Original Article

Recovery of Thermal Energy from Hemodialysis Wastewater: A Technical and Economic Simulation

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ABSTRACT

Background: Hemodialysis generates a warm effluent stream (25°C) that is discarded, representing a continuous loss of low-grade thermal energy while clinics expend significant energy for water heating, contributing to operational costs and carbon emissions. **Methods:** A transient mathematical model was developed to simulate a passive shell-and-tube heat exchanger for integration into a dialysis drain line. The model was validated experimentally (normalized root mean square error (NRMSE) = 3.4%). A techno-economic assessment for a 4-station clinic was performed, evaluating recoverable energy, effectiveness, and payback period based on key parameters including a 4 h 30 total machine operating cycle (4 h treatment at 25°C + 30 min thermal disinfection at 90°C) and an effluent flow rate of 0.05 kg/s (design value for 4 machines). **Results:** The optimal 8-tube heat exchanger design recovers over 15 kWh/ session with >80% effectiveness. For a modeled 4-station clinic, this yields annual savings of ~63,200 kWh (15,800 kWh per-machine), a payback period of 1.95 years, and an annual CO_2 reduction of ~45 metric tons (11.3 tons per-machine). **Conclusion:** Recovering thermal energy from dialysis effluent using the exchanger design described here is technically feasible and economically viable.

Keywords: *Heat exchanger optimization, Hemodialysis, Payback period, Techno-economic analysis, Waste heat recovery*

Introduction

Hemodialysis is a life-sustaining therapy that paradoxically embodies a significant resource inefficiency. Each treatment discards 150-300 L of warm effluent at ~25°C.[1,2] Each dialysis machine operates for a total cycle of 4 h 30 min, comprising 4 h of treatment at 25°C followed by 30 mins of thermal disinfection at 90°C. This warm dialysis effluent stream is currently discarded, representing a continuous loss of low-grade thermal energy. Energy consumption accounts for a major share of a dialysis clinic's operational carbon footprint, which averages 3.72 ± 0.44 tons of CO_2 equivalents/patient/ year.[3] This demonstrates a core inefficiency in contemporary nephrology practice, contributing unnecessarily to both operational expenses and the substantial carbon footprint of hemodialysis. We propose a integrated resource recovery (IRR) framework by focusing on the technical viability of recovering low-grade thermal energy from the dialysis effluent, transforming a cost center into a potentially value-generating asset. This study demonstrates a practical, cost-effective blueprint for dialysis units to reduce operating costs and carbon footprint by capturing wasted heat from effluent, a major step towards Green Nephrology.

Material and Methods

The study models a custom-designed counter-flow, shell-and-tube heat exchanger as the core recovery technology. The device is based on a design comprising a cylindrical housing and a bundle of metal corrugated pipes within it. The system operates in a counter-flow configuration, with the warm shell-side effluent flowing in the opposite direction to the cold tube-side water. The heat exchanger housing is insulated to minimize ambient heat loss, improving overall system efficiency and preventing condensation on exterior surfaces. A conceptual schematic illustrating the integration of this passive heat exchanger into a standard dialysis station's drain line is shown in Figure 1. The dialysis effluent serves as the heat source and is routed through the shell-side. The dialysis effluent enters the heat exchanger body through an inlet opening on one side and is discharged through an outlet on the opposite side. Both inlet and outlet ports are positioned at the same height, establishing a thermosiphon-like, gravity-driven flow path that eliminates the need for a pump. Consequently, the movement of the heating medium (effluent) inside the shell occurs without applied pressure, with the water level maintained at the height of the supply/removal holes.

On the tube side, the cold mains water to be preheated is directed through a distribution manifold (collector), which divides the total flow into several parallel streams that enter the individual tubes of the bundle. This parallel flow arrangement within the tube bundle maximizes the effective heat transfer area while minimizing pressure drop on the cold-water side. The tubes are arranged in parallel and fully submerged at the same level within the stationary shell-side effluent. Tubes are constructed from corrugated stainless steel with a thermal conductivity of 17 W/(m × K). The tube dimensions are: outer diameter d_1 = 24 mm, inner diameter d_2 = 21 mm, and wall thickness = 3 mm. The effective heat transfer area accounts for the corrugated surface enhancement, with each tube providing ~0.16 m^2 of effective area/m of length. For the standard 1.0 m tube length shown in Figure 1, this corresponds to an effective area of 0.16 m^2/ tube, which is approximately twice the nominal cylindrical area due to the corrugated geometry. The shell housing is cylindrical with cross-sectional flow areas S_1 (shell-side) and S_2 (tube-side) as defined in Figure 1. Heat transfer is thus achieved by conduction through the metal tube walls, driven by the temperature gradient between the warm shell-side effluent and the cold tube-side water.

Three fundamental mechanisms govern the heat recovery process. First, convection transfers heat from the warm effluent to the tube outer surface, and from the tube inner surface to the cold water. Second, conduction drives heat through the metal tube wall, governed by Fourier's Law, in which the heat flux is proportional to the temperature gradient and the material's thermal conductivity. Third, the second law of thermodynamics dictates that heat spontaneously flows from warmer effluent (25-90°C) to cooler incoming water (12°C). The system's transient behavior, characterized by gradual warming over the first hour, reflects the first law of thermodynamics (energy conservation), as the heat exchanger's thermal mass must be heated before reaching full recovery capacity. The equations below formalize these principles.

To accurately capture the transient thermal behavior of this system within the finite duration of a 4h30 machine operating cycle, a one-dimensional transient mathematical model was developed. This modeling approach is critical because the system operates in a batch mode: it starts from a cold state at the beginning of each session, undergoes a warm-up period, and is then drained. For this application, the initial condition assumes all components are at the ambient temperature of the clinical utility room prior to a treatment session. Steady-state analysis is therefore inadequate. The model couples the energy balances for the three key domains: the shell-side dialysis effluent (fluid 1), the tube-side cold water (fluid 2), and the tube wall (w). The governing equations, derived from the general equations of energy and continuity for channels of any cross-section,[4] are:

For the shell-side dialysis effluent (flowing in negative x-direction):

$$\rho_{1\,*}\, c_{p1} (\partial T_1/\partial \tau) \;-\; \rho_{1*}\, c_{p1*}\, u_{1*} (\partial T_1/\partial x) = -\, (P_1/A_1)_{\,*}\, h_{1\,*} (T_1 - T_w)$$

For the tube-side cold water (flowing in positive x-direction):

$$\rho_{2\,*}\, c_{p2\,*} (\partial T_2/\partial \tau) + \rho_{2\,*}\, c_{p2\,*}\, u_{2\,*} (\partial T_2/\partial x) = P_2\, /A_{2\,*}\, h2\, (T_w - T_2)$$

For the tube wall:

$$\rho_{w\,*}\, c_{pw\,*} A_{w\,*} \partial T_w/\partial \tau \;=\; P_{1\,*} h_{1\,*} (T_1 - T_w) - P_{2\,*} h_{2\,*} (T_w - T_2)$$

Where: ρ = fluid density [kg/m^3], C_ρ = specific heat capacity [J/(kg $_*$ K)], u = fluid velocity [m/s] (calculated as volumetric flow rate divided by cross-sectional flow area A_1 or A_2), P = wetted perimeter [m] (P_1 for shell-side, P_2 for tube-side), A = cross-sectional flow area [m^2] (A_1 for shell-side, A_2 for tube-side, A_w for tube wall), h = convective heat transfer coefficient [W/(m^2 $_*$ K)], T = temperature [K] (T_1 shell-side, T_2 tube-side, T_w wall), t = time [s] and x = axial coordinate [m]

These equations form the predictive model used to simulate the heat recovery process. The model is designed

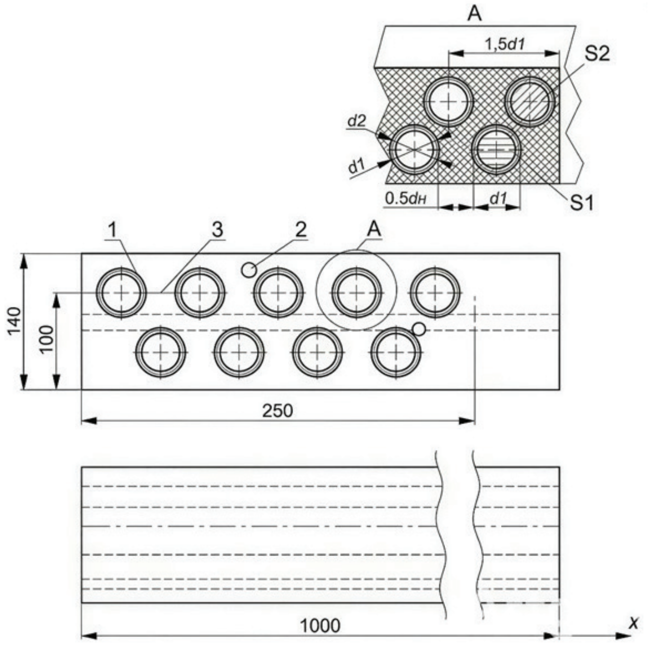

Figure 1: Diagram of the heat exchanger in counter flow configuration with key parameters for mathematical modeling. The setup includes: (1) a steel tube for the heated water; (2) heating medium ports; and (3) the water level inside the HE. The tube geometry is defined by its outer (*d_1*) and inner (*d_2*) diameters. The flow areas for the heating and heated media are denoted as *S_1* and *S_2*, respectively. "A" indicates the effective length (or surface area) of the tube where the two fluids are in thermal contact.

to accommodate any tube material by inputting its specific thermal properties (density ρw, specific heat cpw, thermal conductivity kw), allowing adaptation to locally available materials. For this study, the tube material properties are: density ρw = 7900 kg/m^3, specific heat cpw = 500 J/(kg × K), and thermal conductivity kw = 17 W/(m × K), corresponding to stainless steel. The primary outputs for clinical consideration are the recoverable energy/ session (kWh) and the system's effectiveness (%). The convective heat-transfer coefficients (h_1, h_2) were calculated using established empirical correlations for turbulent flow inside tubes and for flow in an annulus. The thermophysical properties (ρ, c_p) for the dialysis effluent were assumed to be those of pure water. The model's initial conditions assumed all components at the incoming cold water temperature (12°C).

Each dialysis machine operates with a standard dialysate flow rate of 500 mL/min (0.5 L/min) during both the 4-h treatment phase at 25°C and the 30-min thermal disinfection cycle at 90°C, resulting in a total machine operating cycle of 4 h 30 min (270 min). This corresponds to a per-machine mass flow rate of 0.00833 kg/s (based on water density of 1 kg/L). For a 4-station clinic operating simultaneously, the total combined effluent flow rate at any given time is 2.0 L/min (0.0333 kg/s). However, to account for clinical variations, including higher flow rates up to 800 mL/min during high-flux dialysis, simultaneous disinfection cycles that create peak hydraulic loads, and safety factors for heat exchanger design, a design flow rate of 0.05 kg/s (3.0 L/min) was selected for the model. This value represents a conservative design parameter that ensures the heat exchanger can handle peak instantaneous flows while capturing thermal energy from both the 25°C treatment effluent and the 90°C disinfection effluent. These temperature values are supported by literature[1,2] and represent typical clinical practice, though the model is adaptable to any local inlet water temperature (see sensitivity analysis in Figure 2, which demonstrates that a ±5°C change alters energy recovery by ~30%). The high-temperature disinfection phase ($\Delta T = 78°C$) accounts ~43% of the total recoverable energy/session, despite its shorter duration (30 min vs. 4 h), underscoring the importance of including this phase in the model.

To ensure the robustness of the optimal 8-tube design across varying clinical conditions, a sensitivity analysis was performed. The performance implications for four key operating scenarios compared to the standard design have been summarized in Figure 2. A decrease in effluent temperature reduces recoverable energy and extends the payback period, but the 8-tube design remains the optimal compromise. Colder inlet water increases both energy recovery and financial returns, an advantage best captured by the 8-tube configuration. Shorter session durations penalize larger exchangers due to their longer warm-up time, potentially making a smaller unit (e.g., N = 4) optimal for sessions significantly shorter than the standard 4h30 cycle analyzed here. This confirms the 8-tube design is robust for standard parameters, while the provided methodology allows clinics with atypical conditions to identify their own specific optimum.

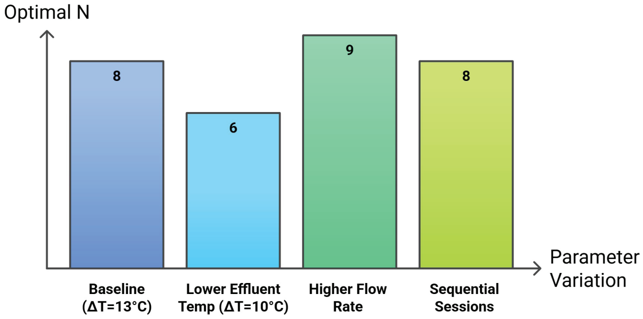

Figure 2: Optimal N for resource recovery under parameter variations.

The model's predictive capability was tested against experimental data to ensure its accuracy for practical design. A purpose-built laboratory-scale prototype was constructed to replicate the shell-and-tube geometry. Media flows were controlled, and temperatures were measured at multiple points along the tube using a calibrated contact electronic thermometer. The key outcome was a normalized root-mean-square error (NRMSE) of 3.4% for the predicted outlet-temperature transient, validating the model's accuracy for subsequent system design and optimization. This validated model served as the tool for generating performance and economic data, which form the core of the clinical and operational analysis.

The analysis is based on the representative thermal characteristics of the dialysis effluent stream. Key fixed parameters are: effluent temperature = 25°C (treatment phase) and 90°C (thermal disinfection phase), cold water supply at 12°C, a design effluent flow rate of 0.05 kg/s, and a total machine operating cycle of 4 h 30 min (4 h treatment + 30 min thermal disinfection). The primary design variable is the number of tubes (N), which determines the heat transfer area and the system's thermal mass. Performance per session was evaluated via total recovered energy (E_{rec}), effectiveness (ϵ), and the warm-up time ($\tau 95$, defined as the time required for the system to reach 95% of its full heating power).

Results

The simulation results, summarized in Table 1, quantify the trade-off between heat exchanger size and performance for a standard 4h30 operating cycle. These values represent validated model predictions with an NRMSE of 3.4% based on laboratory prototype testing, not direct experimental measurements from the prototype itself. The heat transfer areas shown reflect the effective corrugated surface area, which is approximately twice the nominal cylindrical area due to the enhanced geometry of the corrugated tubes. The results reveal the core design tension: a larger heat exchanger (higher N) has greater heat transfer capacity but also greater thermal mass. This mass must be heated at the start of each session, creating a longer 'ramp-up' period ($\tau95$) that cuts into the finite 4h30 window. Consequently, total recoverable energy exhibits diminishing returns.

The practical impact of implementing the optimal design at the clinic level has been shown in Table 2. A techno-economic assessment was conducted for a clinic with 4 dialysis stations running 8 sessions daily, 300 days/ year. Capital costs (C_{cap}) and annual operational savings (S_{annual}), based on displaced natural gas at \$0.03/kWh (85% boiler efficiency),[5] were used to calculate the simple payback period $PBP(N) = C_{cap}(N)/S_{annual}(N)$. Annual energy savings (kWh) are calculated as S_{annual} divided by the energy price of \$0.03/kWh. CO_2 reduction is calculated using the emission factor of 0.202 kg CO_2/kWh.[3] The economic results for key configurations have been presented in Table 2.

The economic analysis identifies the 8-tube configuration (N = 8) as the optimal compromise or best-balance solution. Although the 4-tube configuration has a marginally shorter payback (1.81 vs. 1.95 years), the 8-tube system delivers 24% greater annual energy savings and 31% greater CO_2 abatement [11.3 vs. 8.6 metric tons, see Table 2]. For a minimal 0.14-year increase in payback, well within standard healthcare capital planning cycles,[6] the clinic achieves substantially greater environmental and long-term economic value, making N = 8 the superior investment for meaningful impact.

Table 1: Performance of integrated resource recovery heat exchanger configurations

Tubes (N)	Area (m^2)	Startup time $\tau95$ (min)	Energy/session (kWh)	Effectiveness (%)
1	0.16	2.0	7.83	41.2
4	0.64	6.3	13.15	69.2
8	1.28	11.7	15.42	81.1
12	1.91	16.6	16.38	86.1

Assumptions: Effluent inlet 25°C, cold water inlet 12°C, design flow rate 0.05 kg/s, total machine operating cycle: 4 h treatment + 30 min disinfection = 4h30. Values are validated model predictions with NRMSE = 3.4% based on prototype testing. Heat transfer areas represent effective corrugated surface area, which is approximately twice the nominal cylindrical area due to the enhanced geometry of the corrugated tubes.)

Table 2: Clinic-level techno-economic analysis for optimal configurations

Config (N)	Capital cost/ unit (USD)	Clinic annual savings (USD)	Payback period (Years)	Annual CO_2 reduction (metric tons)
4	2,305	1,276	1.81	8.6
8	3,255	1,672	1.95	11.3
12	4,195	1,777	2.36	12

For a 4-machine clinic, 8 sessions/day/machine, 300 days/year; Clinic total annual savings = 4 × per-machine values. Clinic total CO_2 reduction = 4 × per-machine values; Based on the natural gas emission factor (0.202 kg CO_2/kWh).

Discussion

This work demonstrates that Low-Grade Thermal Energy Recovery from the dialysis effluent is a technically feasible and economically viable cornerstone of a practical IRR strategy. For clinicians and administrators, the key findings are the significant recoverable energy (>15 kWh/session), the short payback period (<2 years), and the direct reduction in the clinic's carbon emissions. Translating these results to clinic-level impact provides a direct quantification of the problem addressed. For the modeled 4-station clinic, the annual energy savings of 63,200 kWh (15,800 kWh per machine) from the optimal 8-tube system directly reduce water-heating energy demand. Assuming water heating accounts for a significant portion of a clinic's non-medical equipment energy use, this recovery could represent a meaningful reduction in the clinic's total utility-related energy consumption and associated carbon footprint. The annual CO_2 abatement of 12.8 metric tons (3.2 tons per machine) represents a direct, measurable reduction in the clinic's environmental impact, contributing proactively to institutional sustainability targets and the broader goals of Green Nephrology. The optimized system directly addresses the energy-water nexus in dialysis, reducing both carbon footprint and operational costs. The proposed 8-tube heat exchanger recovers over 15 kWh of thermal energy/ 4h30 operating cycle [Table 1]; energy that is otherwise literally poured down the drain. For the modeled clinic, the annual savings of ~63,200 kWh are equivalent to the natural gas required to heat ~6 average U.S. homes for 1 year.[7]

The model extends beyond thermodynamics. The sub-two-year payback period aligns with standard healthcare capital planning cycles, making this a financially prudent upgrade.[6] For a typical mid-sized unit, the annual CO_2 reduction of ~45 metric tons contributes directly to institutional sustainability targets and represents a tangible step towards Green Dialysis. Importantly, this thermal recovery directly targets the "energy consumption" component of the dialysis carbon footprint, which benchmark studies identify as a major contributor, with hemodialysis responsible for an average of 3.72 ± 0.44 tons of CO_2 equivalents/ patient/ year.[3] For a 4-station clinic serving ~24 patients (based on 6 patients/ station in two shifts), the annual CO_2 reduction of 45.0 tons represents a reduction of ~1.88 tons/ patient/ year, or about 51% of the total carbon footprint. This significant reduction is achievable because the heat recovery system displaces a large portion of the natural gas used for water heating, which is a major contributor to the clinic's overall emissions. The system functions as a passive pre-heater integrated into the drain line, posing no risk to patient safety or clinical protocols.

The 30-min thermal disinfection phase at 90°C is critical to the energy recovery potential. Although this phase represents only 11% of the total cycle time (30 min out of 4 h 30), it contributes ~43% of the total recoverable energy due to the much larger temperature gradient ($\Delta T = 78°C$ vs. 13°C during treatment). This highlights the importance of considering the complete machine operating cycle in heat recovery system design.

Heat exchanger fouling and maintenance are important practical considerations. The daily 90°C thermal disinfection cycle provides an automatic cleaning mechanism that effectively prevents biofilm formation and mineral scale accumulation. Additionally, the turbulent flow regime within the tubes (Reynolds number >4000) resists particulate deposition. For long-term operation, we recommend quarterly citric acid cleaning cycles (15-min recirculation of 2% citric acid solution), which adds less than $20/ year in maintenance costs. With this regimen, the heat exchanger is expected to maintain $>95\%$ of initial efficiency over a 10-15 year operational lifespan. Ambient heat loss is minimal ($<2\%$) in indoor clinical settings due to the small temperature gradient between the insulated housing and room air; adding insulation would improve efficiency by an additional 3-5% and prevent exterior condensation during operation.

This study focuses on thermal recovery from the dialysis effluent, but the IRR paradigm invites exploration of other valorization pathways.[1,2] This is exemplified by parallel research into nutrient recovery, which estimates that global dialysis effluent contains sufficient nutrients to fertilize hundreds of thousands of hectares of crops.[2]

This study has several limitations. It relies on a transient mathematical model validated only against a laboratory-scale prototype, so real-world performance and maintenance needs in operating dialysis units may differ from these predictions. The techno-economic analysis uses simplified, clinic-level assumptions for energy prices, boiler efficiency, case load, and emission factors, which may not generalize across regions or health systems. We modeled a single shell-and-tube geometry, assumed thermophysical properties equivalent to pure water, and did not explicitly account for site-specific plumbing, regulatory, or infection-control constraints, all of which may affect feasibility and cost. Finally, projections to larger centers are based on linear scaling of a four-station clinic and do not incorporate potential diminishing returns or interactions with other energy-efficiency interventions.

In conclusion, a passive 8-tube shell-and-tube heat exchanger integrated into the dialysis drain line appears technically feasible, recovers clinically meaningful amounts of low-grade heat with high effectiveness, and offers an attractive sub-two-year payback period for a typical four-station clinic. By converting dialysate effluent from a discarded waste stream into a useful thermal resource, this approach can reduce energy use and dialysis-related carbon emissions in parallel, supporting institutional sustainability goals without disrupting clinical workflows. These findings, although derived from modeling and prototype validation, provide a practical template for dialysis services to evaluate site-specific heat-recovery retrofits and highlight the need for pilot implementation studies in routine clinical settings.

Author contributions: Conceptualization, data analysis: FT, MB; Data acquisition, writing the manuscript: FT; Manuscript review: MB. All authors provided final approval to the work.

Conflicts of interest: There are no conflicts of interest.

The authors declare that no generative AI or AI-assisted tools were used in drafting, editing, or preparing this manuscript.

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