigated the impact of variable condensation conditions and suggested employing a single screw expander with quasi two-stage expansion to enhance ORC performance under various condensing conditions.

In addition to the aforementioned research on ORC systems, this Special Issue also highlights other power cycles designed for low-grade waste heat recovery. Liu et al. [23] proposed integrating the KC with a high-temperature proton exchange membrane fuel cell and a concentrating photovoltaic (PV) system, using a KC system to recover waste heat generated by the fuel cell. They enhanced the output power of the system by implementing a half-effect absorption refrigeration cycle driven by the low-grade heat from the concentrating PV system. Kumar et al.[24] investigated the integration of KC with a parabolic trough collector (PTC), with a focus on employing and optimizing the PTC coating. They reported improvements in the levelized electricity cost and payback period, reducing them from 0.16 USD per kWh and 7 years to 0.15 USD per kWh and 6.4 years through the proposed coated PTC-driven KC. Jin et al. [25] introduced a novel recompression S-CO_2 cycle model, accounting for factors such as finite temperature difference heat transfer, irreversible compression, irreversible expansion, and other irreversibility losses. They conducted multi-objective coordinated optimization and suggested using artificial neural networks to reduce computational load. Wang et al. [26] put forward a computer-aided molecular design method to optimize CO_2-based mixtures for T-CO_2 cycles. The results highlighted the effectiveness of this method in globally ranking CO_2 mixtures, offering valuable guidance for the optimal design of CO_2 mixtures. This research contributes to the advancement of T-CO_2 cycle technology by exploring the potential of CO_2 mixtures to improve system performance and address technical challenges. Additionally, the Stirling cycle is considered as a type of highly compact waste heat recovery system. In this Special Issue, Yang et al. [27] focused on the stability and energy consumption of the helium face seal in Stirling cycle engines. They developed a numerical model to investigate heat dissipation and energy transfer routes under cryogenic conditions. The results obtained offer valuable insights for the future structural designs of Stirling cycle engines.

2.3 Thermoelectric generators

TEGs have garnered extensive attention and practical utilization in direct heat-to-electricity conversion due to their modular design, cost-effectiveness, and superior safety features. Current research in TEG applications primarily revolves around structural optimization. In this Special Issue, Yang et al. [28] studied annular TEGs and optimized the thermal design of individual annular thermoelectric couples. They developed a high-fidelity multiphysics model and performed simulations using a dual-finite-element method to reduce computational cost. The results demonstrated an impressive 1.7× enhancement in net power when compared to conventional design methods. Cai et al. [29] introduced a novel sizing methodology to determine the ideal number of thermoelectric modules and geometric parameters. The performance of this optimization method was validated through a case study involving truck engine exhaust gas. Miao et al. [30] contributed to this special issue by optimizing the heat collector structural parameters, including length, height, and the number of fins. They harnessed industrial radiant heat as the power source and conducted numerical calculations to analyse the heat transfer process and the impact of the heat collector structure. Through extensive industrial experiments, their work provides valuable measured data for further research. He et al. [31] employed a combination of theoretical derivation and numerical calculations to optimize the structural design of TEGs with various circuit layouts. Their findings revealed a significant difference in optimal lengths across different circuit layouts, suggesting the utilization of the optimal length under full-series circuit mode for maximizing net power output. Liao et al. [32] developed and experimentally examined the compact TEGs incorporating mini-channel liquid–liquid heat exchangers. Their economic analysis indicates the competitiveness and higher power performance of the proposed TEG design for large-scale geothermal energy utilization. Yu et al. [33] established a test bench for aqueous ferricyanide/ferrocyanide thermocells and experimentally investigates performance under different thermal boundary conditions. The results indicate that natural convection significantly reduces internal resistance, leading to higher Seebeck coefficient and power density.

In addition to the aforementioned studies on TEG structural design and heat transfer, the Special Issue also addresses the integration of TEG with other systems. Notably, Gao et al. [34] and Yin et al. [35] conducted comprehensive modelling and simulation work on the integration of TEG into PV systems. Gao et al. [34] compared two layouts of PV-TEG combined systems under both uniform and non-uniform radiation conditions. They analysed the effects of sun concentration ratio, inlet temperature, and leg height, providing various conclusions and recommendations for system structure and operating parameters. Their findings offer valuable insights into system design, particularly regarding thermal stress distribution. Yin et al. [35] focused on concentrated spectrum splitting in PV-TEG systems and introduced a multi-objective optimization method that combines sensitivity analysis, parameter evaluation, and genetic algorithms. Their results underscore the significant impact of TEG structural factors on system performance and emphasize the importance of considering system cost and longevity.

2.4 Thermal storage

Thermal storage technologies are developed and utilized to effectively manage thermal loads and flows. They play a pivotal role in various low-grade thermal utilization systems. The articles collected in the Special Issue concentrate on thermal storage materials, the heat transfer process, and system integration.

Inorganic phase change materials have several advantages, including high thermal conductivity, storage density and safety, but they encounter challenges related to supercooling and limited shape flexibility. In this Special Issue, Liu et al. [36] investigated sodium acetate trihydrate as a TES medium and proposed a method that involves acrylamide, aqueous starch and graphite to address these issues. Characterization results indicate that the prepared inorganic phase change material has a latent heat of 0.13 J kg^{-1}, and its cyclability has been improved while successfully addressing the supercooling problem.

To enhance heat transfer performance, Ghalambaz et al. [37] proposed the use of two layers of metal foams in phase change material (PCM). Heavy and light foams were strategically placed in regions with low and high convection, respectively, to achieve rapid thermal charging while keeping the storage weight low. They introduced and compared three different configurations, with the optimal configuration demonstrating a 32% improvement in thermal charging speed. The incorporation of highly conductive nanofillers has also been considered for enhancing thermal conductivity. However, in this Special Issue, Ribezzo et al. [38] pointed out that high thermal resistances at the nanofiller-matrix interfaces could have a negative effect. They conducted numerical estimations and analyses to address this issue. The predicted thermal conductivities served as input for experiments, offering a novel multi-scale analysis method that bridges plant-scale system performance with material properties. This numerical-experimental approach was reported to enhance computational efficiency and accuracy.

In addition to the PCM-based thermal storage technologies discussed earlier, the current Special Issue also addresses the sensible thermal storage method. Li et al. [39] conducted a detailed study on a hydrothermal reactor, thoroughly investigating its flow and heat transfer characteristics. They considered non-uniform solar heat flux and simulated the natural convection of water within the cylindrical reactor. Using the numerical results, they analysed temperature distribution, fluid motion, and wall heat transfer under various heating schemes and physical property conditions. They identified the key factors that dominate different heat flux ratios, offering valuable insights for the further optimization of solar-driven hydrothermal reactors.

El Kouihen et al. [40] integrated a thermal storage system with the mining industry to enhance the matching of daily power demand and supply, thereby improving overall energy efficiency. They captured and stored waste heat using a thermal energy storage system, which was subsequently used to generate power during the night. Their research encompassed comprehensive computational and experimental investigations into the storage material. Additionally, they conducted an economic evaluation of the proposed system's feasibility for use within the mining industrial process. This work exemplifies the vital role of thermal storage in managing thermal loads within distributed energy systems and offers a practical solution for achieving a circular economy.

2.5 Solar thermal energy utilization technologies

It is worth noting that many articles included in this Special Issue were focused on harnessing and utilizing solar thermal energy. In this regard, a selection of representative studies has been introduced, offering a broader perspective on the utilization of solar energy.

This section begins with research conducted by Li et al. [41] on solar-driven interfacial evaporation, which holds promise for addressing freshwater shortages. In their study, they developed a novel interfacial evaporation material with exceptional solar absorption and photothermal conversion properties. The method involved using renewable wood and incorporating reduced graphene oxide through impregnation and reduction. Outdoor testing resulted in a daily freshwater production of 6.4 kg m^{-2}. The test results and analysis revealed that the enhanced evaporation performance can be attributed to three factors: the improved hydrophilicity facilitated by the nanowood cellulose network, the introduced impregnation-reduction method, and the 2D water supply strategy. The study also underscored the potential of harnessing the evaporation driving force for freshwater-electricity cogeneration purposes.

Another technology for utilizing solar energy in freshwater production in this Special Issue was introduced and examined by An et al. [42]. They conducted experiments and utilized machine learning calculations to investigate a solar-driven humidification-dehumidification unit for freshwater production. Initially, they measured the system's freshwater productivity through outdoor experiments and subsequently employed the measured data in machine learning models to make performance predictions. They employed four machine learning algorithms, and the Bayesian optimization algorithm was used to optimize their hyperparameters. In terms of comparison results, the artificial neural network and random forest exhibited the highest prediction accuracy.

Batuecas et al. [43] directed their attention to solar concentrators, conducting a comparative analysis of different configurations of a beam-down Fresnel solar field using a life cycle assessment methodology. They assessed the thermal energy production and environmental impacts as the key criteria. In comparison to natural gas, the solar field case under examination demonstrated a significant maximum reduction in carbon footprint, reaching 34%, and a reduction of 41% in ozone depletion potential. This research highlighted the optimal configuration for a solar concentrator field and provided comprehensive evaluation data for practical projects.

Alongside interfacial evaporation and solar concentrators, solar photothermal conversion fluids represent another promising technology for harnessing solar energy. In this Special Issue, Li et al. [44] conducted tests and comparisons of the performance of water-based Ti_3C_2 MXene/TiN composite nanofluids and mono-component nanofluids in photothermal conversion. The results highlighted the impact of TiN nanoparticles on enhancing fluid stability and the positive correlation between thermal conductivity and optical absorption capacity. The photothermal conversion efficiency of the optimal composite nanofluid reached 64%. Their work offers valuable insights and a method for the further advancement of photothermal conversion nanofluids.

In addition to the previous research focusing on specific technologies and devices, Osorio et al. [45] introduced and investigated a combined solar thermal-power system. This system is designed to contribute to the partial electricity demand of the electric grid and primarily consists of flat plate collectors, a thermal energy storage tank, and an ORC system. They conducted a comprehensive analysis of the proposed system, considering different seasons and climate zones, taking into account local conditions such as solar radiation, climate variables, and residential loads. The results indicated that the system achieved maximum efficiencies of approximately 9.5% in cold and marine climate zones, while the electricity supply fraction reached around 50% in mixed-humid and hot-humid zones. Additionally, they analysed the impact of the scale of solar fields and thermal energy storage tank volume and made comparisons with a solar PV-battery system.

2.6 Other thermal energy technologies

In this Special Issue, a broad range of papers on thermal energy was collected, and some studies fall outside the categories mentioned above. This section offers an overview of these papers, covering extensive topics such as heat pipes, thermally regenerative electrochemical cycle (TREC), and thermal management technologies.

This section begins with the studies on heat pipes. Su et al. [46] presented a novel design of an annular pulsating heat pipe tailored for evacuated solar collectors to address the issue of significant contact thermal resistance. Their study employs a three-factors three-levels Box-Behnken Design model with the response surface method for the efficient optimization of operational parameters, demonstrating the feasibility and efficiency of the method in understanding and optimizing heat transfer performance. Shi et al. [47] developed a micro heat pipe array for heating and cooling in a fresh-air system, showing substantial improvements in thermal and electric efficiency and achieving nearly zero energy consumption during the winter season compared to conventional heat recovery. Chen et al. [48] investigated the super-long gravity heat pipe for deep geothermal energy exploitation, identifying desirable working fluid properties that offer valuable guidance for practical geothermal applications, supporting the technology's development and commercialization. In the same realm of geothermal energy, Xiao et al. [49] introduced a techno-economic coupling model for the economic evaluation of closed-loop geothermal systems. Applied to the Gonghe Basin in Qinghai, China, the model demonstrated high accuracy and consistency with experimental and classical model results.

TREC is an emerging technology for low-grade heat recovery and power generation. In this Special Issue, He et al. [50] introduced a novel concept employing two rotating layers of TREC units, improving energy conversion efficiency, enabling uninterrupted power output, and reducing heat absorption. The innovative rotating TREC device demonstrates an impressive heat-to-electricity efficiency of 10.32%, making it a promising solution for continuous and highly efficient energy output with practical application viability. Xiao et al. [51] studied the non-aqueous thermally regenerative battery, an alternative to TREC for heat-to-electricity conversion. Their theoretical calculations demonstrate a thermal efficiency of 6.6%, showcasing the competitive performance of this technology and promoting its development and application.

Riaz et al. [52] and Xiao et al. [53] contributed to the current Special Issue by focusing on the low-grade waste heat of combustion. Torrefaction is a low-temperature thermochemical treatment for enhancing solid biomass fuel properties. Riaz et al. [52] explored the utilization of real-time low-grade combustion waste heat and flue gases to produce torrefied biomass pellets at 225 °C and 250 °C. Their results indicate that flue gas torrefaction improves the heating value by up to 11%, suggesting it as a viable and cost-effective method for upgrading biomass fuel quality. Coalfield fires, located at relatively shallow depths, offer high-temperature heat storage, resembling the reservoir conditions of shallow geothermal energy. Xiao et al. [53] suggested that the thermal energy from coalfield fires could be harnessed as low to medium-grade geothermal resources. Utilizing a two-phase closed thermosyphon for heat transfer and thermoelectric conversion devices for the direct transformation of thermal energy into electricity are identified as effective methods for extracting and converting thermal energy in coalfield fire areas, with proposed enhancements to improve overall efficiency.

In addition to low-grade heat recovery and utilization technologies, this Special Issue gathered various papers on thermal management, with a primary focus on cooling technologies. Wang et al. [54] assessed newly designed skeleton porous-medium heat exchangers for cooling high-power chips. Their study pinpointed a partially encrypted cylinder-based skeleton porous medium heat exchanger as the optimal choice for temperature control, showcasing a 19.62% reduction in maximum temperature and a 23.38% improvement in temperature distribution compared to a conventional finned heat exchanger. In the research by Xiang et al. [55], a high-performance spray cooling system for high-power LEDs was designed, considering factors such as nozzle configuration, flow rate, and nozzle-to-surface distance. Experimental and numerical investigations highlighted that the double-nozzle configuration exhibited the highest single-phase heat transfer coefficient at 20.7 kW m^{-2} K, indicating exceptional heat dissipation capacity. Yang et al. [56] focused on dew-point evaporative cooling for PV panels to enhance solar electricity production. They introduced a novel cooling configuration with two wet channels, resulting in a significant increase in PV energy efficiency. The proposed system maintained over 15% efficiency, marking a 16.4% improvement compared to air cooling. In contrast to cooling technologies, Wei et al. [57] concentrated on monitoring the internal temperature distribution and addressing radial and axial thermal inhomogeneities in lithium-ion batteries. They introduced a hybrid lumped-thermal-neural-network model, combining a mechanism-driven distributed lumped thermal model with machine learning-based axial thermal gradient compensation. This approach enables real-time and accurate estimation of the internal multi-point temperature of lithium-ion batteries, providing an advanced method for precise and spatially resolved internal thermal diagnostics.

3. Conclusions

The Special Issue ‘Low-grade thermal energy utilization: technologies and applications’ served as a platform for presenting state-of-the-art research on technologies being current under development in the context of managing and utilizing low-grade thermal energy. This editorial article reviewed the articles featured in the Special Issue, and provided commentary on these contributions. The diverse research topics covered in the Special Issue include aspects related to the most cutting-edge heat pump, power cycle, TEG, thermal storage, solar thermal energy utilization, and other thermal energy technologies for various applications, offering a comprehensive overview and guidance for future research and development. Our appreciation goes out to all authors, reviewers and editors who have contributed to this endeavour.

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