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Organic Rankine Cycle for Low-to-Medium Temperature Heat Recovery: Working Fluids, Architectures, Expanders, Control, and Deployment Pathways

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A R T I C L E I N F O

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A B S T R A C T

Organic Rankine cycles (ORCs) have matured into a leading technology for converting low-to-medium temperature heat into electricity in applications spanning industrial waste heat, geothermal, biomass, and solar thermal systems. Their competitiveness stems from the ability to match diverse heat-source temperature profiles using organic fluids, flexible architectures (subcritical, recuperated, regenerative, transcritical, and supercritical variants), and compact turbomachinery or volumetric expanders. This review consolidates the state of the art across (i) working-fluid selection under simultaneous thermodynamic, environmental, safety, and cost constraints; (ii) plant architectures and heat-exchanger design that govern pinch losses and off-design behavior; (iii) expander choices from radial turbines to scroll, screw, and piston machines; and (iv) modeling, control, and techno-economic assessment frameworks for robust deployment. The paper synthesizes performance trends drawn from experimental surveys and system demonstrations, highlighting that heat exchangers dominate irreversibilities and dynamic response, while expander efficiency and stable condensation strongly shape net output in small-to-mid scale systems. Recent advances in off-design optimization, moving-boundary dynamics, and supervisory control improve annual energy production and operational reliability. Remaining bottlenecks include fluid regulation transitions, high-temperature stability of "dry" fluids, cost-effective scaling below ~100 kWe, and integration constraints (cooling availability, fouling, and transient heat-source behavior).

1. Introduction

Converting low-to-medium temperature heat into electricity is a persistent challenge because thermodynamic efficiency decreases rapidly as source temperature approaches ambient, while component and balance-of-plant losses become comparatively more important. ORCs address this challenge by replacing water with an organic working fluid whose saturation curve and critical properties can be tuned to the available heat source, enabling improved thermal matching, reduced moisture formation during expansion, and compact components across a wide power range [1–3]. Modern ORC deployment spans industrial WHR, geothermal power, biomass-fired combined heat and power, and solar-driven systems, with extensive research focused on selecting fluids and architectures that increase net power while remaining safe, affordable, and environmentally acceptable [1,2,4,7].

The foundational thermodynamic concept is straightforward: an organic fluid is pressurized by a pump, heated and vaporized in an evaporator (often through a preheater–evaporator–superheater sequence), expanded through an expander to produce mechanical power, and condensed back to liquid. Yet this apparent simplicity masks several coupled design decisions that dominate real-world performance. First, the working fluid influences not only cycle efficiency but also heat-exchanger sizing, pinch-point constraints, expander design, lubrication strategy, and operating pressures [5,6]. Screening studies have long shown that "dry" and "isentropic" fluids can reduce or eliminate wet expansion, allowing higher expander durability and simpler turbine staging, but these fluids may impose large volumetric flow rates or require higher evaporating pressures depending on the heat-source temperature [3,6]. As a result, fluid selection is inseparable from component technology and economic context [4–6].

Second, the heat-source profile and its variability shape both architecture choice and annual energy production. Recuperated or regenerative ORCs can recover internal heat to raise cycle efficiency, especially when the expander exhaust remains superheated and the source temperature is high enough to support internal recuperation without overly penalizing evaporator pinch [4,12]. Conversely, for very low-grade sources, overly complex architectures can increase cost and pressure drop, and may reduce net output once realistic parasitics and exchanger irreversibilities are included [1,8]. Large-scale surveys of experimental ORC data emphasize that component-level efficiencies, pressure losses, and heat-exchanger effectiveness often determine net output more than ideal-cycle thermodynamics, particularly in small-scale plants where auxiliary power and off-design operation are pronounced [8].

Third, expander selection is central because expander isentropic efficiency, leakage, and mechanical losses directly cap the recoverable work. Radial inflow turbines dominate higher power and higher temperature ORCs, whereas scroll, screw, piston, and vane expanders are used in micro-to-small scale systems due to robustness and tolerance to two-phase flow in some configurations [5,9,13]. Experimental demonstrations using scroll expanders have provided valuable validation datasets.

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Nomenclature

Abbreviation

ORC	Organic Rankine Cycle
WHR	Waste Heat Recovery
IHE	Internal Heat Exchanger (recuperator)
T–s	Temperature–entropy diagram
LMTD	Log-Mean Temperature Difference
UA	Overall heat-transfer conductance
GWP	Global Warming Potential
ODP	Ozone Depletion Potential
PID	Proportional–Integral–Derivative control

Symbol

η – Efficiency [%]

$\dot{W}$net – Net power output

$\dot{Q}$in – Heat input rate to evaporator

2. Methodology

This review follows a system-centric synthesis methodology that organizes ORC knowledge into four interdependent layers: thermodynamic cycle design, working-fluid screening, component technology and sizing, and plant-level off-design performance including control. Foundational ORC performance trends and application breadth are anchored in widely cited review literature and techno-economic surveys [1,2,4,7]. To avoid over-reliance on ideal-cycle metrics, the methodology prioritizes results that include component efficiencies, pressure drops, and experimentally informed constraints, consistent with experimental data trend analyses and validated prototype studies [8,15].

At the thermodynamic layer, cycle performance is represented using net power and net efficiency, with explicit accounting for pump work, expander efficiency, generator efficiency, and auxiliary power (cooling fans, pumps, and control hardware). Heat addition and rejection are treated using pinch-point and heat-exchanger effectiveness perspectives, because the temperature glide of both source and working fluid determines feasible heat recovery more directly than heat-source temperature alone [1,4]. Architecture selection is structured by increasing complexity from basic subcritical ORC to recuperated/regenerative layouts and then to transcritical/supercritical variants. The architecture mapping is guided by established architecture reviews for WHR and by studies emphasizing the importance of matching to source profile and cooling constraints [3,11].

Working-fluid screening is handled as a constrained multi-criteria process. Thermodynamic suitability is assessed through critical temperature/pressure relative to source temperature, slope of the saturated vapor line (wet/isentropic/dry behavior), vapor density and volumetric expansion ratio (linked to expander size), and heat-transfer implications (viscosity, thermal conductivity, latent heat). Environmental and safety screening is included through GWP/ODP awareness and safety classes (toxicity/flammability), reflecting the contemporary reality that “best” fluids thermodynamically may be impractical or non-compliant [2,5,14]. The methodology emphasizes that screening must be done jointly with architecture and expander choice, consistent with classic expander/fluid co-selection reviews and refinery-focused screening studies [5,13].

Component technology synthesis centers on heat exchangers and expanders because they dominate capital cost and performance sensitivity in many ORCs. Heat exchanger design is summarized through compactness (UA per volume), allowable pressure drops, fouling tolerance, and manufacturability, with recognition that heat-exchanger dynamics strongly influence control performance [18]. Expander technology is synthesized by matching typical power ranges and pressure ratios to turbine or volumetric machines, using experimental validation studies (e.g., scroll expander prototypes) and surveys of expander selection principles [5,15]. Off-design behavior is treated as a first-class requirement, using approaches that incorporate component maps, condenser constraints, and variable-geometry or variable-speed strategies, as shown in off-design modeling and control strategy research [17,18].

Finally, the methodology integrates evidence by triangulating three types of literature. The first is review and survey papers that consolidate large bodies of work and provide macro-trends across applications [1,4,7,8,11]. The second is component-validated studies that provide experimental grounding for expander behavior and system-level prototypes [15,16]. The third is modeling and control research that targets year-round operation and dynamic stability, which often reveals constraints invisible at design point [17–19]. This layered evidence integration is used to produce practical design heuristics, highlight consensus findings, and identify unresolved tradeoffs among performance, cost, regulation-driven fluid transitions, and operability.

Table 1. ORC architecture families and typical use-cases.

Architecture	Defining feature	Typical source range	Key advantage
Subcritical basic ORC	Evaporation below critical point	~80–250°C	Simplicity and robustness
Recuperated ORC	Internal heat exchanger (IHE)	~120–350°C	Higher efficiency when exhaust is superheated
Regenerative ORC	Bleed or feed heating	~150–350°C	Improved cycle efficiency in some layouts

Table 2. Working-fluid families and screening dimensions.

Fluid family	Thermodynamic note	Safety note	Environmental note
Hydrocarbons (e.g., pentanes)	Often favorable “dry” behavior	Flammable	Typically low GWP, zero ODP
HFC/HFO refrigerants	Good low-temp properties	Varies by fluid	HFOs lower GWP than many HFCs
Siloxanes	Stable at moderate-high T	Combustibility/toxicity vary	Generally low ODP

Table 3. xpander options and typical operating envelope.

Expander type	Typical scale	Strength
Radial inflow turbine	~100 kWe to multi-MWe	High efficiency at design point
Axial turbine	Multi-MWe	High flow capability
Scroll	~1–50 kWe	Robust, compact

3. Results

Across ORC literature, performance outcomes are best interpreted as the combined effect of thermal matching, component efficiencies, and operating envelope rather than as a single "cycle efficiency" number. Large experimental trend reviews show that real ORC systems frequently underperform idealized expectations because heat-exchanger pinch constraints, pressure drops, expander inefficiency, and auxiliary power erode net output, especially in small-scale plants [8]. When results are reorganized by heat-source temperature, three broad regimes emerge: very low-grade sources where the primary task is minimizing irreversibilities and parasitics; medium-grade sources where recuperation and expander choice dominate; and higher-grade sources where fluid stability, pressure limits, and turbine design constraints become decisive [1,3,4].

Figure 1 illustrates the basic ORC energy-conversion pathway as a compact block schematic.

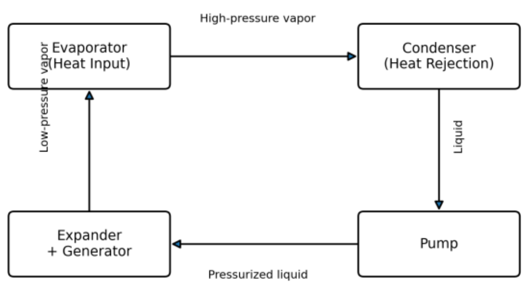

Fig. 1. Basic ORC schematic showing evaporator, expander–generator, condenser, and pump, emphasizing the closed-loop working-fluid path.

Even in this simple representation, two practical conclusions follow. First, the evaporator and condenser are typically the largest components and frequent cost drivers, because low temperature differences imply large UA requirements for meaningful heat recovery [4]. Second, the expander and condenser performance interact strongly: expander exhaust state determines whether recuperation is beneficial and also sets condenser load and feasible condensing pressure under cooling constraints [11,17].

Thermodynamic visualization via T–s diagrams remains useful for interpreting architecture choices. Figure 2 provides a stylized T–s representation that highlights the typical ORC path and the importance of avoiding deep wet expansion for blade erosion and efficiency reasons.

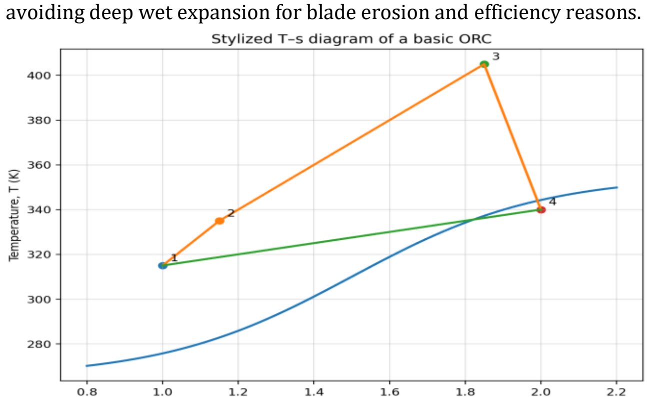

Fig. 2. Stylized T–s diagram of a basic ORC cycle, showing the role of evaporation, expansion, condensation, and pumping.

Reviews comparing fluids and architectures repeatedly indicate that "dry" fluids can keep the expansion end state superheated, enabling recuperation and improving efficiency when the added IHE pressure drop is not excessive [5,6]. However, the same property can increase condenser duty at higher temperatures, potentially raising condensing pressure and reducing pressure ratio across the expander, which may reduce net work if cooling is limited [4,17].

A consistent cross-application result is that ORC net efficiency rises with heat-source temperature class, but with diminishing returns if system design is not adapted. Figure 3 summarizes this trend qualitatively using illustrative temperature classes.

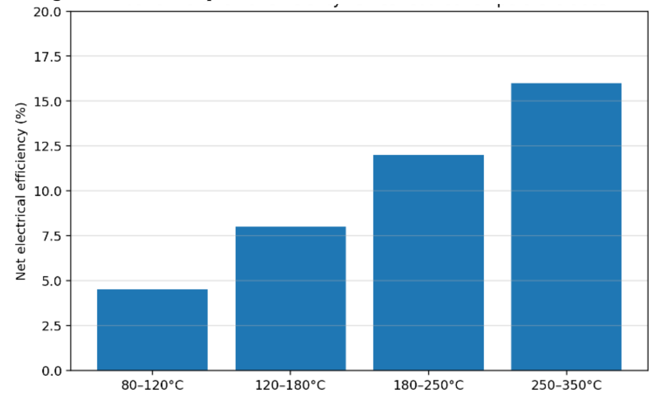

Fig. 3. Illustrative net efficiency increase with heat-source temperature class, reflecting typical ORC behavior under comparable component assumptions.

While such bars are not a substitute for site-specific modeling, they align with the broad conclusion that very low-grade sources require aggressive reduction of irreversibilities, whereas higher-grade sources allow more architectural sophistication and higher expander efficiency to translate into meaningful net gains [1,8].

Application-dependent scatter is substantial because heat-source stability, available cooling, and scale drive component selection and off-design behavior.

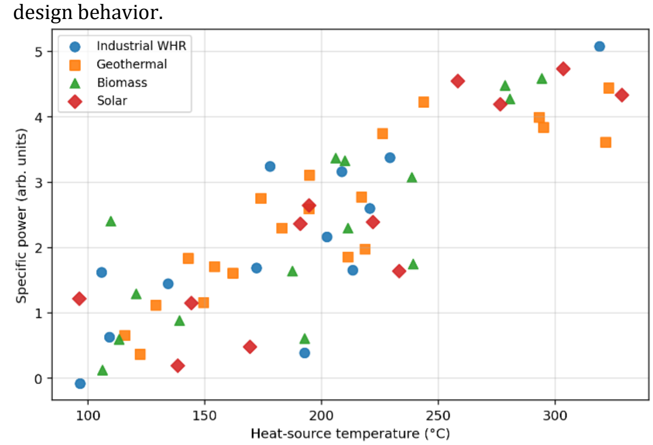

Fig. 4. Illustrative scatter of ORC performance across applications, emphasizing that source temperature alone does not determine outcome.

This aligns with shipboard WHR analyses and other integration-focused studies where packaging constraints, transient operation, and cooling-water availability can dominate feasibility even when heat-source temperature is adequate [9]. Similarly, architecture reviews for WHR emphasize that the same ORC configuration can be attractive in steady industrial duty but underperform in highly transient sources unless control and component sizing are tailored for part-load conditions [11,18].

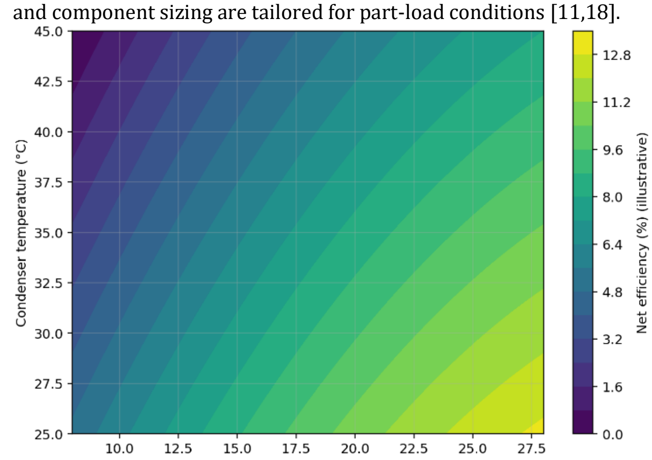

Fig. 5. Illustrative sensitivity of net efficiency to evaporating pressure and condenser

temperature, highlighting the strong penalty of elevated condensing temperature.

Sensitivity analyses consistently show that condenser conditions and evaporating pressure are among the strongest levers for net output, yet they are constrained by cooling resources, ambient conditions, and equipment limits. Figure 5 shows an illustrative sensitivity surface in which efficiency varies with evaporating pressure and condenser temperature.

Off-design modeling studies demonstrate that optimal control actions may include adjusting pump speed, expander inlet valves, turbine guide vanes, and cooling flow to maintain acceptable superheat and minimize irreversibility as conditions drift [17,18]. Dynamic modeling and control reviews further point out that heat exchangers often govern transient response; therefore, aggressive pressure setpoint changes can cause unstable superheat or pinch violations unless the controller explicitly accounts for exchanger dynamics [18].

Working-fluid selection results increasingly emphasize multi-criteria tradeoffs rather than single-metric optimization. Thermodynamic screening of dozens of candidate fluids shows that high performance candidates can differ drastically in volumetric flow ratio, operating pressure, and condensation approach, leading to different expander families and different costs [2,6]. In practice, reviews of working fluids and expander co-selection conclude that fluid choice must be made with explicit expander constraints, because a fluid that yields high theoretical efficiency may require an impractically large volumetric expander or operate too close to critical conditions for stable control in small machines [5,13].

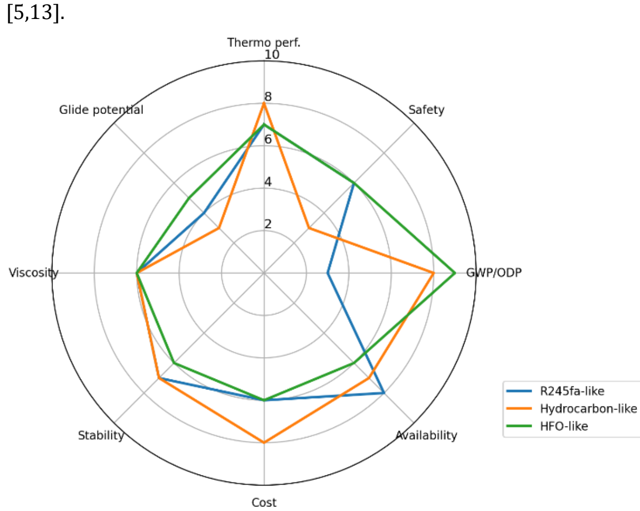

Fig. 6. Illustrative multi-criteria screening of working fluids, contrasting thermodynamic performance against safety and environmental constraints.

Component-level evidence reinforces that expander technology selection can be decisive at small scale. Scroll expander prototype studies show that leakage, built-in volume ratio mismatch, and lubrication strategy can impose strong penalties at off-design pressure ratios, but they also demonstrate robust operation and practical feasibility for micro-ORC systems [15]. Meanwhile, broader expander selection reviews summarize that turbines tend to outperform volumetric expanders in higher power and higher temperature regimes when design-point operation dominates, whereas volumetric machines often win in simplicity and tolerance to variability at smaller scales [5]. These findings are consistent with architecture reviews indicating that cost-effectiveness hinges on matching component technology to the duty cycle and the realistic operating envelope rather than maximizing peak-point efficiency [11].

Experimental trend databases further highlight a recurring irreversibility distribution: heat addition and rejection processes typically dominate exergy destruction due to finite temperature differences, followed by expander losses and pressure drops, with pump work often small but not negligible in micro-scale plants where parasitics are large [8]. This supports the common design strategy of investing in improved heat exchanger effectiveness and reduced pressure losses before pursuing more complex cycle architectures, particularly for low-grade sources where recuperation may deliver marginal gains once exchanger and control penalties are included [1,4,11]. At the same time, recent studies propose advanced exergy-based design views, such as Exergy–Enthalpy diagram approaches, to guide where architectural changes yield true system-level improvements rather than shifting irreversibilities between components [12].

4. Discussion

The aggregated evidence supports a central conclusion: ORC design is most successful when treated as an integrated thermo-fluid–component–control problem, not as a stand-alone thermodynamic cycle selection. Reviews that focus on low-grade heat conversion and WHR consistently stress that thermal matching and component losses define the feasible net output envelope [1,4]. This explains why many apparently promising cycle modifications deliver modest real-world gains; they often increase heat exchanger area, pressure drop, and control complexity, which erode net power or reduce operating stability [11,18].

Working-fluid choice illustrates integration most clearly. Classic screening and selection studies demonstrate that fluid properties strongly shape optimal evaporating pressures, volumetric expansion ratios, and the viability of recuperation, while also influencing heat transfer coefficients and pressure drop [2,6]. Modern selection must incorporate environmental acceptability, which narrows the feasible set and shifts emphasis toward hydrocarbons, HFOs, and other alternatives, each introducing its own safety and stability constraints [14]. The practical implication is that the "best" fluid is application-dependent and must be selected together with expander type, condenser technology, and expected ambient range. For example, a fluid that enables superheated exhaust and recuperation may improve design-point efficiency, yet it may raise condenser temperature or condensing pressure under hot climates, shrinking the expander pressure ratio and reducing net power during the very periods when heat-source availability might be highest [17].

Architecture selection is similarly constrained by operating envelope. The popularity of recuperated ORCs reflects the recurring observation that exhaust superheat can be exploited to reduce required external heat input per unit work, but architecture reviews show that recuperation is not universally beneficial, particularly when the heat source is strongly gliding or when the added IHE pressure loss forces higher pump work and lower expander inlet pressure [11]. Transcritical and supercritical ORCs can improve thermal matching for sensible heat sources, a conclusion emphasized by broader low-grade heat cycle reviews and off-design geothermal studies, yet these gains come with elevated pressures and increased sensitivity to property uncertainties and control actions near critical conditions [2,17]. The design and control community increasingly responds by coupling optimization with off-design simulation, choosing architectures that maximize annual energy rather than peak efficiency, and embedding constraints on pinch, superheat, and equipment limits directly in the optimization [18].

Expander technology remains a practical bottleneck below roughly tens of kilowatts, where turbines are challenging to manufacture and maintain at acceptable cost and efficiency. Scroll expander and other volumetric expander demonstrations show that compact ORCs are feasible and can be experimentally modeled with good fidelity, but they also reveal persistent losses from leakage, friction, and mismatch between built-in and operating pressure ratios [15,16]. Expander selection reviews reconcile these findings by recommending volumetric expanders for broad operating ranges and smaller scales, while reserving turbines for larger plants and more stable duty cycles, where high isentropic efficiency and long life can be achieved [5]. This perspective is reinforced by experimental trend reviews, which show wide scatter in small-scale net efficiency and underscore the importance of auxiliary power and condenser conditions in determining net output [8].

Control and dynamics have moved from a secondary concern to a primary enabler of reliable ORC deployment, especially for WHR in engines, ships, and industrial processes with variable loads. Dynamic modeling and control surveys highlight that heat exchangers dominate system dynamics, creating time delays and nonlinearities that can destabilize superheat control if controllers do not account for moving boundaries and phasechange behavior [18]. Off-design control strategy research proposes coordinated manipulation of pump speed, expander inlet throttling or geometry, and cooling flow to maximize net power while satisfying thermal constraints, suggesting that the achievable annual performance depends substantially on control architecture, sensor placement, and constraint handling [17].

Finally, the discussion points toward research directions that align with deployment needs. First, validated component models and performance maps for expanders and compact heat exchangers are essential for trustworthy off-design optimization and bankable techno-economics. Second, future fluid screening should explicitly incorporate regulatory trajectories and life-cycle considerations while remaining realistic about supply chains and code compliance [14]. Third, integrated design that simultaneously sizes condenser systems for hot climates, mitigates fouling, and ensures stable part-load operation is likely to yield larger real-world gains than further incremental cycle complexity alone [11-45].

5. Conclusion

ORC technology has evolved into a deployable pathway for converting low-to-medium temperature heat into electricity across WHR and renewable heat sources. The literature converges on several robust insights: realistic performance is governed by thermal matching and heat exchanger irreversibilities, expander choice and efficiency dominate net output at small-to-mid scale, condenser conditions impose a strong penalty in hot or cooling-limited environments, and off-design control strongly shapes annual energy yield. Fluid selection is no longer a purely thermodynamic exercise but a multi-constraint decision involving safety and environmental acceptability. Future progress will be driven by integrated optimization with validated component models, environmentally compliant working-fluid portfolios, and control strategies designed for lifetime energy production under real operating envelopes rather than for peak-point efficiency.

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