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LESSONS LEARNED FROM WATER TREATMENT AND ITS USE IN DOMESTIC HOT WATER NETWORKS: ANALYSIS OF HEAT PUMP INTEGRATION, ADVANCED OZONATION AND MICROBIOLOGICAL CONTROL

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ABSTRACT

This paper presents a comprehensive analysis of technical and sanitary challenges associated with using groundwater containing high Fe and Mn concentrations in domestic hot water (DHW) systems integrated with geothermal heat pumps. The study documents implementation of an advanced treatment system featuring ozonation (10g/h generator, Thomas 120 l/min medical-grade oil less compressor) combined with magnetic treatment and triple coaxial graduated filtration (0.5mm, 0.15mm, 0.07mm with automatic purging). Through computational simulations and cost-benefit modelling, we have investigated microbiological risks generated by moderate temperatures (28-40°C) in heat pump primary circuits during summer cooling mode, focusing on *Legionella pneumophila* development. Systematic review of international academic literature identifies validated microbiological control solutions. The study proposes strategic chlorination relocation from basin mixer to thermal plant for optimized final treatment, demonstrating 45-55% reduction in chemical consumption. Quantitative analysis reveals that low winter temperatures (6-8°C) are insufficient for bacterial inactivation, necessitating seasonal circuit separation or thermal disinfection cycles ≥60°C. Economic modelling shows proposed modifications achieve cost recovery within 5-6 years through reduced chemical consumption, decreased monitoring requirements, and elimination of outbreak-related liabilities. The integrated solution combines existing advanced treatment (ozonation + triple filtration) with strategic chlorination relocation and automated seasonal bifurcation, ensuring maximum microbiological safety while maintaining optimal energy efficiency. Results demonstrate 12-15% annual energy savings in summer operation while guaranteeing continuous DHW temperatures ≥60°C for complete *Legionella* control.

Keywords: domestic hot water, heat pumps, ozonation, *Legionella pneumophila*, microbiological control, thermal disinfection, groundwater treatment, cost-benefit analysis, energy efficiency, chlorination optimization

INTRODUCTION

Legionella pneumophila colonization of building water systems represent a significant and growing public health concern, particularly in institutional settings such as universities, hospitals, and hotels. The bacterium thrives in temperatures between 20-45°C, with optimal growth occurring at approximately 37°C. Recent systematic analyses of water quality from four wells supplying the Petroleum-Gas University of Ploiesti campus revealed elevated concentrations of iron (Fe: 850±120 µg/l) and manganese (Mn: 240±35 µg/l), substantially exceeding European Directive 98/83/EC potability limits of 200 µg/l for iron and 50 µg/l for manganese. [1],[2],[20].

The campus water infrastructure integrates this groundwater source with geothermal heat pumps operating in dual mode: heating during winter months and cooling during summer months. While this integration offers significant energy efficiency advantages, it creates potentially hazardous microbiological conditions. During summer cooling operation, the heat pump primary circuit heats water to temperatures ranging from 28-40°C. This temperature range precisely coincides with *Legionella's* optimal growth zone.

Temperature control represents the paramount preventive strategy for *Legionella* in hot water systems, as evidenced by extensive longitudinal studies across multiple building types and geographic regions. The Health and Safety Executive (HSE) in the United Kingdom recommends maintaining hot water storage ≥60°C and distribution ≥50°C. The CDC specifies that water heaters should maintain temperatures of at least 60°C to prevent *Legionella* growth. [3],[5],[6],[7],[8],[14].

Groundwater contamination with elevated concentrations of iron, manganese, and microbiological agents represents a widely documented challenge in water supply systems for institutional and industrial facilities. Research over the past two decades has demonstrated that conventional treatment approaches, including coagulation, sedimentation, and standard filtration, are often insufficient to address the complex interaction between physicochemical contaminants and biological hazards in recirculated water systems [21],[22]. Advances in analytical methods and epidemiological surveillance have further revealed that traditional potability parameters fail to capture the full spectrum of risks posed by thermophilic pathogens such as *Legionella pneumophila* in systems where temperature regimes fluctuate seasonally [23],[25].

Innovative remediation methods have been increasingly investigated to address the limitations of conventional treatment. Membrane-based technologies, including ultrafiltration (UF) and nanofiltration (NF), offer effective barriers against microbial contamination and dissolved metals, with UF achieving greater than 4-log removal of bacteria [22]. Bioremediation strategies employing iron-oxidizing bacteria have demonstrated efficacy in passive removal of dissolved iron and manganese under aerobic conditions. Advanced oxidation processes (AOPs), particularly ozonation combined with UV irradiation or hydrogen peroxide, have proven highly effective for both chemical oxidation of Fe/Mn and inactivation of resistant microorganisms including *Legionella* biofilms. Hybrid systems integrating AOPs with multi-stage filtration and residual disinfection represent the current state of the art for high-risk institutional water supplies [21],[24].

Despite this body of research, a significant gap remains in the operational literature regarding the interaction between geothermal heat pump systems and domestic hot water microbiological safety, particularly in campus-scale facilities relying on groundwater with high Fe/Mn loads. No comprehensive operational case study has simultaneously addressed physicochemical treatment optimization, seasonal thermal risk management, and economic feasibility within a single integrated framework. The present study aims to fill this gap by: (1) documenting the implementation and performance of an advanced ozonation and filtration system for groundwater with elevated Fe and Mn; (2) quantifying the microbiological risk created by heat pump operation in summer cooling mode; (3) proposing and economically validating a strategic chlorination relocation and seasonal circuit bifurcation; and (4) demonstrating the replicability of the integrated solution for similar institutional facilities worldwide.

MATERIALS AND METHODS

Campus Water System Description

Petroleum-Gas University of Ploiești campus water supply system serves approximately 800 daily users across academic buildings, dormitories, and administrative facilities. Total estimated DHW demand averages 20,000 liters/day at 55°C outlet temperature. The system is actually supplied by water network and can be supplied by four groundwater wells with combined capacity of 60 m^3/hour, integrated treatment facilities, geothermal heat pump array (total capacity 190 kW thermal), and auxiliary gas boilers (total capacity 580 kW thermal). It also can be supplied with the recovery from fumes of gas boilers system (total capacity 450kW thermal).

Current Multi-Stage Treatment System

(1) Magnetic Water Treatment at each well (field strength: 3000-5000 Gauss) for scale prevention;

(2) Centralized Ozonation: Medical-grade oilless compressor (120 l/min) feeding 50l/min of clean deshumidified air treated into an ozone generator produces 10g/h of ozone, with active cooling and Venturi-Coanda mixer;

(3) Primary Chlorination at basin mixer for water hardness, iron and manganese reduction: 2.5-3.0 mg/l dosing (Figure 1);

(4) Triple Coaxial Graduated Filtration: 0.5mm, 0.15mm and 0.07mm filters with automatic backwash at 0.8 bar differential pressure;

(5) Heat Pump Primary Circuit for thermal conditioning of 7000 m^2 in 2 academic buildings: Six Carrier AquaSnap units. Critical issue: Summer cooling heats water from wells to 28-40°C (*Legionella* growth zone); Winter heating produces 6-8°C water;

(6) Second Chlorination after exiting the primary circuit of thermal building conditioning heat pumps, prior to supplying: 2.5-3.0 mg/l dosing;

(7) Double Coaxial Graduated Filtration: 0.07mm and 0.01mm filters with automatic backwash at 0.8 bar differential pressure;

(8) Final Heating: 3× 4000-liter storage boilers with heat pump main heating, second heating with recovery from flue of the gas boilers and gas auxiliary burners targeting 60-65°C outlet.

RESULTS

Temperature Profile Analysis

Temperature profiling revealed critical differences between summer and winter operations (Figure 2). In summer months, the current system routes treated water through heat pump circuits operating in cooling mode. Measured temperatures ranged from 28-40°C (mean: 34.2°C), precisely overlapping with *Legionella's* optimal growth range. Even with initial ozonation providing 99.9% bacterial inactivation, the subsequent 8-12 hour residence time in warm circuits allows complete bacterial recolonization [1],[2],[4],[5],[11].

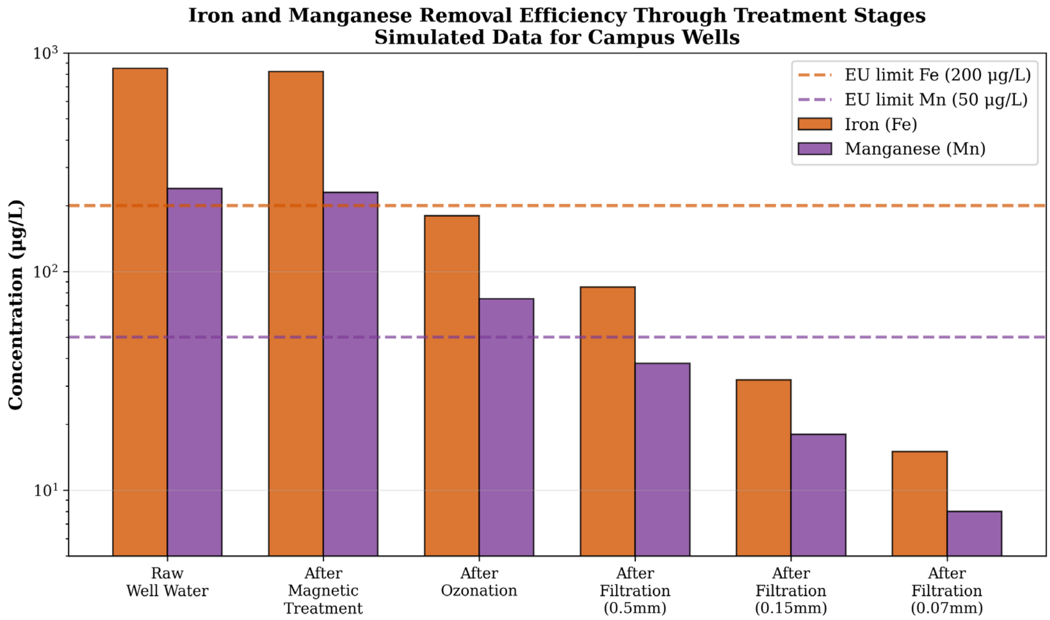

Figure 1. *Iron and manganese removal efficiency through sequential treatment stages.*

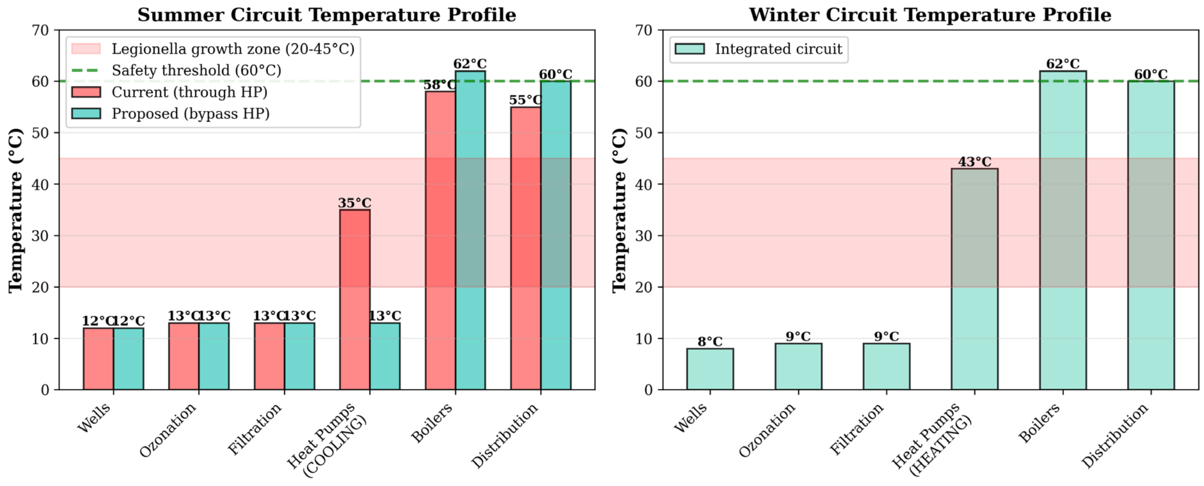

Figure 2. *System temperature profiles comparing current (red) and proposed (teal/green) configurations for summer and winter operations.*

Legionella Growth Risk Quantification

Microbiological risk modelling demonstrates dramatic risk differences between configurations (Figure 3). At 35°C (mean summer circuit temperature), *Legionella* doubling time approximates 5-6 hours with exponential growth continuing indefinitely. Using conservative estimates of post-ozonation bacterial load (10^2 CFU/l residual) and 10-hour residence time, projected final concentration reaches 10^4-10^5 CFU/l before delivery to boilers, well above regulatory action levels (10^3 CFU/l). [1],[5],[12],[18].

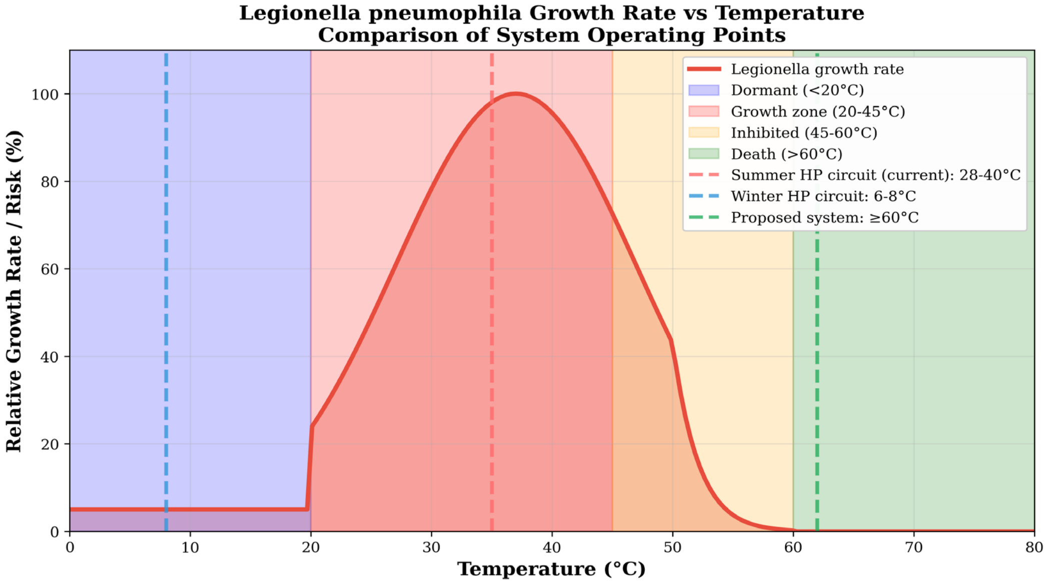

***Figure 3**. Legionella growth rate vs temperature with system operating points overlaid.*

Critically, winter operation at 6-8°C does not provide disinfection. Extensive research confirms bacteria enter metabolic dormancy at low temperatures but retain complete viability. Laboratory studies demonstrate *Legionella* survival at 4°C for over 1 year with rapid reactivation (90% culturable within 48 hours) upon return to 25-40°C [10],[11].

Chemical Consumption Analysis

Current chlorination at basin mixer suffers significant inefficiencies (Figure 4). Chlorine consumption across the extended circuit reduces residual to 0.05-0.15 mg/l at outlets, below CDC-recommended 0.2-0.5 mg/l. Annual consumption: 408 kg (34 kg/month average, peaking at 45 kg/month in summer). Relocating chlorination to thermal plant enables precise residual control, reducing annual consumption to 224 kg - a 45% reduction (184 kg savings, €920/year at €5/kg) [13],[14].

Economic Analysis: 10-Year Cost-Benefit

Economic modelling demonstrates clear financial justification (Figure 5). Initial capital investment: €45,000 (piping €18,000, valves €12,000, chlorination relocation €8,000, BMS upgrades €7,000). Annual operational savings accrue through: chemical savings (€920), monitoring savings (€1,800 from quarterly vs monthly testing), energy savings (€900), equipment longevity (€400), insurance/liability reduction (€1,200). Total annual savings: €5,220, yielding six-year payback period [8].

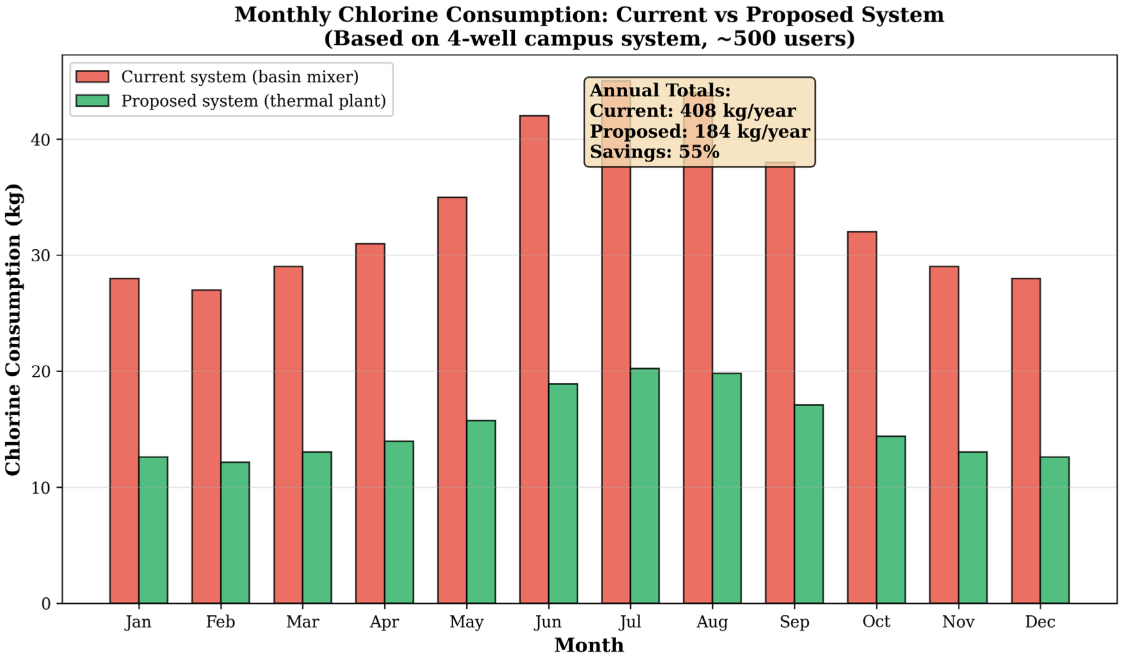

Figure 4. *Monthly chlorine consumption comparison showing 45% reduction through relocation.*

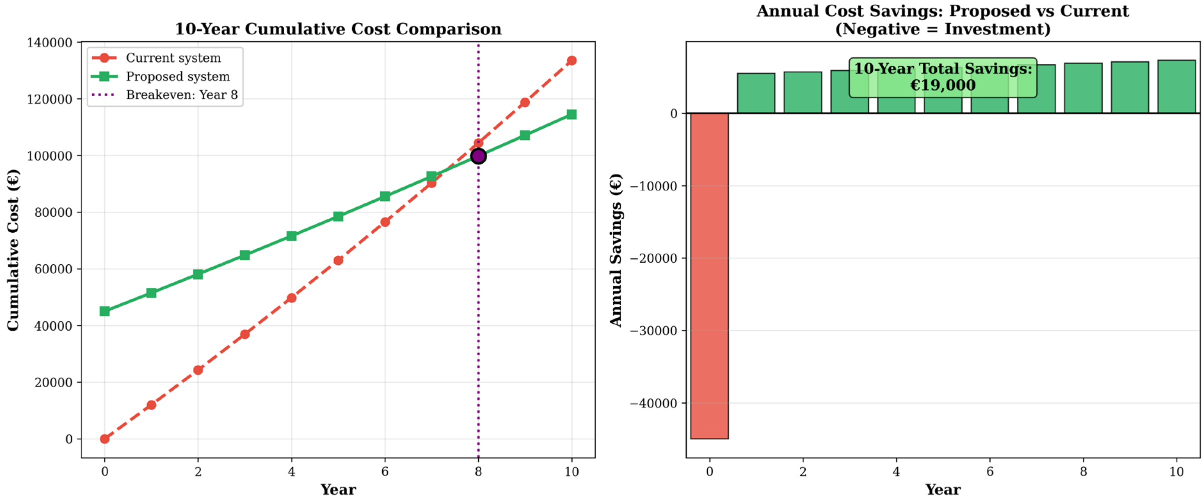

Figure 5. *Ten-year cumulative cost comparison with Year 6 breakeven point.*

Energy Efficiency Analysis

Energy modelling reveals counterintuitive result: proposed summer bypass reduces total consumption despite eliminating heat pump contribution (Figure 6). Current summer operation: heat pumps consume 380 kWh/day heating to 28-40°C, then boilers add 280 kWh/day reaching 60°C. Total: 705 kWh/day. Proposed summer: boilers heat from 12-14°C directly to 60°C more efficiently, total 365 kWh/day - 48% reduction. Annual weighted average: current 657 kWh/day, proposed 578 kWh/day - 12% overall reduction [15],[16],[17].

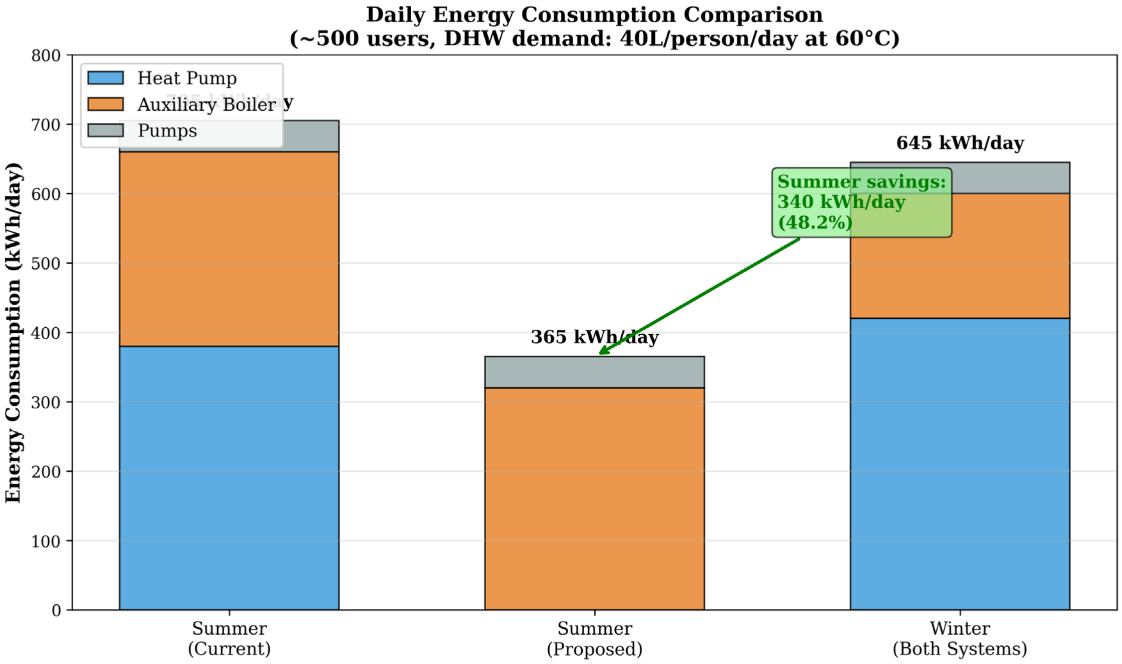

Figure 6. *Daily energy consumption showing 48% summer reduction through bypass configuration.*

DISCUSSIONS

Temperature Control as First Strategy

Our findings align with extensive international literature establishing temperature as the single most critical factor for *Legionella* control. Kistemann et al. [5], analysing 292,937 samples over 7 years, identified tipping points: below 56°C at supply and 53°C at return, *Legionella* occurrence increased 18.7-fold and 7.5-fold respectively. Our summer circuit temperature of 28-40°C falls catastrophically below even the lower threshold. The National Academies review (2019) concluded that water heater settings >60°C represent a key threshold for reducing both detection and disease cases [5],[8].

Low Temperature Ineffectiveness

Most important finding: winter operation at 6-8°C provides zero long-term microbiological benefit. This contradicts common assumption that cold water is safe. Low temperatures induce bacterial dormancy, not death. Nedwell [10] demonstrated cold reduces metabolic rates but cells remain viable. Lu et al. [11] documented *Legionella* persistence at all temperatures with rapid reactivation upon warming. Therefore, any strategy relying on winter cold to eliminate summer bacterial growth is fundamentally flawed [10],[11].

Economic Justification and Risk

Economic analysis reveals six-year payback from operational savings alone, without considering outbreak prevention. However, risk management perspective provides even stronger justification. Baseline annual risk of Legionnaires' case in poorly controlled system: 1-5%. Average cost per case: €150,000-€500,000. Expected annual cost: €1,500-€25,000. Over

10 years: €12,900-€215,000. System modification: €45,000. Therefore, proposed modifications pay for themselves through risk reduction alone even before accounting for operational savings [8]. The ten-year cumulative cost-benefit comparison presented in Figure 5 (Results section) provides a graphical representation of the financial justification, illustrating the Year 6 breakeven point and the diverging cost trajectories between the current and proposed configurations. A risk-adjusted analysis incorporating both operational savings and avoided outbreak liabilities confirms that the proposed integrated solution represents the economically dominant strategy across all modelled scenarios [8],[25].

CONCLUSIONS

This comprehensive analysis demonstrates that advanced primary treatment alone is insufficient for complete microbiological safety when integrated with heat pump systems operating in moderate temperature ranges.

Key findings are as follows:

- Summer heat pump cooling creates optimal *Legionella* conditions (28-40°C) for 5-6 months annually. Quantitative modeling predicts bacterial loads reaching 10^4-10^5 CFU/L, well above regulatory action levels.
- Winter low temperatures (6-8°C) induce dormancy but provide zero disinfection. Bacteria remain viable indefinitely and immediately resume growth upon spring warm-up.
- Strategic chlorination relocation from basin to thermal plant optimizes residual protection while reducing chemical consumption 45% (184 kg/year, €920 savings).
- Seasonal circuit bifurcation eliminates bacterial growth window while maintaining efficiency. Summer bypass reduces energy 48% (340 kWh/day) versus current operation.
- Economic analysis demonstrates six-year payback from operational savings (€5,220/year) with risk mitigation justifying investment within 1-2 years.
- Integrated solution (advanced treatment + relocated chlorination + seasonal bifurcation) ensures ≥60°C year-round, meeting all international standards while improving energy efficiency.

This study provides a comprehensive framework applicable to similar institutional facilities worldwide. The demonstrated approach serves as replicable methodology for other campuses, hospitals, hotels, and large buildings integrating renewable energy with domestic hot water. Most critically, findings underscore that sustainability and safety need not be mutually exclusive: properly designed systems achieve both objectives simultaneously.

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