



OPEN ACCESS

EDITED BY

Vincenza Brancato,
National Research Council (CNR), Italy

REVIEWED BY

Ahmed M. Salem,
Tanta University, Egypt
Saeed Tiari,
Widener University, United States

*CORRESPONDENCE

Val Hyginus Udoka Eze,
✉ udoka.eze@kiu.ac.ug

RECEIVED 08 July 2025

ACCEPTED 29 August 2025

PUBLISHED 12 September 2025

CITATION

Eze VHU (2025) Innovations in thermal energy systems, bridging traditional and emerging technologies for sustainable energy solutions. *Front. Therm. Eng.* 5:1654815. doi: 10.3389/fther.2025.1654815

COPYRIGHT

© 2025 Eze. This is an open-access article distributed under the terms of the [Creative Commons Attribution License \(CC BY\)](https://creativecommons.org/licenses/by/4.0/). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.

Innovations in thermal energy systems, bridging traditional and emerging technologies for sustainable energy solutions

Val Hyginus Udoka Eze  *

Department of Electrical, Telecommunications and Computer Engineering, Kampala International University, Ishaka, Uganda

Introduction: Thermal energy systems (TES) have been foundational to global industrialization and power generation, with fossil fuel-based technologies providing nearly 81% of the global primary energy supply as of 2024. However, their dependence on finite resources and low conversion efficiencies, often below 40% in conventional steam power plants, has led to significant greenhouse gas (GHG) emissions, accounting for over 35% of global CO₂ output. The urgent need for sustainable, efficient, and low-carbon alternatives has prompted transformative innovations in TES over the past two decades, particularly in hybridization and digital optimization.

Methods: This study employed the PRISMA methodology to systematically review 163 peer-reviewed articles published between 2004 and 2024. The analysis focused on trends and advancements in TES, including enhancements in Rankine cycle efficiency, deployment of advanced storage media such as phase change materials (PCMs), thermochemical options, nano-enhanced composites, and hybrid configurations integrating biomass, concentrated solar power (CSP), and photovoltaic-thermal (PVT) systems. Special emphasis was given to the role of digitalization, including artificial intelligence (AI), machine learning (ML), Internet of Things (IoT), and digital twin technologies in optimizing TES performance.

Results: The findings reveal substantial progress in TES modernization. Digital tools enabled real-time optimization, predictive maintenance, and adaptive control, improving system efficiency by 20%-35% and reducing downtime by up to 40% in pilot projects. Waste heat recovery technologies, notably organic Rankine cycles (ORCs) and thermoelectric generators (TEGs), achieved energy recovery efficiencies exceeding 80% for low- to medium-grade heat streams. Modular and containerized TES solutions demonstrated effectiveness in decentralized applications, reducing post-harvest losses by up to 30% in agriculture and improving vaccine cold chain reliability in sub-Saharan Africa by over 50%. Furthermore, integration with electrochemical storage and green hydrogen pathways has positioned TES at the core of multi-vector decarbonized energy platforms.

Discussion: The review underscores that the future of TES will be defined by interdisciplinary research and development, advanced material innovation, particularly nanostructured composites, and supportive regulatory frameworks. Hybrid renewable integration and digitalization are central to achieving Paris Agreement goals, enhancing energy security, and promoting

global energy equity. The transition toward intelligent, low-carbon thermal networks reflects not only technological evolution but also a paradigm shift essential for long-term sustainability.

KEYWORDS

thermal energy systems, thermal energy storage (TES), phase change materials (PCMs), artificial intelligence (AI) in energy, hybrid renewable thermal technologies

1 Introduction

Thermal energy systems have played a pivotal role in shaping the trajectory of human civilization, underpinning industrialization, urbanization, and global economic growth (Hassan et al., 2024; Caineng et al., 2022). Historically, thermal processes powered early steam engines, fueled the manufacturing revolutions of the Industrial Revolution, and laid the foundation for centralized electricity generation (Jurema and König, 2024). Today, conventional thermal systems, predominantly fueled by coal, oil, and natural gas, continue to deliver a substantial share of global electricity and process heat for residential, commercial, and industrial sectors (Nishad et al., 2024). Despite their historical and ongoing contributions, traditional thermal energy systems are increasingly criticized for their environmental and economic shortcomings (Rad and tke, 2025). Among these are elevated GHG emissions, considerable thermal inefficiencies, reliance on finite fossil fuel reserves, and the release of harmful pollutants such as nitrogen oxides (NO_x) and sulfur oxides (SO_x) (Odubo and Kosoe, 2024; Larki et al., 2023). The urgency of mitigating climate change, amplified by global frameworks like the Paris Agreement, has necessitated a fundamental re-evaluation of thermal energy's role in a sustainable, low-carbon future. In response to these multifaceted challenges, thermal energy systems are undergoing a profound transformation, driven by the convergence of technological innovation, evolving regulatory frameworks, sustainability imperatives, and advancements in digital intelligence (Cavus, 2025; Rajaperumal and Columbus, 2025; Zhou and Liu, 2024).

The shift from conventional combustion-based systems to cleaner, more efficient alternatives is accelerating through the deployment of advanced technologies and hybrid system configurations (Dell'Aversano et al., 2024). Among the most promising emerging solutions are thermal energy storage (TES) systems, which utilize phase change materials (PCMs) and sensible heat storage to enhance grid flexibility and enable temporal decoupling of energy supply and demand (Enescu et al., 2020; Sadeghi, 2022). Waste heat recovery technologies are also gaining prominence, capturing and repurposing excess thermal energy to reduce primary fuel consumption and overall emissions (Ononogbo et al., 2023). In parallel, advanced combined heat and power (CHP) systems are being adopted to improve fuel utilization by simultaneously generating electricity and useful heat from a single energy source (Bagherian and Mehranzamir, 2020). Furthermore, concentrated solar thermal (CST) and concentrated solar power (CSP) technologies, often integrated with TES, are offering dispatchable renewable energy options (Codd et al., 2020). Complementary innovations such as thermoelectric generators, high-temperature superconducting materials, and thermal batteries are expanding the scope of efficient thermal-to-electric energy conversion (Aridi, 2023). Equally critical is the

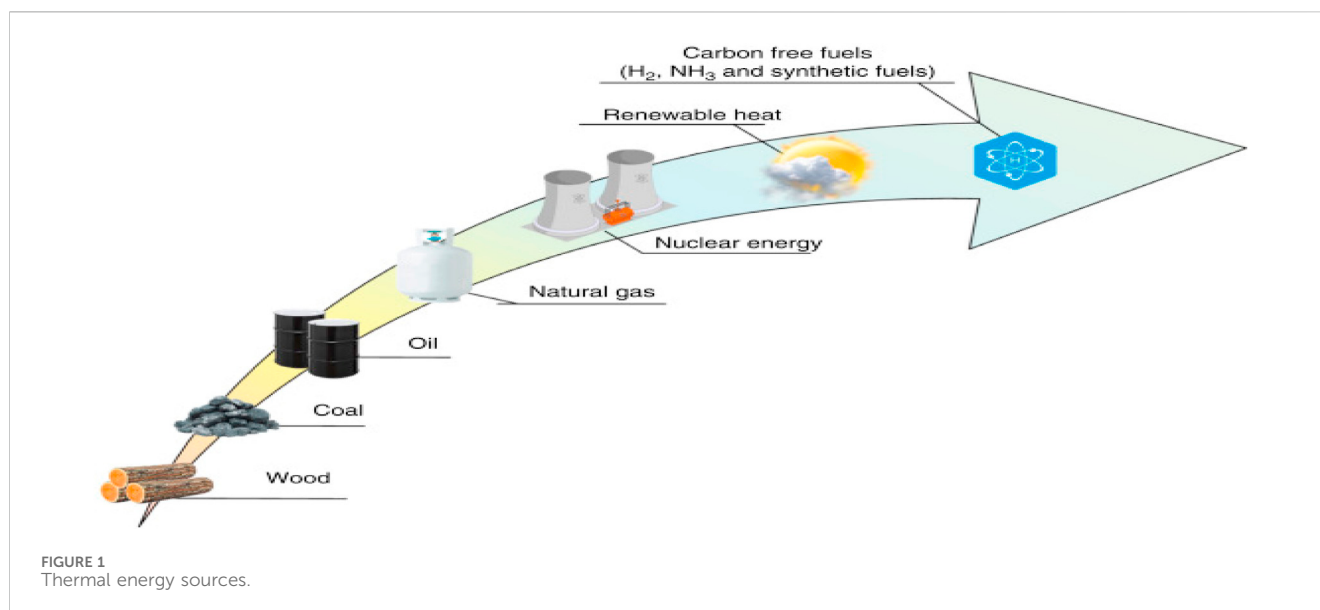
growing integration of renewable energy sources, including solar thermal, geothermal, and biomass, into both centralized and decentralized thermal networks (Kim et al., 2022; Hammerstingl, 2024). These renewable integrations are increasingly supported by digital technologies such as Internet of Things (IoT) platforms, machine learning algorithms, and artificial intelligence (AI)-based thermal management systems, enabling real-time monitoring, predictive diagnostics, and adaptive optimization of system performance (Ukoba et al., 2024). Collectively, these innovations are redefining the thermal energy landscape, making it more intelligent, resilient, and sustainable (Singh and Kaunert, 2024). The convergence of legacy infrastructure with next-generation technologies presents a strategic opportunity to develop thermal energy systems that are not only more resilient, efficient, and low-emission but also intelligent and adaptive. Hybrid configurations such as solar-assisted biomass boilers, thermal-electric cogeneration plants, and district heating networks embedded with smart sensors exemplify the potential for synergistic integration of traditional methods and innovative technologies (Rosales-Pérez et al., 2023; Xu et al., 2024). Figure 1 illustrates the thermal energy sources showing their trends from traditional to emerging technologies for Sustainable Energy Solutions.

This systematic review provides a comprehensive analysis of the evolution, current challenges, and prospects of thermal energy systems. It begins by tracing the historical development and significance of conventional thermal technologies, followed by a critical assessment of their sustainability limitations. The review then explores emerging materials, technological innovations, hybrid systems, and digital enhancements that are poised to redefine thermal energy utilization in the 21st century. By bridging established practices with forward-looking solutions, this work aims to inform policy, industry, and research directions in the pursuit of a smarter, cleaner, and more sustainable thermal energy future.

2 Methodology

2.1 Research design

This study employs a systematic review methodology to critically analyze the evolution, current status, and future potential of TES in light of sustainability, technological advancement, and digital integration imperatives. The review synthesizes findings from peer-reviewed journals, high-impact conference proceedings, institutional reports, patents, case studies, and policy frameworks, focusing on the interplay between traditional Rankine cycle-based systems, emerging TES technologies, hybrid configurations, biomass integration, and artificial intelligence (AI)-driven optimizations. By examining



over two decades of literature, the study aims to highlight transformative innovations, techno-economic trade-offs, environmental implications, and socio-political enablers driving the transition to intelligent, hybridized, and decarbonized thermal infrastructures.

2.2 Review protocol and PRISMA framework

The review follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework to ensure transparency, replicability, and methodological robustness. The process was executed in four structured phases.

2.2.1 Identification

A rigorous and systematic literature search was conducted to capture a comprehensive scope of scholarly and grey literature related to advanced thermal energy systems. The search spanned major scientific databases, including Scopus, Web of Science, ScienceDirect, IEEE Xplore, Google Scholar, and SpringerLink, as well as authoritative grey literature sources such as reports and publications from the International Energy Agency (IEA), International Renewable Energy Agency (IRENA), United Nations Environment Programme (UNEP), World Bank, and Intergovernmental Panel on Climate Change (IPCC). The search strategy employed Boolean logic and advanced keyword combinations encompassing terms such as “thermal energy systems,” “Rankine cycle,” “thermal energy storage (TES),” “phase change materials (PCMs),” “supercritical steam power,” “waste heat recovery,” “organic Rankine cycle (ORC),” “solar-thermal hybrid systems,” “AI thermal optimization,” “biomass CHP,” “nano-enhanced TES,” and “digital twins in thermal energy.” This method yielded a total of 262 relevant records, covering literature published between 2015 and 2025, with a deliberate focus on contemporary advancements that reflect in innovations in thermal energy systems, bridging traditional and emerging technologies for sustainable energy.

2.2.2 Screening

The initial pool of identified records underwent a structured screening process, beginning with a review of titles and abstracts to assess alignment with predefined inclusion criteria. Studies were included if they focused on thermal energy systems applied to power generation, heating, cooling, or hybrid configurations, particularly those incorporating technological innovations such as advanced Rankine cycles, TES, artificial intelligence (AI) applications, or renewable energy integration. Emphasis was placed on literature presenting quantitative data on system performance, energy efficiency, emissions reduction, or techno-economic feasibility. Conversely, studies were excluded if they focused solely on conventional fossil fuel combustion without addressing sustainability enhancements, lacked empirical, simulation-based, or techno-economic evidence, or were limited to grid-tied systems without exploring integration with renewable or smart technologies. After applying these criteria, 193 articles were deemed relevant and selected for full-text evaluation.

2.2.3 Eligibility assessment

Full-text articles were thoroughly assessed to determine their eligibility based on stringent scientific and technical criteria. Priority was given to studies demonstrating scientific rigor, including peer-reviewed publications with substantial citation impact. Technical relevance was evaluated in relation to next-generation TES, advanced Rankine cycle variants, and hybrid configurations integrating renewable sources or digital technologies. Eligible studies also had to clearly articulate outcomes related to environmental performance, energy efficiency, or digitalization, with a particular emphasis on their applicability to global and regional decarbonization strategies, especially within the context of developing economies. Articles that lacked empirical validation, exhibited conceptual ambiguity, or failed to address the integration of hybridized or AI-enhanced TES systems were excluded. Following this comprehensive assessment, 163 high-quality studies were retained for detailed synthesis.

2.2.4 Inclusion

The final inclusion phase resulted in a curated selection of 163 high-quality sources, comprising 129 peer-reviewed journal articles, 12 technical conference proceedings, 8 pilot project and feasibility study reports, and 14 policy and institutional documents. This diverse set of literature provided both empirical evidence and conceptual frameworks essential for the thematic synthesis. The selected sources underpin the analysis of advancements in TES technologies, innovative hybrid system architectures, applications of digital intelligence such as AI and digital twins, and sustainable deployment models aligned with global and regional decarbonization objectives.

2.3 Quality appraisal tools

To uphold analytical integrity and ensure methodological rigor, two complementary evaluation instruments were employed. First, the Critical Appraisal Skills Programme (CASP) checklist was utilized to assess each study's internal validity, data credibility, and overall relevance to the research objectives. Second, a customized TES Evaluation Matrix was developed to quantitatively rate studies across five key dimensions: (1) demonstrated energy efficiency exceeding a 35% baseline, (2) incorporation of advanced TES methods including latent heat, thermochemical, or nano-enhanced storage, (3) deployment of hybrid systems such as solar-thermal, biomass-CHP, or ORC integrations, (4) application of artificial intelligence (AI), machine learning (ML), or digital twins for system optimization, and (5) reported environmental performance indicators such as GHG reduction and exergy enhancement. Only studies achieving a composite score of 7 or higher out of 10 were retained for final thematic synthesis, ensuring a robust and high-impact evidence base.

2.4 Thematic coding and data analysis

A combined deductive and inductive thematic analysis was performed using NVivo 14 software to systematically organize and interpret the data across four principal thematic domains. The first domain, *Technological Innovations and Performance Enhancements*, encompassed advancements such as supercritical and ultra-supercritical Rankine cycle systems, AI-integrated thermal management, innovative TES materials, including PCMs, thermochemical salts, nano-enhanced PCMs (NePCMs), and metal oxides, as well as waste heat recovery technologies like ORC, thermoelectric generators (TEGs), and multi-vector TES coupled with hydrogen systems. The second domain, *Hybrid and Renewable-Integrated Thermal Systems*, covered biomass-solar CHP configurations, photovoltaic-thermal (PV-T) hybrid modules, district heating integrated with TES, CSP systems with latent heat storage, and design considerations for modularity and containerization enabling deployment in off-grid or resource-constrained environments. The third domain, *Digital Tools and Artificial Intelligence*, focused on machine learning applications for predictive diagnostics and load forecasting, reinforcement learning for adaptive control strategies, and the use of digital twins and IoT

platforms to enhance operational orchestration and fault tolerance. Lastly, the *Socio-Technical, Economic, and Policy Dimensions* domain addressed cost-benefit analyses and levelized cost of heat (LCOH), performance-based subsidies and carbon pricing mechanisms, as well as frameworks for community energy ownership, energy justice, and inclusive deployment policies. This structured coding framework facilitated a comprehensive synthesis of the multidisciplinary advancements shaping the future of thermal energy systems.

2.5 PRISMA flow diagram

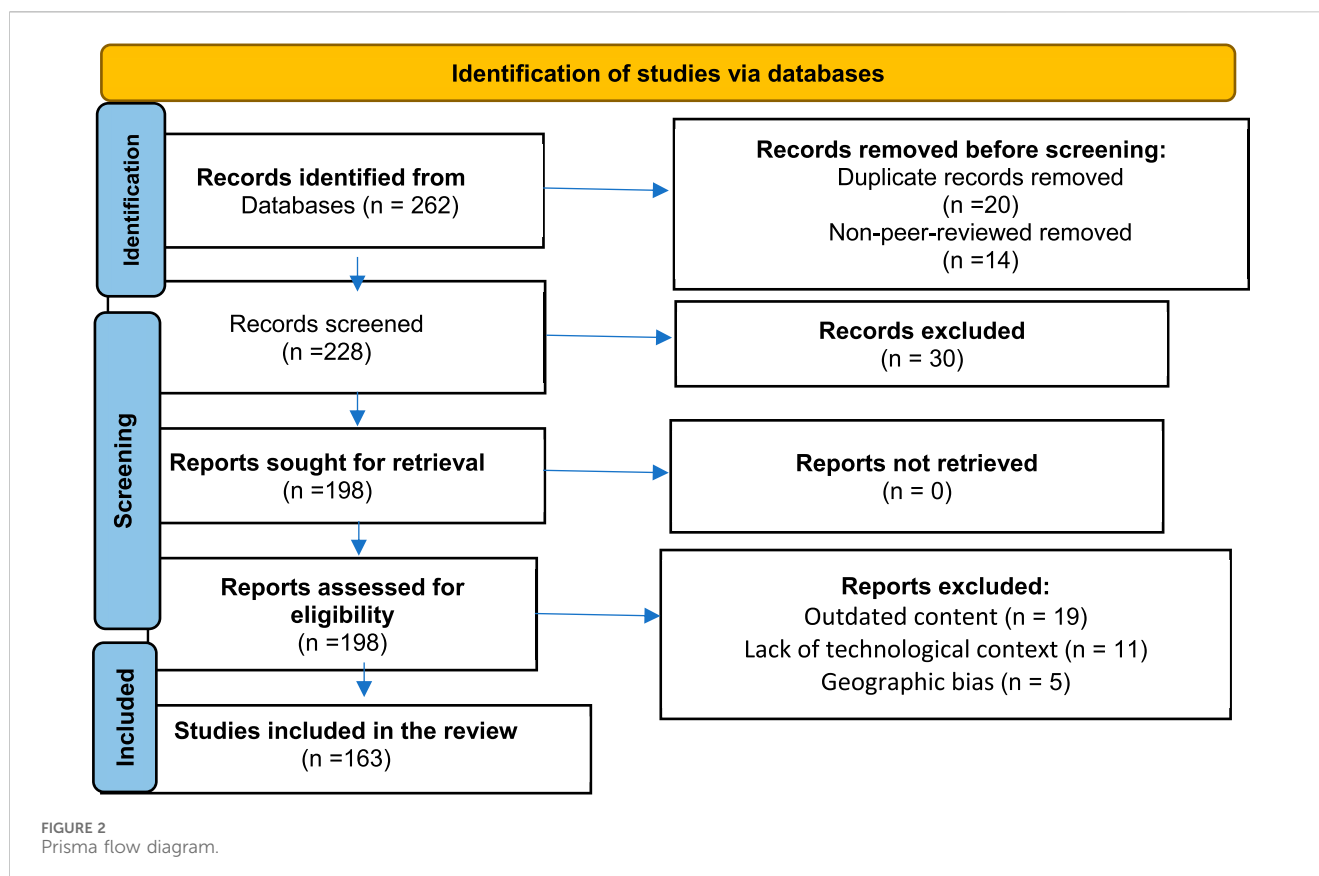
The systematic review process is visually summarized in Figure 2, which presents the PRISMA flow diagram illustrating the sequential stages of identification, screening, eligibility assessment, and final inclusion. This diagram offers clear transparency into the study selection methodology, highlighting the number of records at each phase and the rationale for exclusions. It thereby reinforces the methodological rigor and reproducibility of the data curation process underpinning this review.

3 Literature review

3.1 Traditional thermal energy systems

Traditional thermal energy systems represent a cornerstone of modern industrialization and have played a pivotal role in shaping global energy infrastructure (Hassan et al., 2024). These systems operate on the fundamental principle of converting thermal energy, derived primarily from the combustion of fossil fuels or organic matter, into mechanical or electrical energy using heat engines, turbines, and thermodynamic cycles such as the Rankine or Brayton cycles (Islam et al., 2020). The widespread deployment of these systems has facilitated the growth of heavy industries, transportation, urbanization, and centralized electricity generation for over a century (Di Silvestre et al., 2018). At the heart of traditional thermal energy systems is combustion, wherein chemical energy stored in fuels like coal, oil, natural gas, or biomass is released as heat (Kundu et al., 2023; Brown, 2019). This heat is then used to generate high-pressure steam or hot gases, which expand through turbines or reciprocating engines to perform mechanical work. In most power generation applications, this mechanical work drives generators to produce electricity. The thermal efficiency of such systems depends on the temperature gradients, the thermodynamic cycle in use, and the fuel quality (Kim et al., 2024; Dahham et al., 2022). Technologies like CHP and combined cycle gas turbines (CCGT) have been introduced to enhance overall energy conversion efficiency by capturing and reusing waste heat (Wijesekara et al., 2025).

Historically, these systems enabled large-scale, centralized power plants capable of meeting the growing energy demands of urban and industrial centers (Safari et al., 2024). Their reliability, well-established supply chains, and technological maturity contributed to their dominance throughout the 20th century (Echefaj et al., 2024). Fossil fuel-based plants, in particular,



offered high energy densities, predictable performance, and dispatchable power generation, attributes critical for grid stability and industrial processes (Kabeyi and Olanrewaju, 2022). However, the continued use of traditional thermal energy systems is increasingly challenged by their environmental and sustainability drawbacks. The combustion of fossil fuels is the largest anthropogenic source of GHG emissions, notably carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O), which contribute to global warming and climate change. Moreover, these systems are significant sources of air pollutants such as sulfur oxides (SO_x), nitrogen oxides (NO_x), and particulate matter (PM), which degrade air quality and pose public health risks (Filonchyk et al., 2024).

In addition to emissions, traditional thermal systems are heavily dependent on finite and geopolitically sensitive resources. The extraction, transport, and refinement of fossil fuels are associated with ecological disruption, water use, energy security risks, and market volatility (Blondeel et al., 2021). Biomass-based thermal systems, though renewable in theory, are often constrained by unsustainable harvesting practices, low conversion efficiency, and competing land use demands, which limit their long-term viability unless managed under strict sustainability frameworks (Makepa and Chihobo, 2024). Furthermore, the thermodynamic limitations of traditional cycles, especially those operating under subcritical conditions, impose efficiency ceilings, with a significant portion of the input energy lost as waste heat. This inefficiency not only affects fuel consumption rates but also exacerbates thermal pollution when excess heat is discharged into water bodies or the atmosphere (Gough et al., 2018). In response to these challenges, the global energy landscape is undergoing a paradigm shift toward

decarbonized, decentralized, and digitalized energy systems (Shaukat et al., 2023). The limitations of traditional thermal technologies underscore the urgent need for cleaner and more efficient alternatives, including renewable energy integration, waste heat recovery, advanced thermal storage, and hybrid systems. Nevertheless, understanding the role, structure, and limitations of conventional thermal energy systems remains essential for informing the design and transition pathways toward sustainable energy futures (Singh et al., 2025).

3.1.1 Fossil fuel-based thermal systems

Fossil fuel-based thermal systems have long been the dominant source of global energy supply, powering a wide range of applications including electricity generation, industrial heating, and mechanical work (Chen et al., 2023). The primary fossil fuels, coal, oil, and natural gas, have underpinned energy-intensive sectors due to their high energy density, ease of storage and transport, and compatibility with established technologies and infrastructure (Nurdiawati and Urban, 2021; Tuller, 2017). Thermal power plants utilizing these fuels operate by converting chemical energy into heat through combustion, which is then transformed into mechanical and electrical energy via thermodynamic cycles such as the Rankine and Brayton cycles (Tuller, 2017). Coal-fired power plants as shown in Figure 3, typically burn pulverized coal in boilers to produce high-pressure steam, which drives steam turbines (Khalid et al., 2025). Oil-based systems are used in both stationary and mobile applications, including backup generators and marine propulsion, while natural gas, owing to its cleaner combustion profile and flexibility, has become the preferred fuel for modern

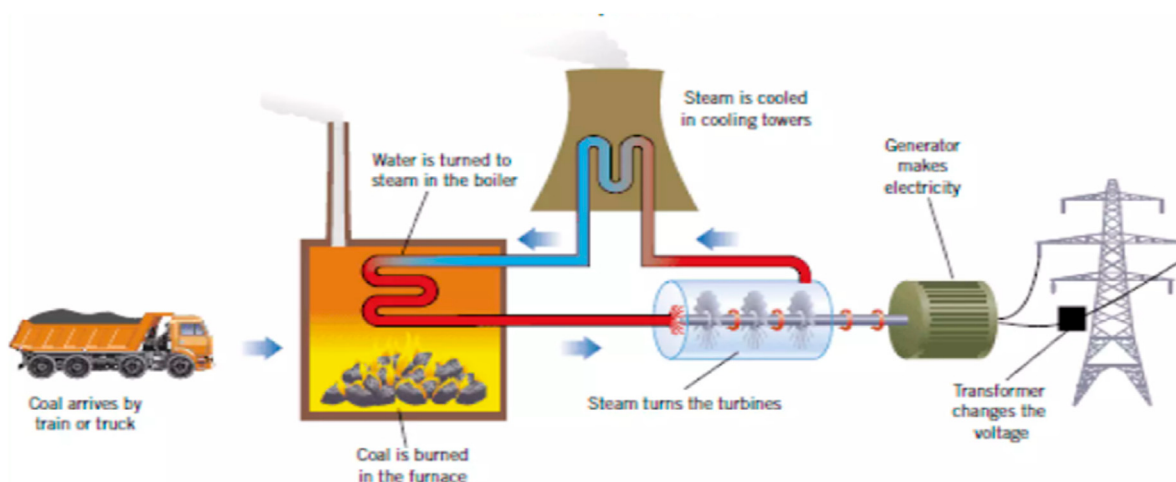


FIGURE 3
Coal-fired power station (Khalid et al., 2025).

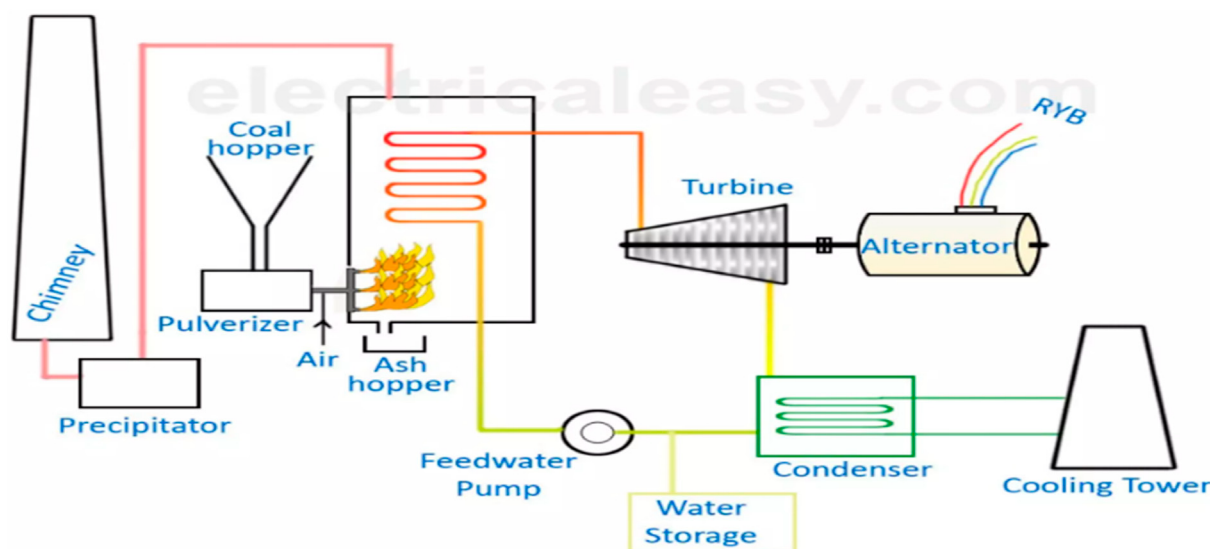


FIGURE 4
Fossil Fuel-Based Thermal Systems processes.

combined cycle gas turbine (CCGT) plants (Seo et al., 2019). These CCGT plants use gas turbines followed by steam turbines to achieve higher efficiencies, often exceeding 60%, and are well-suited for load-following and peaking operations in modern power grids.

Despite these advantages, the environmental drawbacks of fossil fuel combustion are profound. The process emits large quantities of greenhouse gases (GHGs), most notably carbon dioxide (CO_2), which is the primary driver of anthropogenic climate change (Perera, 2018). Methane (CH_4), a potent GHG with a global warming potential over 25 times that of CO_2 over 100 years, is frequently released during natural gas extraction and transport (Balcombe et al., 2017). In addition to GHGs, fossil fuel combustion emits sulfur oxides (SO_x), nitrogen oxides (NO_x),

volatile organic compounds (VOCs), and particulate matter (PM), which contribute to acid rain, smog formation, respiratory diseases, and premature mortality. Beyond atmospheric pollution, the lifecycle of fossil fuel use, from extraction and processing to transportation and combustion, poses significant ecological risks (Howarth et al., 2021; Stern, 2020). Coal mining, particularly through surface and mountaintop removal techniques, leads to deforestation, soil erosion, and water contamination (Burke et al., 2023). Oil drilling, including offshore operations, threatens marine ecosystems through spills and habitat disruption. Hydraulic fracturing (fracking) for shale gas extraction has raised concerns over groundwater contamination, induced seismicity, and land degradation (Deng and Guo, 2024; Xing et al., 2024).

TABLE 1 Comparative overview of fossil fuel-based thermal systems.

Feature	Coal-based systems	Oil-based systems	Natural gas systems (CCGT)
Primary Application	Base-load power generation	Backup generators, marine propulsion, and industrial heating	Electricity generation (baseload, load-following, peaking)
Energy Conversion Cycle	Rankine cycle with steam turbines	Rankine or internal combustion (diesel/gas turbines)	Combined Cycle (Brayton + Rankine)
Efficiency (%)	33%–38% (Subcritical) 40%–45% (Super/U-Supercritical)	30%–35% (diesel engines); lower in simple combustion systems	Up to 60% (modern CCGT systems)
Combustion Emissions	High CO ₂ , SO _x , NO _x , PM emissions	CO ₂ , NO _x , VOCs, PM; depends on engine type	Lower CO ₂ per kWh; CH ₄ leakage during extraction/transmission
Environmental Impacts	Deforestation, acid rain, water contamination, and land degradation	Oil spills, marine ecosystem threats, soil and groundwater contamination	Methane leakage, groundwater contamination (fracking), seismic risks
Fuel Characteristics	Abundant, high-carbon content, bulk transport required	High energy density, mobile, relatively easier to store	Cleaner combustion, flexible supply, fast ramp-up
Technological Variants	Supercritical, Ultra-Supercritical, Carbon Capture Integration	Diesel and gas engines; limited CCS application	CCGT with CCS compatibility; hybrid renewable integration
Air Pollutant Byproducts	SO _x , NO _x , CO ₂ , PM, VOCs	CO ₂ , NO _x , PM, VOCs	Mainly CO ₂ and CH ₄ ; lower SO _x /NO _x levels
Water Usage	High for steam and cooling systems	Moderate; cooling in stationary plants	Lower water footprint; dry cooling more feasible
Geopolitical/Economic Vulnerabilities	Energy security risks, price volatility, resource curse in some regions	Subject to oil market fluctuations and geopolitical instability	Moderate vulnerability; increasing LNG trade flexibility
Current Transition Outlook	Gradual phase-out; CCS and efficiency upgrades under consideration	Declining usage; transition toward electrification and alternative fuels	Preferred bridge fuel; expanding role with renewables and hydrogen

A typical fossil fuel-based thermal processing system is illustrated in [Figure 4](#). Fossil fuel dependence exposes nations to geopolitical and economic vulnerabilities ([Gupta and Chu, 2018](#)). Energy supply disruptions due to political instability, trade restrictions, or resource monopolization can lead to energy insecurity and price volatility ([Bordoff and O’Sullivan, 2023](#)). Many fossil fuel-rich countries face the “resource curse,” where overreliance on hydrocarbon revenues hampers economic diversification and social development. In recognition of these environmental and socio-economic impacts, international frameworks such as the Paris Agreement (2015) have catalyzed global efforts to decarbonize energy systems ([Ives et al., 2021](#); [Cochran and Pauthier, 2019](#)). Governments and regulatory bodies are increasingly implementing carbon pricing mechanisms, emissions trading schemes, and stringent air quality standards to curb fossil fuel use. Financial institutions and investors are divesting from fossil fuel assets in favor of cleaner energy portfolios, reflecting a broader shift toward sustainable development ([Samuel, 2025](#); [Narassimhan et al., 2018](#)). Nonetheless, the transition away from fossil fuel-based thermal systems remains a complex and regionally variable challenge. Many developing countries continue to rely on fossil fuels for economic growth and energy access, given the affordability and availability of these resources ([Garcia et al., 2024](#)). Bridging this transition requires integrated approaches that combine technological innovation, policy reform, international cooperation, and investment in low-carbon alternatives such as renewables, carbon capture and storage (CCS), and energy efficiency improvements ([Eze et al., 2024a](#); [Eze et al., 2024b](#)). [Table 1](#) compares the three fossil fuel-based thermal systems of performance and impact.

3.1.2 Steam and Rankine cycle technologies

The Rankine cycle is a cornerstone of classical thermodynamic engineering and remains one of the most widely utilized systems for thermal-to-mechanical energy conversion, particularly in large-scale power generation ([Arabkoohsar, 2020](#)). At its core, the Rankine cycle involves the heating of a working fluid, typically water, into high-pressure, high-temperature steam, which expands through a steam turbine to perform mechanical work before being condensed back into liquid form for recirculation ([Konur et al., 2022](#)). This closed-loop process is the operational foundation of most steam-based power plants, including fossil-fueled and nuclear facilities. In its basic configuration, the Rankine cycle consists of four principal processes: isentropic compression in a feedwater pump, constant-pressure heat addition in a boiler, isentropic expansion in a turbine, and constant-pressure heat rejection in a condenser ([Ohji and Haraguchi, 2022](#); [Figure 5](#)). The efficiency of the cycle is governed by the temperature and pressure differentials between the heat source and sink, constrained by the second law of thermodynamics. Over the decades, considerable research and development have led to the evolution of the Rankine cycle into more advanced variants, namely, supercritical (SC) and ultra-supercritical (USC) cycles ([Mohamed et al., 2020](#)). In these systems, the operating pressures and temperatures exceed the critical point of water (22.1 MPa and 374 °C), eliminating the liquid-vapor boundary and enabling higher thermal efficiencies, typically in the range of 40%–45% compared to 33%–38% for subcritical units. These advancements reduce fuel consumption per unit of electricity generated, thereby lowering emissions intensity and operational costs. Further improvements include reheating and regenerative feedwater heating, both of which enhance cycle efficiency. Reheat

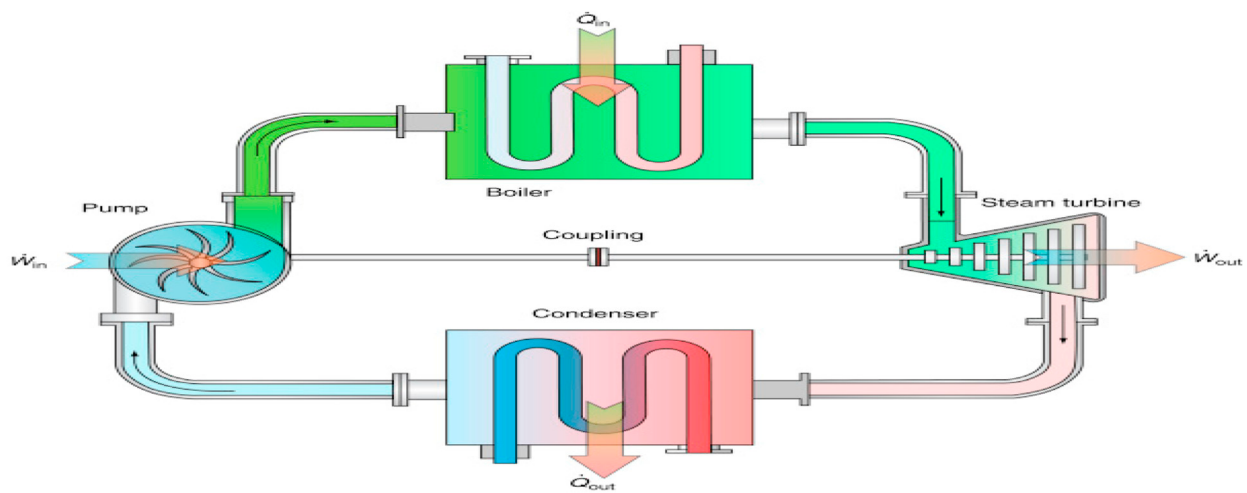


FIGURE 5
A schematic diagram of a simple Rankine cycle, showing the correct location of the components and the correct direction of energy and mass flows (Tiktas et al., 2022).

Rankine cycles involve partially expanding the steam in the turbine, returning it to the boiler for reheating, and then expanding it further, thus reducing moisture content and mechanical stress in low-pressure turbine stages (Tiktas et al., 2022). Regenerative cycles preheat feedwater using steam extracted from intermediate turbine stages, reducing the heat input required in the boiler and improving overall efficiency. Despite these technological enhancements, the Rankine cycle's traditional deployment remains largely dependent on non-renewable heat sources such as coal, oil, and nuclear fission (Bagherian and Mehranzamir, 2020). This dependence not only contributes to greenhouse gas emissions and resource depletion but also limits the adaptability of the cycle to decarbonized energy systems. Although renewable alternatives such as CSP and geothermal systems have begun to implement modified Rankine cycles, their global penetration remains limited due to high capital costs and geographical constraints (Aridi, 2023).

Another critical limitation of Rankine-based systems is their significant water consumption, both for steam generation and for cooling in the condenser. Power plants using once-through or wet recirculating cooling systems withdraw large volumes of freshwater, making them vulnerable in arid or drought-prone regions (Zhu et al., 2025). This raises sustainability and operational risks, particularly in the context of increasing climate variability and water scarcity. Dry cooling systems, though available, entail efficiency penalties and increased capital costs. The Rankine cycle's compatibility with Carbon Capture and Storage (CCS) technologies in coal-fired plants introduces a potential pathway for cleaner operation. However, the energy penalty associated with CO₂ capture and compression (typically reducing net plant efficiency by 7–10 percentage points) has hindered widespread deployment. In conclusion, while the Rankine cycle remains a mature and reliable workhorse of global thermal power generation, its future viability in a low-carbon energy landscape depends on the integration of cleaner heat sources, efficiency-boosting innovations, hybridization with renewables, and water-conscious cooling technologies. A transition toward flexible, low-

emission adaptations of the Rankine cycle is imperative to align with contemporary energy and environmental sustainability targets (Lu et al., 2022). Table 2 compares the features of Rankine and advanced steam cycle technologies in thermal systems.

3.1.3 Biomass and traditional heating systems

Biomass has been a fundamental source of thermal energy since prehistoric times, representing one of humanity's earliest fuels for cooking, heating, and even rudimentary industrial applications (Zhang et al., 2020). It includes a diverse range of organic materials such as wood, agricultural residues (e.g., crop stalks, husks), animal manure, and other biodegradable waste products (Ericsson and Werner, 2016). Biomass combustion releases stored solar energy captured through photosynthesis, making it a potentially sustainable and renewable energy source when managed within a closed carbon cycle (Jaiswal et al., 2023). Traditionally, biomass has been predominantly used in rural and developing regions for domestic cooking and space heating due to its local availability and affordability (Ahmad et al., 2022; Mehetre et al., 2017). However, traditional combustion technologies, such as open fires, simple mud stoves, and basic kilns, are characterized by low thermal efficiency (often below 10%–15%) and incomplete combustion. These inefficiencies generate substantial amounts of smoke, particulate matter, carbon monoxide, and other harmful pollutants, contributing to indoor air pollution that severely impacts respiratory health, especially among women and children (Zhang et al., 2021). The World Health Organization estimates that household air pollution from inefficient biomass combustion causes 3.8 million premature deaths annually worldwide (Balmes, 2019).

Table 3 extensively compares the characteristics of biomass and traditional heating systems. In modern contexts, biomass combustion has been integrated into CHP systems and industrial boilers, where controlled combustion produces both electricity and useful thermal energy with higher efficiencies as depicted in Figure 6 (Rezaei et al., 2021). Biomass CHP plants typically achieve electrical

TABLE 2 Comparative features of rankine and advanced steam cycle technologies (Aridi, 2023; Zhu et al., 2025; Lu et al., 2022).

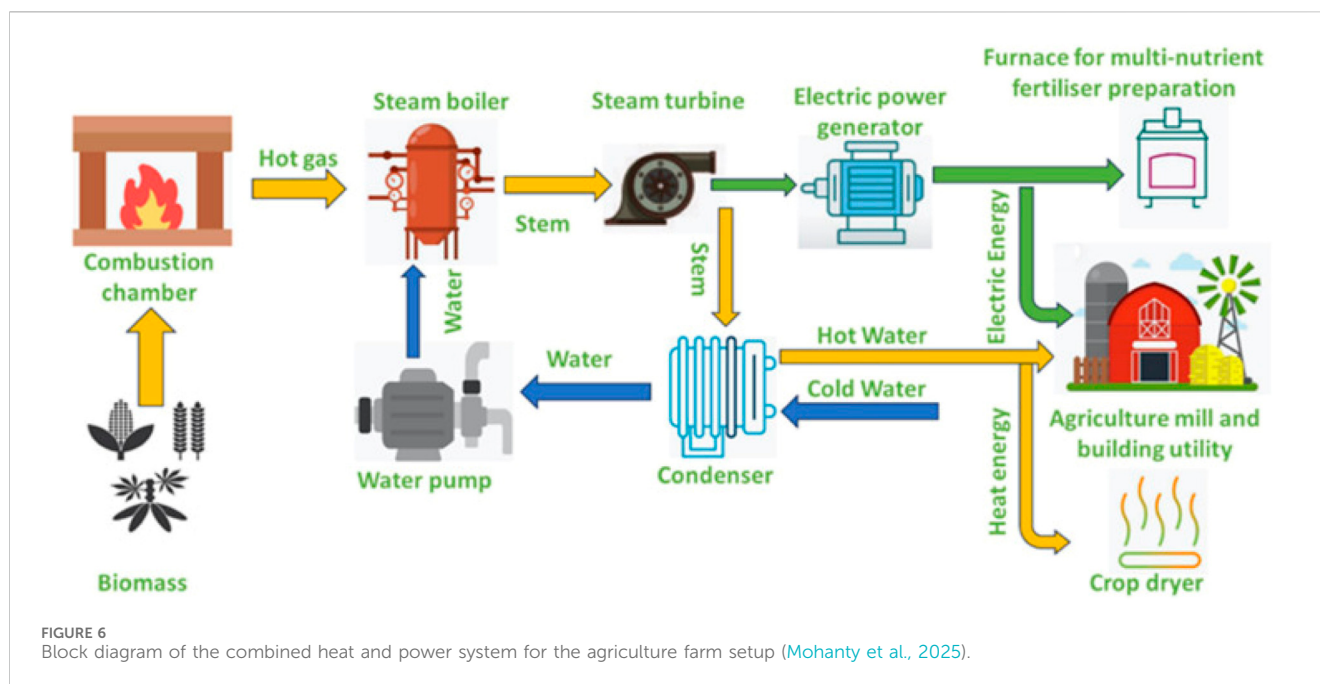
Feature	Subcritical rankine cycle	Supercritical (SC) and ultra-supercritical (USC)	Reheat and regenerative cycles	Renewable-based rankine systems (e.g., CSP, geothermal)
Typical Applications	Conventional coal, oil, and nuclear power plants	High-efficiency fossil fuel and nuclear plants	Enhanced fossil-fueled and nuclear systems	Solar thermal (CSP), geothermal energy
Operating Pressure	<22.1 MPa	>22.1 MPa (above water's critical point)	Similar to the base cycle with modifications	Depends on resource; typically, < 20 MPa
Steam Temperature Range	Up to ~540 °C	600 °C–620 °C (USC); ~565 °C (SC)	Multiple expansion and reheating stages	~300 °C–500 °C depending on resource
Thermal Efficiency (%)	33%–38%	40%–45%	Up to 46%–48% (with both reheat and regeneration)	25%–40% (resource/geography dependent)
Cycle Modifications	Basic four-step process (pump, boiler, turbine, condenser)	Eliminates the phase boundary, enhancing thermodynamic performance	Reduces moisture content in turbines and improves feedwater heating	Modified for lower-temperature heat sources
Water Usage	High; requires cooling towers or water bodies	Similar or higher than subcritical	High unless dry cooling adopted	Variable; CSP often water-intensive
Integration with CCS	Compatible, but with energy penalty (7%–10% efficiency loss)	More favorable due to higher efficiency base	CCS integration possible but complex	Limited CCS applicability
Environmental Drawbacks	GHG emissions, thermal pollution, and high water use	Slightly lower emissions per MWh; still reliant on fossil fuels	Same as parent cycle unless hybridized	Land use, water scarcity, and intermittency
Deployment Barriers	Technically mature, but inefficient by modern standards	High capital cost, material constraints	Complex design; higher maintenance	High CAPEX, geographic constraints

TABLE 3 Comparative characteristics of biomass and traditional heating systems.

Feature	Traditional biomass use	Modern biomass combustion (CHP, boilers)	Gasification and pellet systems	Other advanced biomass techniques
Feedstock Type	Wood, crop residues, dung, charcoal	Woodchips, agro-waste, dedicated energy crops	Pellets, woodchips, syngas from biomass	Biogas (anaerobic digestion), biochar, black liquor
Combustion Technology	Open fires, mud stoves, kilns	Controlled combustion in industrial boilers or CHP	Fixed/Fluidized-bed gasifiers, pellet stoves	Anaerobic digesters, gasifiers, pyrolysis units
Thermal Efficiency (%)	10%–15%	20%–30% electric; up to 70%–80% total efficiency in CHP	25%–35% electric; higher for heating applications	Varies: Biogas ~60%, biochar as soil amendment
Pollutant Emissions	High PM, CO, VOCs, indoor air pollution	Reduced emissions with flue gas treatment	Low PM and NO _x with proper design	Low emissions; biogas is clean-burning
Health and Environmental Impact	Severe indoor air pollution, deforestation	Lower health risks; potential deforestation if unsustainable	Cleaner combustion, lower fuel demand	Methane capture, nutrient recovery (e.g., digestate)
Energy Conversion	Direct heat	Heat + electricity (CHP)	Syngas used for heat, power, or fuels	Methane for cooking/power; biochar for carbon sequestration
Technology Complexity	Very low	Medium	Medium–High	Medium–High
Sustainability Challenges	Overharvesting, inefficient use	Biomass supply chain sustainability	Feedstock standardization, system cost	Competing land use, lifecycle emissions
Adoption Context	Common in rural/low-income regions	Agro-industrial zones, district heating	Decentralized rural electrification, urban heating	Integrated farming systems, circular bioeconomy

efficiencies around 20%–30% and total efficiencies (electric plus thermal) exceeding 70%, offering an attractive option for decentralized energy generation in rural areas and agro-industrial zones (Uzoagba et al., 2024). Despite these benefits, biomass use is not without significant environmental and sustainability challenges.

Unsustainable harvesting practices, including over-reliance on woodfuel, can accelerate deforestation, soil erosion, and habitat loss, undermining biodiversity and ecosystem services (Sreelekshmi and Nandan, 2025). This is particularly concerning in regions with high population pressures and limited forest



management policies. The carbon neutrality of biomass combustion hinges on sustainable feedstock management; otherwise, net carbon emissions may exceed those of fossil fuels when land-use changes and biomass regrowth delays are factored in (Makepa and Chihobo, 2024).

To address the limitations of traditional biomass use, there has been a growing emphasis on the development and deployment of advanced biomass conversion technologies (Adams et al., 2018). Gasification converts solid biomass into a combustible synthesis gas (syngas) through partial oxidation, enabling cleaner and more efficient combustion in engines or turbines (Ram and Mondal, 2022). Gasifiers can support small to medium-scale distributed power generation with reduced emissions. Similarly, pellet stoves and boilers utilize densified biomass pellets with standardized moisture and energy content, improving combustion efficiency, fuel handling, and emissions control (Pradhan et al., 2018). Sustainable biomass supply chains are critical to ensuring long-term viability and environmental integrity. This includes responsible sourcing from managed forests and agricultural residues, minimizing competition with food production, and integrating life cycle assessments to optimize carbon and energy balances. Innovations such as anaerobic digestion for biogas production, agroforestry systems, and biochar application further enhance the sustainability of biomass energy (Subbarao et al., 2023). In conclusion, while biomass remains a vital renewable energy resource, particularly in developing regions, its broader adoption and environmental benefits depend on transitioning from inefficient traditional practices to advanced combustion and conversion technologies, supported by sustainable resource management and policy frameworks. These improvements can enhance energy access, reduce health impacts, and contribute meaningfully to climate mitigation goals (Silva et al., 2025). Table 4 presents a comparative analysis of fossil fuel systems, Rankine cycle technologies, and biomass-based systems, as synthesized from sources (Makepa and Chihobo, 2024; Chen et al., 2023;

Nurdiawati and Urban, 2021; Tuller, 2017; Khalid et al., 2025; Seo et al., 2019; Perera, 2018; Balcombe et al., 2017; Howarth et al., 2021; Stern, 2020; Burke et al., 2023; Deng and Guo, 2024; Xing et al., 2024; Gupta and Chu, 2018; Bordoff and O'Sullivan, 2023; Ives et al., 2021; Cochran and Pauthier, 2019; Samuel, 2025; Narassimhan et al., 2018; Garcia et al., 2024; Eze et al., 2024a; Eze et al., 2024b; Arabkoohsar, 2020; Konur et al., 2022; Ohji and Haraguchi, 2022; Mohamed et al., 2020; Tiktas et al., 2022; Zhu et al., 2025; Lu et al., 2022; Zhang et al., 2020; Ericsson and Werner, 2016; Jaiswal et al., 2023; Ahmad et al., 2022; Mehrete et al., 2017; Zhang et al., 2021; Balmes, 2019; Rezaei et al., 2021; Uzoagba et al., 2024; Sreelekshmi and Nandan, 2025; Mohanty et al., 2025; Adams et al., 2018; Ram and Mondal, 2022; Pradhan et al., 2018; Subbarao et al., 2023; Silva et al., 2025).

3.2 Emerging technologies in thermal energy systems

Recent breakthroughs across materials science, electronic engineering, and computational data analytics have ushered in a new era of innovation in thermal energy systems (Enescu et al., 2020). These emerging technologies are fundamentally reshaping how thermal energy is stored, converted, and managed, enabling systems to achieve higher efficiency, improved reliability, and enhanced sustainability (Kumar et al., 2023). Central to these advancements are novel materials that offer superior thermal properties, solid-state devices capable of direct heat-to-electricity conversion, and intelligent control algorithms that optimize system operation in real-time. Together, these technologies address critical limitations of traditional thermal systems, such as low energy density storage, heat losses, and inflexible operation, while enabling integration with renewable energy sources and digital infrastructure (Zhang et al., 2022). The evolution from conventional combustion-centric frameworks toward flexible,

TABLE 4 Comparative analysis of fossil fuel systems, rankine cycle technologies, and biomass-based systems (Makepa and Chihobo, 2024; Chen et al., 2023; Nurdiawati and Urban, 2021; Tuller, 2017; Khalid et al., 2025; Seo et al., 2019; Perera, 2018; Balcombe et al., 2017; Howarth et al., 2021; Stern, 2020; Burke et al., 2023; Deng and Guo, 2024; Xing et al., 2024; Gupta and Chu, 2018; Bordoff and O’Sullivan, 2023; Ives et al., 2021; Cochran and Pauthier, 2019; Samuel, 2025; Narassimhan et al., 2018; Garcia et al., 2024; Eze et al., 2024a; Eze et al., 2024b; Arabkoohsar, 2020; Konur et al., 2022; Ohji and Haraguchi, 2022; Mohamed et al., 2020; Tiktas et al., 2022; Zhu et al., 2025; Lu et al., 2022; Zhang et al., 2020; Ericsson and Werner, 2016; Jaiswal et al., 2023; Ahmad et al., 2022; Mehetre et al., 2017; Zhang et al., 2021; Balmes, 2019; Rezaei et al., 2021; Uzoagba et al., 2024; Sreelekshmi and Nandan, 2025; Mohanty et al., 2025; Adams et al., 2018; Ram and Mondal, 2022; Pradhan et al., 2018; Subbarao et al., 2023; Silva et al., 2025).

Parameter	Fossil fuel systems	Rankine cycle technologies	Biomass-based systems
Primary Energy Source	Non-renewable (coal, oil, natural gas)	Can use fossil fuels, nuclear, and some renewable sources (e.g., CSP, geothermal)	Renewable (biomass, biogas, waste residues)
System Type	Direct combustion and thermodynamic conversion	Thermodynamic cycle (Rankine variants)	Combustion, gasification, anaerobic digestion, pyrolysis
Conversion Technology	Combustion → Thermal → Mechanical → Electrical (via Rankine/Brayton)	Steam turbine-driven thermal cycles (subcritical, SC, USC, reheat, etc.)	Combustion, CHP, gasification, biogas production
Typical Efficiency (%)	30%–60% depending on system (CCGT highest)	33%–48% (depending on cycle and enhancements)	Traditional: 10%–15%; Modern CHP: up to 70%–80% (total); Gasifiers: 25%–35%
GHG Emissions	High (CO ₂ , CH ₄ , NO _x , SO _x)	High with fossil fuels; moderate with nuclear; low with CSP/geothermal	Low to moderate; dependent on feedstock and technology
Pollutant Emissions	SO _x , NO _x , PM, VOCs, CH ₄	Thermal pollution, high water usage; SO _x /NO _x if fossil-based	PM, CO, VOCs in traditional systems; low in advanced technologies
Water Use	High (especially for steam and cooling)	High for subcritical and SC/USC Rankine systems; dry cooling available	Moderate; varies widely depending on conversion route
Technological Maturity	Highly mature and globally deployed	Technologically mature but evolving with CCS and renewables integration	Wide spectrum: from primitive stoves to advanced CHP and gasification
Environmental Impact	Severe: GHGs, ecosystem disruption, water and air pollution	Depends on heat source; fossil-based is still problematic; water-intensive	Can be sustainable or harmful based on the harvesting and conversion method
Geopolitical/Economic Risk	High: volatile fuel markets, import dependency, resource curse	Medium: tied to fuel sources and water availability	Low: feedstock can be locally sourced; rural economic potential
Sustainability Profile	Low without CCS; decarbonization needed	Moderate; compatible with low-carbon sources but needs hybridization	High when using sustainable biomass and clean tech
Capital and Operating Cost	Varies; CCGT and USC are capital-intensive	USC and reheat/regenerative cycles are expensive	Traditional: low cost; Advanced systems: moderate to high CAPEX
Deployment Region Suitability	Widely used in industrialized and developing nations	Industrial and utility-scale applications; CSP/geothermal are site-specific	Rural/agrarian settings; also useful for distributed, off-grid energy access
Integration with Renewables	Limited; transition to hybrid or CCS systems is ongoing	Possible via CSP, geothermal, biomass heat	High potential; biogas and biomass integrate well with hybrid systems

hybridized, and smart thermal platforms positions these innovations as essential enablers for meeting growing global energy demands, reducing environmental impacts, and advancing the transition to low-carbon energy economies.

3.2.1 Phase change materials (PCMs) for thermal storage

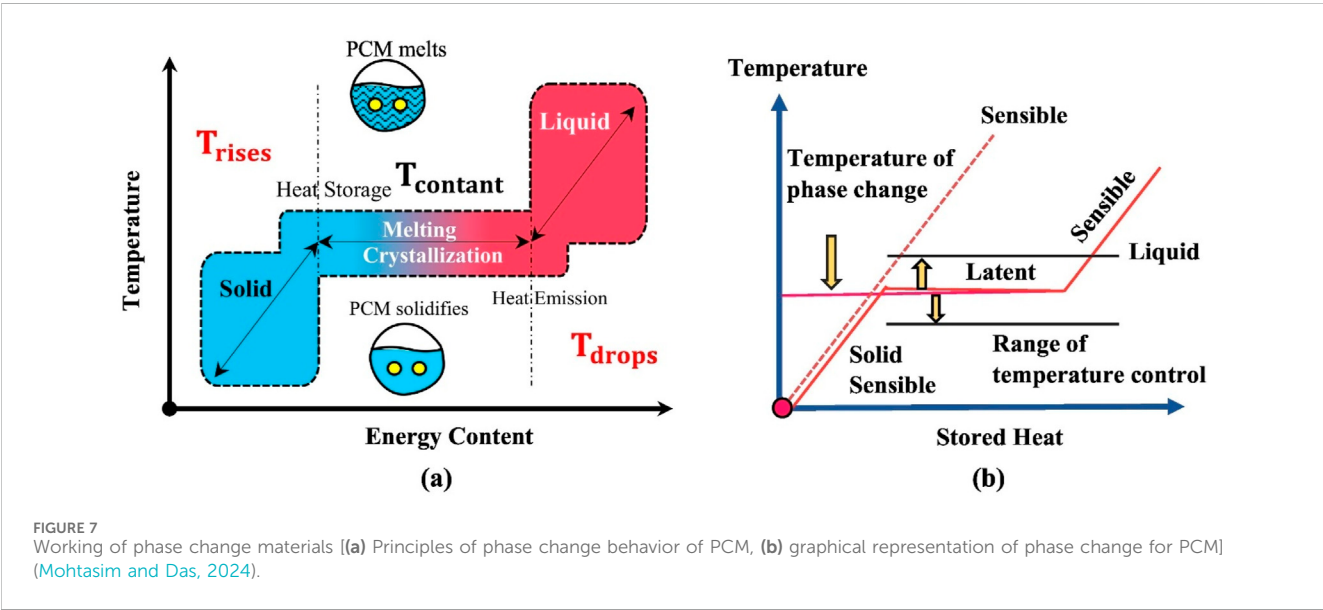
PCMs represent a critical advancement in TES by exploiting the latent heat absorbed or released during phase transitions, typically solid-liquid, to store and release thermal energy at near-constant temperatures, enabling significantly higher energy densities than conventional sensible heat storage (Togun et al., 2024; Patil et al., 2025). This is especially advantageous for applications requiring compact form factors or precise thermal management, such as building energy systems, solar thermal power plants, and electronics cooling. PCMs are categorized into organic (e.g., paraffins, fatty acids), inorganic (e.g., salt hydrates, metallic alloys), and eutectic mixtures, each with unique thermal, chemical, and physical properties (Mehling, 2024). Organic PCMs offer chemical stability and minimal supercooling but have

low thermal conductivity and flammability risks; inorganic PCMs generally exhibit higher latent heat and thermal conductivity but suffer from phase segregation, corrosion, and subcooling, complicating long-term durability; eutectics provide customizable melting points but can combine the limitations of both classes (Jebasingh and Arasu, 2020). Key performance criteria include phase transition temperature aligned with operating conditions, high latent heat capacity to maximize energy storage per volume, thermal conductivity to ensure efficient charging/discharging rates, chemical inertness, and cycle stability over thousands of phase changes (Vitorino et al., 2016). Table 5 outlines representative examples and typical compositions of various PCMs used in thermal energy storage applications.

In practical deployments, PCMs have been successfully integrated into building envelope components, such as wallboards, ceiling panels, and window films, where their latent heat absorption reduces peak cooling loads by buffering diurnal temperature swings, leading to up to 30% reductions in HVAC energy use (Draou and Brakez, 2024). In CSP plants, molten salt-based PCMs enable thermal energy to be stored during peak

TABLE 5 Examples and compositions of phase change materials.

Name	Types	Composition	Melting point
Paraffin Waxes	Organic	Hydro-carbon chains	Between 20 °C and 60 °C
Fatty Acids	Organic	Carboxylic acids	Between 20 °C and 50 °C
Salt Hydrates	Inorganic	Inorganic salt with water molecules	Varies widely depending on the specific salt and its hydration level
Eutectic Mixtures		Mixture of two or more salts	Customized based on the mixture ratio



insulation and dispatched during cloudy periods or at night, enhancing plant capacity factors and grid reliability; notable commercial installations like the Gemasolar plant in Spain demonstrate multi-hour storage with molten salt PCMs enabling 24-h power output (Elkelawy et al., 2024). Additionally, PCMs are utilized for thermal regulation in lithium-ion batteries to prevent overheating, extending battery life and safety, and in cold chain logistics for maintaining precise temperature control of pharmaceuticals and perishable goods (Weng et al., 2022). The working principles of PCM are illustrated in Figure 7; Table 6 shows the performance, costs, scalability, and deployment.

Despite these advantages, PCM technologies face significant barriers. The inherently low thermal conductivity of many PCMs limits rapid heat transfer, requiring the integration of conductive fillers such as expanded graphite, carbon nanotubes, or metal foams, as well as engineered heat exchanger geometries to enhance heat exchange rates (Wu et al., 2020). Phase separation and subcooling in salt hydrates degrade storage capacity and reliability over cycling, necessitating encapsulation techniques and chemical stabilizers to maintain integrity. Moreover, chemical incompatibility between PCMs and containment materials poses corrosion or leakage risks, necessitating rigorous material compatibility assessments and protective coatings. The relatively high cost of advanced PCMs and challenges in scalable manufacturing further restrict widespread adoption, particularly in large-scale industrial TES applications (Huang et al., 2021). Current research trends

emphasize hybrid TES configurations that combine PCMs with sensible heat storage media, like molten salts or concrete, to synergistically balance energy density and cost while optimizing operational flexibility. Cutting-edge developments in nano-enhanced PCMs, which incorporate nanomaterials to improve thermal conductivity and stability, and “smart” PCMs with tunable phase change properties responsive to external stimuli, are poised to address current limitations and expand PCM applicability across emerging sectors such as wearable thermal management and electric vehicle thermal regulation (Abdullah et al., 2025; Mohtasim and Das, 2024).

3.2.2 Thermoelectric generators (TEGs)

TEGs exploit the Seebeck effect, a fundamental thermoelectric phenomenon where a temperature difference across certain conductive or semiconductive materials induces a voltage difference, thus enabling direct conversion of thermal energy into electrical energy without mechanical moving parts (Jaziri et al., 2020). This solid-state energy conversion mechanism offers several intrinsic advantages, including high reliability, minimal maintenance, compactness, and scalability, making TEGs well-suited for applications requiring robust and long-lasting power sources. The operational principle of a TEG involves creating a temperature gradient across a thermoelectric module composed of pairs of n-type and p-type semiconductor elements connected electrically in series and thermally in parallel (Siddique et al.,

TABLE 6 Performance, costs, scalability, and deployment status of PCMs in TES.

PCM category	Performance metrics (latent heat and conductivity)	Cost range (USD/kg)	Scalability potential	Deployment status
Paraffin Waxes (Organic)	Latent heat: 150–210 kJ/kg; Thermal conductivity: 0.2–0.3 W/m·K	2–5	High (abundant, easy to process)	Widely deployed in buildings and electronics
Fatty Acids (Organic)	Latent heat: 180–220 kJ/kg; Thermal conductivity: 0.2–0.4 W/m·K	4–8	Moderate (biodegradable, but costlier)	Limited commercial use (niche cooling, packaging)
Salt Hydrates (Inorganic)	Latent heat: 250–350 kJ/kg; Thermal conductivity: 0.4–0.6 W/m·K	1–3	High (low cost, wide availability)	Deployed in TES and cold chain; stability issues remain
Eutectic Mixtures (Organic–Inorganic)	Latent heat: 150–300 kJ/kg; Tunable conductivity depending on mixture	3–10	Moderate–High (customizable, but complex synthesis)	Pilot-to-commercial applications in HVAC and CSP
Molten Salts (CSP-focused)	Latent heat: ~120–150 kJ/kg; Conductivity: 0.5–1.0 W/m·K	0.5–1.5	Very High (used in multi-MWh scale storage)	Mature, widely deployed in CSP plants (e.g., Gemasolar)
Nano-enhanced PCMs	Latent heat: 150–250 kJ/kg; Enhanced conductivity: up to 1.5 W/m·K	10–30	Emerging (cost barrier, scalability challenges)	Research and pilot stage (battery and EV cooling)

2017). Heat absorbed at the hot junction generates charge carrier diffusion, driving an electrical current through an external load at the cold junction.

3.2.2.1 Efficiency and performance

The effectiveness of a thermoelectric material is commonly characterized by the dimensionless values of merit, ZT, defined as in Equation 1 (Snyder and Snyder, 2017; Rath i et al., 2024)

$$ZT = \frac{S^2 \sigma T}{k}$$
 (1)

Where; S is the Seebeck coefficient, σ is the electrical conductivity, T is the absolute temperature, and k is the thermal conductivity. High-performance materials require a high Seebeck coefficient and electrical conductivity, paired with low thermal conductivity to maintain temperature gradients.

A TEG comprises N pairs of p-type and n-type semiconductor elements, electrically connected in series and thermally in parallel, as illustrated in Figure 8. A key feature of TEGs is the absence of moving parts, which enhances their mechanical robustness and makes them highly suitable for reliable energy harvesting applications (Rath i et al., 2024; Zamanipour et al., 2024). Recent research has intensified the exploration of cost-effective and environmentally friendly thermoelectric materials for TEG microfabrication. These advancements position TEGs as promising candidates for powering autonomous wireless sensor networks and other low-power electronic systems (Zamanipour et al., 2024).

The fundamental parameters that characterize the performance of a TEG include:

- Seebeck coefficient ($\alpha = \alpha_p - \alpha_n$): This parameter reflects the voltage generated per unit temperature difference across the p-type and n-type thermoelectric materials and is highly dependent on the material properties.
- Electrical resistance (R_c): This includes the intrinsic resistance of the semiconductor elements and the contact resistance of the electrical interfaces connecting the TEG to the external load.
- Thermal resistances (θ_m and θ_c):
 - Internal thermal resistance (θ_m) arises from heat conduction through the thermoelectric materials themselves.

◦ Contact thermal resistance (θ_c) is associated with the interfaces between the TEG and the external thermal source or sink.

Despite decades of research, commercial TEGs have historically exhibited modest conversion efficiencies in the range of 5%–8%, limited by the intrinsic properties of available materials and thermal management challenges. Recent advances in thermoelectric materials, such as bismuth telluride (Bi_2Te_3) for near-room-temperature applications, lead telluride (PbTe), skutterudites, and emerging nanostructured compounds, have significantly improved ZT values (Sharma et al., 2021). Nanostructuring and quantum confinement effects reduce lattice thermal conductivity while preserving electrical transport, boosting material performance (Siddique et al., 2017; Snyder and Snyder, 2017; Rath i et al., 2024; Zamanipour et al., 2024).

3.2.2.2 System integration

Effective deployment of TEGs involves optimizing heat exchanger designs to maximize the temperature differential across thermoelectric modules, enhancing power output (Chen et al., 2024). Modular TEG arrays allow scalability for different power requirements. Integration with existing waste heat sources requires thermal coupling to exhaust gases or hot surfaces, and thermal sinks to maintain low-temperature gradients, often employing heat pipes or liquid cooling (Jabbar et al., 2024; Singh, 2023).

3.2.2.3 Applications

- Waste Heat Recovery: TEGs can reclaim energy from industrial exhaust stacks, furnaces, and automotive exhaust systems, converting otherwise lost heat into usable electricity. Automotive thermoelectric generators (ATEGs) have been explored to improve vehicle fuel economy by converting exhaust heat, with the potential to reduce CO₂ emissions (Singh, 2023).
- Remote and Harsh Environments: Due to their robustness and lack of moving parts, TEGs power sensors and devices in remote or hostile environments, including deep-sea instrumentation, unmanned aerial vehicles (UAVs), and

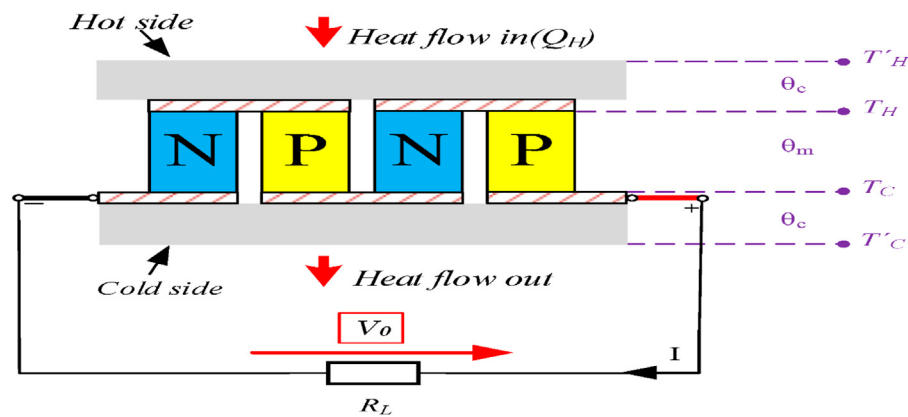


FIGURE 8
General structure of a Thermoelectric Generator (Zamanipour et al., 2024).

space probes. Notably, Radioisotope Thermoelectric Generators (RTGs) have powered spacecraft like Voyager and Mars rovers for decades (Jabbar et al., 2024).

- Hybrid Systems: TEGs increasingly serve as auxiliary power sources complementing conventional power generation or renewable systems, improving overall system efficiency (Singh, 2023).

3.2.2.4 Challenges and future directions

Key limitations remain, including material cost, brittleness, and relatively low efficiency compared to mechanical generators. Research is focusing on discovering new materials with higher ZT, improving thermal interface materials, and developing flexible or thin-film thermoelectric devices to expand application versatility (Snyder and Snyder, 2017; Singh, 2023). Additionally, combining TEGs with thermophotovoltaic systems and other energy harvesting technologies represents a promising avenue to enhance overall conversion efficiency. Table 7 illustrates the performance characteristics and deployment status of TEG.

3.2.3 Nanofluids and heat transfer enhancements

Nanofluids are engineered colloidal suspensions consisting of nanometer-sized particles, typically metals (e.g., copper, silver), metal oxides (e.g., Al_2O_3 , TiO_2), carbides (e.g., SiC), or carbon-based materials such as graphene and carbon nanotubes, dispersed in conventional heat transfer fluids like water, ethylene glycol, or mineral oils (Hussain, 2016). These nanoparticles significantly modify the thermophysical properties of the base fluids, most notably enhancing thermal conductivity, specific heat capacity, and convective heat transfer coefficients (Solangi et al., 2015). The underlying mechanisms for these enhancements include increased surface area for heat exchange, intensified Brownian motion, liquid layering at the solid-liquid interface, and altered micro-convection patterns within the fluid medium. Consequently, nanofluids have emerged as promising candidates for boosting heat transfer performance in a wide array of applications, including microchannel heat sinks for electronics cooling, compact automotive radiators, solar thermal collectors, industrial boilers, and high-efficiency heat exchangers (Mehta et al., 2022).

Beyond their superior thermal conductivity, nanofluids also offer operational benefits such as reduced pumping power requirements for equivalent thermal outputs, owing to improved convective heat transfer performance and lower viscosity increases compared to conventional additives (Younes et al., 2022). These advantages make nanofluids particularly appealing for compact and energy-efficient systems, especially where enhanced heat dissipation is essential under space-constrained or high-heat-flux conditions. However, the practical implementation of nanofluids is currently hindered by several challenges. These include nanoparticle agglomeration and sedimentation over time, which compromise fluid stability and thermal performance; increased risk of component erosion and fouling due to particle abrasion; and uncertainties related to the environmental toxicity and health implications of nanoparticle exposure (Gul et al., 2025). To mitigate these limitations, ongoing research focuses on advanced nanoparticle synthesis methods (e.g., sol-gel, hydrothermal, and laser ablation techniques), surface functionalization using surfactants or chemical coatings to improve colloidal stability, and the development of eco-friendly, biodegradable nanomaterials (Mohite et al., 2024). Furthermore, comprehensive lifecycle analyses and techno-economic evaluations are being conducted to assess the scalability, safety, and sustainability of nanofluid technologies in real-world systems. As these scientific and engineering barriers are systematically addressed, nanofluids are poised to play a transformative role in next-generation thermal management systems, contributing significantly to the efficiency and sustainability of both conventional and renewable energy platforms (Gul et al., 2025; Mohite et al., 2024). Table 8 illustrates the performance, cost, scalability, and deployment status of Nanofluids.

3.2.4 Artificial intelligence and optimization Techniques

The integration of AI, ML, and advanced optimisation methodologies is fundamentally transforming the design, control, and operational efficiency of thermal energy systems (Shaban et al., 2024; Eze et al., 2025a). These intelligent technologies enable the development of predictive and adaptive control frameworks capable of managing the dynamic behavior of complex thermal infrastructures, including district heating networks, HVAC

TABLE 7 Performance metrics, costs, scalability, and deployment status of TEGs.

TEG type/ Material	Performance metrics (ZT/Efficiency)	Cost (USD/W)	Scalability potential	Deployment status
Bismuth Telluride (Bi2Te3)	ZT ~1.0 at 300 K; Efficiency 5%–8%	0.5–1.5	Moderate; suitable for small- to medium- scale applications	Widely deployed in sensors, ATEGs
Lead Telluride (PbTe)	ZT ~0.8–1.2 at 500–800 K; Efficiency 6%–9%	1.0–2.5	Moderate; high-temperature applications	Pilot to commercial use in industrial waste heat
Skutterudites	ZT ~1.5–1.8 at 600–900 K; Efficiency 8%–12%	2–4	High; suitable for large-scale and high- temperature TES	Emerging; some industrial adoption
Nano-structured Compounds	ZT ~2.0+; Efficiency 10%–15%	5–10	Low–Moderate; research-stage scalability	Research and prototype stage
Radioisotope TEGs (RTGs)	ZT ~0.8–1.0; Efficiency 6%–8%	>50 (highly specialized)	Low; spacecraft and deep-space missions	Mature; space applications

TABLE 8 Performance metrics, costs, scalability, and deployment status of nanofluids.

Nanofluid type	Thermal performance enhancement	Cost (USD/L)	Scalability potential	Deployment status
Metal-based (Cu, Ag)	Thermal conductivity ↑ 30%–50%; Heat transfer coefficient ↑ 20%–35%	10–20	Moderate; cost and sedimentation limit large-scale adoption	Pilot and lab-scale; electronics cooling
Metal oxide (Al2O3, TiO2)	Thermal conductivity ↑ 15%–30%; Heat transfer ↑ 10%–25%	5–12	High, stable, cost-effective, widely studied	Laboratory and industrial prototypes
Carbide-based (SiC, B4C)	Thermal conductivity ↑ 25%–40%; High thermal stability	15–25	Moderate; high-temperature industrial applications	Pilot stage: concentrated solar and boilers
Carbon-based (Graphene, CNTs)	Thermal conductivity ↑ 50%–200%; Enhanced convective coefficients	50–200	Low–Moderate; high cost, dispersion challenges	Research and prototype stage; high- performance cooling
Hybrid nanofluids	Combination of the above; synergistic heat transfer ↑ 50%–100%	30–100	Emerging; optimization required for stability	Research and small-scale experimental use

(Heating, Ventilation, and Air Conditioning) systems, CHP units, and industrial process heat exchangers (Mira et al., 2023). AI-driven models, leveraging historical and real-time data from sensors, supervisory control systems, and external environmental inputs (e.g., weather forecasts, occupancy levels, production schedules), are used to forecast thermal loads, optimize dispatch strategies, identify operational anomalies, and proactively recommend control actions (Thapa, 2022). Advanced optimisation algorithms, including Genetic Algorithms (GA), Particle Swarm Optimization (PSO), Ant Colony Optimization (ACO), and Reinforcement Learning (RL), have been successfully applied to improve thermal energy distribution efficiency, reduce energy consumption, minimize operational costs, and enhance the longevity of thermal equipment (Li et al., 2023). Reinforcement learning, in particular, supports autonomous decision-making in highly dynamic environments by learning optimal policies through interaction with system states and feedback mechanisms. Moreover, hybrid models combining physics-based simulations with data-driven AI approaches have shown superior performance in capturing the nonlinear and time-variant characteristics of thermal processes (Sarmah, 2019). Comparative Analysis of AI and Optimization Techniques in Thermal Energy Systems is shown in Table 9.

AI also plays a critical role in facilitating the seamless integration of intermittent renewable energy sources, such as solar thermal collectors, geothermal units, and biomass boilers, into thermal

networks, along with energy storage systems (e.g., phase change materials, hot water tanks) (Ukoba et al., 2024). Through real-time optimization and load balancing, AI enables enhanced flexibility and resilience of thermal grids under varying supply and demand conditions. The advent of digital twin technologies, virtual replicas of physical systems, augmented with AI and IoT connectivity, further strengthens operational intelligence. These platforms offer high-fidelity simulations, real-time diagnostics, and predictive maintenance capabilities, significantly reducing unplanned downtime, extending asset lifespans, and improving system-level reliability and economic performance. As AI and optimisation techniques continue to evolve, their role in achieving sustainable, efficient, and intelligent thermal energy systems is becoming increasingly indispensable (Raghuvanshi et al., 2025). Table 10 provides a comparative analysis of emerging technologies in thermal energy systems, highlighting their operational principles, efficiency metrics, advantages, and limitations.

Figure 9 presents a comparative analysis of traditional and emerging thermal energy technologies in terms of efficiency and capital cost. Traditional systems, fossil-fuel boilers (≈35%), steam turbines (≈42%), and CSP (≈32%), show moderate efficiencies but relatively higher cost ranges. Emerging technologies display a wider performance spectrum: PCMs achieve notably higher efficiency (≈80%) at the lowest capital cost, underscoring their potential for

TABLE 9 Comparative analysis of AI and optimization techniques in thermal energy systems.

Technology/ Method	Key performance metrics	Cost considerations	Scalability	Deployment status
Genetic Algorithms (GA)	Convergence speed, solution optimality, energy savings (5%–12%)	Moderate (computational resources)	Medium to high, suitable for large-scale thermal systems	Widely used in research and industrial optimization projects
Particle Swarm Optimization (PSO)	Energy efficiency improvement, reduced peak load, and convergence reliability	Moderate	Medium, suitable for network-level optimization	Implemented in pilot-scale and commercial thermal networks
Ant Colony Optimization (ACO)	Routing efficiency, operational cost reduction	Moderate to high (complexity increases with system size)	Medium, effective for distributed systems	Mostly experimental; limited industrial adoption
Reinforcement Learning (RL)	Adaptive control accuracy, system resilience, and real-time decision-making	High (training and computational overhead)	High potential, can handle complex, dynamic systems	Early-stage deployment; used in advanced research and digital twin environments
Hybrid AI-Physics Models	Forecast accuracy, predictive maintenance reliability, and nonlinear system handling	High (integration of models and sensors)	High, suitable for district heating and large CHP systems	Emerging deployment in smart thermal grids
Digital Twins + AI	System-level reliability, downtime reduction, lifecycle cost savings	Very high (requires sensors, IoT, computing infrastructure)	High, applicable to both centralized and distributed networks	Emerging technology; limited but growing commercial adoption

TABLE 10 Comparative assessment of emerging technologies in thermal energy systems.

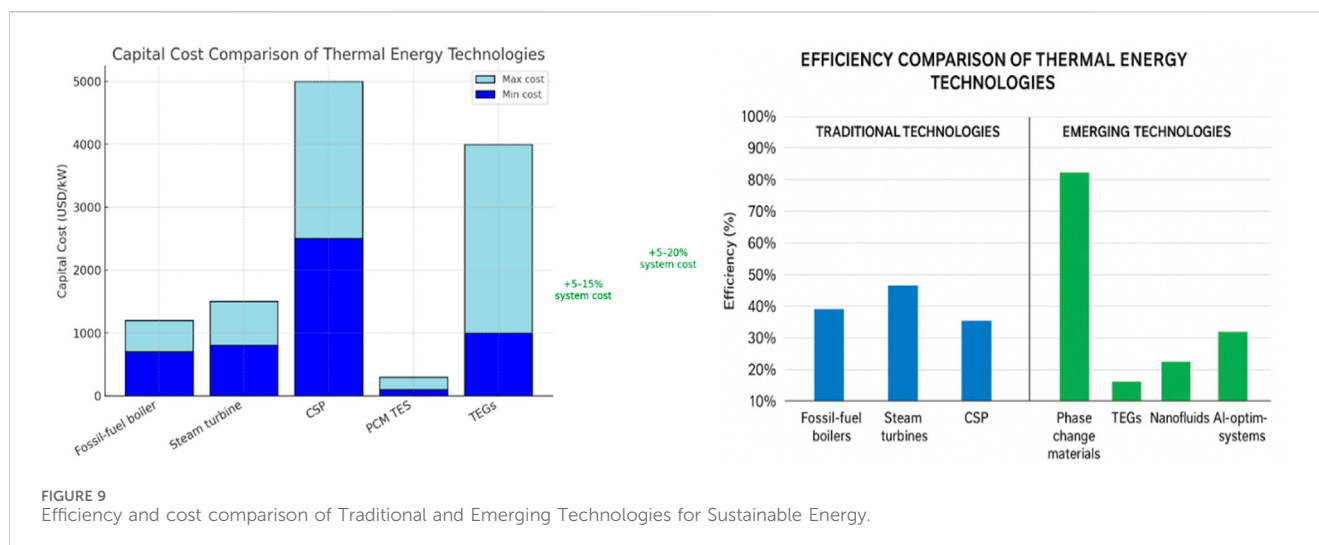
Technology	Advantages	Technology readiness level (TRL)	Scalability	Commercialization barriers
Phase Change Materials (PCMs)	High energy density, compact storage, near-constant temperature output, suitable for building and industrial TES	TRL 6–8 (pilot to early commercial)	Moderate: scalable for buildings, industrial heat storage, and solar thermal plants	High material cost, limited long-term thermal stability, heat transfer inefficiencies, and integration complexity
Thermoelectric Generators (TEGs)	Direct conversion of heat to electricity, silent operation, solid-state, modular	TRL 5–7 (lab to pilot)	Low to moderate: modular but low efficiency limits large-scale deployment	Low conversion efficiency (~5–10%), high cost of thermoelectric materials, thermal interface losses, and reliability under cyclic loads
Nanofluids and Heat Transfer Enhancements	Enhanced thermal conductivity, improved convective heat transfer, potential for compact heat exchangers	TRL 4–6 (lab to pilot)	Moderate: can be retrofitted into existing systems or integrated into new designs	Nanoparticle stability and sedimentation, high material and preparation costs, environmental and health concerns, and limited long-term performance data
Artificial Intelligence and Optimization Techniques	Adaptive control, predictive maintenance, real-time optimization, improved efficiency, and system reliability	TRL 6–9 (pilot to commercial)	High: software-based, easily scalable across industrial, commercial, and district-scale systems	Data availability and quality requirements, cybersecurity risks, integration complexity with legacy infrastructure, and reliance on operator expertise

transformative thermal storage. In contrast, thermoelectric generators ($\approx 12\%$) and nanofluids ($\approx 18\%$) remain at lower efficiency levels, reflecting their developmental stage. AI-based optimization systems ($\approx 28\%$) provide moderate gains with only marginal cost increases (+5–20%). Overall, the comparison highlights PCMs as the most promising solution while emphasizing the need for further R&D to enhance other next-generation approaches.

3.3 Integration of thermal energy storage with renewables

The integration of TES systems with renewable energy technologies is pivotal to the advancement of resilient and decarbonized energy infrastructures (Elkhatat and Al-Muhtaseb,

2023). TES addresses the fundamental intermittency challenges associated with variable renewable energy sources such as solar and wind by temporally shifting energy availability. By decoupling energy generation from end-use consumption, TES systems facilitate real-time grid balancing, reduce curtailment of excess renewable power, and enable demand-side flexibility (Scafuri, 2025). This capability is particularly critical in scenarios where renewable generation exceeds immediate demand or where generation drops below consumption levels. TES technologies, ranging from short-duration ice storage to long-duration molten salt and underground storage, allow surplus thermal or electrically converted thermal energy to be efficiently captured, stored, and discharged during peak demand periods or resource deficits (Hayati et al., 2025). As a result, TES significantly enhances the stability and reliability of both centralized power grids and decentralized microgrids, while also contributing to emissions reduction,



enhanced energy equity, and long-term energy cost savings across residential, commercial, and industrial sectors (Elkhatat and Al-Muhtaseb, 2023; Hayati et al., 2025).

3.3.1 TES for solar and wind power

TES technologies play a pivotal role in overcoming the temporal disparities between renewable energy generation and end-use demand, thus ensuring energy reliability and operational flexibility (Elkhatat and Al-Muhtaseb, 2023; Eze et al., 2024c). In solar energy systems, particularly CSP plants, TES is indispensable for enabling dispatchable electricity production. Among the most mature and commercially implemented solutions is molten salt storage, wherein a mixture of sodium and potassium nitrates stores thermal energy at high temperatures exceeding 500 °C (Codd et al., 2020). This heat can later be used to generate steam and drive turbines, even after solar irradiance declines (Yang et al., 2025). Iconic installations such as the Crescent Dunes Solar Energy Plant in the United States and Gemasolar in Spain demonstrate the feasibility of this technology, achieving over 15 h of thermal autonomy and supporting baseload electricity generation (Camacho et al., 2024). In the context of wind energy, which inherently produces fluctuating electrical outputs, TES can serve as an effective indirect storage mechanism. During periods of low demand and high generation, excess electricity can be converted into thermal energy using resistive heating elements, heat pumps, or electro-thermal energy storage units. The resulting thermal energy can then be stored in media such as hot water tanks, PCMs with high latent heat capacities, or thermochemical storage systems that leverage reversible chemical reactions for high-density storage (Togun et al., 2024; Mehling, 2024; Camacho et al., 2024).

Underground Thermal Energy Storage (UTES) systems, including Aquifer Thermal Energy Storage (ATES) and Borehole Thermal Energy Storage (BTES), offer scalable, seasonal solutions by exploiting the natural thermal inertia of subsurface geological formations (Brown et al., 2024). These systems are especially effective for large-scale district heating and cooling networks in urban environments, providing high volumetric energy density, minimal thermal losses, and long operational lifespans. Additionally, ice thermal storage, widely used in commercial

buildings and HVAC systems, stores cooling energy by producing ice during off-peak periods, which is then used for air conditioning during peak hours, significantly reducing grid stress and operational costs (Brown et al., 2024; Eze et al., 2025b). Overall, the integration of TES with solar and wind energy enhances the stability, dispatchability, and cost-effectiveness of renewable power systems, facilitating a transition toward resilient and low-carbon energy infrastructures.

3.3.2 Hybrid solar-thermal systems

Hybrid solar-thermal systems, particularly Photovoltaic-Thermal (PVT) configurations, offer a synergistic approach to maximizing the utility of solar radiation by concurrently generating electricity and harvesting thermal energy within a single integrated system (Verma et al., 2022). In PVT systems, conventional photovoltaic (PV) modules are coupled with thermal collectors, allowing a working fluid, typically air, water, or a refrigerant, to extract waste heat from the PV surface. This dual functionality not only produces usable heat for direct consumption or storage but also enhances electrical efficiency by lowering the operating temperature of the PV cells, which is known to degrade performance under thermal stress (Pandey et al., 2025). These systems are highly effective in cogeneration applications where simultaneous demand for electricity and heat exists, such as in residential water heating, space heating and cooling, greenhouse temperature regulation, and small-scale industrial processes (Sarvar-Ardeh et al., 2024). Their modular design makes them particularly well-suited for deployment in remote, off-grid, or energy-poor regions, where infrastructure for separate thermal and electrical systems is either lacking or economically infeasible. When paired with TES systems, such as water tanks, PCMs, or thermochemical storage, PVT installations can deliver round-the-clock thermal services and buffer the inherent intermittency of solar irradiance (see Figure 10) (Verma et al., 2022; Sarvar-Ardeh et al., 2024).

Recent innovations in Concentrated Photovoltaic-Thermal (CPVT) systems further extend the utility of hybrid technologies by employing optical concentrators (e.g., Fresnel lenses or parabolic mirrors) to focus solar energy onto high-efficiency PV and thermal

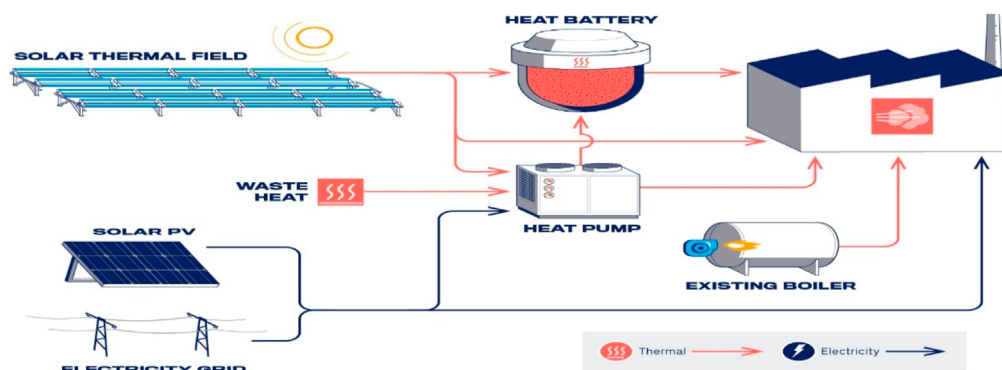


FIGURE 10
Hybrid solar-thermal systems (Yapp et al., 2025).

receivers (Wang et al., 2025). These systems achieve significantly higher energy densities, making them suitable for medium-to high-temperature industrial processes. Additionally, solar-assisted absorption refrigeration technologies, which utilize captured thermal energy to drive cooling cycles via lithium bromide or ammonia-water absorption systems, enable solar-based cooling solutions for both residential and industrial applications. Altogether, hybrid solar-thermal systems represent a promising paradigm for multi-functional, decentralized, and sustainable energy generation, advancing energy efficiency, reducing land use per unit of output, and lowering dependence on fossil-based thermal energy sources (Cameron et al., 2022).

3.4 Waste heat recovery and circular economy approaches

The recovery and utilization of industrial waste heat represent a strategic intervention in advancing circular economy objectives and enhancing thermal energy efficiency across energy-intensive sectors (Khayyam et al., 2021). A substantial fraction of thermal energy generated in industrial operations, particularly in metallurgy, cement manufacturing, glass production, and petrochemical refining, is typically lost to the environment as low-to medium-grade heat (Farhat et al., 2022). Capturing this underutilized resource not only reduces primary energy consumption but also mitigates greenhouse gas emissions and improves overall process sustainability. Technologies such as the ORC, Kalina cycle, and CHP systems have emerged as key enablers in this domain (Wieland et al., 2023).

ORC systems are well-suited for the conversion of low-temperature waste heat, starting from approximately 80 °C, into electricity using organic working fluids with low boiling points and favorable thermodynamic properties (Bora et al., 2020). These systems are inherently modular and scalable, allowing deployment in varied industrial contexts ranging from small manufacturing plants to geothermal and biomass facilities. CHP systems, also known as cogeneration units, deliver both electricity and useful heat from a single fuel source, such as natural gas, biogas, or industrial waste fuels, with system efficiencies often exceeding 80%. By replacing separate electricity and heat generation systems,

CHP reduces energy losses and carbon intensity (Wieland et al., 2023). When integrated with TES systems, the recovered thermal energy can be time-shifted and redistributed to nearby buildings, industrial units, or district heating networks, thereby enabling energy symbiosis and load leveling across interconnected facilities. TES-enhanced waste heat systems improve grid responsiveness, reduce reliance on peaking power plants, and facilitate greater use of renewable energy in hybrid configurations (Daniarta, 2024).

Beyond technical efficiency gains, waste heat recovery is a cornerstone of industrial ecology and circular economy models, where energy cascading and resource valorization are central. By promoting closed-loop thermal networks and inter-plant energy exchanges, industrial zones can evolve into energy-efficient ecosystems, where thermal waste streams from one process serve as inputs for another (Wieland et al., 2023; Bora et al., 2020). This approach supports national and global decarbonization goals, enhances energy security, and contributes to low-carbon industrial development by reducing the demand for fresh fossil energy inputs and aligning production systems with environmental sustainability (Farhat et al., 2022).

3.5 Case studies and practical implementations

The practical deployment of TES technologies across diverse energy systems demonstrates their pivotal role in advancing energy efficiency, operational flexibility, and long-term sustainability. Through strategic integration with renewable energy sources, smart thermal grids, and industrial waste heat recovery systems, TES solutions have delivered measurable improvements in grid stability, carbon footprint reduction, and economic performance. The case studies presented herein provide evidence-based insights into successful TES applications in both centralized and decentralized energy contexts. From large-scale solar power plants in arid regions to AI-optimized district heating systems in temperate climates, and from industrial symbiosis models in Europe to process heat recovery innovations in Asia, these implementations serve as scalable and replicable models for accelerating the global energy transition.

3.5.1 Concentrated solar power (CSP) plants

CSP plants represent a cutting-edge integration of renewable energy generation and TES, offering dispatchable and stable electricity in regions with high solar irradiance. A flagship example is the Noor Ouarzazate Solar Complex in Morocco, which stands among the world's largest CSP facilities. The complex features a combination of parabolic trough collectors and a central solar tower system, both equipped with molten salt TES to store thermal energy at temperatures exceeding 500 °C (Laaroussi et al., 2023). This enables the facility to supply electricity continuously for up to 7–8 h after sunset, providing baseload capacity and significantly reducing reliance on fossil fuel-based peaking plants (Laaroussi et al., 2023; Salime, 2021).

The Noor complex exemplifies how TES empowers time-shifting of solar energy, enabling generation during periods of low or no irradiance and enhancing grid flexibility. Additionally, the plant contributes to national energy security and climate commitments by displacing conventional generation and lowering carbon emissions. A similar achievement is demonstrated by Gemasolar in Spain, which utilizes a central tower receiver and a molten salt storage system with over 15 h of thermal autonomy, achieving near-constant solar power generation. Unlike intermittent photovoltaic systems, CSP-TES configurations provide both energy storage and controllability, making them ideal for large-scale grid integration and hybridization with other renewable or backup sources (Benbba et al., 2024). These high-impact examples underscore the technical viability, economic attractiveness, and environmental benefits of CSP-TES systems. Their success validates their potential as scalable solutions for decarbonizing power sectors in solar-rich countries and as strategic infrastructure for meeting net-zero energy goals, particularly in desert and semi-arid regions where solar resources are abundant and consistent (Laaroussi et al., 2023; Benbba et al., 2024).

3.5.2 Smart thermal grids

The integration of TES into smart thermal grids, primarily district heating and cooling systems, constitutes a transformative advancement in urban energy infrastructure. These grids are fundamental to achieving decarbonization, operational flexibility, and cost efficiency in increasingly electrified and renewable-based energy systems. By embedding TES solutions within these networks, cities can effectively decouple heat generation from consumption, enabling better alignment of thermal supply with variable demand profiles while harnessing intermittent renewable sources.

In Denmark, a global leader in district heating innovation, cities such as Aalborg exemplify this integration through the deployment of large-scale hot water storage tanks and UTES facilities (Johan et al., 2022). UTES leverages geological media such as aquifers or boreholes to store thermal energy seasonally, enabling heat captured during warmer months, often from excess renewable generation or waste heat, to be retained and dispatched during colder periods. The coupling of TES with AI-driven demand forecasting and optimization algorithms allows the system to dynamically adjust heat production from sources like solar thermal arrays, biomass boilers, and wind-powered heat pumps. These advanced control strategies optimize operational scheduling, reduce reliance on fossil

fuel peaking units, and improve cost-effectiveness by shifting energy use to off-peak periods (Johan et al., 2022).

Sweden's district energy networks showcase further innovation by integrating seasonal TES with large-scale heat pump technology and extensive industrial waste heat recovery infrastructure (Brange et al., 2016). These networks benefit from sophisticated ML and AI frameworks that continuously analyze vast datasets, from meteorological forecasts to consumer behavior, to optimize thermal supply chains holistically. By managing generation assets, TES dispatch, and user consumption patterns, these intelligent systems enhance load matching, minimize peak demand spikes, and maximize renewable heat utilization (Brange et al., 2016). The digital convergence of TES, AI, and renewable heat sources significantly improves system resilience, allowing the grid to adapt in real-time to fluctuating external conditions such as weather variability, grid constraints, and dynamic occupancy levels. Moreover, this integration supports demand response initiatives and predictive maintenance, which collectively lower operational costs and extend infrastructure lifespans (Fernqvist et al., 2023).

Importantly, smart thermal grids act as critical enablers for urban sustainability and climate action plans by enabling deep decarbonization of heating and cooling, a sector traditionally reliant on fossil fuels and representing a major share of urban carbon emissions (Khaleel et al., 2024). Through the flexible integration of TES and digital controls, these grids reduce energy waste, promote efficient utilization of renewable resources, and foster the transition towards net-zero emissions in cities. Overall, the Danish and Swedish cases provide replicable models demonstrating how the fusion of digitalization, TES technologies, and renewable energy integration forms the backbone of next-generation thermal grids, essential for sustainable, resilient, and low-carbon urban energy systems globally (Fernqvist et al., 2023; Khaleel et al., 2024).

3.5.3 Industrial waste heat recovery projects

Industrial sectors in Germany and Japan have been at the forefront of adopting advanced waste heat recovery technologies, driving significant improvements in energy efficiency, cost reduction, and carbon emissions mitigation.

In Germany, particularly within the cement and steel manufacturing industries, the integration of ORC systems has become widespread. These systems efficiently convert medium-temperature waste heat, often in the range of 150 °C–300 °C, into electricity by utilizing organic working fluids with low boiling points (Pili et al., 2020). The implementation of ORC technology in these plants has led to enhanced energy self-sufficiency, reducing grid electricity dependence and increasing overall process efficiency by up to 20%. When combined with TES units, the recovered thermal energy can be temporally shifted, stored, and dispatched during peak load periods or used to supply adjacent industrial or district heating facilities, maximizing utilization and system flexibility (Shahid et al., 2025; Larrinaga et al., 2021).

In Japan, the Energy Conservation Center has catalyzed the diffusion of waste heat recovery solutions across diverse sectors, including chemical manufacturing, automotive production, and general manufacturing (Dou et al., 2018). Leading corporations such as Toyota have integrated CHP systems alongside TES to

capture and recycle thermal energy from processes such as engine testing and paint curing. This holistic approach not only curtails energy expenses but also delivers substantial reductions in CO₂ emissions, bolstering the environmental and economic sustainability of manufacturing operations (Thekdi and Nimbalkar, 2015). These exemplary projects underscore the strategic value of coupling TES with waste heat recovery technologies to foster industrial symbiosis, where excess thermal energy from one process is efficiently redirected to others, thereby embodying circular economy principles. Moreover, these initiatives contribute to national decarbonization agendas and energy security objectives by decreasing fossil fuel consumption, enhancing energy system resilience, and promoting sustainable industrial competitiveness. Collectively, they illustrate a scalable pathway for industrial sectors worldwide to transition toward low-carbon, energy-efficient production paradigms.

3.6 Policy and future perspectives

The successful evolution and broad deployment of thermal energy technologies hinge on the establishment of supportive policy frameworks, targeted research initiatives, and the effective mitigation of ongoing technological and socio-economic barriers (Liu et al., 2025). Robust regulatory environments, coupled with financial incentives and standardization efforts, provide the necessary foundation for scaling innovations in thermal energy storage, waste heat recovery, and hybrid renewable systems. Concurrently, addressing challenges such as high upfront capital costs, material limitations, and public acceptance through multidisciplinary collaboration is vital to accelerate market penetration. This section synthesizes existing regulatory approaches, critically examines the principal obstacles and opportunities facing the sector, and delineates key research priorities that will guide the advancement and integration of sustainable thermal energy solutions in future low-carbon energy systems (Adewumi et al., 2024).

3.6.1 Regulatory frameworks and incentives

Governments and international organizations worldwide are increasingly adopting comprehensive regulatory frameworks and incentive mechanisms designed to accelerate the integration of renewable energy and improve overall energy efficiency, with thermal energy technologies playing a critical role in this transition. Key policy instruments such as feed-in tariffs (FITs), renewable portfolio standards (RPS), carbon pricing mechanisms, and investment tax credits directly stimulate capital flows into TES, CSP, and industrial waste heat recovery systems by improving project economics and reducing financial risk (Filho et al., 2023).

Complementing these market-based incentives are targeted research, development, and demonstration (RD&D) funding programs that prioritize next-generation materials, innovative TES system architectures, and advanced digital controls, including artificial intelligence and machine learning for real-time optimization. Regions with progressive and coordinated energy policies exemplify effective frameworks: the European Union's Green Deal mandates ambitious decarbonization targets supported by substantial funding for clean energy infrastructure

(Marelli et al., 2025); the U.S. Inflation Reduction Act provides extensive tax credits and grants that catalyze renewable and storage deployment (Guha, 2025); and China's Renewable Energy Law enforces mandatory renewable capacity additions alongside supportive financial mechanisms (Liu, 2019) (see Figure 11). Beyond fiscal incentives, the development and harmonization of technical standards for TES performance, safety, environmental compliance, and interoperability are fundamental to fostering investor and stakeholder confidence. Standardization accelerates market acceptance by reducing uncertainty and enabling economies of scale in manufacturing and deployment. Collectively, these regulatory and incentive frameworks constitute a multidimensional policy ecosystem that is essential for scaling thermal energy technologies, enhancing grid flexibility, and achieving climate goals at the national and global levels. Table 11 presents the examples of policy measures that have accelerated TES adoption in different countries.

3.6.2 Challenges and opportunities

Despite notable technological progress in TES and related systems, the widespread adoption of these solutions continues to face a series of interrelated technical, economic, and social barriers (Simó-Solsona et al., 2021). One of the foremost challenges is the high upfront capital expenditure associated with TES infrastructure, including costs linked to advanced materials, system components, and installation. Moreover, the complexity of integrating TES within existing energy networks, which often requires sophisticated control architectures and compatibility with diverse energy sources and loads, adds to deployment hurdles (Saxena et al., 2024). Material durability also remains a concern, as thermal cycling, corrosion, and long-term stability of phase change materials and heat transfer fluids can affect system reliability and lifespan (Adesusi et al., 2023). Beyond technical and financial constraints, public acceptance issues frequently impede project development. These challenges stem from limited awareness of TES benefits, perceived operational or safety risks, and concerns about potential disruptions to local environments or communities. Such social factors can delay permitting processes and hinder stakeholder engagement, underscoring the need for proactive community involvement and transparent communication.

Addressing these obstacles demands comprehensive policy interventions that include risk mitigation strategies such as government-backed guarantees, targeted subsidies, and streamlined regulatory and permitting frameworks to accelerate deployment. On the innovation front, advances in materials science, notably the development of high-temperature stable phase change materials, thermochemical storage media, and corrosion-resistant fluids, offer pathways to enhance system efficiency and durability. Simultaneously, the design of modular and scalable TES units can reduce installation complexity and lower capital costs. The integration of AI-driven optimization algorithms and predictive analytics facilitates operational improvements by enhancing energy management, forecasting demand, and optimizing charge-discharge cycles, which collectively improve economic viability. To navigate the multifaceted nature of TES adoption, interdisciplinary collaboration among engineers, policymakers, economists, and social scientists is essential. Such cross-sectoral efforts enable the development of holistic solutions

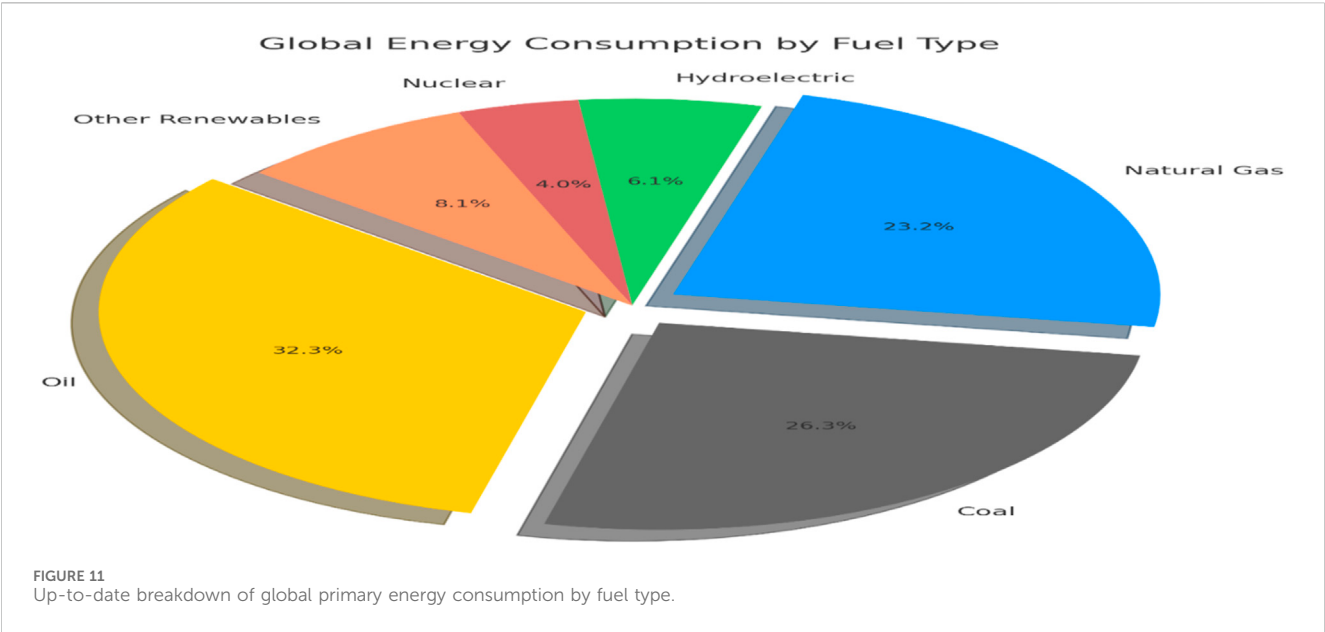


TABLE 11 Comparative policy measures driving TES adoption.

Region/ Country	Policy instrument	TES technology supported	Concrete example/Impact
European Union (EU)	<i>European Green Deal</i> , Horizon Europe RD&D funding, ETS (carbon pricing)	District heating TES, PCM, industrial waste heat recovery	Over €10 billion allocated to clean energy RD&D, supporting TES pilots in Germany, Denmark, and Sweden. ETS incentivizes TES to reduce CO2 emissions in energy-intensive industries
Spain	Feed-in Tariffs (2007–2013) for CSP + TES	Molten salt storage integrated with CSP	Enabled Gemasolar (20 MW CSP + 15 h storage), first 24/ 7 CSP plant; over 2 GW CSP with TES installed by 2013
Germany	Renewable Energy Sources Act (EEG), energy efficiency regulations	TES in district heating and CHP	Deployment of large-scale TES in Hamburg HafenCity (5,000 m3 water storage) and seasonal pit TES in Munich
United States	<i>Inflation Reduction Act</i> (2022), Investment Tax Credit (ITC)	Molten salt, phase change materials, and advanced heat batteries	ITC expanded to standalone storage → pipeline of >5 GWh TES projects; e.g., Malta Inc. thermal battery projects supported by federal incentives
China	Renewable Energy Law (2005, 2009), state subsidies, and mandatory renewable quotas	CSP + molten salt TES, industrial waste heat recovery	Delingha 50 MW CSP plant with 6 h TES; China now has >500 MW CSP with TES in operation
Denmark	Carbon tax, district heating legislation, public-private partnerships	Seasonal pit storage, water tank TES	Vojens Pit Storage (200,000 m ³) and widespread adoption in district heating; Denmark covers >60% of heating demand via TES-supported DH.
India	National Solar Mission tenders requiring CSP + TES, viability gap funding	CSP with molten salt TES	Planned Auraiya 150 MW CSP + TES project, designed to supply power round-the-clock
United Kingdom	Contracts for Difference (CfD), BEIS innovation funding	TES integrated with CHP and renewable heating	TES demonstration projects like CryoBattery (liquid air storage with TES) funded under £10 m BEIS scheme

that balance technical feasibility, market competitiveness, and social acceptability. Taken together, these challenges and opportunities frame a roadmap for scaling TES and thermal integration technologies within decarbonized energy systems, contributing to resilient, efficient, and sustainable energy infrastructures worldwide.

3.6.3 Future research directions

The advancement of thermal energy systems hinges on sustained innovation across several interdisciplinary domains. Central to this progress is the development of advanced materials, including novel

PCMs with enhanced thermal conductivity and stability, thermochemical storage media capable of reversible energy storage through chemical reactions, and corrosion-resistant high-temperature molten salts that extend operational lifetimes and broaden application temperature ranges. These material innovations are critical for increasing TES system efficiency, durability, and economic viability. Simultaneously, the integration of AI and ML into thermal energy systems is poised to transform their management and control. AI-driven techniques enable real-time system optimization, predictive maintenance, and adaptive

control of increasingly complex thermal grids, improving performance, reducing downtime, and maximizing energy utilization. These capabilities facilitate dynamic balancing of supply and demand, integration with variable renewable energy sources, and enhanced grid resilience.

Emerging hybrid energy systems that synergize TES with complementary technologies, such as electrochemical battery storage, renewable power generation, and green hydrogen production, represent a frontier for creating flexible and resilient multi-vector energy infrastructures. These integrated systems can leverage the unique strengths of each technology to deliver reliable, low-carbon energy across sectors and timescales. Further research into digital twins and IoT-enabled monitoring promises substantial gains in system modeling fidelity, operational transparency, and fault detection. By creating virtual replicas of physical thermal systems, digital twins allow for scenario testing, performance optimization, and proactive maintenance, supporting more efficient and cost-effective system operation. Beyond technical innovations, interdisciplinary investigations encompassing policy frameworks, economic modeling, and behavioral science are essential to overcoming non-technical barriers and facilitating the scale-up of TES technologies from pilot demonstrations to commercial adoption. Understanding regulatory impacts, market dynamics, and end-user acceptance will guide the design of enabling environments and adoption strategies. Collectively, these research trajectories will drive the emergence of the next-generation of sustainable, efficient, and smart thermal energy infrastructures, which are indispensable for achieving global energy transition goals and fostering resilient, low-carbon energy systems worldwide.

4 Research findings

The review uncovers a set of cutting-edge and thematically integrated findings that mark a transformative shift in the design, operation, and deployment of TES. Central to these insights is the emergence of hybridized thermal configurations that synergize technologies like solar thermal collectors, biomass CHP units, and PV-Thermal modules with latent heat storage. These integrated systems not only boost exergy efficiencies, reaching up to 85% in some configurations, but also provide multifaceted energy outputs (heat, electricity, cooling), particularly benefiting rural and off-grid communities. Parallel advancements in thermochemical and nano-enhanced TES reveal energy densities as high as 300–500 kWh/m³ and thermal conductivity improvements of 150%–200%, enabled by novel materials such as metal oxides and nano-enhanced phase change materials (NePCMs). These materials offer long-duration storage, thermal flexibility, and enhanced cyclability.

Crucially, the integration of AI and digital intelligence is redefining TES operational paradigms. AI-driven platforms, including reinforcement learning and digital twins, are enabling predictive load management, system diagnostics, and adaptive control, reducing operational costs by up to 30% and energy losses by 20%. This intelligence supports the seamless incorporation of renewables into thermal grids, improving system

resilience and sustainability. In the context of the circular economy, waste heat valorization through technologies like Organic Rankine Cycles and TEG systems is reclaiming energy from low-to mid-grade heat sources with efficiencies exceeding 80%, while enabling industrial symbiosis and substantial reductions in primary energy consumption.

Additionally, modular and containerized TES systems are emerging as critical solutions for distributed and humanitarian energy needs, providing thermal services for off-grid healthcare, education, and agricultural cold chains. Coupling TES with electrochemical and hydrogen systems further expands its role in multi-energy vector platforms, where hybrid TES–battery architectures and high-temperature storage assist in green hydrogen production, achieving notable reductions in electrolyzer energy demands. The review also highlights the influence of socio-technical and policy innovations, where performance-based subsidies, community-owned microgrids, and climate-aligned regulations are accelerating TES adoption and scalability. These novel findings collectively underscore a paradigm shift: from standalone thermodynamic optimization toward intelligent, hybridized, and policy-supported TES networks. The future of TES lies in leveraging advanced materials, digital infrastructures, and cross-sectoral integration to build resilient, low-carbon, and circular energy ecosystems globally.

5 Conclusion

The evolution of thermal energy systems marks a critical juncture in the global transition toward sustainable, resilient, and intelligent energy infrastructures. Historically anchored in fossil fuel combustion, traditional thermal systems have become increasingly unsustainable due to their high greenhouse gas emissions, thermodynamic inefficiencies, and dependency on finite resources. Bridging these legacy technologies with cutting-edge innovations is essential to address the pressing environmental, economic, and operational challenges of the 21st century. This review underscores that the transformation underway is not incremental but paradigmatic, characterized by the convergence of advanced materials, renewable integration, and digital intelligence. Emerging technologies such as PCMs, nano-enhanced TES systems, and thermochemical storage are enabling high-density, long-duration, and flexible heat storage capabilities. When synergized with renewable sources, such as concentrated solar power, biomass CHP, and PVT systems, these TES innovations significantly enhance overall energy efficiency, exergy utilization, and service reliability. Digital technologies, particularly AI and ML, are revolutionizing thermal system control, optimization, and predictive maintenance. Through real-time energy flow orchestration, intelligent fault diagnostics, and adaptive system behavior, these tools facilitate the development of autonomous and responsive thermal networks. The integration of IoT platforms and digital twins further enhances system resilience, lifecycle performance, and cost-effectiveness. Moreover, the recovery and valorization of waste heat through systems such as ORCs, Kalina cycles, and TEGs exemplify the circular economy approach, transforming thermal losses into productive outputs and pushing system efficiencies beyond 80%. The coupling of TES with

electrochemical batteries, green hydrogen production, and multi-energy vector architectures paves the way for decarbonized solutions across electricity, heating, cooling, and transportation sectors. The successful scaling of these solutions hinges on enabling policy frameworks, including carbon pricing, climate-aligned regulations, and performance-based incentives, as well as overcoming barriers such as material degradation, high capital costs, and system integration challenges. Interdisciplinary collaboration across academia, industry, and government is vital for advancing research in durable TES materials, modular deployment, and AI-optimized thermal architectures. Finally, the future of thermal energy lies in hybridized, digitally enhanced, and decarbonized configurations that balance performance, affordability, and sustainability. These integrated systems will be central to achieving global energy and climate goals, ensuring energy justice, environmental stewardship, and long-term resilience amid an increasingly uncertain global energy landscape.

5.1 Actionable recommendations

1. **Prioritize Research and Development of High-Performance TES Materials:** Governments and research institutions should increase funding and collaborative efforts focused on developing next-generation TES materials, such as nano-enhanced phase change materials and thermochemical compounds. These materials should aim to improve thermal conductivity, cycling stability, and cost-effectiveness to enable broader deployment across industrial, residential, and off-grid applications.
2. **Integrate AI-Driven Control Systems into Thermal Networks:** Energy utilities, developers, and technology providers should invest in AI and machine learning platforms for real-time monitoring, predictive maintenance, and optimization of thermal systems. Implementing digital twins and IoT-based architectures can enhance operational efficiency, enable autonomous fault detection, and support dynamic energy load balancing in multi-source thermal grids.
3. **Establish Policy Incentives and Standards for Hybrid Thermal-Renewable Systems:** Policymakers should implement targeted regulatory frameworks, including carbon pricing, tax credits, and performance-based subsidies, to incentivize the adoption of hybrid thermal systems integrated with renewables. Additionally, developing standardized guidelines for system interoperability and TES deployment will accelerate market uptake and ensure technology scalability across sectors.

References

- Abdullah, M., Obayedullah, M., and Musfika, S. A. (2025). Recent advances in phase change energy storage materials: developments and applications. *Int. J. Energy Res.* 2025 (1), 6668430. doi:10.1155/er/6668430
- Adams, P., Bridgwater, T., Lea-Langton, A., Ross, A., and Watson, I. (2018). "Biomass conversion technologies," in *Greenhouse gas balances of bioenergy systems* (Academic Press), 107–139.
- Adesusi, O. M., Adetunji, O. R., Kuye, S. I., Musa, A. I., Erinle, T. J., Gbadamosi-Olatunde, O. B., et al. (2023). A comprehensive review of the materials degradation phenomena in solid-liquid phase change materials for thermal energy storage. *Int. J. Thermofluids* 18, 100360. doi:10.1016/j.jijft.2023.100360
- Adeyemi, A., Olu-lawal, K. A., Okoli, C. E., Usman, F. O., and Usiagu, G. S. (2024). Sustainable energy solutions and climate change: a policy review of emerging trends and global responses. *World J. Adv. Res. Rev.* 21 (2), 408–420. doi:10.30574/wjarr.2024.21.2.0474
- Ahmad, R., Ilyas, H. N., Li, B., Sultan, M., Amjad, M., Aleem, M., et al. (2022). Current challenges and future prospect of biomass cooking and heating stoves in Asian countries. *Front. Energy Res.* 10, 880064. doi:10.3389/ferg.2022.880064

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

VE: Formal Analysis, Visualization, Data curation, Project administration, Resources, Validation, Methodology, Software, Supervision, Writing – review and editing, Conceptualization, Funding acquisition, Investigation, Writing – original draft.

Funding

The author(s) declare that no financial support was received for the research and/or publication of this article.

Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

Any alternative text (alt text) provided alongside figures in this article has been generated by Frontiers with the support of artificial intelligence and reasonable efforts have been made to ensure accuracy, including review by the authors wherever possible. If you identify any issues, please contact us.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

- Arabkoohsar, A. (2020). Combined steam based high-temperature heat and power storage with an organic rankine cycle, an efficient mechanical electricity storage technology. *J. Clean. Prod.* 247, 119098. doi:10.1016/j.jclepro.2019.119098
- Aridi, R. (2023). *Advanced heat recovery systems: use of vortex generators and hybridization with thermoelectric generators, considering renewable energy sources and life cycle assessment*. Doctoral dissertation, Angers, France: Université d'Angers.
- Bagherian, M. A., and Mehranzamir, K. (2020). A comprehensive review on renewable energy integration for combined heat and power production. *Energy Convers. Manag.* 224, 113454. doi:10.1016/j.enconman.2020.113454
- Balcombe, P., Anderson, K., Speirs, J., Brandon, N., and Hawkes, A. (2017). The natural gas supply chain: the importance of methane and carbon dioxide emissions. *ACS Sustain. Chem. and Eng.* 5 (1), 3–20. doi:10.1021/acssuschemeng.6b00144
- Balmes, J. R. (2019). Household air pollution from domestic combustion of solid fuels and health. *J. Allergy Clin. Immunol.* 143 (6), 1979–1987. doi:10.1016/j.jaci.2019.04.016
- Bebb, R., Barhdadi, M., Ficarella, A., Manente, G., Romano, M. P., El Hachemi, N., et al. (2024). Solar energy resource and power generation in Morocco: current situation, potential, and future perspective. *Resources* 13 (10), 140. doi:10.3390/resources13100140
- Blondeel, M., Bradshaw, M. J., Bridge, G., and Kuzemko, C. (2021). The geopolitics of energy system transformation: a review. *Geogr. Compass* 15 (7), e12580. doi:10.1111/gec3.12580
- Bora, R. R., Richardson, R. E., and You, F. (2020). Resource recovery and waste-to-energy from wastewater sludge via thermochemical conversion technologies in support of circular economy: a comprehensive review. *BMC Chem. Eng.* 2 (1), 8. doi:10.1186/s42480-020-00031-3
- Bordoff, J., and O'Sullivan, M. L. (2023). The age of energy insecurity: how the fight for resources is upending geopolitics. *Foreign Aff.* 102, 104.
- Brange, L., Englund, J., and Lauenburg, P. (2016). Prosumers in district heating networks—A Swedish case study. *Appl. Energy* 164, 492–500. doi:10.1016/j.apenergy.2015.12.020
- Brown, R. C. (2019). *Thermochemical processing of biomass: conversion into fuels, chemicals and power* (John Wiley and Sons).
- Brown, C. S., Kolo, I., Lyden, A., Franken, L., Kerr, N., Marshall-Cross, D., et al. (2024). Assessing the technical potential for underground thermal energy storage in the UK. *Renew. Sustain. Energy Rev.* 199, 114545. doi:10.1016/j.rser.2024.114545
- Burke, R. A., Fritz, K. M., Johnson, B. R., and Price, R. (2023). Mountaintop removal coal mining impacts on structural and functional indicators in central appalachian streams. *Front. water* 4, 988061. doi:10.3389/frwa.2022.988061
- Caineng, Z. O. U., Feng, M. A., Songqi, P. A. N., Minjie, L. I. N., Zhang, G., Xiong, B., et al. (2022). Earth energy evolution, human development and carbon neutral strategy. *Petroleum Explor. Dev.* 49 (2), 468–488. doi:10.1016/s1876-3804(22)60040-5
- Camacho, E. F., Ruiz-Moreno, S., Aguilar-López, J. M., Gallego, A. J., and García, R. A. (2024). Control of solar energy systems. *Annu. Rev. Control, Robotics, Aut. Syst.* 7, 175–200. doi:10.1146/annurev-control-071023-103936
- Cameron, W. J., Reddy, K. S., and Mallick, T. K. (2022). Review of high concentration photovoltaic thermal hybrid systems for highly efficient energy cogeneration. *Renew. Sustain. Energy Rev.* 163, 112512. doi:10.1016/j.rser.2022.112512
- Cavus, M. (2025). Advancing power systems with renewable energy and intelligent technologies: a comprehensive review on grid transformation and integration. *Electronics* 14 (6), 1159. doi:10.3390/electronics14061159
- Chen, S., Zhang, C., and Lu, X. (2023). “Energy conversion from fossil fuel to renewable energy,” in *Handbook of air quality and climate change* (Singapore: Springer Nature Singapore), 1–44.
- Chen, C. Y., Du, K. W., Chung, Y. C., and Wu, C. I. (2024). Advancements in thermoelectric generator design: exploring heat exchanger efficiency and material properties. *Energies* 17 (2), 453. doi:10.3390/en17020453
- Cochran, I., and Pauthier, A. (2019). *A framework for alignment with the paris agreement: why, what and how for financial institutions*, 56. Paris, France: Institute for Climate Economics.
- Codd, D. S., Gil, A., Manzoor, M. T., and Tetreault-Friend, M. (2020). Concentrating solar power (CSP)—Thermal energy storage (TES) advanced concept development and demonstrations. *Curr. Sustainable/Renewable Energy Rep.* 7, 17–27. doi:10.1007/s40518-020-00146-4
- Dahham, R. Y., Wei, H., and Pan, J. (2022). Improving thermal efficiency of internal combustion engines: recent progress and remaining challenges. *Energies* 15 (17), 6222. doi:10.3390/en15176222
- Daniarta, S. (2024). “Analysis of the low-boiling working fluid expansion processes in the volumetric expander operating in the ORC system,” in *Doctoral dissertation, Budapest university of technology and economics Hungary*.
- Dell'Aversano, S., Villante, C., Gallucci, K., Vanga, G., and Di Giuliano, A. (2024). E-fuels: a comprehensive review of the most promising technological alternatives towards an energy transition. *Energies* 17 (16), 3995. doi:10.3390/en17163995
- Deng, C., and Guo, L. (2024). The impact of offshore drilling activities on marine ecosystems. *Int. J. Eng. Sci. Technol.* 2 (1), doi:10.58531/ijest/2/1/2
- Di Silvestre, M. L., Favuzza, S., Sanseverino, E. R., and Zizzo, G. (2018). How decarbonization, digitalization and decentralization are changing key power infrastructures. *Renew. Sustain. Energy Rev.* 93, 483–498. doi:10.1016/j.rser.2018.05.068
- Dou, Y., Togawa, T., Dong, L., Fujii, M., Ohnishi, S., Tanikawa, H., et al. (2018). Innovative planning and evaluation system for district heating using waste heat considering spatial configuration: a case in Fukushima, Japan. *Resour. Conservation Recycl.* 128, 406–416. doi:10.1016/j.resconrec.2016.03.006
- Draou, M., and Brakez, A. (2024). Multi-objective optimization of a diverter-driven photovoltaic water heater: a residential case study in Morocco. *Appl. Therm. Eng.* 242, 122500. doi:10.1016/j.applthermaleng.2024.122500
- Echefaj, K., Cherrafi, A., Charkaoui, A., Gruchmann, T., and Ivanov, D. (2024). Firm survivability during long-term disruptions: an adaptation-based view. *Supply Chain Manag. An Int. J.* 29 (6), 978–995. doi:10.1108/scm-04-2024-0293
- Elkelawy, M., M El-Ashmawy, W., and Ahmed, S. M. (2024). State of the art in concentrated solar power: latest technological advancements and innovations in efficiency and energy storage. *Pharos Eng. Sci. J.* 1 (1), 17–28. doi:10.21608/pesj.2025.344983.1007
- Elkhatat, A., and Al-Muhtaseb, S. A. (2023). Combined “renewable energy-thermal energy storage (RE-TES)” systems: a review. *Energies* 16 (11), 4471. doi:10.3390/en16114471
- Enescu, D., Chicco, G., Porumb, R., and Seritan, G. (2020). Thermal energy storage for grid applications: current status and emerging trends. *Energies* 13 (2), 340. doi:10.3390/en13020340
- Ericsson, K., and Werner, S. (2016). The introduction and expansion of biomass use in Swedish district heating systems. *Biomass bioenergy* 94, 57–65. doi:10.1016/j.biombioe.2016.08.011
- Eze, V. H. U., Tamba, J. S., Eze, M. C., Okafor, W. O., and Bawor, F. H. (2024a). Integration of carbon capture utilization and storage into sustainable energy policies in Africa: the case of Liberia. *Oxf. Open Energy* 3, oiae011. doi:10.1093/ooenergy/oiae011
- Eze, V. H. U., Robert, O., Sarah, N. I., Tamball, J. S., Uzoma, O. F., and Okafor, W. O. (2024b). Transformative potential of thermal storage applications in advancing energy efficiency and sustainability. *IDOSR J. Appl. Sci.* 9 (1), 51–64. doi:10.59298/idosrjas/2024/1.8.9.295
- Eze, V. H. U., Mwenyi, J. S., Ukagwu, K. J., Eze, M. C., Eze, C. E., and Okafor, W. O. (2024c). Design analysis of a sustainable techno-economic hybrid renewable energy system: application of solar and wind in sigulu Island, Uganda. *Sci. Afr.* 26, e02454. doi:10.1016/j.sciaf.2024.e02454
- Eze, V. H. U., Eze, E. C., Alaneme, G. U., Bubur, P. E., Nnadi, E. O. E., and Okon, M. B. (2025a). Integrating IoT sensors and machine learning for sustainable precision agroecology: enhancing crop resilience and resource efficiency through data-driven strategies, challenges, and future prospects. *Discov. Agric.* 3 (1), 83–34. doi:10.1007/s44279-025-00247-y
- Eze, V. H. U., Eze, E. C., Alaneme, G. U., and Bubur, P. E. (2025b). Recent progress and emerging technologies in geothermal energy utilization for sustainable building heating and cooling: a focus on smart system integration and enhanced efficiency solutions. *Front. Built Environ.* 11, 1594355. doi:10.3389/fbuil.2025.1594355
- Farhat, O., Faraj, J., Hachem, F., Castelain, C., and Khaled, M. (2022). A recent review on waste heat recovery methodologies and applications: comprehensive review, critical analysis and potential recommendations. *Clean. Eng. Technol.* 6, 100387. doi:10.1016/j.clet.2021.100387
- Fernqvist, N., Broberg, S., Torén, J., and Svensson, I. L. (2023). District heating as a flexibility service: challenges in sector coupling for increased solar and wind power production in Sweden. *Energy Policy* 172, 113332. doi:10.1016/j.enpol.2022.113332
- Filho, R. D., Monteiro, A. C., Costa, T., Vasconcelos, A., Rode, A. C., and Marinho, M. (2023). Strategic guidelines for battery energy storage system deployment: regulatory framework, incentives, and market planning. *Energies* 16 (21), 7272. doi:10.3390/en16217272
- Filonchik, M., Peterson, M. P., Zhang, L., Hurynovich, V., and He, Y. (2024). Greenhouse gases emissions and global climate change: examining the influence of CO₂, CH₄, and N₂O. *Sci. Total Environ.* 935, 173359. doi:10.1016/j.scitotenv.2024.173359
- Garcia, J. A., Villen-Guzman, M., Rodriguez-Maroto, J. M., and Paz-Garcia, J. M. (2024). Comparing CO₂ storage and utilization: enhancing sustainability through renewable energy integration. *Sustainability* 16 (15), 6639. doi:10.3390/su16156639
- Gough, C., Thornley, P., Mander, S., Vaughan, N., and Lea-Langton, A. (2018). *Biomass energy with carbon capture and storage (BECCS): unlocking negative emissions*.
- Guha, M. (2025). Role of the inflation reduction acts in financing hydrogen energy projects: opportunities and challenges. *Role Green Transition Finance Achiev. Carbon Neutrality Sustain. Energy*, 207–236. doi:10.1016/b978-0-443-24736-1.00009-8
- Gul, M., Kashif, M., Muhammad, S., Azizi, S., and Sun, H. (2025). Various methods of synthesis and applications of gold-based nanomaterials: a detailed review. *Cryst. Growth and Des.* 25 (7), 2227–2266. doi:10.1021/acs.cgd.4c01687
- Gupta, J., and Chu, E. (2018). Inclusive development and climate change: the geopolitics of fossil fuel risks in developing countries. *Afr. Asian Stud.* 17 (1–2), 90–114. doi:10.1163/15692108-12341402

- Hammerstingl, A. (2024). Techno-economic assessment and optimization of seasonal borehole thermal energy storage in district heating networks.
- Hassan, Q., Viktor, P., Al-Musawi, T. J., Ali, B. M., Algburi, S., Alzoubi, H. M., et al. (2024). The renewable energy role in the global energy transformations. *Renew. Energy Focus* 48, 100545. doi:10.1016/j.ref.2024.100545
- Hayati, M. M., Aminlou, A., Abapour, M., Shafie-khah, M., Shahinzadeh, H., and Gharehpetian, G. B. (2025). The Power-to-X (PtX) effect in ancillary service markets: from opportunities and challenges toward future directions. *Power-to-X Regional Energy Syst.*, 432–451. doi:10.1201/9781032719436
- Howarth, R. W. (2021). “Methane and climate change,” in *Environmental impacts from development of unconventional oil and gas reserves*. Editors F. John, W. Stolz, M. Griffin, and D. J. Bain
- Huang, J., Luo, Y., Weng, M., Yu, J., Sun, L., Zeng, H., et al. (2021). Advances and applications of phase change materials (PCMs) and PCMs-based technologies. *ES Mater. and Manuf.* 13 (25), 23–39. doi:10.30919/esmm5f458
- Hussain, S. K. (2016). *Heat transfer to graphene nanoplatelets and Metaloxides-Studies in thermophysical properties and particle characterization*. Malaysia: University of Malaya.
- Islam, M. M., Hasanuzzaman, M., Pandey, A. K., and Rahim, N. A. (2020). “Modern energy conversion technologies,” in *Energy for sustainable development* (Academic Press), 19–39.
- Ives, M., Righetti, L., Schiele, J., De Meyer, K., Hubble-Rose, L., Teng, F., et al. (2021). A new perspective on decarbonising the global energy system.
- Jabbar, M. Y., Ahmed, S. Y., and Waheed Khafaji, S. O. (2024). A scoping review of the thermoelectric generator systems designs (heat exchangers and coolers) with locations of application to recover energy from internal combustion engines. *J. Appl. and Comput. Mech.* 10 (3). doi:10.22055/jacm.2024.45491.4376
- Jaiswal, K. K., Dutta, S., Banerjee, I., Pohrmen, C. B., and Kumar, V. (2023). Photosynthetic microalgae-based carbon sequestration and generation of biomass in biorefinery approach for renewable biofuels for a cleaner environment. *Biomass Convers. Biorefinery* 13 (9), 7403–7421. doi:10.1007/s13399-021-01504-y
- Jaziri, N., Boughamou, A., Müller, J., Mezghani, B., Tounsi, F., and Ismail, M. (2020). A comprehensive review of thermoelectric generators: technologies and common applications. *Energy Rep.* 6, 264–287. doi:10.1016/j.egyr.2019.12.011
- Jebasingh, B. E., and Arasu, A. V. (2020). A detailed review on heat transfer rate, supercooling, thermal stability and reliability of nanoparticle dispersed organic phase change material for low-temperature applications. *Mater. Today Energy* 16, 100408. doi:10.1016/j.mtener.2020.100408
- Johansen, K., and Werner, S. (2022). Something is sustainable in the state of Denmark: a review of the Danish district heating sector. *Renew. Sustain. Energy Rev.* 158, 112117. doi:10.1016/j.rser.2022.112117
- Jurema, B., and König, E. (2024). “State power and capital in the climate crisis: a theory of fossil imperialism,” in *Confronting climate coloniality* (London, New York: Routledge), 62–77. doi:10.4324/9781003465973-5
- Kabeyi, M. J. B., and Olanrewaju, O. A. (2022). Sustainable energy transition for renewable and low carbon grid electricity generation and supply. *Front. Energy Res.* 9, 743114. doi:10.3389/fteng.2021.743114
- Khaleel, M., Yusupov, S., Alfal, B., Guneser, M. T., Nassar, Y., and El-Khozondar, H. (2024). Impact of smart grid technologies on sustainable urban development. *Int. J. Electr. Eng. Sustain.*, 62–82. doi:10.5281/zenodo.11577746
- Khalid, S., Azad, M. M., and Kim, H. S. (2025). A generalized autonomous power plant fault detection model using deep feature extraction and ensemble machine learning. *Mathematics* 13 (3), 342. doi:10.3390/math13030342
- Khayyam, H., Naebe, M., Milani, A. S., Fakhroesini, S. M., Date, A., Shabani, B., et al. (2021). Improving energy efficiency of carbon fiber manufacturing through waste heat recovery: a circular economy approach with machine learning. *Energy* 225, 120113. doi:10.1016/j.energy.2021.120113
- Kim, D., Lee, J., Do, S., Mago, P. J., Lee, K. H., and Cho, H. (2022). Energy modeling and model predictive control for HVAC in buildings: a review of current research trends. *Energies* 15 (19), 7231. doi:10.3390/en15197231
- Kim, S., Lee, J., Lee, S., Lee, S., Kim, K., and Min, K. (2024). Effects of various compression ratios on a direct injection spark ignition hydrogen-fueled engine in a single-cylinder engine. *Int. J. Automot. Technol.* 25 (5), 1159–1172. doi:10.1007/s12239-024-00096-6
- Konur, O., Colpan, C. O., and Saatcioglu, O. Y. (2022). A comprehensive review on organic rankine cycle systems used as waste heat recovery technologies for marine applications. *Energy Sources, Part A Recovery, Util. Environ. Eff.* 44 (2), 4083–4122. doi:10.1080/15567036.2022.2072981
- Kumar, A., Singh, V. P., Meena, C. S., and Dutt, N. (2023). *Thermal energy systems: design, computational techniques, and applications* (United Kingdom, India: CRC Press). doi:10.1201/9781003395768
- Kundu, A., Kumar, A., Dutt, N., Meena, C. S., and Singh, V. P. (2023). “Introduction to thermal energy resources and their smart applications,” in *Thermal energy systems* (CRC Press), 1–15.
- Laaroussi, A., Laaroussi, O., and Bouayad, A. (2023). Environmental impact study of the NOOR 1 solar project on the southern region of Morocco. *Renew. Energy Environ. Sustain.* 8, 9. doi:10.1051/rees/2023007
- Larki, I., Zahedi, A., Asadi, M., Forootan, M. M., Farajollahi, M., Ahmadi, R., et al. (2023). Mitigation approaches and techniques for combustion power plants’ flue gas emissions: a comprehensive review. *Sci. Total Environ.* 903, 166108. doi:10.1016/j.scitotenv.2023.166108
- Larrinaga, P., Campos-Celador, Á., Legarreta, J., and Dierce, G. (2021). Evaluation of the theoretical, technical and economic potential of industrial waste heat recovery in the Basque Country. *J. Clean. Prod.* 312, 127494. doi:10.1016/j.jclepro.2021.127494
- Li, L., He, Y., Zhang, H., Fung, J. C., and Lau, A. K. (2023). Enhancing IAQ, thermal comfort, and energy efficiency through an adaptive multi-objective particle swarm optimizer-grey wolf optimization algorithm for smart environmental control. *Build. Environ.* 235, 110235. doi:10.1016/j.buildenv.2023.110235
- Liu, J. (2019). China’s renewable energy law and policy: a critical review. *Renew. Sustain. Energy Rev.* 99, 212–219. doi:10.1016/j.rser.2018.10.007
- Liu, T., Hanna, R., and Kountouris, Y. (2025). Decarbonising heating and cooling: barriers and opportunities facing aquifer thermal energy storage in the United Kingdom. *Energy Res. and Soc. Sci.* 122, 104006. doi:10.1016/j.erss.2025.104006
- Lu, B., Shi, L., Tian, H., Wang, X., Zhang, M., and Shu, G. (2022). A four-dimensional interaction-based appraisal approach towards the performance enhancement of a vehicular waste heat recovery system. *Sci. China Technol. Sci.* 65 (12), 2921–2941. doi:10.1007/s11431-022-2153-5
- Makepa, D. C., and Chihobo, C. H. (2024). Sustainable pathways for biomass production and utilization in carbon capture and Storage—a review. *Biomass Convers. Biorefinery* 15, 11397–11419. doi:10.1007/s13399-024-06010-5
- Marelli, L., Trane, M., Barbero, V. G., Gastaldi, C., Guerreiro, M. M., Delgado, C. L., et al. (2025). Delivering the EU green deal-progress towards targets.
- Mehetre, S. A., Panwar, N. L., Sharma, D., and Kumar, H. (2017). Improved biomass cookstoves for sustainable development: a review. *Renew. Sustain. Energy Rev.* 73, 672–687. doi:10.1016/j.rser.2017.01.150
- Mehling, H. (2024). Review of classification of PCMs, with a focus on the search for new, suitable PCM candidates. *Energies* 17 (17), 4455. doi:10.3390/en17174455
- Mehta, B., Subhedar, D., Panchal, H., and Said, Z. (2022). Synthesis, stability, thermophysical properties and heat transfer applications of nanofluid—A review. *J. Mol. Liq.* 364, 120034. doi:10.1016/j.molliq.2022.120034
- Mira, K., Bugiotti, F., and Morosuk, T. (2023). Artificial intelligence and machine learning in energy conversion and management. *Energies* 16 (23), 7773. doi:10.3390/en16237773
- Mohamed, O., Khalil, A., and Wang, J. (2020). Modeling and control of supercritical and ultra-supercritical power plants: a review. *Energies* 13 (11), 2935. doi:10.3390/en13112935
- Mohanty, T., Dash, S., Pattanaik, P., Tripathy, H. P., Gulati, J. M. L., Mishra, D. K., et al. (2025). Utilization of biomass ash generated from combined heat and power generation system as a multi-nutrient source for crops. *Int. J. Thermofluids* 25, 101037. doi:10.1016/j.ijft.2024.101037
- Mohite, D. D., Goyal, A., Singh, A. S., Ansari, M. I., Patil, K. A., Yadav, P. D., et al. (2024). Improvement of thermal performance through nanofluids in industrial applications: a review on technical aspects. *Mater. Today Proc.* doi:10.1016/j.matpr.2024.04.083
- Mohtasim, Md S., and Das, B. K. (2024). Biomimetic and bio-derived composite phase change materials for thermal energy storage applications: a thorough analysis and future research directions. *J. Energy Storage* 84, 110945. doi:10.1016/j.est.2024.110945
- Narassimhan, E., Gallagher, K. S., Koester, S., and Alejo, J. R. (2018). Carbon pricing in practice: a review of existing emissions trading systems. *Clim. Policy* 18 (8), 967–991. doi:10.1080/14693062.2018.1467827
- Nishad, D., Maurya, R., Srivastava, A., Prakash, S., and Singh, A. K. (2024). “A concise review on the advancement in solar thermal technology: harnessing sustainable energy for a greener future,” in *2024 IEEE region 10 symposium (TENSYP)* (IEEE), 1–6.
- Nurdiawati, A., and Urban, F. (2021). Towards deep decarbonisation of energy-intensive industries: a review of current status, technologies and policies. *Energies* 14 (9), 2408. doi:10.3390/en14092408
- Odubo, T. C., and Kosoe, E. A. (2024). “Sources of air pollutants: impacts and solutions,” in *Air pollutants in the context of one health: fundamentals, sources, and impacts* (Cham: Springer Nature Switzerland), 75–121.
- Ohji, A., and Haraguchi, M. (2022). “Steam turbine cycles and cycle design optimization: the rankine cycle, thermal power cycles, and integrated gasification-combined cycle power plants,” in *Advances in steam turbines for modern power plants* (Woodhead Publishing), 11–40. doi:10.1016/B978-0-12-824359-6.00020-2
- Ononogbo, C., Nwosu, E. C., Nwakuba, N. R., Nwaji, G. N., Nwufor, O. C., Chukwuezie, O. C., et al. (2023). Opportunities of waste heat recovery from various sources: review of technologies and implementation. *Heliyon* 9 (2), e13590. doi:10.1016/j.heliyon.2023.e13590
- Pandey, C., Wu, M., Oyeniran, A., Chougule, S. S., Acosta Pazmiño, I., Rivera-Solorio, C. I., et al. (2025). Numerical study of a parabolic-trough CPV-T collector with spectral-splitting liquid filters. *Front. Energy*, 1–20. doi:10.1007/s11708-025-1028-y

- Patil, B., Salunke, N., Diware, V., Raheman Ar, S., and Ansari, K. B. (2025). Stability assessment of emerging phase change materials for solar thermal storage in absorption refrigeration: a review. *Int. J. Green Energy* 22 (2), 253–280. doi:10.1080/15435075.2024.2413678
- Perera, F. (2018). Pollution from fossil-fuel combustion is the leading environmental threat to global pediatric health and equity: solutions exist. *Int. J. Environ. Res. public health* 15 (1), 16. doi:10.3390/ijerph15010016
- Pili, R., Martínez, L. G., Wieland, C., and Spliethoff, H. (2020). Techno-economic potential of waste heat recovery from German energy-intensive industry with organic rankine cycle technology. *Renew. Sustain. Energy Rev.* 134, 110324. doi:10.1016/j.rser.2020.110324
- Pradhan, P., Mahajani, S. M., and Arora, A. (2018). Production and utilization of fuel pellets from biomass: a review. *Fuel Process. Technol.* 181, 215–232. doi:10.1016/j.fuproc.2018.09.021
- Radtke, J. (2025). Understanding the complexity of governing energy transitions: introducing an integrated approach of policy and transition perspectives. *Environ. Policy Gov.* 35, 595–614. doi:10.1002/eet.2158
- Raghuvanshi, N. S., Johri, A., Saxena, M., Kumar, A., Dutt, N., Awasthi, M. K., et al. (2025). “Innovative technologies in heat exchangers for renewable energy systems,” in *Heat exchanger technologies for sustainable renewable energy systems* (CRC Press), 1–29.
- Rajaperumal, T. A., and Columbus, C. C. (2025). Transforming the electrical grid: the role of AI in advancing smart, sustainable, and secure energy systems. *Energy Inf.* 8 (1), 51. doi:10.1186/s42162-024-00461-w
- Ram, M., and Mondal, M. K. (2022). “Biomass gasification: a step toward cleaner fuel and chemicals,” in *Biofuels and bioenergy* (Elsevier), 253–276.
- Rathi, V., Brajpuria, R., Gupta, R., Parmar, K. P. S., and Kumar, A. (2024). Graphene-derived composites: a new frontier in thermoelectric energy conversion. *Energy Adv.* 3 (2), 389–412. doi:10.1039/d3ya00526g
- Rezaei, M., Sameti, M., and Nasiri, F. (2021). Biomass-fuelled combined heat and power: integration in district heating and thermal-energy storage. *Clean. Energy* 5 (1), 44–56. doi:10.1093/ce/ckaa031
- Rosales-Pérez, J. F., Villarruel-Jaramillo, A., Romero-Ramos, J. A., Pérez-García, M., Cardemil, J. M., and Escobar, R. (2023). Hybrid system of photovoltaic and solar thermal technologies for industrial process heat. *Energies* 16 (5), 2220. doi:10.3390/en16052220
- Sadeghi, G. (2022). Energy storage on demand: thermal energy storage development, materials, design, and integration challenges. *Energy Storage Mater.* 46, 192–222. doi:10.1016/j.ensm.2022.01.017
- Safari, A., Daneshvar, M., and Anvari-Moghaddam, A. (2024). Energy intelligence: a systematic review of artificial intelligence for energy management. *Appl. Sci.* 14 (23), 11112. doi:10.3390/app142311112
- Salime, Z. (2021). Life in the vicinity of Morocco’s noor solar energy project. *Middle East Rep.* 298.
- Samuel, S. A. (2025). Carbon pricing mechanisms for reducing greenhouse gas emissions and encouraging sustainable industrial practices. *World J. Adv. Res. Rev.* 25, 001–024. doi:10.30574/wjarr.2025.25.2.0350
- Sarmah, D. K. (2019). “A survey on the latest development of machine learning in genetic algorithm and particle swarm optimization,” in *Optimization in machine learning and applications* (Singapore: Springer Singapore), 91–112.
- Sarvar-Ardeh, S., Rashidi, S., Rafae, R., and Li, G. (2024). Recent advances in the applications of solar-driven co-generation systems for heat, freshwater and power. *Renew. Energy* 225, 120256. doi:10.1016/j.renene.2024.120256
- Saxena, V., Manna, S., Rajput, S. K., Kumar, P., Sharma, B., Alsharif, M. H., et al. (2024). Navigating the complexities of distributed generation: integration, challenges, and solutions. *Energy Rep.* 12, 3302–3322. doi:10.1016/j.egy.2024.09.017
- Scafuri, A. (2025). Thermal energy storage integration in electrical grids and in energy industries for decarbonization.
- Seo, D., Oh, S., Shin, S., Lee, M., Hwang, Y., and Seo, S. (2019). Smartphone compatible on-site fluorescence analyzer for spilled crude oil based on CMOS image sensor. *Sensors Actuators B Chem.* 289, 93–99. doi:10.1016/j.snb.2019.03.086
- Shaban, W. M., Kabeel, A. E., Attia, M. E. H., and Talaat, F. M. (2024). Optimizing photovoltaic thermal solar systems efficiency through advanced artificial intelligence driven thermal management techniques. *Appl. Therm. Eng.* 247, 123029. doi:10.1016/j.applthermaleng.2024.123029
- Shahid, M. I., Farhan, M., Rao, A., Hussain, M. S., Salam, H. A., Chen, T., et al. (2025). Hydrogen production by waste heat recovery of hydrogen-enriched compressed natural gas via steam methane reforming process. *Int. J. Hydrogen Energy* 117, 374–392. doi:10.1016/j.ijhydene.2025.03.105
- Sharma, P. K., Senguttuvan, T. D., Sharma, V. K., and Chaudhary, S. (2021). Revisiting the thermoelectric properties of lead telluride. *Mater. Today Energy* 21, 100713. doi:10.1016/j.mtener.2021.100713
- Shaukat, N., Islam, M. R., Rahman, M. M., Khan, B., Ullah, B., Ali, S. M., et al. (2023). Decentralized, democratized, and decarbonized future electric power distribution grids: a survey on the paradigm shift from the conventional power system to micro grid structures. *IEEE Access* 11, 60957–60987. doi:10.1109/access.2023.3284031
- Siddique, A. R. M., Mahmud, S., and Van Heyst, B. (2017). A review of the state of the science on wearable thermoelectric power generators (TEGs) and their existing challenges. *Renew. Sustain. Energy Rev.* 73, 730–744. doi:10.1016/j.rser.2017.01.177
- Silva, I., Lapa, N., Ribeiro, H., and Duarte, E. (2025). Pig slurry anaerobic digestion: the role of biochar as an additive towards biogas and digestate improvement. *Appl. Sci.* 15 (3), 1037. doi:10.3390/app15031037
- Simó-Solsona, M., Palumbo, M., Bosch, M., and Fernandez, A. I. (2021). Why it’s so hard? Exploring social barriers for the deployment of thermal energy storage in Spanish buildings. *Energy Res. and Soc. Sci.* 76, 102057. doi:10.1016/j.erss.2021.102057
- Singh, B. S. B. (2023). “Thermoelectric generators: design, operation, and applications,” in *New materials and devices for thermoelectric power generation* (IntechOpen).
- Singh, B., and Kaunert, C. (2024). “Dynamic landscape of artificial general intelligence (AGI) for advancing renewable energy in urban environments: synergies with SDG 11—Sustainable cities and communities lensing policy and governance,” in *Artificial general intelligence (AGI) security: smart applications and sustainable technologies* (Singapore: Springer Nature Singapore), 247–270.
- Singh, R., Arya, P. K., and Agrawal, A. (2025). “The global energy landscape and the smart grid: a paradigm shift towards sustainability,” in *Green machine learning and big data for smart grids*, 221–234.
- Snyder, G. J., and Snyder, A. H. (2017). Figure of merit ZT of a thermoelectric device defined from materials properties. *Energy and Environ. Sci.* 10 (11), 2280–2283. doi:10.1039/c7ee02007d
- Solangi, K. H., Kazi, S. N., Luhur, M. R., Badarudin, A., Amiri, A., Sadri, R., et al. (2015). A comprehensive review of thermo-physical properties and convective heat transfer to nanofluids. *Energy* 89, 1065–1086. doi:10.1016/j.energy.2015.06.105
- Sreelekshmi, S., and Nandan, S. B. (2025). Sustainability challenges of mangrove ecosystems in the anthropocene: current perspectives and prospects. *Habitable Planet* 1 (1and2), 129–144. doi:10.63335/j.hp.2025.0011
- Stern, J. P. (2020). *Methane emissions from natural gas and LNG imports: an increasingly urgent issue for the future of gas in Europe* (no. 165). Oxford: The Oxford Institute for Energy Studies. OIES Pap. NG.
- Subbarao, P. M., D’Silva, T. C., Adlak, K., Kumar, S., Chandra, R., and Vijay, V. K. (2023). Anaerobic digestion as a sustainable technology for efficiently utilizing biomass in the context of carbon neutrality and circular economy. *Environ. Res.* 234, 116286. doi:10.1016/j.envres.2023.116286
- Thapa, N. (2022). AI-driven approaches for optimizing the energy efficiency of integrated energy system.
- Thekdi, A., and Nimbalkar, S. U. (2015). Industrial waste heat recovery-potential applications, available technologies and crosscutting r&d opportunities (no. ORNL/TM-2014/622). Oak Ridge, TN (United States): Oak Ridge National Lab. ORNL.
- Tiktas, A., Gunerhan, H., and Hepbasli, A. (2022). Single and multigeneration rankine cycles with aspects of thermodynamical modeling, energy and exergy analyses and optimization: a key review along with novel system description figures. *Energy Convers. Manag.* 14, 100199. doi:10.1016/j.ecmx.2022.100199
- Togun, H., Sultan, H. S., Mohammed, H. I., Sadeq, A. M., Biswas, N., Hasan, H. A., et al. (2024). A critical review on phase change materials (PCM) based heat exchanger: different hybrid techniques for the enhancement. *J. Energy Storage* 79, 109840. doi:10.1016/j.est.2023.109840
- Tuller, H. L. (2017). Solar to fuels conversion technologies: a perspective. *Mater. Renew. Sustain. Energy* 6, 3–16. doi:10.1007/s40243-017-0088-2
- Ukoba, K., Olatunji, K. O., Adeoye, E., Jen, T. C., and Madyira, D. M. (2024). Optimizing renewable energy systems through artificial intelligence: review and future prospects. *Energy and Environ.* 35 (7), 3833–3879. doi:10.1177/0958305x241256293
- Uzoagba, C., Onwualu, P. A., Okoroigwe, E., Kadivar, M., Oribu, W. S., Mguni, N. G., et al. (2024). A review of biomass valorization for bioenergy and rural electricity generation in Nigeria. *Cureus* 1 (1). doi:10.7759/s44388-024-00065-w
- Verma, S. K., Kumar, R., Barthwal, M., and Rakshit, D. (2022). A review on futuristic aspects of hybrid photo-voltaic thermal systems (PV/T) in solar energy utilization: engineering and technological approaches. *Sustain. Energy Technol. Assessments* 53, 102463. doi:10.1016/j.seta.2022.102463
- Vitorino, N., Abrantes, J. C., and Frade, J. R. (2016). Quality criteria for phase change materials selection. *Energy Convers. Manag.* 124, 598–606. doi:10.1016/j.enconman.2016.07.063
- Wang, G., Chou, P., Li, Y., Xia, L., Liu, Y., and Wei, G. (2025). Solar spectral beam splitting simulation of aluminum-based nanofluid compatible with photovoltaic cells. *Energies* 18 (10), 2460. doi:10.3390/en18102460
- Weng, J., Huang, Q., Li, X., Zhang, G., Ouyang, D., Chen, M., et al. (2022). Safety issue on PCM-Based battery thermal management: material thermal stability and system hazard mitigation. *Energy Storage Mater.* 53, 580–612. doi:10.1016/j.ensm.2022.09.007
- Wieland, C., Schiffler, C., Braimakis, K., Kaufmann, F., Dawo, F., Karellas, S., et al. (2023). Innovations for organic rankine cycle power systems: current trends and

future perspectives. *Appl. Therm. Eng.* 225, 120201. doi:10.1016/j.applthermaleng.2023.120201

Wijesekara, D., Amarasinghe, P., Induranga, A., Vithanage, V., and Koswattage, K. R. (2025). Energy, exergy, and environmental impact analysis and optimization of coal-biomass combustion combined cycle CHP systems. *Sustainability* 17 (6), 2363. doi:10.3390/su17062363

Wu, S., Yan, T., Kuai, Z., and Pan, W. (2020). Thermal conductivity enhancement on phase change materials for thermal energy storage: a review. *Energy Storage Mater.* 25, 251–295. doi:10.1016/j.ensm.2019.10.010

Xing, J., Zhang, Y., Li, B., Cao, Z., Zhan, C., Liu, Y., et al. (2024). Terrestrial oil spills recognition based on small samples from UAV multispectral images. *IEEE Sensors J.* 24, 37786–37799. doi:10.1109/jsen.2024.3467698

Xu, H., Wang, J., Zhou, Y., and Jiang, H. (2024). Thermodynamic analysis of trigeneration system with controlled thermal-electric ratio by coupling liquefied natural gas cold energy and biomass partial gasification. *Energy* 308, 132973. doi:10.1016/j.energy.2024.132973

Yang, Z., Zhang, Y., Jie, Z., Yang, Y., Yufei, J., Song, H., et al. (2025). AI-Driven safety and security for UAVs: from machine learning to large language models. *Drones* 9 (6), 392. doi:10.3390/drones9060392

Yapp, E. H. T., Jamil, N., Lee, L. S. G., Chooi, Y. T., and Chen, C. O. (2025). Urban farming: the challenges of hydroponic and vertical farming in Malaysia. *Cogent Food Agri.* 11 (1), 2448601. doi:10.1080/23311932.2024.2448601

Younes, H., Mao, M., Murshed, S. S., Lou, D., Hong, H., and Peterson, G. P. (2022). Nanofluids: key parameters to enhance thermal conductivity and its applications. *Appl. Therm. Eng.* 207, 118202. doi:10.1016/j.applthermaleng.2022.118202

Zamanipour, Z., Thallapelly, S. K., and Pirmahalleh, S. M. S. (2024). Advances in the performance of hybrid photovoltaic-thermoelectric generators: a review. *Future Technol.* 3 (4), 1–11. doi:10.55670/fptll.futech.3.4.1

Zhang, X., Yang, J., Fan, Y., Zhao, X., Yan, R., Zhao, J., et al. (2020). Experimental and analytic study of a hybrid solar/biomass rural heating system. *Energy* 190, 116392. doi:10.1016/j.energy.2019.116392

Zhang, C., Liu, C., Li, X., Liu, P., Zhang, Y., Du, Q., et al. (2021). A novel clean combustion technology for solid fuels to efficiently reduce gaseous and particulate emissions. *J. Clean. Prod.* 320, 128864. doi:10.1016/j.jclepro.2021.128864

Zhang, S., Ocloń, P., Klemes, J. J., Michorczyk, P., Pielichowska, K., and Pielichowski, K. (2022). Renewable energy systems for building heating, cooling and electricity production with thermal energy storage. *Renew. Sustain. Energy Rev.* 165, 112560. doi:10.1016/j.rser.2022.112560

Zhou, Y., and Liu, J. (2024). Advances in emerging digital technologies for energy efficiency and energy integration in smart cities. *Energy Build.* 315, 114289. doi:10.1016/j.enbuild.2024.114289

Zhu, B., Deng, Y., Cao, F., Li, B., and Yao, M. (2025). Research on the thermal management system of extended-range electric vehicles based on exhaust heat recovery using thermal battery.