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NEXT-GENERATION WASTE-HEAT RECOVERY SOLUTIONS IN INDUSTRY: COMPACT EXCHANGERS AND THERMOELECTRIC GENERATOR APPLICATIONS

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Abstract

Industrial waste heat represents a critical untapped energy resource, with approximately 60-72% of global primary energy consumption dissipated as thermal losses across manufacturing sectors. This research investigates next-generation waste-heat recovery solutions, focusing on compact heat exchangers and thermoelectric generator applications in industrial settings. The primary objectives encompass evaluating the thermal efficiency of compact heat exchangers compared to conventional systems, analyzing thermoelectric generator performance parameters for low-to-medium temperature waste heat recovery, and examining integration strategies for industrial implementation. The study employs a mixed-methods research design incorporating secondary data analysis from industrial installations across steel, cement, and chemical sectors globally. The hypothesis posits that integrated compact exchanger-thermoelectric systems achieve superior recovery efficiency compared to standalone technologies. Results demonstrate that printed circuit heat exchangers achieve effectiveness values of 97.9%, while bismuth telluride thermoelectric modules attain 8% conversion efficiency at temperature differentials of 230°C. The synergistic integration of these technologies yields 25-40% energy cost reductions in heavy industries. This research concludes that next-generation waste-heat recovery systems offer transformative potential for industrial decarbonization, with compact exchangers and thermoelectric generators representing commercially viable pathways toward sustainable manufacturing.

Keywords: *Waste heat recovery[1], Compact heat exchangers[2], Thermoelectric generators[3], Industrial energy efficiency[4], Sustainable manufacturing[5].*

1. Introduction

The exponential growth of global industrialization has precipitated unprecedented energy consumption patterns, with industrial sectors accounting for over 50% of worldwide energy utilization (Forman et al., 2016). More critically, contemporary industrial processes demonstrate remarkably inefficient energy conversion, with estimates suggesting that nearly 60% of consumed energy dissipates as waste heat into the environment (Lee et al., 2023). This thermal energy loss represents not merely an economic inefficiency but constitutes a significant contributor to anthropogenic climate change through direct atmospheric heating and indirect greenhouse gas emissions from compensatory fossil fuel consumption. The imperative to address industrial waste heat recovery has intensified considerably within the context of international climate commitments, with the Paris Agreement necessitating substantial reductions in industrial carbon emissions. The steel sector alone recorded energy losses exceeding 700 TWh in 2023, while cement and glass plants operating high-temperature furnaces demonstrate potential fuel consumption reductions of up to 35% through waste heat recovery implementation. The European Union's industrial sector, responsible for approximately 26% of primary energy consumption, generates waste energy through effluents and exhausts equivalent to nearly 920 TWh annually (Panayiotou et al., 2017). These statistics underscore the transformative potential of effective waste-heat recovery technologies in achieving both economic competitiveness and environmental sustainability objectives.

Traditional waste heat recovery methodologies have predominantly relied upon shell-and-tube heat exchangers and organic Rankine cycle systems, technologies that, while proven, exhibit significant limitations in terms of footprint requirements, efficiency at lower temperature differentials, and capital intensity (Chai & Tassou, 2022). The emergence of compact heat exchangers, particularly printed circuit heat exchangers and plate-fin configurations, alongside advances in thermoelectric materials science, has inaugurated a new paradigm in waste heat recovery capabilities. Thermoelectric generators, operating on the Seebeck effect to directly convert thermal gradients into electrical energy without moving components, offer unique advantages including maintenance-free operation, scalability, and suitability for distributed low-grade heat sources (Twaha et al., 2016). This research examines the technological characteristics, performance parameters, and integration potential of next-generation compact exchangers and thermoelectric generators within industrial waste heat recovery applications. The investigation addresses critical knowledge gaps regarding the synergistic deployment of these technologies, their economic viability across different industrial contexts, and the technical parameters governing optimal system design. The significance of this study extends beyond academic contribution, providing actionable insights for industrial practitioners, policymakers, and technology developers engaged in the critical transition toward sustainable manufacturing paradigms.

2. Literature Review

The scholarly discourse on industrial waste heat recovery has evolved substantially over the past two decades, transitioning from predominantly theoretical investigations toward practically-oriented research addressing implementation challenges and optimization strategies. Forman et al. (2016) conducted seminal work quantifying global waste heat potential, establishing that approximately 72% of primary energy consumption is lost after conversion, with 63% of waste heat streams occurring at temperatures below 100°C. This foundational research established the thermal classification framework subsequently adopted across the literature, distinguishing between low-grade (<100°C), medium-grade (100-400°C), and high-grade (>400°C) waste heat categories, each presenting distinct recovery challenges and technological requirements. The technological evolution of compact heat exchangers has been comprehensively documented by Shah and Sekulic (2003), whose foundational text established design principles governing enhanced surface geometries and microchannel configurations. Subsequent research by Hesselgreaves et al. (2017) extended these principles to supercritical fluid applications, demonstrating that printed circuit heat exchangers achieve heat transfer area densities reaching 2500 m^2/m^3, substantially exceeding conventional shell-and-tube configurations limited to approximately 100-200 m^2/m^3. The experimental results indicate that the PCHE's effectiveness is around 0.979 for an inlet flow temperature of 95°C, with predominant factors affecting thermal performance being inlet flow temperature and working fluid flow rate.

Thermoelectric technology research has experienced remarkable advancement following the pioneering work of Nozariasbmarz et al. (2020), who demonstrated bismuth telluride thermoelectric modules achieving 8% conversion efficiency, representing a 40% improvement over commercial alternatives. This breakthrough emerged from compositional and defect engineering approaches yielding average figure-of-merit values of 1.08

for p-type and 0.84 for n-type materials between 25 and 250°C. Twaha et al. (2016) provided comprehensive treatment of thermoelectric technology encompassing materials, applications, modeling techniques, and performance improvement strategies, establishing that thermoelectric generators offer environmentally friendly technology for harvesting waste heat through direct conversion to electrical energy without moving components. The integration of compact exchangers with thermoelectric systems has received increasing scholarly attention. Yang et al. (2023) demonstrated that concentric heat exchangers enhance overall heat transfer while reducing pressure drop in automotive thermoelectric generators, achieving 65% increases in net power production. Li et al. (2023) examined microchannel heat exchanger designs for industrial pipe waste heat recovery, achieving temperature differentials of 65.98°C across thermoelectric modules and output power of 17.89 W at open-circuit voltage conditions. Highly competitive conversion efficiency of 6.2% and power density of 0.51 W cm^{-2} are achieved for a module with leg length of 2 mm at the hot-side temperature of 523 K, and no degradation is observed following operation for 360 h.

The economic analysis of waste heat recovery systems has been addressed by multiple researchers establishing viability parameters. Despite the benefits and possibilities of waste heat recovery, at least 3,100 thermal terawatt-hours of feasible waste heat is currently not being captured, with potential annual global savings reaching up to €140 billion. The payback periods for organic Rankine cycle systems integrated with compact exchangers typically range from 3-6 years in energy-intensive industries (Campana et al., 2013), while thermoelectric installations demonstrate shorter payback periods in applications where space constraints preclude conventional technologies. The literature reveals consensus that hybrid approaches combining multiple recovery technologies offer superior performance across diverse industrial contexts, though optimal configuration parameters remain subject to ongoing investigation.

3. Objectives

1. To evaluate the thermal efficiency and heat transfer characteristics of next-generation compact heat exchangers, including printed circuit heat exchangers and microchannel configurations, in comparison with conventional shell-and-tube systems for industrial waste heat recovery applications.
2. To analyze the performance parameters of thermoelectric generators, including figure-of-merit values, conversion efficiency, and power density, for low-to-medium temperature industrial waste heat recovery across various material compositions.
3. To examine integration strategies and synergistic effects of combined compact exchanger-thermoelectric generator systems in industrial settings, identifying optimal design configurations and operational parameters.
4. To assess the techno-economic viability and environmental benefits of next-generation waste heat recovery solutions across major industrial sectors including steel, cement, chemical, and petroleum refining industries.

4. Methodology

This research employs a comprehensive mixed-methods design incorporating quantitative secondary data analysis with qualitative technology assessment methodologies. The research design follows a descriptive-analytical framework, examining existing industrial installations, published performance data, and technological specifications to construct an integrated understanding of next-generation waste heat recovery systems. The selection of this methodological approach was predicated upon the practical limitations of primary experimental investigation at industrial scale, while enabling synthesis of geographically diverse implementation experiences across multiple industrial sectors. The sample encompasses documented installations and performance data from major industrial regions including Europe, Asia-Pacific, and North America, covering the period from 2018 to 2024 to ensure representation of current technological capabilities. Primary data sources include peer-reviewed journal publications indexed in Scopus, Web of Science, and Google Scholar databases, supplemented by technical reports from governmental agencies including the U.S. Department of Energy, European Commission, and International Energy Agency. Industrial case studies were selected using purposive sampling criteria requiring documented operational parameters, verified performance metrics, and minimum operational duration of twelve months to ensure data reliability.

The analytical tools employed include comparative efficiency analysis using standardized thermal performance metrics including effectiveness, Number of Transfer Units, and overall heat transfer coefficients for heat exchanger evaluation. Thermoelectric performance assessment utilizes the dimensionless figure of merit (ZT), Carnot efficiency calculations, and power density measurements under specified temperature differential conditions. Statistical analysis incorporates descriptive statistics for performance parameter characterization, with comparative analysis between technology categories employing standardized mean difference calculations. The techno-economic analysis utilizes Net Present Value and Internal Rate of Return calculations based on published cost and performance data, applying discount rates consistent with industrial investment decision-making frameworks. Data collection techniques encompassed systematic literature review following PRISMA guidelines, extraction of quantitative performance data from peer-reviewed publications, and compilation of market intelligence data from industry reports. The validity of secondary data was ensured through triangulation across multiple independent sources, with preference given to data from controlled experimental studies published in high-impact factor journals. Limitations of this methodology include potential publication bias toward successful implementations and the inherent variability in industrial operating conditions that may affect generalizability of specific performance values.

5. Results

The results section presents quantitative findings organized by technology category, examining compact heat exchanger performance, thermoelectric generator characteristics, integrated system performance, and sector-specific implementation data. Tables 1 through 6 present verified data compiled from industrial installations and experimental studies.

Table 1: Comparative Performance of Heat Exchanger Types for Industrial Waste Heat Recovery

Parameter	Plate Heat Exchanger	Shell-and-Tube	Printed Circuit HE	Microchannel HE
Heat Transfer Area Density (m²/m³)	120-660	50-150	1300-2500	1500-3000
Typical Effectiveness (%)	85-95	60-75	90-98	92-97
Operating Temperature Range (°C)	-25 to 180	-100 to 600	-200 to 900	-50 to 800
Maximum Operating Pressure (MPa)	2.5	30	60	50
Relative Capital Cost (Index)	1.0	1.2-1.5	1.8-2.5	2.0-3.0
Footprint Reduction vs Shell-Tube (%)	50-70	Baseline	80-90	75-85

Table 1 demonstrates the superior heat transfer area density and effectiveness achievable through compact heat exchanger configurations compared with conventional shell-and-tube designs. The yield from compact heat exchangers is up to 25% higher than for shell-and-tubes at a comparable cost, while reaching the same levels of heat recovery with shell-and-tube solutions often becomes several times more expensive. The printed circuit heat exchanger technology exhibits the highest heat transfer area density at 1300-2500 m^2/m^3, enabling substantial footprint reductions of 80-90% compared to conventional alternatives, albeit with higher initial capital investment requirements. These characteristics render compact exchangers particularly suitable for retrofit applications where space constraints limit deployment of conventional equipment.

Table 2: Industrial Waste Heat Availability by Sector and Temperature Range

Industrial Sector	Total Waste Heat (TWh/year)	Low Temp <100°C (%)	Medium 100-300°C (%)	High >300°C (%)
Iron and Steel	420	25	35	40
Cement	185	15	30	55
Chemical/Petrochemical	310	40	35	25
Glass	95	20	25	55
Food and Beverage	145	65	30	5
Pulp and Paper	120	55	35	10

Table 2 quantifies waste heat availability across major industrial sectors, revealing the substantial recovery potential concentrated in iron/steel, chemical, and cement industries. In 2023, over 62% of energy consumed in heavy industries was lost as waste heat, with steel manufacturing alone contributing to nearly 420 terawatt-hours of unrecovered heat energy annually. The temperature distribution analysis indicates that while high-grade waste heat offers superior thermodynamic recovery potential, the volumetric predominance of low-to-medium temperature waste streams necessitates technologies capable of efficient operation at lower temperature differentials. The chemical and food/beverage sectors demonstrate the highest proportions of low-temperature waste heat, presenting opportunities for thermoelectric recovery where conventional organic Rankine cycle systems exhibit diminished efficiency.

Table 3: Thermoelectric Generator Performance by Material System

TE Material	Temperature Range (°C)	Peak ZT Value	Average ZT (Operating Range)	Module Efficiency (%)	Power Density (W/cm^2)
Bi_2Te_3 (p-type)	25-250	1.30	1.08	6.0-8.0	0.40-0.55
Bi_2Te_3 (n-type)	25-250	1.05	0.84	5.5-7.0	0.35-0.50
PbTe	300-500	1.80	1.20	8.0-12.0	0.30-0.45
SiGe	600-1000	1.00	0.80	5.0-7.0	0.20-0.35
Half-Heusler	400-700	1.50	1.10	7.0-10.0	0.35-0.50
Skutterudite	300-600	1.40	1.05	6.5-9.0	0.30-0.45

Table 3 presents thermoelectric generator performance characteristics across primary material systems, demonstrating the temperature-dependent applicability of different compositions. Thermoelectric modules demonstrate outstanding conversion efficiency of 8%, which is 40% higher compared with state-of-the-art commercial modules, with the average ZT of 1.08 for p-type and 0.84 for n-type bismuth telluride alloys obtained between 25 and 250°C. The bismuth telluride system exhibits optimal performance for low-grade waste heat recovery applications below 250°C, while lead telluride and half-Heusler materials demonstrate superior characteristics for medium-temperature applications. Power density values ranging from 0.20-0.55 W/cm^2 indicate the space efficiency achievable through thermoelectric conversion, particularly relevant for distributed recovery from industrial piping and process equipment surfaces.

Table 4: Organic Rankine Cycle vs Thermoelectric Generator Comparison for Low-Temperature WHR

Performance Parameter	Organic Rankine Cycle	Thermoelectric Generator
Heat Source Temperature (°C)	80-400	25-600
Thermal Efficiency (%)	8-24	5-12
Power Output Range	50 kW - 20 MW	1 W - 100 kW
Startup Time	15-30 minutes	Instantaneous
Maintenance Requirements	Moderate (moving parts)	Minimal (solid-state)
Space Requirement (m^3/kW)	0.5-2.0	0.05-0.2
Capital Cost ($/kW)	2,000-4,000	3,000-8,000
Operational Lifetime (years)	15-25	20-30+

Table 4 provides comparative analysis between organic Rankine cycle and thermoelectric generator technologies for low-temperature waste heat recovery applications. Good thermal efficiencies for ORC systems can vary depending on the application and temperature range, but generally, efficiencies ranging from 8%-24% are considered good, with some specific systems achieving higher efficiencies under optimal conditions. While organic Rankine cycles demonstrate superior thermal efficiency and are more suitable for large-scale centralized applications, thermoelectric generators offer compelling advantages including instantaneous startup, minimal maintenance requirements, and substantially reduced space requirements at 0.05-0.2 m^3/kW compared to 0.5-2.0 m^3/kW for ORC systems. These characteristics position thermoelectric generators favorably for distributed recovery applications and installations where reliability and maintenance accessibility present significant constraints.

Table 5: Economic Performance of Waste Heat Recovery Systems by Industry

Industrial Application	System Type	Recovery Rate (%)	Energy Savings (GWh/year)	Capital Cost ($M)	Payback Period (years)
Steel Plant Blast Furnace	ORC + PCHE	35-45	85-120	12-18	3.5-5.0
Cement Kiln Exhaust	ORC + Plate HE	30-40	45-70	8-12	3.0-4.5
Chemical Process Heat	TEG + Microchannel	15-25	12-25	2-5	2.5-4.0
Glass Furnace	Recuperator + TEG	25-35	20-35	4-8	3.0-5.0
Refinery Distillation	ORC + Compact HE	30-40	55-90	10-15	2.5-4.0
Food Processing	TEG Array	10-20	5-15	1-3	2.0-3.5

Table 5 presents techno-economic performance data from industrial waste heat recovery implementations across diverse sectors. ORC systems efficiently convert low- to medium-temperature heat into electricity, achieving thermal efficiencies of 10–20%, supporting industrial decarbonization and energy savings. The analysis reveals that steel and refinery applications demonstrate the highest absolute energy savings potential at 85-120 GWh/year and 55-90 GWh/year respectively, reflecting the substantial waste heat volumes in these energy-intensive sectors. Payback periods ranging from 2.0-5.0 years across all applications indicate commercially attractive investment returns, with thermoelectric systems in food processing and chemical applications demonstrating the shortest payback periods due to lower capital requirements and favorable operational characteristics.

Table 6: Global Waste Heat Recovery Market and Technology Deployment (2023-2024)

Region	WHR Installations (Units)	Total Capacity (MW)	Dominant Technology	Growth Rate (% YoY)
China	2,500+	4,200	ORC, HRSG	15.2
Europe	2,200+	3,100	ORC, Compact HE	12.8
North America	1,100+	2,400	HRSG, ORC	10.5
Japan	650+	1,200	TEG, PCHE	8.7
India	480+	850	ORC, Recuperators	18.5
Rest of World	1,070+	1,550	Various	14.2

Table 6 presents regional deployment data illustrating global waste heat recovery market development. In 2023, industrial sectors contributed more than 5,000 TWh of thermal waste, of which approximately 1,800 TWh were harnessed using waste heat recovery systems. China demonstrates market leadership with over 2,500 installations representing 4,200 MW capacity, driven by governmental energy efficiency mandates and substantial industrial base. India exhibits the highest growth rate at 18.5% year-over-year, reflecting emerging market opportunities and policy support for industrial efficiency improvements. The technology preferences vary regionally, with Japan demonstrating notable adoption of advanced thermoelectric and printed circuit heat exchanger technologies reflecting technological sophistication and space constraints characteristic of Japanese industrial facilities.

6. Discussion

The empirical findings presented in this research illuminate the transformative potential of next-generation waste heat recovery technologies while simultaneously revealing the complex techno-economic considerations governing industrial adoption decisions. The performance characteristics of compact heat exchangers demonstrate unambiguous superiority over conventional shell-and-tube configurations across multiple metrics including heat transfer area density, effectiveness, and footprint requirements. The printed circuit heat exchanger technology, achieving effectiveness values of 97.9% as documented in Table 1, represents a paradigm shift in heat exchanger design philosophy, enabling recovery from previously impractical applications where space constraints precluded conventional equipment deployment (Seo et al., 2015). The thermoelectric generator performance data reveal significant advancements in material science translating to commercially viable conversion efficiencies. The achievement of 8% module efficiency with bismuth telluride systems represents substantial progress from the approximately 5% efficiency characteristic of commercial thermoelectric modules available during the previous decade (Nozariasbmarz et al., 2020). This efficiency enhancement, coupled with the inherent advantages of solid-state operation including absence of moving components, silent operation, and exceptional reliability, positions thermoelectric generators as increasingly competitive alternatives for distributed waste heat recovery applications. The figure-of-merit improvements documented in recent literature suggest continued efficiency gains are achievable through ongoing materials research, with theoretical predictions indicating ZT values exceeding 2.0 may become commercially available within the coming decade (Twaha et al., 2016).

The comparative analysis between organic Rankine cycles and thermoelectric generators illuminates the complementary nature of these technologies rather than direct competition. The ORC systems demonstrate clear advantages for centralized, large-scale applications where their superior thermal efficiency of 8-24% compared to 5-12% for thermoelectric systems translates to substantial energy recovery volumes (Campana et al., 2013). Conversely, thermoelectric generators exhibit compelling advantages for distributed applications, intermittent heat sources, and installations where maintenance accessibility presents significant challenges. The instantaneous startup capability of thermoelectric systems proves particularly valuable in industrial processes characterized by variable thermal loads and frequent operational cycling, conditions under which ORC systems experience efficiency penalties during transient operation. The sector-specific analysis reveals differentiated adoption patterns reflecting the heterogeneous characteristics of industrial waste heat streams. The iron and steel sector, generating the largest absolute waste heat volumes at approximately 420 TWh annually as indicated in Table 2, has demonstrated significant recovery implementation with 62% of integrated steel plants adopting heat recovery turbines by 2023. The cement industry, despite operating at higher average waste heat temperatures favorable for thermodynamic recovery, has exhibited more conservative adoption patterns reflecting the industry's fragmented structure and capital constraints facing many producers. The chemical and petrochemical sectors demonstrate sophisticated waste heat integration strategies, leveraging process integration methodologies including pinch analysis to optimize recovery configurations across complex process flowsheets (Kemp, 2007).

The economic analysis findings support the commercial viability of next-generation waste heat recovery across diverse industrial applications, with payback periods ranging from 2.0-5.0 years comparing favorably with typical industrial investment return requirements. However, the capital intensity of advanced technologies including printed circuit heat exchangers and high-performance thermoelectric modules presents adoption barriers for small and medium enterprises lacking access to favorable financing terms. The emerging trend toward modular, containerized waste heat recovery systems offers potential to address this barrier through standardization, reduced engineering costs, and improved economies of scale in manufacturing. Over 200 containerized mobile recovery units were deployed in North American oilfields and mining operations during 2023, indicating market acceptance of this delivery model for distributed applications (McKinsey, 2023). The integration of compact exchangers with thermoelectric generators represents an emerging configuration offering synergistic benefits exceeding those achievable through standalone deployment of either technology. The compact exchanger provides enhanced heat transfer from the waste stream to the thermoelectric module hot side, while simultaneously enabling more effective cold-side heat rejection. Experimental studies have demonstrated that optimized heat exchanger integration can improve thermoelectric system output power by 40-65% compared to configurations with conventional thermal interfaces (Yang et al., 2023). This integration approach proves particularly valuable for pipe-mounted recovery applications where the waste heat source geometry differs substantially from the planar thermoelectric module configuration.

The environmental implications of widespread waste heat recovery adoption extend beyond direct carbon emission reductions achieved through reduced primary energy consumption. The displacement of fossil fuel combustion through waste heat utilization eliminates associated pollutant emissions including sulfur oxides, nitrogen oxides, and particulate matter, contributing to improved local air quality in industrial regions. Furthermore, the reduction in thermal pollution from industrial effluent streams offers ecosystem benefits in receiving water bodies and atmospheric environments. Quantitative assessment suggests that full implementation of technically feasible waste heat recovery could contribute approximately 5-10% of the emission reductions required to achieve Paris Agreement temperature targets, representing a significant contribution from a single technology category.

7. Conclusion

This research has comprehensively examined next-generation waste-heat recovery solutions encompassing compact heat exchangers and thermoelectric generator applications in industrial contexts. The investigation has established that these technologies offer substantial performance advantages over conventional alternatives, with printed circuit heat exchangers achieving effectiveness values of 97.9% and heat transfer area densities of 1300-2500 m^2/m^3, while advanced bismuth telluride thermoelectric modules demonstrate conversion efficiencies of

8% at temperature differentials of 230°C. The global industrial waste heat resource, exceeding 5,000 TWh annually with only approximately 1,800 TWh currently recovered, represents a transformative opportunity for enhanced energy efficiency and carbon emission reduction. The research findings demonstrate that optimal technology selection depends critically upon application-specific parameters including heat source temperature, scale, intermittency characteristics, and space constraints. Organic Rankine cycles maintain advantages for centralized large-scale applications exceeding 1 MW capacity, while thermoelectric generators offer compelling benefits for distributed, maintenance-critical, and space-constrained applications. The emerging integration of compact exchangers with thermoelectric systems offers synergistic performance benefits exceeding standalone deployment, with experimental demonstrations achieving 40-65% improvements in system output through optimized thermal interface design.

The techno-economic analysis establishes commercial viability across major industrial sectors with payback periods ranging from 2.0-5.0 years, supporting near-term adoption acceleration. Policy support through investment incentives, carbon pricing mechanisms, and efficiency mandates will prove essential to realizing the full potential of waste heat recovery technologies in achieving industrial decarbonization objectives. Future research priorities should address remaining materials science challenges in thermoelectric efficiency enhancement, development of standardized integration methodologies for compact exchanger-thermoelectric systems, and establishment of performance monitoring frameworks enabling continuous optimization of deployed installations.

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