Advances in Industrial Energy Systems for Production, Storage and Utilization of Energy

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Abstract

This vision article accompanies a *Special Issue* of Applied Thermal Engineering dedicated to the 18th Sustainable Development of Energy, Water and Environment Systems (SDEWES) conference held in Dubrovnik, Croatia from 24 - 29 September 2023. This article presents a selection of papers presentet at the conferences, published in Applied Thermal Engineering journal, all focused on advancing sustainable thermal energy systems together with clean energy technologies. The research encompasses a diverse range of innovations, with particular attention to heat exchangers, thermal energy storage, thermal system simulations, and their integration with chemical processes and pollutant control. Based on recent advancements in the field, this vision article examines the development and application of cutting-edge technologies while addressing key challenges that require further investigation. The progress of both emerging and established technologies will rely on breakthroughs in fundamental research, cost reduction measures, expansion of operational capabilities, and the implementation of advanced control strategies. Furthermore, optimizing systems will necessitate the integration of multiple renewable energy sources and sophisticated modeling tools. By synthesizing the latest trends and critical research needs, this article offers valuable perspectives for scientists, researchers, and engineers, providing direction for future studies and innovations in sustainable thermal energy systems.

Keywords:

energy technologies, heat exchangers, thermal energy, thermal processes, thermal system simulations

1. Introduction

The Sustainable Development of Energy, Water, and Environment Systems (SDEWES) conferences are annual international events that bring together top scientists, researchers, engineers, professionals, and other stakeholders interested in addressing challenges related to energy, water, and environmental system development. These conferences have fostered strong collaborations with scientific journals [1], contributing to special issue organization and advancing shared research topics [2]

The 18th SDEWES Conference, held in Dubrovnik, Croatia from 24 - 29 September 2023, brought together more than 600 scientists and researchers working on topics of sustainable development. From more than 550 oral presentations, the best work committed to the area of applied thermal engineering has been selected and invited to be submitted to the *Special Issue*. Together with the present Vision paper, the selected papers within this special issue present the continued and successful cooperation between the SDEWES conference and the Applied Thermal Engineering journal, and showcase the recent developments and novel applications of technologies in the research field.

This Special Issue features 19 carefully selected articles from the 18th SDEWES conference, recognized for their quality and collective impact on advancing energy generation, efficiency, and conservation within sustainable engineering systems. The research encompasses experimental, numerical, and analytical methodologies, covering both fundamental principles and cutting-edge applications in four main areas: (i) heat exchanger analysis for various applications, (ii) development and optimization of thermal energy storage solutions, (iii) system simulations for thermal applications, and (iv) integration of chemical processes and pollutant control within thermal systems.

These studies highlight the latest advancements in thermal engineering, offering innovative solutions for contemporary challenges. This vision article provides an in-depth overview of the featured research, examines emerging trends and applications, and discusses critical challenges that will shape the future of the field.

2. Overview

The integration of heat exchangers, thermal energy storage, system simulations, and chemical processes represents a foundational approach to advancing sustainable thermal energy systems. These components collectively contribute to improving energy efficiency, enhancing system flexibility, and supporting the transition to clean energy technologies.

Heat exchangers remain central to thermal systems, enabling efficient heat transfer and minimizing energy losses. Their continued development is essential for optimizing energy conversion processes, particularly in renewable energy applications. Parallel efforts in thermal energy storage aim to balance supply and demand by capturing excess energy and releasing it when needed. This capability is vital for stabilizing energy systems and improving the utilization of intermittent renewable sources.

System simulations play a critical role in evaluating and optimizing the performance of integrated thermal systems. Advanced modeling techniques enable the analysis of complex interactions, guiding design improvements and operational strategies. These tools also facilitate the integration of thermal systems with chemical processes, enhancing overall system efficiency and enabling more sustainable energy conversion pathways.

The coupling of chemical processes with thermal systems introduces new opportunities for emissions reduction and resource recovery. Applications such as carbon capture, waste treatment, and synthetic fuel production benefit from thermal integration, supporting broader environmental and energy goals.

As global energy systems evolve, the convergence of these technologies will be key to addressing technical, economic, and environmental challenges. Future research should prioritize interdisciplinary collaboration and system-level innovation to unlock the full potential of integrated thermal energy solutions.

3. Use of Heat Exchangers in Modern Thermal Engineering Applications

Heat exchangers are integral components of modern thermal engineering, playing a critical role in enhancing energy efficiency and resource conservation across a wide range of applications. These devices facilitate the transfer of thermal energy between fluids without mixing them, thereby allowing systems to reclaim heat, optimize energy use, and reduce environmental impacts. As technology evolves and industries face increasing pressure to improve sustainability, the application of heat exchangers continues to expand. This chapter provides a comprehensive overview of various applications where heat exchangers are utilized, illustrating their importance in contemporary thermal engineering. Table I summarizes the main applications and research topics revolving around heat exchangers, with main findings from the included papers showcasing the recent research developments.

Table I. Overview of the heat exchangers research and the main findings

Application	Research Topics	Main findings
Geothermal systems	Heat transfer optimization Water consumption reduction Dimensions reduction, use of multiple boreholes	Accurate simulations (+/- 5%) for multiple borehole heat exchangers [3]
Residential heating	Residential heating (dual-source heat pumps; plate exchangers) Multiple sources (solar + geothermal energy)	Increased electricity production with CO2 heat pump with direct-expansion air-finned coil heat exchanger [4] Analysis of improved efficiency of blown plate heat exchanger [5] Solar and geothermal energy system with 3x reduction in exchanger length [6]
Waste heat recovery	Organic Rankine cycle – increase of efficiency Steam generators – use of high-pressure configurations Design optimization – fouling/pollutant reduction	Ethanol proven best as working medium in ORC with recuperator [7] For heat recovery steam generators without reheating, optimal high pressure in subcritical region; with reheating in supercritical region [8] Ash accumulation analysis on serrated fins lowest under 7 m/s, with good heat transfer [9] Fluorine plastic heat exchangers show good heat transfer (275 W/m2K) while enabling water recovery efficiency of 85 % [10]
Power electronics	Investigating novel designs and power electronics applications	FEM and CFD simulations of novel design approach with reduced hot spot temperature of 58 °C [10]
Geometry optimization	Design improvement – geometry optimization, nanomaterials, novel designs	Experimental and numerical analysis of novel heat exchanger and thermal separation [11]

		Literature reviews on phase change materials: letter-shaped fins [12], nano-enhanced medium [13], and cold energy storage [14]
Hydrogen production systems	Investigating heat exchange in reactors and novel applications	New strategy for designing reactor with heat transfer and power consumption developed [15]

One significant application of heat exchangers is within heat recovery systems, particularly in steam generators. Recent studies have emphasized the importance of optimizing the layout of heat exchangers in heat recovery steam generators to achieve maximum thermodynamic efficiency. The analysis suggests that high-pressure configurations are more effective under certain operational conditions, thereby paving the way for improved energy recovery in industrial processes Čehil et al. [8]. This highlights how tailoring heat exchanger design can enhance performance metrics across diverse thermal systems.

Within this special issue, the paper by Brettschneider and Perković presents a theoretical analysis of utilizing multiple borehole heat exchangers for the production of heating and cooling energy from shallow geothermal reservoirs characterized by underground water flow [3]. Geothermal energy systems also illustrate the versatility of heat exchangers. The use of multiple borehole heat exchangers has been analyzed for their effectiveness in extracting heating and cooling energy from shallow geothermal reservoirs. In this research, the authors investigate the interactions between heat exchangers and the surrounding geological conditions, focusing on how these factors affect thermal energy transfer, while also demonstrating the potential for utilizing underground water flows to optimize energy consumption for residential heating and cooling. Such applications not only contribute to energy efficiency but also advance the global transition towards renewable energy sources.

Within the context of residential heating, there is a growing recognition of the effectiveness of dual-source heat pumps that employ heat exchangers. Recent research has demonstrated that CO2-based heat pumps combined with photovoltaic-thermal (PVT) systems can drastically improve energy utilization in residential settings, with photovoltaic electricity production being increased up to 8%. The findings confirm that employing innovative heat exchanger configurations can enhance performance and provide a sustainable option for household heating needs [4]. Additionally, advancements in the technology of blown plate heat exchangers have also shown promise for specific applications like cabinet cooling systems, thereby showcasing the niche utilities of heat exchanger technologies [5].

Heat exchangers are also pivotal in waste heat recovery processes. For instance, the integration of compact heat exchangers in organic Rankine cycles has been shown to optimize waste heat conversion, significantly improving overall system efficiency [7]. This is particularly relevant in industrial settings where excess heat is routinely generated and represents a lost opportunity for energy reuse. The ability of heat exchangers to recover thermal energy from sources such as flue gas further highlights their importance in reducing waste and enhancing the overall energy cycle in various applications [16].

The exploration of waste heat utilization also reflects innovative applications of heat exchangers. Tian et al. [9] investigate ash accumulation characteristics in serrated spiral finned tube heat exchangers within the context of waste heat recovery. Their numerical study provides insights into the fouling mechanisms that can impact heat exchanger performance in industrial applications. By addressing these challenges, the research contributes to the optimization of heat exchangers for recovering waste heat, ensuring that industries can maximize energy efficiency while reducing emissions and proving useful for specific applications in various sectors.

Recently, an additional novel use of heat exchangers has been within the ocean thermal energy conversion systems, with a vital development and investigation of their use. These systems utilize heat differentials between warm surface water and cold deep water, incorporating heat exchangers to generate electricity and support processes such as desalination [17]. This innovative approach showcases the multifaceted benefits of heat exchangers in addressing pressing global challenges, including energy production and water scarcity.

Another paper within the special issue describes the work by Rogkas et al. on the use of heat exchangers in power electronics [10]. In this paper, the authors investigate a novel high-frequency inductive power transfer system, focusing specifically on its heat transfer mechanisms. The assessment employs finite element analysis (FEA) for simulation, which allows for an in-depth understanding of thermal behavior within the system. By identifying the efficiency of thermal conduction and inductive heating, this research contributes insights into improving heat transfer methods in electrical applications, which is crucial for enhancing overall energy efficiency in thermal and energy systems. While the primary focus leans towards physics, the implications of effective heat transfer techniques are valuable within the context of thermal engineering.

The multipurpose nature of heat exchangers is evident, making them especially useful in thermal engineering applications. Additional connection to the chemical engineering can be seen in the work by Alabrudziński et al. [11], where they investigate the energy expenditure of a Z-type plate heat and mass exchanger. By basing their concept on heat-integrated distillation columns, the authors illustrate how heat exchangers can enhance energy efficiency in chemical processes. The used approach not only optimizes the heat and mass transfer characteristics, but also aligns with the growing need for energy conservation in the chemical industry. Integrating advanced heat exchanger designs in processes such as distillation can significantly reduce energy requirements, thus contributing to more sustainable industrial operations.

Heat exchangers have a central application in energy storage and hydrogen production systems, with the thermal design and heat transfer optimization of reactors for liquid organic hydrogen carriers, and the utilization of heat exchangers to improve hydrogen storage being investigated [15]. Advances in thermal energy storage systems that couple heat pumps and heat exchangers also pave the way for efficient energy use in integrated energy systems [18]. On the other hand, the innovative systems integrating solar thermal collectors with thermal storage for building heating applications enable effective solar energy utilization, thereby aligning with sustainable development goals by reducing reliance on fossil fuels [6]. With a diverse role in thermal engineering applications heat exchangers represent a backbone of the research done within the field. Their role within the modern technological solutions is crucial and diverse in applications. From improving the industrial energy recovery systems to supporting faster renewable energy technologies integration, the research is centred around improving their efficiency and adapting them within a variety of novel contexts. Research will continue their improvement and with the development of gnu configurations and applications, heat exchangers will continue to play a central role in shaping the future of thermal engineering.

4. Advancing of Thermal Energy Storage Solutions

Thermal energy storage (TES) is an increasingly vital technology in the context of improving energy efficiency and facilitating the integration of renewable energy sources. The need for the improvement of thermal energy storage technologies can be best seen in two areas. The first one is the need to introduce advanced long term heat storage systems which will enable improved operations of the district heating and waste heat utilization. TES systems allow for the storage of excess thermal energy generated during low-demand periods or high energy availability, which can be released during peak demand times, facilitating load levelling, peak shaving, and effective energy management strategies. Besides the temporal shift of energy on different temporal scales (hourly, daily, seasonaly), Figure 1 shows different approaches to energy shifting with thermal energy storage. Another focal point is the electrification of industrial processes which depend on high temperature heat sources. The advanced solutions for thermal energy storage in industry could enable greater flexibility and the higher use of electric energy. Various innovative approaches to thermal energy storage, particularly those utilizing phase change materials [19], thermochemical processes, and advanced materials [20], have been explored in recent literature. Figure **2** provides a general classification of the phase change materials

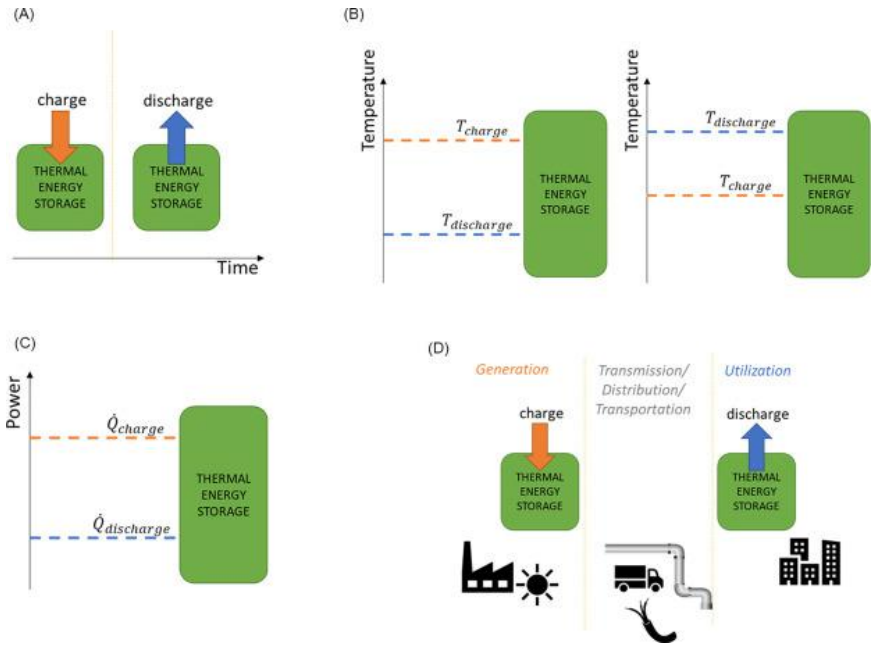

Figure 1. Thermal energy storage and a) temporal, b) temperature, c) power level, d) spatial shift of energy [21]

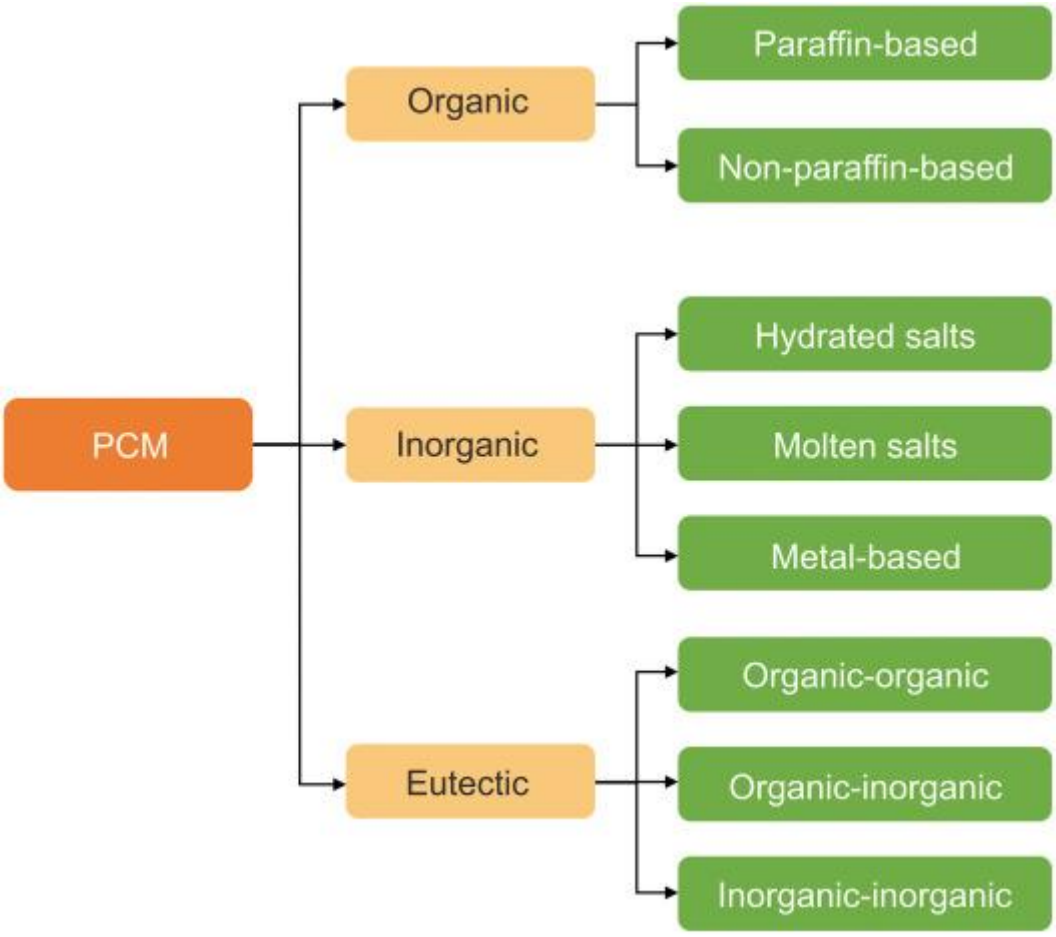

Figure 2. Categorization of phase change materials **[22]**

Recent advancements demonstrate the efficiency of caloric materials and thermochemical storage systems. For instance, the work by Wedl et al. discusses a continuously stirred tank reactor designed for thermochemical energy storage using CuSO4·5H2O, an organic hydrate, as a medium. This method reveals the potential for significant energy density and efficiency, facilitating the capture and release of thermal energy [23]. Likewise, Schmieder et al. provide insights into the utilization of calcium chloride dihydrate in seasonal heat storage, emphasizing its capabilities within a suspension reactor. The study highlights the practicality of using such materials for long-term energy storage, optimizing low-cost energy absorption from intermittent renewable sources like solar power [24]. These findings underline the versatility of chemical reactions in harnessing waste heat and enhancing the overall efficiency of energy systems, and Table II provides the overview of the commonly used organic and inorganic PCMs. The investigation of advanced materials and nanoparticles might expand the use cases for hot and cold energy storage, expanding to new applications. For example, the integration of thermal storage with smart grid technology allows HVAC systems to operate more efficiently by charging the thermal storage during off-peak hours and discharging it during peak periods, which maximizes cost efficiency [25].

Table II. Thermophysical properties of various types of PCMs [26]

	Name	**Type**	**Tm**	**Latent heat**	**ρ**	**Cp**	**K**	**Heat Capacity**
			(°C)	**(kJ/kg)**	**(kg/m3)**	**(kJ/kg K)**	**(W/m K)**	**(ρ Cp)**
								$\times 10^6$
ORGANIC PCMs	Octadecane	Paraffin	29	244	814 (sol) 724 (liq)	2150 (sol) 2180 (liq)	0.358 (sol) 0.152 (liq)	1.75
						(liq)	(liq)	1.58
	Heneicosane		41	294.9	773 (liq)	2386 (liq)	0.145 (liq)	1.84
	Tricosane		48.4	302.5	777.6 (liq)	2181 (liq)	0.124 (liq)	1.70
	Tetracosane		51.5	207.7	773.6 (liq)	2924 (liq)	0.137 (liq)	2.26
	Oleic acid	Fatty acid	13	75.5	871 (liq)	1744 (liq)	0.103 (liq)	1.52
	Lauric acid		44	178	1007 (sol) 965 (liq)	1760 (sol) 2270 (liq)	0.147 (liq)	1.77 2.19
	Palmitic acid		64	185	989 (sol) 850 (liq)	2200 (sol) 2480 (liq)	0.162 (liq)	2.18 2.11
	Stearic acid		69	202	965 (sol) 848 (liq)	2830 (sol) 2380 (liq)	0.172 (liq)	2.73 2.02
INORGANIC PCMs	CaCl2·6H2O	Calcium chloride hexahydrate	29	170–192	1562 (liq) 1802 (sol)		0.561 (liq) 1.008 (sol)	

	NaSO4·10H2O	Glauber's salts	32	251	1485 (sol)		0.544	
	MgCl2·6H2O	Magnesium chloride hexahydrate	117	168.6	1450 (liq) 1569 (sol)		0.579 (liq)	

In industrial contexts, TES materials and systems optimize energy usage and contribute to economic improvements. The use of phase change materials offers significant advantages in energy density and storage capability, making them suitable for high-temperature applications [27]. Advanced modeling techniques are employed to optimize operational strategies of industrial energy systems, effectively balancing electricity and thermal load management alongside emissions costs [28]. Moreover, the effective implementation of TES in industrial processes can lead to economic optimization, as illustrated in the integration of thermal storage in aluminum production processes using organic Rankine cycles [29]. However, heat transfer poses as a major issue in using the phase change materials, limiting the heat exchange and the application purposes. Recent studies, summarized in a review paper [12] , have focused on optimizing the geometries for improved heat exchange, both for the applications with and without novel approaches such as nano-enhanced phase change materials [13].

The potential of carbon dioxide in transcritical cycles for electrothermal energy storage is explored by Carro et al. This research emphasizes the integration of geological carbon storage with thermal energy systems, showcasing an innovative approach to both managing carbon emissions and enhancing thermal storage capacity [30]. The combination of geological features with thermal mechanisms provides a promising avenue for large-scale energy storage solutions, which is critical for balancing supply and demand in modern energy systems.

Moreover, the recycling of metallurgical wastes using concentrated solar energy is investigated by González et al. This paper illustrates how renewable energy sources, particularly solar, can be exploited in metallurgical processes to enhance energy efficiency and reduce the carbon footprint of traditional thermochemical cycles [31]. This interconnection of renewable energy applications with metallurgical energy storage offers a dual benefit: waste reduction and enhanced thermal energy recovery, highlighting the innovation potential in the sector.

Emerging materials like ferromagnetic nanofluids also showcase promising thermal properties that can optimize thermal energy transfer processes. Du et al.'s experimental study on the boiling performance of Fe3O4 nanofluids reflects the potential improvements in heat transfer efficiency in thermal systems, suggesting that nanomaterials may play a critical role in future thermal energy storage applications [32]

The evolving landscape of TES technology increasingly incorporates digital tools and predictive management strategies. For instance, multi-level predictive management has been shown to optimize phase-change energy storage systems effectively under dynamic electricity tariffs, enhancing both economic viability and operational efficiency [33]. Furthermore, advancements in digital tools for monitoring and managing energy flows within buildings signify a significant progress toward smarter energy systems that leverage the advantages of thermal energy storage.

Thermal Energy Storage (TES) systems are fundamental to improving the efficiency and sustainability of thermal management across multiple sectors. By enhancing energy utilization, supporting the integration of renewable energy sources, and optimizing economic performance, TES technologies contribute significantly to the advancement of sustainable energy systems. Integrated systems connecting thermal energy storage and power production (either as main or a byproduct) introduce flexibility in the operation and enable added efficiency improvements. Figure 3 illustrates a possible recuperation of waste heat from a thermal process.

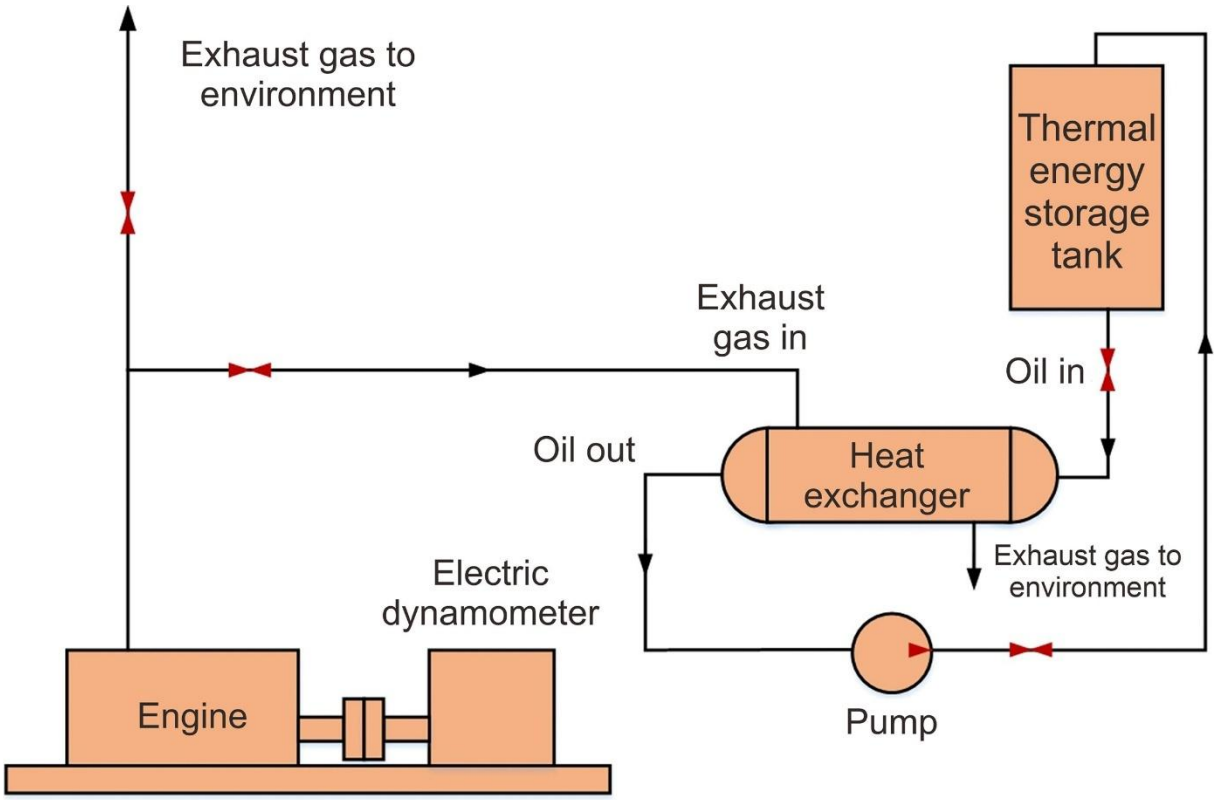

Figure 3. Schematic representation of a integrated thermal system, combining thermal energy storage, heat exchanger utilization, and energy supply [22]

The integration of advanced materials and innovative TES solutions opens new avenues for increasing efficiency and maximizing renewable energy potential. Research contributions in this field explore diverse approaches, including thermochemical storage, phase change materials, nanofluids, and hybrid energy systems, all of which play a crucial role in expanding the applicability and effectiveness of TES. These advancements not only address the challenges of energy storage capacity, thermal stability, and system compatibility but also contribute to reducing costs and environmental impact. In thermal energy storage the novel technologies and approaches are constantly being developed in a search for the improved efficiency, or a breakthrough in a new area. One example is the use of phase change materials for the cold thermal energy storage, expanding a way for innovative approaches in differently-sized cooling systems [14].

Looking ahead, continued research and development in TES technologies will be essential for meeting the growing demand for efficient and resilient thermal management. Future efforts should focus on material innovations, improved system integration, and enhanced control strategies to optimize TES performance in real-world applications. As the need for sustainable energy solutions intensifies, TES will remain a key enabler in achieving higher energy efficiency and a more sustainable global energy landscape.

5. System Simulations as a Novel Tool for the Improvement of Thermal Systems

Recent advancements in engineering research have underscored the significance of system simulations, technology integration, optimization processes, and the utilization of digital twins. This interdisciplinarity has enabled advanced control of the systems and processes, as well as opened the new alleyway for future research. Within the multidisciplinary topics, the integration of heat pumps within water networks poses as an interesting one, growing outside the usual framework of polygeneration. Ibrić et al. in their work on heat-integrated water networks emphasize a systematic simulation approach to optimizing thermal systems, which enhances energy efficiency in water treatment and distribution

processes [34]. By incorporating heat pumps, the authors demonstrate how simulations can yield insights that lead to more sustainable water management practices. This application of system simulations plays a vital role in integrating various engineering components to achieve optimal performance. Further exploring the theme of optimization in thermal systems, Tajalli-Ardekani et al. delve into the transition of a district in Rome towards optimal and sustainable heat and power generation [35]. Their simulation studies focus on assessing different strategies for energy production, evaluating sustainability metrics, and ultimately providing data-driven recommendations for policy and infrastructure decisions, showing the reduction in energy generation cost and CO2 emissions of 48.9% and 56%, respectively. This work exemplifies how inter-system optimizations can enhance energy consumption profiles and reduce carbon footprints, highlighting the importance of integrated simulations in achieving sustainability in urban energy infrastructures. Ibrić et al. also address the detailed design of heat exchangers within heat-integrated water networks, indicating the need for precise simulation tools to understand the thermodynamic behavior of these systems [36]. This research integrates advanced modeling techniques that allow for an in-depth analysis of heat exchanger performance, illustrating how detailed simulations can lead to better design efficiencies and operational optimizations.

Another relevant contribution is found in the work of Cvetinović et al., who detail the optimization of operating parameters in a thermal plasma system using thermodynamic modeling. Their approach emphasizes the critical role of system simulations in determining optimal parameters to enhance the conversion efficiency of industrial waste [37]. This optimization not only improves technical performance but also aligns with principles of sustainability by reducing the environmental impact.

Additionally, Urbaniec et al. propose a holistic approach to the sustainable development of energy, water, and environmental systems through integrated simulations [38]. Their work supports the argument that system integration is imperative for realizing sustainable development goals, as it facilitates a comprehensive analysis of interconnected systems and helps identify optimal pathways for resource utilization and waste reduction.

The use of digital twins in energy systems, particularly in environments such as buildings and industrial facilities, has been gaining traction, as described by Calise et al. in their study on a novel polygeneration system integrating various renewable energy technologies [39]. Their dynamic modeling and energy-economic analysis illustrate how digital twins can provide real-time insights into system performance, allowing for continual adjustments that optimize energy management and promote efficiency throughout the operational lifecycle.

Furthermore, research by Testasecca et al. examines dynamic simulations within a fourth-generation district heating network, indicating significant potential for engaging prosumers—entities that both produce and consume energy—within the energy system to enhance overall efficiency [40]. This integration reflects the modern energy landscape's shift towards more decentralized systems, enabled by digital twins and real-time simulation capabilities. Additionally, it has recently been shown that the primary energy saving for the 4th and 5th generation districts are equal to 97% and 81%, respectively, with a reduction of the CO2 emissions by the 98% and the 87%, respectively [41].

Digital twins have gained traction in applied thermal engineering for their ability to create virtual representations of physical systems. Tagliabue et al. demonstrate the leveraging of digital twin technology for sustainability assessments, offering real-time insights into the operations of buildings and associated energy systems [42]. The integration of digital twins allows engineers to model complex interactions within thermal systems and to conduct virtual testing, which can lead to optimized designs and operational strategies. Silva et al. showcase how the combination of simulation techniques with digital twins can facilitate the optimization of sewage sludge co-digestion processes, impacting methane yield and bioenergy recovery [43]. Their findings reflect the broader applicability of these technologies in optimizing operations across diverse energy scenarios, including waste management.

Lastly, the dynamic nature of thermal systems is captured through advanced simulation techniques. Huang et al. focus on visualizing refrigerant distribution in thermal systems, showcasing how simulation can improve design parameters for more efficient heat transfer [44]. This line of research emphasizes the critical need for a detailed understanding and modeling of thermal dynamics to guide the engineering of more effective thermal systems.

A pivotal contribution to the realm of energy simulation tools is made by Buonomano et al., and included in this special issue, who assess the reliability of a ship energy performance simulation tool using onboard data [45]. Their focus on the fidelity of simulation models captures the vital link between theoretical performance assessments and practical applications in maritime contexts. By analyzing real operational data, they refine the models used for performance simulations, ensuring that the simulations provide realistic predictions and effective optimization strategies.

The collective insights from these studies highlight the critical role of system simulations, optimization techniques, and digital twins in enhancing the efficiency and sustainability of applied thermal engineering. By bridging the gap between theoretical modeling and practical implementation, these methodologies enable more precise analysis, predictive capabilities, and performance improvements across a wide range of engineering applications. System simulations provide a structured approach to analyzing complex thermal processes, identifying inefficiencies, and optimizing energy use. Digital twins further extend this capability by creating real-time, data-driven models that facilitate continuous monitoring, predictive maintenance, and adaptive system control. The integration of these tools enhances the design and operation of thermal energy systems, making them more robust, adaptable, and capable of addressing the evolving demands of energy management.

Looking forward, the advancement of these digital methodologies will be instrumental in achieving greater energy efficiency, reducing environmental impact, and supporting the widespread adoption of renewable energy solutions. Further research should focus on refining simulation accuracy, improving computational efficiency, and expanding real-world applications of digital twins to ensure their full potential is realized. As engineering systems become increasingly complex, the synergy between simulation, optimization, and practical deployment will be key to shaping a more sustainable and technologically advanced future.

6. Integration of Chemical Processes and Pollutant Abatement in Thermal Engineering Systems

The study of chemical processes and pollutant management in applied thermal engineering is essential for advancing sustainable practices, optimizing energy efficiency, and reducing environmental impact. The integration of innovative technologies and methodologies enhances energy systems, waste management, and emissions reduction strategies, contributing to the development of cleaner and more efficient thermal processes.

A key focus of recent research is the interplay between chemical processes and pollutant formation, with studies exploring techniques such as pyrolysis and thermal decomposition. These processes play a crucial role in waste treatment, energy recovery, and emission control, offering valuable insights into minimizing environmental harm while maximizing efficiency. This overview, summarized in Table III, synthesizes findings from selected papers that significantly contribute to this growing field, highlighting advancements in pollutant mitigation and sustainable thermal engineering solutions.

Table III. Overview of the technologies, improvement proposals, and their effects

Technology	Process improvement	Aimed effect
Waste thermal treatment	Solar pyrolysis tars treatment by oxidation	Reduced environmental toxicity and improved efficiency
	Domestic waste co-pyrolysis	Reduction of dioxins
Thermal utilization of fossil fuels	Biomass co-firing in pulverized coal furnace	NOx control
	Retrofitting with CO2 capture	Minimization of CO2 emissions
	Self-preheating pulverized coal at ultra-low loads	Power optimization with NOx reduction

Sewage sludge	Co-digestion with biomass	Enhanced methane yield and pollutant reduction
	Effects of struvite presence	Control of NOx emissions
	Nanoparticles for improved microbial activity	Performance enhancement
Synthetic methane production	Hydrogenation of CO2 from direct air capture	Improved efficiency and pollutant reduction
Chemical (calcium) looping	High temperature dolomite decomposition analysis	CO2 emissions reduction
IC engine	Novel pre-chamber design	Combustion optimization and emissions reduction

To start with, several studies focus on the thermal treatment of waste materials, particularly in managing pollutants effectively. For example, Dudziak et al. analyze the treatment of solar pyrolysis tars through oxidation processes. Their findings reveal that the effective destruction of these tars can significantly reduce environmental toxicity and improve energy recovery, demonstrating the role of careful thermal management in processing biomass waste [46]. This study highlights the intersection of chemical transformations, pollutant management, and thermal efficiency, underscoring a need for advanced control strategies in thermal processing. The research by Sun et al. on biomass co-firing in pulverized coal furnaces provides pertinent insights. Their computational fluid dynamics modeling indicates that without proper management during combustion, biomass can contribute to increased emissions, such as nitrogen oxides (NOx). This study highlights the inherent challenges and solutions in blending alternative fuels within conventional energy systems to mitigate the formation of harmful emissions while maintaining overall thermal efficiency [32]. By optimizing co-firing techniques, the findings pave the way for more eco-friendly power generation strategies. Moreover, the work of Silva et al. on sewage sludge co-digestion presents innovative solutions to enhance methane yields while managing the formation of pollutants during anaerobic digestion. The incorporation of biomass, such as mango peel liquor, demonstrates an effective strategy for optimizing recovery processes in the anaerobic digestion system while reducing methane emissions [43]. This approach emphasizes the need for holistic evaluations in thermal treatment processes to ensure sustainability in waste management. Additionally, Grosser et al. focus on the application of silver nanoparticles to enhance anaerobic digestion performance of sewage sludge, emphasizing their role in promoting microbial activity and reducing operational challenges associated with the treatment process. This connection between chemical interventions and operational efficiencies is significant for closing the sustainability loop in waste treatment [47]. Their findings underscore the potential for innovative material use within thermal processing frameworks to enhance overall energy recovery and emissions performance. On a broader scale, Tregambi et al. present a techno-economic assessment of synthetic methane production through hydrogenation of CO2 from direct air capture. This research illustrates the importance of integrating advanced chemical processes within thermal energy systems to produce sustainable fuels while managing atmospheric pollutants [48]. The study effectively demonstrates multifaceted approaches to energy sustainability that leverage both innovative technologies and established thermal engineering principles.

In Calise et al.'s study on the thermoeconomic analysis for energy refurbishment in the Italian building sector, a comprehensive evaluation of different energy systems reveals insights into improving the thermal dynamics and energy efficiency of existing structures. Their work emphasizes the importance of retrofitting systems to optimize thermal performance and manage emissions effectively in urban environments [49]. Such studies are crucial for understanding the interplay between thermal engineering and chemical processes in improving building sustainability and energy performance.

Finally, the integration of carbon capture and storage (CCS) technologies presents another critical area of research within applied thermal engineering. Gerbelová et al. discuss the implications of retrofitting

fossil fuel power plants with CCS solutions, which are vital for minimizing CO2 emissions while maintaining energy output. Their findings provide insights into the economic and environmental benefits of adopting such systems in existing thermal plants [50]. The research exemplifies the necessity of innovative solutions to meet emissions targets in a transitioning energy landscape.

Mao et al. present a comprehensive study on the process system simulation of coupled pyrolysis disposal of domestic waste within a coal-fired boiler [51]. Their research focuses on the thermal conversion of waste materials and its associated dioxin emissions. The study employs modeling techniques to analyze the combined effects of pyrolysis and combustion processes, shedding light on the conditions under which dioxin formation occurs and how it can be minimized. This investigation underscores the critical need to optimize thermal processes to reduce harmful emissions and improve waste management approaches in energy production.

Similarly, the work by Žnidarčič et al. examines the thermal decomposition of sewage sludge with a particular focus on the influence of struvite presence on pollutant formation. Their findings indicate that struvite contributes to the generation of nitrogen oxides (NOx) emissions during the thermal processing of sewage sludge. This study highlights the complex interactions between chemical constituents in waste materials and their resultant emissions, emphasizing the importance of managing waste composition to mitigate environmental impacts [52]. The research provides valuable insights for engineers seeking to design more efficient thermal treatment systems that minimize harmful emissions.

In another related study, Zhang et al. investigate computational fluid dynamics (CFD) modeling of a self-preheating pulverized coal burner operating under ultra-low load conditions. Their work is significant for understanding how combustion stability is affected by variations in coal concentration and how this can influence pollutant formation, specifically during suboptimal combustion conditions [53]. The application of CFD allows for a nuanced analysis of combustion behavior, which is essential for enhancing the combustion processes used in thermal power generation while controlling emissions.

Sandu et al. delve into high-temperature dolomite decomposition as it relates to calcium looping processes, which are critical for capturing CO2 emissions in industrial applications. Their study integrates experimental data with computational fluid dynamics to assess how efficiently the decomposition process can be managed to minimize pollutant production, particularly in the context of enhanced carbon capture systems [54]. This research extends the understanding of thermal chemical processes and their role in reducing greenhouse gas emissions, aligning with global sustainability goals.

While not directly focused on pollutants, the work of Krajnović et al. introduces an innovative engine concept that could indirectly affect emissions through improved combustion efficiency. By developing a novel active pre-chamber engine design, the researchers aim to optimize combustion processes, thereby potentially reducing the formation of pollutants [55]. Although their primary focus is on the mechanical design, the implications of efficient combustion on emissions are relevant in discussions surrounding applied thermal engineering.

In conclusion, the intersection of chemical processes and pollutant management within applied thermal engineering is critical for advancing sustainable energy production and waste treatment solutions. The studies reviewed demonstrate a variety of approaches to understanding and mitigating the emissions associated with thermal processes, highlighting the importance of integrated research and development in this field.

7. List of Issues and Research Guidelines

This paper addresses current and emerging research directions aimed at enhancing the efficiency, cost-effectiveness, and environmental performance of thermal engineering systems, while expanding their range of applications. Although the overarching objectives—improved efficiency, reduced emissions, and economic viability—are common across technologies, specific challenges define the focal points for future investigations.

As a core technology in thermal systems, heat exchangers remain central to efficiency improvements. Research continues to focus on advanced designs, geometry optimization, and the integration of novel materials, including nanofluids, to enhance heat transfer performance. Miniaturization and application-

specific optimization, particularly in sectors such as power electronics, are gaining prominence, driven by the global trend toward electrification.

In thermal energy storage, the main goal of developing the technology for short, long, and seasonal energy storage still remains. Therefore, the search for the best working medium for different applications will still remain the main topic of research, followed by the relevant technoeconomic and environmental analyses. The research will include the even wider range of materials, tested for the increasing variety of applications. Besides the issues with chemistry of phase change materials and their thermal properties, the optimization of geometry and simulations of phase change front have still not shown the optimized solutions for best efficiency.

Integrated simulation approaches are increasingly adopted to optimize system control and operational strategies. Digital twins, in particular, are emerging as powerful tools for real-time monitoring, predictive maintenance, and process optimization. Their application spans complex thermal systems, polygeneration configurations, and challenging environments. This approach has been tested in novel applications such as plasma systems, where control is challenging due to the chemical or physical processes. On the other hand, digital twins have proved useful in system integration applications, where multiple systems are combined, polygeneration approaches, remote technical applications, and complex thermal systems. The research pathway in this area does not seem to have a clear-cut direction, besides the work on expanding the models and development of more advanced control strategies.

Pollutant reduction in thermal systems will continue the general trend it has been following so far. In conventional combustion systems, NOx and SOx emissions will continue to lower either by the geometry and combustion optimization, or by including novel technologies and materials. Co-combustion still requires research for further improvements, and the reliable reduction of emissions in pyrolysis remains to be achieved. Other technologies such as sewage sludge utilization and methanation will see the inclusion of novel materials, nanoparticles and similar for the improvement of efficiency and pollutant reduction, while chemical processes still require simulation research to achieve the potential in emissions reduction.

8. Conclusion

This vision article complements a Special Issue of Applied Thermal Engineering, featuring research from the 18th SDEWES conference held in Dubrovnik in 2023. It presents an overview of selected articles that explore clean energy technologies and systems aimed at advancing sustainable thermal energy solutions. Positioned at the cutting edge of scientific and engineering innovation, this research provides valuable insights that can shape future studies and drive the development of sustainable engineering technologies and systems.

In the contemporary landscape of energy systems, the integration of heat exchangers, thermal energy storage, system simulations, and chemical processes emerges as a pivotal approach to enhance efficiency, sustainability, and operational efficacy. Each of these components serves a distinct yet interrelated role in the broader spectrum of energy management and optimization. Heat exchangers represent a cornerstone technology in thermal systems, facilitating the efficient transfer of heat between different mediums. Their design and optimization are crucial in minimizing energy losses and maximizing the overall thermal efficiency of processes, particularly in industries where large quantities of heat are generated or consumed. The choice of materials, flow configurations, and operational parameters can significantly influence the effectiveness and durability of these devices. Future research should focus on innovative designs, such as advanced materials and compact heat exchanger configurations, to accommodate increased thermal demands and tighter performance criteria.

Thermal energy storage (TES) systems offer a critical solution for buffering the discrepancies between energy supply and demand, particularly in renewable energy applications. By storing excess thermal energy for later use, TES facilitates a more stable and reliable energy supply. The integration of phase change materials, sensible heat storage, and thermochemical storage technologies presents promising avenues for enhancing the storage capacity and efficiency of these systems. Investigating the coupling of TES with heat exchangers can yield synergistic benefits, allowing for more effective temperature management and energy recovery strategies. System simulations are indispensable in the design,

evaluation, and optimization of complex thermal systems. Advanced modeling techniques, such as computational fluid dynamics (CFD) and system dynamics simulations, provide insights into the thermal behavior and performance of integrated systems under various operational scenarios. These simulations not only illuminate potential areas for improvement but also aid in the identification of optimal control strategies. A comprehensive understanding of how various components interact within the system can lead to innovative approaches in system design and sustainability. Finally, the integration of chemical processes with thermal systems stands to revolutionize energy utilization and conversion efficiencies. The synergy between heat transfer processes and chemical reactions, particularly in processes like cogeneration or thermochemical energy storage, demonstrates the potential to enhance energy production while minimizing waste. Research into the integration of catalysis and heat exchange processes can lead to more resilient and economically viable energy solutions.

In conclusion, the amalgamation of heat exchangers, thermal energy storage, system simulations, and chemical processes presents a holistic framework for addressing the challenges of energy efficiency and sustainability. Ongoing research and development in these areas will not only contribute to the advancement of thermal systems but also promote the transition to a more sustainable energy future. Future investigations should focus on interdisciplinary approaches that foster collaborations among mechanical, chemical, and energy engineers, ensuring that innovative solutions are leveraged to realize the full potential of integrated energy systems.

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