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SYSTEMATIC REVIEW

Technological Mapping and Emerging Applications of Free-Piston Engine Systems: A Comparative Review of FPSE and FPCE Architectures

Mapeo Tecnológico y Aplicaciones Emergentes de los Sistemas de Motores de Pistón Libre: Una Revisión Comparativa de las Arquitecturas FPSE y FPCE

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ABSTRACT

Introduction: Free-Piston Engine (FPE) technology provides flexible energy conversion for applications such as hybrid vehicles and micro-CHP systems. However, studies on Free-Piston Stirling Engines (FPSE) and Free-Piston Combustion Engines (FPCE) are still scattered, with limited analysis of their designs, subsystems, and applications. The aim is to describe recent technical gains and highlight promising avenues for deployment in energy supply and mobile applications.
Method: a Systematic Literature Review (SLR) was conducted using the PRISMA-PCF protocol. Of the 263 articles identified in the Scopus database, 77 were selected based on three research questions. NVivo software supported thematic content analysis.
Result: the review identified two primary FPE types: FPSE, which is suitable for external heat sources such as solar and cryogenic systems, and FPCE, which features variable compression and adaptability for hybrid vehicles. Key subsystems, such as linear alternators and return mechanisms, support distinct technical functions. Applications span energy generation, waste heat recovery, and renewable energy systems.
Conclusions: this study maps the progress and application areas of FPSE and FPCE, highlighting opportunities for integration and providing direction for future development in design and performance optimization.

Keywords: Free-Piston Engine; FPSE; FPCE; Energy Conversion; Linear Alternator.

RESUMEN

Introducción: la tecnología de motores de pistón libre (FPE) ofrece una conversión de energía flexible para aplicaciones como vehículos híbridos y sistemas micro-CHP. Sin embargo, los estudios sobre los motores Stirling de pistón libre (FPSE) y los motores de combustión de pistón libre (FPCE) aún están dispersos, con un análisis limitado de sus diseños, subsistemas y aplicaciones. El objetivo es describir los avances técnicos recientes y destacar vías prometedoras para su implementación en el suministro energético y aplicaciones móviles.
Método: se realizó una Revisión Sistemática de la Literatura (SLR) siguiendo el protocolo PRISMA-PCF. De los 263 artículos identificados en la base de datos Scopus, se seleccionaron 77 con base en tres preguntas de investigación. El software NVivo apoyó el análisis temático de contenido.
Resultados: la revisión identificó dos tipos principales de FPE: el FPSE, adecuado para fuentes de calor externas como sistemas solares y criogénicos, y el FPCE, que presenta compresión variable y adaptabilidad para vehículos híbridos. Subsistemas clave, como los alternadores lineales y los mecanismos de retorno, cumplen funciones técnicas distintas. Las aplicaciones abarcan la generación de energía, la recuperación de calor residual y la integración con fuentes de energía renovable.

Conclusiones: este estudio traza el desarrollo y las áreas de aplicación del FPSE y FPCE, subrayando oportunidades de integración y brindando orientación para el desarrollo futuro en el diseño y la optimización del rendimiento.

Palabras clave: Motor de Pistón Libre; FPSE; FPCE; Conversión de Energía; Alternador Lineal.

INTRODUCTION

The internal combustion free-piston engine (FPE) is an innovative engine design, as it eliminates the crankshaft and flywheel; thus, the engine's pistons oscillate linearly, greatly reducing friction loss. The critical appeal of FPEs in remote power generation and the propulsion of hybrid vehicles stems from high thermal efficiency and the capability of direct energy conversion using linear alternators.[1,2] The compact construction allows for the flexible use of fuels, including biofuels and other alternative fuels, without any compression ratio limits, resulting in optimized engine performance.[3,4] Combustion instability can be minimized through accurate motion control, while simulation innovations can enhance designs and improve overall system dependability.[5,6,7] The thermal efficiency of FPEs is reported to surpass that of conventional engines, aligning with sustainability goals in the energy industry. In light of these considerations, the authors underline the need for a systematic and comparative review to stimulate academic research and industrial innovation.

Free Piston Stirling Engines (FPSE) and Free Piston Combustion Engines (FPCE) are types of Free Piston Engines (FPE) that are researched for their use in sustainable power systems and modular power systems. In Europe and East Asia, FPSEs are commonly used in off-grid power systems as well as in solar thermal systems and micro combined heat and power (micro-CHP) units.[8,9] On the contrary, FPCEs are primarily used in the development of hybrid electric vehicles and unmanned aerial vehicles in the US and China. Although FPEs have high efficiency and are mechanically simple, their adoption in the market is limited due to the complicated controls, limited scalability, and integration problems.[10,11] Investigative literature is essential for understanding FPSEs and FPCEs and their advantages, disadvantages, and optimal use cases.[12,13]

Both Free-Piston Stirling Engines (FPSEs) and Free-Piston Combustion Engines (FPCEs) have two important parts in common: a linear alternator that converts piston motion into electricity through electromagnetic induction and a return mechanism that sustains oscillatory motion through pneumatic, hydraulic, or spring systems.[14] Even though these parts are similar, FPSEs and FPCEs differ in operations due to their heat sources: FPSEs fire externally, cleaner, but FPCEs use internal, more complex control.[15,16] The return mechanism also impacts reliability and efficiency; FPSEs are more reliable due to their use of hydraulics and lower mechanical strain, along with no needed upkeep. These structural and thermal features determine their applications—FPSEs are used in long-life, low-emission systems, while FPCEs are used in compact, high-output power units.[17] Despite these differences, integrated analyses are rare, highlighting both technologies about each other to inform prospective development paths.

Table 1. Research Questions, Objectives and Motivation.

RQ	Research Question	Objective	Motivation
RQ1	How have FPSE and FPCE technologies evolved in terms of structural design and function?	To map the chronological development of free-piston engine systems based on design and functional aspects.	Understanding how architectural differences shape performance and guide application choices across domains.
RQ2	What are the core components of FPSE and FPCE, and how do they influence performance?	To identify and compare key components—particularly the linear alternator and return mechanism—used in both engine types.	Clarifying the engineering factors that determine operational efficiency and reliability in free-piston systems.
RQ3	In which application domains have FPSE and FPCE been implemented, and what trends can be identified?	To classify and analyze real-world and experimental applications of FPSE and FPCE across sectors.	Revealing trends and gaps in usage to inform future development, commercialization, and interdisciplinary integration.

Free-Piston Stirling Engines (FPSEs) and Free-Piston Combustion Engines (FPCEs) research appears to focus on single components like control mechanisms[6], thermodynamic performance[18], or application-tuned prototypes[15,19] without providing an integrated juxtaposition of both systems. Such an approach is counterproductive as it impedes researchers and engineers from computing the architecture, dynamics, and real-world impact of the systems. Enhanced control strategies show promise for FPCEs, including neural network-based compression ratio contro. Likewise, some studies have shown that the absence of crankshafts in FPEs reduces friction, thereby improving thermodynamic efficiency.[20] However, the detailed and comparative analysis of FPSE and FPCE technologies is lacking, which in turn impedes optimal design and industrial utilization. This is crucial in guiding innovation and future advancements toward energy efficiency and environmental impact.

The primary objective of this study is to systematically map the technological development and emerging applications of free-piston engine systems, with a focus on Free-Piston Stirling Engines (FPSE) and Free-Piston Combustion Engines (FPCE). Using a Systematic Literature Review (SLR) approach, this study aims to explore how these two models have evolved in design, core components, and practical implementation (table 1).

Specifically, this review aims to address the research question: How have FPSE and FPCE technologies evolved in terms of structural development and application trends, and what are the key differences in their trajectories? The study aims to provide a structured synthesis of existing knowledge, highlight technological gaps, and identify potential innovation pathways. In doing so, it contributes a comparative perspective that is currently underrepresented in the literature on free-piston engines. The findings are expected to assist researchers, engineers, and policymakers in making informed decisions for future developments.

METHOD

Research Design

This work focused on finding and reviewing peer-revised literature on Free-Piston Engine Systems, specifically Free-Piston Stirling Engines and Free-Piston Combustion Engines, using a Systematic Literature Review (SLR) with the PRISMA framework.(21,22) An assessment and integration of the literature on the performance, architecture, and other integrating features of Free-Piston Engine Systems was conducted using the SLR method. This method was built upon the work of other researchers and filled existing gaps in the literature concerning FPSE performance evaluation.(1,23) Answering the research objectives, the review focused on the literature to uncover barriers to future applications of sustainable energy and hybrid powertrains.(24)

Data Collection

The Scopus database was the primary source of information for this research project because it offers coverage of over 23 000 peer-reviewed journals, cross-disciplinary availability, and supports strong filtering, which helps to minimize selection bias.(25,26) With Scopus, conducting literature reviews becomes more thorough and reliable, as it allows for refined searches tailored to the specific research question at hand. Terms such as “free piston engine”, “FPSE”, “FPCE”, “linear alternator”, “return mechanism”, and “application” were used to capture studies related to Free-Piston Engine Systems (table 2). These precise searches facilitate the collection of literature for the review, considering performance, design, and application to be as robust as possible.

Table 2. Advanced Searching Query for Scopus Database

Database	Keywords	Query Code
Scopus	“free piston engine” OR “FPSE” OR “FPCE” OR “linear alternator” OR “return mechanism”	(“free piston engine” OR “FPSE” OR “FPCE”) AND (“linear alternator” OR “return mechanism”) AND PUBYEAR > 1999 AND PUBYEAR < 2025 AND (LIMIT-TO (DOCTYPE, “ar”) OR LIMIT-TO (DOCTYPE, “cp”)) AND (LIMIT-TO (LANGUAGE, “English”))

The first search found 263 documents. To improve precision, refining criteria based on titles and abstracts categorized 161 results. Thereafter, applying rigorous inclusion and exclusion criteria on the remaining texts narrowed the selection down to 77 articles for the final thorough review. The criteria used are detailed in table 3:

Table 3. Criteria for Inclusion and Exclusion

Aspects	Inclusion Criteria	Exclusion Criteria
Research Topics and Focus	Articles focused on FPSE and FPCE technologies, components, or applications	Articles unrelated to free-piston engine technology
Research Subjects	Engine systems with experimental, simulation, or theoretical basis	Studies outside energy/mechanical engineering scope
Publication Period	Published between 1999–2024	Published before 1999
Publication Language	English only	Articles in other languages
Publication Sources and Quality	Journal articles, conference papers	Book chapters, reviews, editorials, notes, short communications
Accessibility	Full-text available articles	Abstract-only or non-retrievable documents

Processing and Data Analysis

In this study, data analysis was conducted in clear, organized steps to maintain consistency and examine all research questions that were formed. Each article was collected and organized, and the first step was to capture all the data using the Paper Classification Form (PCF).[27] It is a structured tool designed to capture relevant bibliographic and contextual data, including the author, date, title, journal, and publisher. This step brought order to the selected articles, allowing researchers to gather and manage them more efficiently and assisting in the subsequent, more detailed analysis.

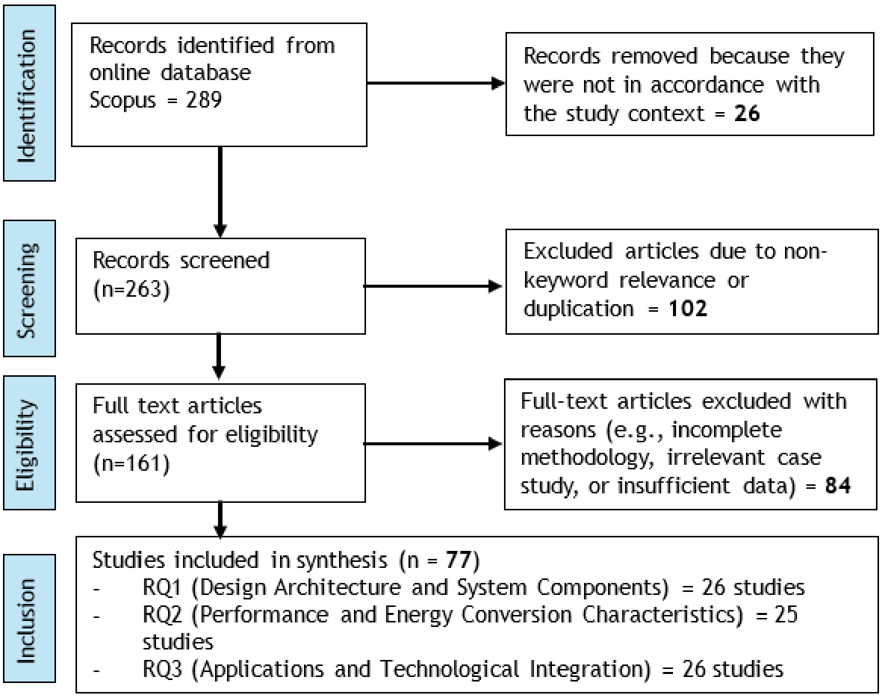

Figure 1. PRISMA Flow Diagram for Identification of Studies

In the first step, all articles were documented and then grouped to address the main research questions, which were established early in the review. These questions are: (1) The history and classification of free-piston engine systems (FPSE and FPCE); (2) The construction and function of the main components, especially the linear alternators and return mechanisms; (3) Their scope and the nature of their applications and characteristics in different sectors. Each of the groups was then provided with a qualitative synthesis mental model applied thematic coding. This approach required a detailed read, multiple reviews, highlighting, categorization, and finally, the synthesis of all relevant thematic concepts or recurring technologies across multiple articles.

The thematic synthesis was conducted inductively, meaning that we did not have predefined categories in the literature. This was done by qualitative principles, which focus on the context. This approach was enhanced by the use of NVivo software, which facilitated effective data handling, complex coding systems, and the visualization of thematic relations, thereby increasing the transparency, consistency, and analytical rigor of the study.[28] With NVivo, diverse sources were compiled and analyzed to identify and refine the prominent and supporting FPSE and FPCE technology themes, informing the design evolution, component integration, and application-based meta-cross-examination. This provided a comparative mapping of technology trajectories and their current states of advancement, revealing uncovered areas of research and encouraging interdisciplinary collaboration tailored to the identified gaps.

RESULTS AND DISCUSSION

Publication Identity and Trends: Year, Journal, and Country

Based on the literature search studies conducted on Free-Piston Engines (FPE), FPE began to appear in publications in 1999 (figure 2), starting with conceptual studies, architectural optimization,[29] application overviews, and historical reviews.[26] Between 2010 and 2015, publications focusing on thermodynamic analysis, working cycle modifications, and the incorporation of linear alternators increased significantly. There was a shift in emphasis toward experimental work, the integration of renewable energy sources, and the optimization of control systems from 2016 to 2020.[30,31] From 1999 to 2020, the two decades of uninterrupted research and innovation can be broadly conceptualized as a movement from conceptual development towards applied research, illustrating a shift in the potential for FPE technologies to be commercially exploited.[32,33,34]

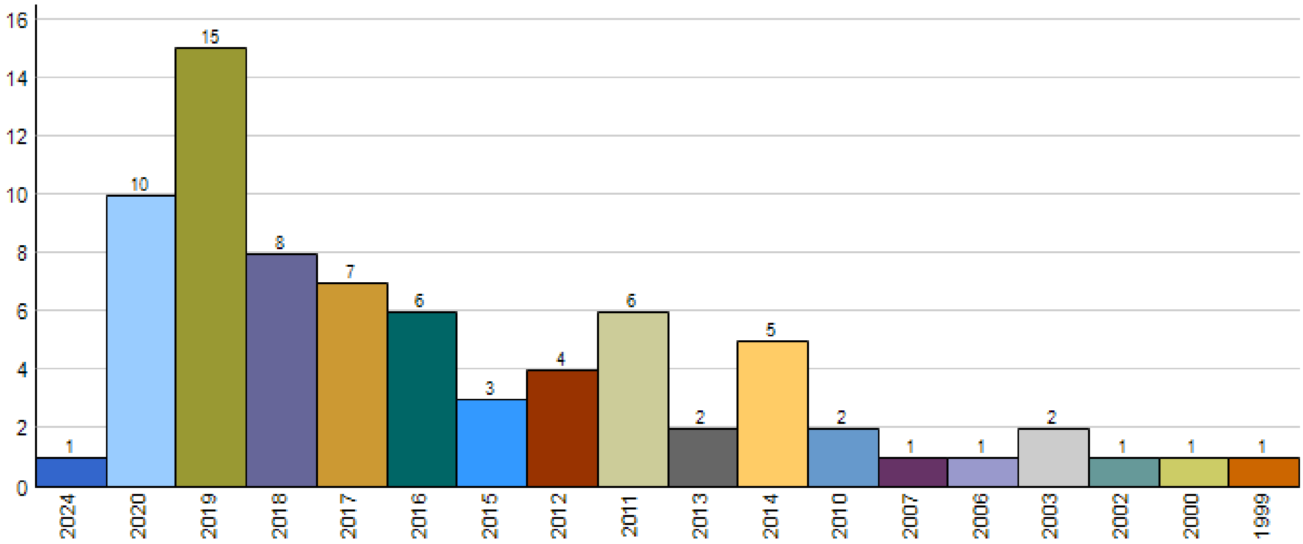

Figure 2. Distribution of Articles by Publication Year

The articles being reviewed are from various known journals in the areas of energy engineering, automotive engineering, or systems engineering. Primary publication outlets include Applied Energy, Energy, Energy Conversion and Management, and Applied Thermal Engineering, which issue articles based on thorough analysis, simulations, and experimentation. Moreover, international engineering conferences such as the SAE Technical Papers and the EVER Conference have contributed significantly to the communication of design innovation and prototype creation. The multidisciplinary journals and conferences showcase the vast research scope of FPE in thermodynamics, mechanical engineering, and system integration, as illustrated in figure 3.

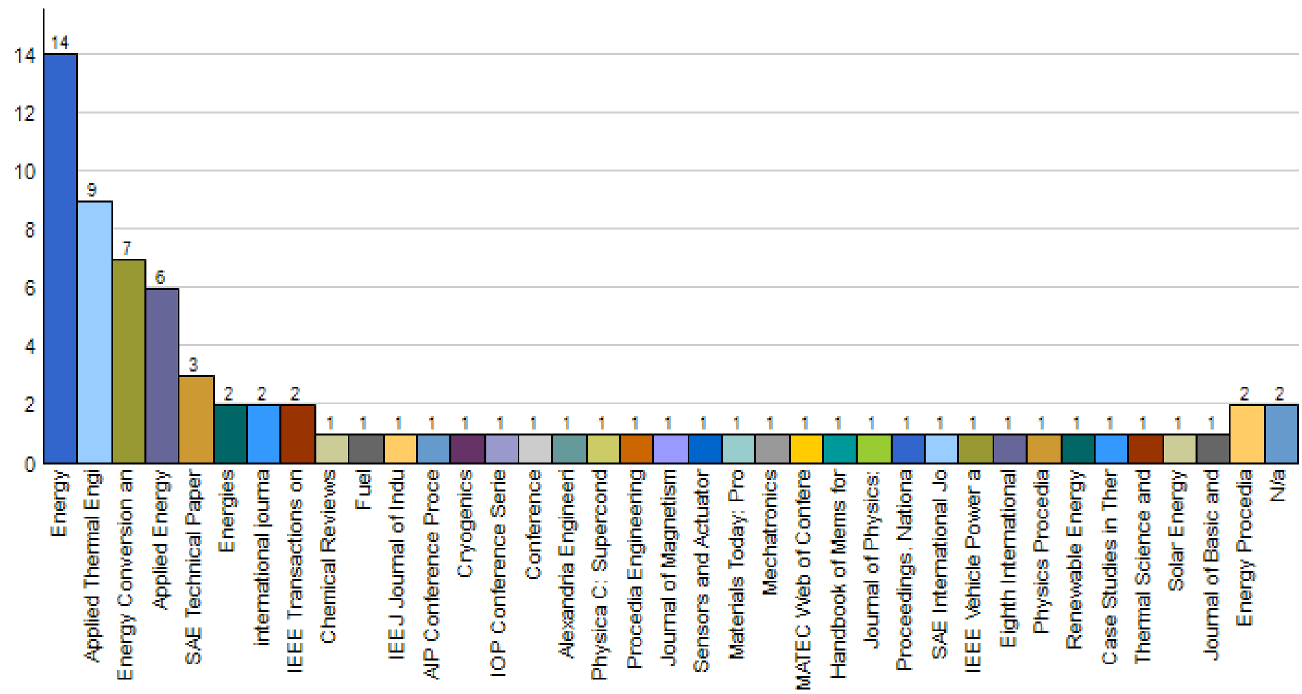

Figure 3. Distribution of Articles by Journals

The Flow of Information and Innovation publications indicate that Europe and East Asia are at the forefront of Free-Piston Stirling Engine innovation, with a focus on its application in concentrated solar power systems and micro-CHP systems. Europe and East Asia are also known to emphasize the clean energy transition. In comparison, the US and China focus more on FPCE development for hybrid vehicles, with a focus on hydrogen combustion and waste heat recovery systems. FPCE use in vehicles is more related to energy efficiency. This outlines how the energy policies and industrial focus differ from region to region. The distribution of articles by country is shown in figure 4.

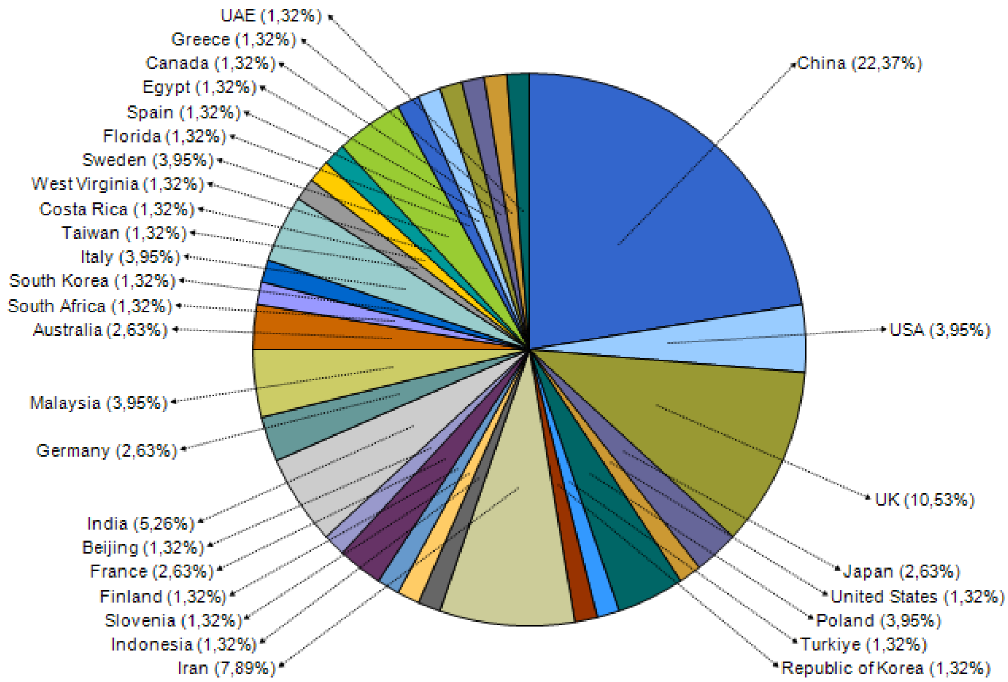

Figure 4. Distribution of Articles by Country

Type of Free Piston Engine

The review uncovered two distinct categories of free-piston engines, which are the Free-Piston Stirling Engine FPSE and Free-Piston Combustion Engine FPCE, as shown in figure 5. FPSE is an improvement of the standard Stirling engine as it uses a crankshaftless α, β, and γ piston configurations with varying degrees of piston-displacer synchronization as shown in table 4. It is known from earlier work that the configuration and drive mechanism, such as a rhombic drive, affect the engine's operating phase and its stability in synchronization.[35] The thermodynamic cycle comprises the work done by the piston and the displacer, the working substance (fluid) in four steps (compression, regenerative heating, expansion, and cooling). The displacer is crucial throughout the cycle in shuttling the working fluid to keep the cycle as efficient as possible.[36]

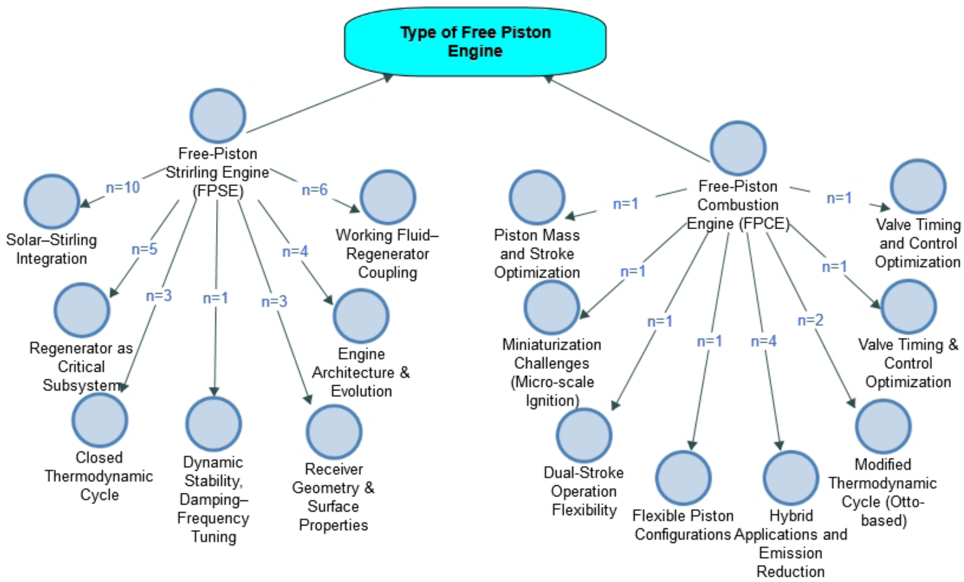

Figure 5. Key Findings of Free Piston Engine (FPE) with FPSE and FPCE Types

The application of FPSE (Free-Piston Stirling Engine) with solar heat sources in dish Stirling systems has achieved peak efficiencies of approximately 32 % due to the optimization in heat collection and transfer provided by cavity receiver designs. These designs consider the radiation flux distribution, the surface coating with high emissivity/absorptivity ratios, and the synchrony of the concentrator with the engine.[37,38] Engine functionality is strongly affected by the type of working fluid and the compatibility of the regenerator design. While helium and hydrogen have better thermal characteristics than air, they are susceptible to regenerator length and real-gas effects, including power-altering thermoacoustic phenomena.[39,40,41]

The thermal efficiency of FPSE is affected by the regenerator subsystem. Achieving high effectiveness requires modularization into at least 19 sub-regenerators while balancing the pressure drop heat transfer capacity tradeoff.[42] Overly small mesh sizes create higher flow resistance, while overly large sizes inhibit heat transfer.[43,44,45] Temperature variations within the regenerator can lead to suboptimal regeneration. Additionally, the surface characteristics of the receiver and heater (hyperboloid cavities with high-emissivity coatings), as well as conical and paraboloid shapes, affect heat absorption efficiency.[46,47]

The geometry of the FPSE (Free Piston Stirling Engine) directly impacts the oscillation frequency and damping, which in turn, affects the dynamic stability of the FPSE. Using a genetic algorithm, these parameters, including damping coefficients and heat transfer rates, can be adaptively solved, and the operating frequency tuned to the geometry for stable oscillation amplitudes.[8] FPSE's combined mechanical, thermal, and material optimization makes them ideally suited for external heat-based power generation, including setups in small to medium-scale renewable energy systems.

Table 4. Type of Free-Piston Stirling Engine (FPSE)

Core Findings	Category/Mechanism	Descriptive Findings	Sources
Piston configuration (α, β, γ); drive mechanism	Piston configuration (α, β, γ); drive mechanism	Influence of piston and rhombic drive configuration on the operating phase Piston-displacer synchronization Basic design architecture	(35,48,49,50)
Piston/displacer interaction with fluid throughout the cycle; oscillatory dynamic control	Piston/displacer interaction with the fluid throughout the cycle; oscillatory dynamic control	Description of the cycle steps (compression, regeneration, heating, expansion, cooling) The role of the displacer in fluid shuttling The need for amplitude/frequency stability	(51,52,53)
Solar-Stirling Integration	Heat collection and transfer from the solar panel to the FPSE; influence of receiver geometry and properties	Receiver cavity design Radiation flux distribution Coating/emissivity; concentrator-to-engine coupling Stirling dish as an efficient heat source (~32 %)	(37,38,46,47,54,55,56,57,58,59)
Working Fluid-Regenerator Coupling	Dependence between fluid type and regenerator design; effects of non-ideal gas	Comparison of working fluids (air, helium, hydrogen) Regenerator length sensitivity to fluid Real-gas and thermoacoustic effects on performance	(39,41,60,61,62,63)
Regenerator as a Critical Subsystem	Sub-regenerator modularity; pressure drop vs. heat transfer trade-off; imperfect regeneration	Requirement of ≥19 sub-regenerators for high effectiveness Effect of mesh size on pressure drop Spatial/temporal temperature variations and their impact on incomplete regeneration	(42,43,44,45,64)
Receiver Geometry & Surface Properties	Receiver shape and surface coating affect thermal input	Comparison of cavity shapes (hyperboloid vs. other) Effect of coating (emissivity/absorptivity) on heat absorption efficiency	(46,47,57)
Dynamic Stability: Damping-Frequency Tuning	Effect of geometry on damping; adaptive parameter estimation	Identification of damping & heat transfer coefficients with genetic algorithm Tuning of oscillation frequency based on geometry for stability	(8)

The Free-Piston Combustion Engine (FPCE) is an internal combustion engine design that does not utilize a crankshaft and exhibits lower mechanical friction and exhaust emissions compared to other engines (table 5). FPCE is most effective in hybrid vehicles because it seamlessly synchronizes the combustion and energy conversion processes, allowing for optimal performance.[29,65] FPCE is designed with a range of adaptability in mind. It features three piston arrangements: single, dual, and opposed, each offering distinct levels of fuel efficiency and power output. The dual and opposed types have a better balance of inertial forces and output stability. The single type is easier to build, but performs poorly under changing load conditions.[26]

From a thermodynamic perspective, FPCE thermally applies the principles of the Otto cycle, making adjustments to the constant-volume section to maintain stability. Zhao et al.[66] model of the Hydraulic Free-Piston Engine (HFPE) demonstrated that these adjustments could be made to the cycle to increase efficiency relative to a conventional Otto engine, due to improved performance during the cycle's expansion and compression. It is also notable that FPCE has a further advantage where the dual piston configuration can operate in 2T and 4T modes, changing only engine control parameters. In 2T mode, the cylinders are coupled as left and right cylinder pairs, providing uninterrupted electrical power.[32]

Fuel-powered compressed engines have specific ways of working with and regulating their energy outputs, and both combinations of valve control have their advantages and disadvantages. At the same time, valve timing control is crucial in terms of energy conversion, considering that the fuel-powered compressed engine utilizes other factors as well.[33] For FPCE, the Time Control Method (TCM) is the best choice when working with thermal-to-work and thermal-to-electric conversions, while the Position Control Method (PCM) is better suited for work-to-electric conversions. Other variables, such as theoretical stroke length, intake pressure, intake duration, and load, also play a role in the engine's operational frequency.

Despite FPCE's advantages, miniaturization of FPCE, for micro-scale applications with a diameter of the combustion chamber of approximately 3 mm, faces issues about combustion stability (Combustion timing and ignition timing optimization). Both combustion stability and cycle repeatability can be improved through specially timed ignition optimization, which can enhance these aspects. Wang et al.[67] also proved that combustion stability can be improved with specially timed ignition optimization.

The effect of piston mass on power output and stroke length is also important. Smaller piston masses lead to greater power output but shorter stroke lengths, as demonstrated by the 0D modeling conducted by Chendong et al.[34]. Their results illustrate the need for coordinated optimization of piston mass and control mechanisms, along with fuel usage and overall engine efficiency, to achieve the desired output. In summary, the FPCE system requires further refinement due to its integration with adaptive technologies and in-depth testing under various loads and conditions, given the combination of precise control and intricate FPCE mechanical design flexibility.

Table 5. Type of Free-Piston Combustion Engine (FPCE)

Core Findings	Category/Mechanism	Descriptive Findings	Sources
Hybrid Applications & Emission Reduction	The free-flow piston configuration reduces friction and emissions; high efficiency for hybrid vehicles.	FPCE enables high efficiency with a variable compression ratio; reduces emissions and friction compared to conventional engines.	[29,65,68,69]
Flexible Piston Configurations	Three piston configurations (single, dual, opposed) → affect power continuity and efficiency.	The piston type (single, dual, opposed) can be adjusted based on application requirements and engine operating conditions.	[26]
The FPCE cycle is derived from the Otto cycle, but modified for constant-volume processes; cycle efficiency is increased.	The FPCE cycle is derived from the Otto cycle, but modified for a constant-volume process; cycle efficiency is increased.	FPCE offers process stability at constant volume; HFPE offers a modified ideal thermodynamic cycle.	[30,31]
Dual-Stroke Operation Flexibility	The dual-piston design allows for 2T or 4T operation; can be controlled via valve timing.	Operation mode can be adjusted through engine parameter control; produces continuous electrical power with 2T mode synchronized between the right and left cylinders.	[70]
Valve Timing & Control Optimization	Timing-based control (TCM) vs. piston position control (PCM) → affects energy conversion efficiency.	TCM excels in thermal-work and thermal-electric efficiency; PCM excels in work-electric conversion; operating frequency is influenced by theoretical stroke, intake pressure, intake timing, and load resistance.	[33]
Miniaturization Challenges (Micro-scale Ignition)	Microcombustion chamber → requires setting the flame limit and ignition timing.	Micro FPCE (Ø 3 mm) suffers from combustion stability difficulties; cycle stabilization can be achieved by adjusting ignition timing and flammability limits.	[67]
Piston Mass and Stroke Optimization	Piston mass affects power output and stroke length.	Smaller piston mass produces greater power but with a shorter stroke; 0D modeling is used for energy performance evaluation.	[71]

The differences between the Free-Piston Stirling Engine (FPSE) and the Free-Piston Combustion Engine (FPCE) reveal changes in their innovation focus, functional movement, and technology utilization. FPSE is a well-established cold-start technology for stationary systems utilizing external heat sources, boasting high efficiency and adaptability to various heat sources. FPCE is being developed as a hybrid multi-purpose mobility technology with a focus on structural control adaptability, changeable compression ratios, and multifunctional design. FPSE has achieved measurable efficiencies of up to 32 % in dish Stirling systems and micro-CHPs. At the same time, FPCE is expected to achieve substantial improvements to emissions and efficiency with advanced control methods such as variable valve timing, cycle control, and mass regulation of the pistons.

Doing so risks missing opportunities where integration could be applied across different areas of application. For instance, FPCE combustion with hydrogen technology can be utilized for portable power generation, while FPSE fitted with high-power linear alternators can serve as range extenders for electric vehicles. Most comparisons between the two are conducted in silos, which is why they require a quantitative analysis using the same metrics, such as power density, dynamic cycle efficiency, and reliability over time, to evaluate the technical feasibility in question. FPSE has issues with controlling intermittent renewable heat sources and thermal losses in the receiver, while FPCE faces problems with system control complexity and combustion regulation at variable loads. There is synergetic potential in the two architectures if design optimization, technology integration, unified control, and multi-strategy dynamic control are applied to the development approach.

Basic Components

In Free-Piston Engine (FPE) systems, linear alternators convert the piston's linear movement into electrical energy through a system of sliding contacts on the rotor (translator) and stator. Linear alternators differ from traditional generators in that the latter use translational movement as opposed to linear, which is connected to the piston shaft. Additionally, their use eliminates numerous intermediate mechanical parts, thereby enhancing efficiency.(72,73) Instead of electromagnets, permanent magnets of Neodymium Iron Boron (NdFeB) type are used on the translator. With no windings or supplementary power sources required, this system is easier to install and maintain. However, high operating temperatures, which are common in engine systems, require robust thermal control.(74,75)

Halbach Array configurations, renowned for their one-sided magnetic flux concentration, are utilized to optimize magnetic flux distribution. The flux is intensified in the stator-facing region, which enhances power conversion efficiency. It has been demonstrated that tubular configurations outperform square models in magnetic flux distribution due to their geometry, which is more favorable to the direction of flux flow within the generator's working space.(76,77)

Improving the performance of a linear alternator involves conducting experiments and numerical simulations to determine how factors such as intake temperature and pressure affect power output. According to the tests, the output voltage increases with both an increase in intake temperature and pressure. Additionally, a modular topology allows for length adjustments to the engine, better tailoring it to its intended application.(78,79) Additionally, one of the most effective ways to enhance system performance is to reduce losses in the iron mover part.(80) In table 6, we present the results of the linear alternator.

Table 6. Basic Components: Linear Alternator

Core Findings	Category/Mechanism	Descriptive Findings	Sources
Linear Alternator Design & Operation	Principles of mechanical-to-electrical energy conversion; rotor-stator translation; integration in FPE	Linear alternators convert the reciprocating motion of pistons into electrical energy; unlike conventional generators (rotation vs. translation), the translator is mounted on the piston shaft.	(73,81,82,83,84,85,86)
Permanent Magnet Technology	Use of NdFeB permanent magnets; advantages over electromagnets; operating temperature limitations	Permanent magnets eliminate the need for coils and power supplies for the translator; improve installation ease; magnetic flux is a critical parameter; NdFeB is susceptible to high temperatures.	(74,75,87)
Halbach Array Integration	Magnet arrangement to maximize flux to the stator; tubular vs. square models	Halbach Arrays focus flux on one side; improve flux distribution efficiency; tubular models are more optimal than square models.	(88,89,90)
Performance Optimization & Simulation	Numerical simulation and experimental validation; influence of intake temperature/pressure; modular topology	Increased output by increasing intake temperature/pressure; modular topology increases engine length flexibility; reduced mover iron losses.	(78,79,80,91)

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In a Free-Piston Engine, the return mechanism is a subsystem that enables the recovery of energy to surpass the equilibrium point, allowing for continuous harmonic motion. This mechanism captures energy during the power stroke and releases it during the next cycle, allowing the piston/displacer to oscillate freely without the need for a crankshaft. Some common design variants are flexure springs, gas springs, and configurations with compression springs. Each of these has different responses and dynamic restitution characteristics. Stirling free-piston designs utilizing flexure springs demonstrate internal control and geometry integration, which is supported by numerical and experimental studies and draws inspiration from systems such as the Oxford Aerospace Cryocooler.(92) On the other hand, gas spring systems store kinetic energy at a controlled pressure with minimal heat loss through a large chamber, one-way valves, and a controlled internal pressure that is maintained above a certain threshold for consistent recovery.(93)

The dynamic stability of the system is significantly affected by the stiffness of the return elements on the power piston and the displacer, which control the onset of stable oscillation. Quantitative profile of the system's stiffness, where dynamic Lyapunov analysis reveals that the system switches from a stable to an unstable area, is bounded between two limits.(94) Reduced stiffness causes instability, and surpassing a certain point leads to a stable equilibrium of the system. Moreover, regarding the simultaneous consideration of impedance and the acoustic field in the applications of cryocooler free-piston engines, the geometric and thermal aspects of the return structure are known to impact the cooling performance. In particular, the high regenerator porosity, coupled with the acoustic power, exhibits a marked alteration in the overall response of the system.(95) In summary, the return mechanism is more than a simple passive energy storage device; instead, it actively regulates the stability, dynamics, and performance of the free-piston system through parameterized design coupled with dynamic control analysis. Findings regarding the return mechanism are outlined in table 7.

Table 7. Basic Components: Return-Mechanism

Core Findings	Category/Mechanism	Descriptive Findings	Sources
Return-Mechanism Function in FPE	Storing and releasing energy to pass through the cycle's equilibrium point; producing harmonic motion	Stores energy from the power stroke and returns it in the next stroke; additional function = creates harmonic oscillations	(96,97,98)
Return-Mechanism Variants	Flexure spring, compression spring, gas spring chamber	Flexure spring: used in FPSE (FEA analysis, Oxford Aerospace Cryocooler model); Gas spring: pressure >0,1 MPa, one-way valve, large area for heat loss minimization	(92,93,94,95,95)
Dynamic Stability via Return-Mechanism	Effect of piston/displacer spring stiffness on dynamic stability	Low stiffness → unstable system; high stiffness → stable; stability is mapped through Lyapunov analysis and linear dynamic FPSE model	(94)

While examining the linear alternator and its return mechanism, we can identify two fundamental subsystems that, although they have different developmental challenges and technical focuses, serve complementary functions. The linear alternator acts as a converter that moves electrical energy to a generator during the direct linear motion between the translator and the stator. This process is performed without any rotational components, allowing it to be integrated into the free-piston system. The optimization goals involve the rotational components and aim for a simpler design utilizing Neodymium Iron Boron (NdFeB) permanent magnets, magnetic flux control with a Halbach array configuration, and enhanced performance through numerical simulations and experiments, focusing on redesigning control and varying conditions.(72,73,78,79,80)

On the other hand, the return mechanism serves not only to store and release energy to sustain oscillation of the piston/displacer past equilibrium, but also serves an important function in damped active balance. Design alternatives include flexure springs, gas springs, and stability onset assessment using Lyapunov techniques, which show the system's response to the stiffness of the restoring components.(92,93,94,95) The differing technical solutions to these two subsystems reveal a conceptual tension: the linear alternator focuses on conversion efficiency and electromagnetic flexibility within various configurations and thermal environments, which stands in contrast to the return mechanism that focuses on oscillatory stability and continuity through mechanical construction and control system design.

Applications of Free Piston Engine Stirling Engine

The use of Free Piston Engines (FPEs) spans a wide array of functions from generating electricity to recovering energy and utilizing heat, cooling, and more. On a micro level, Free Piston Stirling Engines (FPSEs) have recently evolved into micro-combined heat and power (m-CHP) systems, which generate electricity and heat using urban natural gas, achieving a very high efficiency. Thermoacoustic engines based on FPSEs used for recovering waste heat have been studied with various fworking fluids to enhance heat-to-electricity conversion, emphasizing the importance of fluid choice on performance.[62,99] FPSE generators are uniquely developed within concentrated solar power (CSP) technology to enhance the conversion of concentrated solar rays to electric energy.[79]

In trucks used for heavy-duty transport, FPE-based waste heat recovery systems can increase power output while reducing fuel consumption by harnessing the heat of exhaust gas.[100] In the case of residential heating, micro-cogeneration studies FPSEs (fossil-powered Stirling engines) for use as the driving units of heat pumps, show FPSEs to be effective for thermal energy use at home.[101] Furthermore, FPSEs used in cryocoolers have been shown to provide cooling power of 350 W, expanding the field of FPEs to low-temperature applications that require high reliability and efficiency.[95] The wide range of FPSE applications demonstrates its design adaptability in fulfilling needs across various domains, including renewable energy, thermal efficiency, and advanced cooling. FPSE implementation findings are shown in table 8.

Table 8. The Applications of Free Piston Stirling Engines in Researches

Application	Research Summary	Sources
Micro-combined heat and power (m-CMP)	A construction methodology for the free-piston Stirling engine by using a natural gas supply from the urban area.	Park et al.[53]
Thermoacoustic engine	Evaluation of the various fluid used for the free-piston Stirling engine for waste heat recovery	Dong et al.[62]
Concentrated solar power (CSP)	The novel construction of the generator in a free-piston Stirling engine.	Hadžiselimović et al.[79]
Waste heat recovery for heavy-duty truck	Numerical analysis to extract heat from the commercial truck exhaust gas.	Güven et al.[100]
Micro-cogeneration and heat pump	A study of the effectiveness of FPSE for the heating system in residential applications	Remiorz et al.[101]
Cryocooler	An advanced application of cryocooler using free-piston Stirling engine which able to produce cooling capacity up to 350 W	Zhu et al.[102]

The Application of Free-Piston Combustion Engine (FPCE)

Research and applications focus on integrating control technology advances, alternative design fuels, and alternative combustion engines with high efficiency and flexibility. FPCE control systems prioritize and specify engine characteristics, application controllable functions, stroke, pressure, and combustion optimization for stable operation.[103] One structural merit FPCEs have over conventional crankshaft engines is the lowered frictional losses.[104] On the innovation side, research on hydrogen-fueled FPCEs reveals disparate efficiency and emission characteristics in 2T and 4T modes, yet with high flexibility in responding to varying operational demands.

FPCE combustion and ignition characteristics can be improved through thermodynamic cycle optimization by changing ignition timing, gas temperature, and compression ratio.[103] FPCEs powered by gasoline offer improvement in power and performance by reducing the moving mass while maintaining stroke length.[34,105] It is also confirmed that thermal efficiency, power output, and exhaust emissions are affected by stroke length.[106] FPCEs are also known for their strong ability to endure low-quality fuels. Hence, their performance is not significantly damaged by low-quality fuel additives, which makes them a good candidate for places with restricted fuel supply.[107,108]

Examining the electrical energy conversion systems for FPCEs, the optimization of a linear generator can be achieved by reducing copper and iron losses, which increases power conversion efficiency.[109] Moreover, the scavenging process, which is adjustable by intake gas pressure control, can yield a power output comparable to that of crankshaft engines. This suggests that FPCEs have the potential to rival conventional engine performance in specific applications.[103] With diesel-fueled FPCEs, the Injection Advance Position (IAP) has been shown to impact the compression ratio and overall thermal performance of the engine.[110] These findings collectively demonstrate the remarkable flexibility in design and operation of FPCEs, which can be integrated into a wide range of applications, from hybrid vehicles to power generation systems that utilize alternative fuels. More detailed findings from the implementation of FPCEs are presented in table 9.

The use of FPSE and FPCE exemplifies two different ways of utilizing energy and two distinct technologies that can work together in specific ways. Free-Piston Stirling Engines (FPSEs) are used for stationary energy production and heating applications such as micro combined heat and power (CHP) plants fueled by town gas as well as waste heat thermoacoustic engine applications, concentrated solar power (CSP) energy extraction, thermal waste reclamation from heavy-duty trucks, micro-cogeneration for heating residential homes, and high-capacity cryocoolers. FPSEs are helpful due to the high thermal efficiency of closed-cycle heat FPSEs,

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along with the flexibility of heat sources. However, their need for a stable heat supply or buffer mechanisms to dampen fluctuations poses a drawback.

Table 9. The Applications of Free-Piston Combustion Engine in Researches

Research Focus	Short description	Sources
Control system	The various control system is described based on the engine characteristic and application.	Zhang et al.[18]
Comparison in frictional losses	Free-piston configuration is able to reduce the frictional losses up to half a portion compared to the crankshaft engine.	Jia et al.[104]
Hydrogen-powered free-piston engine	Experimental research for a hydrogen-fueled free-piston engine for two and four-stroke engines. Each engine has different characteristics regarding efficiency and emissions.	Ngwaka et al.[70]
Combustion and ignition characteristic	The ignition timing may be adjusted to its maximum value by modifying the gas temperature and compression ratios.	Wang et al.[67]
Parametric analysis for gasoline free-piston engine	A higher generated power and performance of the engine are achieved by setting a fixed stroke length and by utilizing a lower moving mass.	Yamin and Dado[71]
The effect of variable stroke	Different stroke shows a different performance of the engine, particularly in thermal efficiency, power output and gas emissions.	Yuan et al.[106]
Combustion control with renewable fuel	The fuel impurity does affect the FPE performance, and it shows the engine has a high tolerance for using low-quality fuel.	Zhang, Sun[107]
Minimized the engine losses during braking	An optimization in the linear generator for the FPE application can be done by minimizing the iron copper losses.	Sato et al.[109]
Engine optimization with the scavenging process	The generated power of the FPCE is possible to reach the same portion of the crankshaft engine using scavenging ports by adjusting the inlet gas pressure.	Jia et al.[103]
Thermal characteristic of diesel free-piston engine	The injection advance position (IAP) impacts the compression ratio for FPCE.	Yuan et al.[110]

FPCEs are still mobile, as well as internally combustion-driven. Improvements on FPCEs focus on further reducing mechanical friction losses, managing valve control with dynamic management, using hydrogen and alternative fuels, control of combustion and ignition parameters, stroke length, piston weight, and energy recovery from scavenging, and performance of linear generators. Analyzing both systems, it can be noted that FPSEs have an advantage in terms of sustained external heat power output, as well as in their capability to integrate into distributed energy systems, such as microgrids. On the other hand, FPCEs stand out in terms of operational flexibility and mobility due to their controllable combustion cycles and adaptability to varying load conditions. Both systems also show potential in cross-applications, as FPCE waste heat in systems like hybrid vehicles can be utilized by FPSEs as auxiliary power or range extenders. Furthermore, FPSEs can benefit from linear alternator technologies that FPCEs use, thereby increasing power extraction efficiency.

For FPSEs, the need for a consistent heat input and a design that uniformly absorbs and distributes thermal energy puts a demand on the heat input, which sets a limit on thermal efficiency. For FPCEs, combustion control and operational stability have their challenges, especially on a smaller scale and with low-grade fuel. Here, a hybrid approach that combines FPSE thermal stability with FPCE fuel and combustion flexibility might offer a solution, enhancing both the design possibilities and system efficiency.

CONCLUSIONS

The purpose of this study was to comprehensively review FPE technologies to achieve the following goals: determining the categories and configurations of FPSE and FPCE; assessing the component architecture of linear alternators and their return mechanisms; and examining their potential applications in the domains of energy, mobility, and thermal systems. The results show that FPE technologies offer distinct benefits, including a modular and crankless architecture, variable compression ratios, and the flexibility to operate with many fuels and under various conditions. With the help of comparative synthesis, this SLR integrates the literature to provide innovation-driven clarifying pathways toward fragmented literature, illuminating technological innovation pathways and integration pathways that enable further innovation. The study also aids in formulating targeted strategies for focused development and cross-sector applications of FPE systems.

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CONFLICT OF INTEREST

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