VOL. 06 · CLIMATE RESILIENCE & ESG

Lifecycle Integrity as a Decarbonisation and Climate Resilience Strategy

Reducing embodied carbon and climate risk through long-life engineering.

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Based on manufacturer-collected field data · Technical review: Impact Filtration Engineering

PUBLISHED 12 NOVEMBER 2026 · VOL. 06 · SUBMITTED FEBRUARY 2026

> Decarbonization in the water sector is pursued through energy efficiency, renewable power and process optimization. Those strategies overlook a significant contributor to emissions: the repeated manufacture, transport, replacement and disposal of short-lived infrastructure components.

This paper presents **Lifecycle Integrity** as an engineering-led approach that reduces embodied carbon, material waste and climate risk by extending the service life of critical water infrastructure assets — specifically FRP pressure vessels — from a typical ten years to thirty or more. The approach applies to other short-life pressurized components.

By reducing replacement cycles it lowers CO_2 emissions, stabilizes operations and strengthens climate resilience, **without increasing energy demand or requiring new infrastructure.**

SECTION 01

The hidden carbon problem

The overlooked emissions source

Most water decarbonization effort focuses on operational energy, measured in kWh per cubic meter. Embodied carbon — from materials, manufacturing, logistics and replacement — is rarely addressed at the component level at all.

Short-life infrastructure assets generate repeated manufacturing emissions, intercontinental transport emissions, waste streams with limited recycling pathways, and emergency repair logistics during failures. These impacts compound in climate-stressed regions, which is precisely where reliability matters most.

Failure as a climate vulnerability

Infrastructure failures during heatwaves, droughts or energy instability increase unplanned shutdowns, emergency emissions and water supply risk. **Short-lived components amplify climate vulnerability rather than resilience** — they are a liability that compounds exactly when the system is least able to absorb it.

SECTION 02

The innovation

What Lifecycle Integrity is

Lifecycle Integrity is an engineering framework integrating five elements:

- Accelerated aging validation using Arrhenius modeling
- Finite-element fatigue simulation
- Defined end-of-life criteria at a threshold of **2.5×** design pressure
- Residual strength retention at that point of **57.2%** (B series) and **63.3%** (I series)
- Inspection-ready, validation-driven design
  These criteria ensure assets are retired *while still structurally sound*, avoiding failure-driven replacement and enabling predictable, low-emissions lifecycle management. The asset becomes long-life infrastructure rather than a consumable.

Why this is innovation

It reframes durability as a climate solution, delivers emissions reduction without operational compromise, is immediately deployable at scale, and is grounded in validated engineering science rather than aspiration.

> **One long-life asset replaces three or more short-life assets — without increasing energy use.**

SECTION 03

Quantified impact

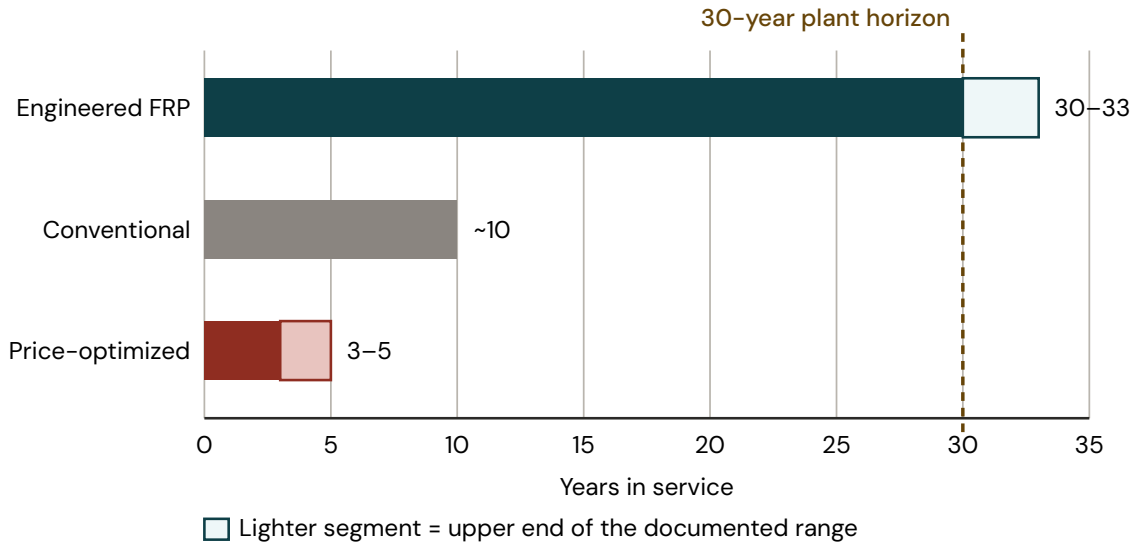


FIGURE 1 — SERVICE LIFE BY GRADE

Only the engineered grade spans a 30-year plant horizon without replacement. Each replacement cycle a grade requires carries its own manufacturing, transport,

installation and disposal emissions.

TIER 1 (ENGINEERED) · TIER 2 (FIELD EVIDENCE)

Embodied carbon reduction

Each avoided replacement cycle eliminates emissions from resin and fiber production, curing and manufacturing energy, global transportation, and installation and commissioning logistics.

Conservative lifecycle modeling shows that extending vessel life from roughly ten years to thirty or more **avoids approximately 1–2 metric tons of CO_2-equivalent per vessel**. That figure covers manufacturing, transport, installation and disposal for each replacement event, on a deliberately conservative boundary that excludes downtime and secondary system impacts. The quantification method is set out in Vol. 04 <https://impactfiltration.com/insights/quantifying-avoided-impact/>.

Material throughput reduction

Each avoided replacement saves approximately **100 kg of composite material**. Over a 30-year horizon two replacements are avoided per vessel, so roughly **200 kg** is prevented from entering waste streams per unit — and multiple tons at plant scale. The derivation is set out in Vol. 04 <https://impactfiltration.com/insights/quantifying-avoided-impact/>.

Replacement cycle comparison

VESSELS REQUIRED OVER A 30-YEAR PLANT HORIZON *

SCENARIO	NOMINAL SERVICE LIFE	VESSELS REQUIRED
Engineered Lifecycle Integrity	30+ years	1
Conventional asset	~10 years	3
Price-optimized asset	3–5 years	6–10

FIGURE 2 — REPLACEMENT CYCLES

Extending service life from ten years to thirty or more reduces replacement cycles by a factor of three. Against the price-optimized grade the factor is six to ten. Each avoided replacement eliminates a further round of manufacturing, transport, installation and disposal emissions — which is what makes durability a direct

decarbonization lever rather than an indirect one.

TIER 2 · DETERMINISTIC LIFECYCLE ARITHMETIC

* **Method.** Counts are derived by deterministic lifecycle arithmetic — plant horizon divided by nominal service life — not by probabilistic failure modeling, consistent with high-level decarbonization assessment. All scenarios assume equivalent operating duty and system function. Service lives of 1–2 years occur in the worst-documented cases and would imply 15–30 vessels; those are not representative and are not used here.

SECTION 04

Climate resilience through reliability

Failure-driven replacement cycles amplify environmental and operational burden over time, creating emissions volatility and climate vulnerability. Engineered long-life assets maintain predictable performance, enabling planned maintenance and resilient operation.

Reliability as climate adaptation

Climate resilience requires predictable asset behavior, reduced failure probability, and planned maintenance rather than reactive response. Lifecycle Integrity strengthens resilience by removing weak links from critical systems before they are tested.

Risk reduction outcomes

Long-life validated assets reduce emergency interventions, stabilize water supply under climate stress, and reduce emissions volatility during extreme events.

> **Climate resilience is built before the event — not after the failure.**

SECTION 05

Technical validation

Service life validation

Lifecycle Integrity is supported by Arrhenius aging models projecting a 30-year-plus lifespan, fatigue simulation validating cyclic pressure endurance, and residual strength of **57.2%** for the B series at a defined scrap point.

Inspection-ready design

Assets are engineered for non-destructive evaluation, inspection-based life extension, and defensible end-of-life decisions — so that retirement is a documented judgment rather than a consequence.

Alignment with recognized standards

- **ISO 15686-5** — service life planning and lifecycle replacement evaluation
- **ISO 55000** — asset-management principles supporting reliability, risk reduction and planned maintenance

> **On the standards cited above.** References to standards indicate alignment with recognized validation, lifecycle planning and asset-management principles. **They do not imply completed testing or certified service-life ratings.**

SECTION 06

Scalability and global relevance

Lifecycle Integrity is immediately deployable, regulator-independent, and broadly applicable across municipal, industrial and desalination systems. It requires no new technology, no additional energy input and no infrastructure investment — only a change in specification.

The highest-impact regions are desalination-dependent ones — MENA and Asia-Pacific — along with drought-prone coastal cities, island nations and industrial water users.

Conclusion

Decarbonization and climate resilience in water infrastructure cannot rely on efficiency alone. They require assets that last.

Lifecycle Integrity turns durability into a measurable climate outcome — reducing embodied carbon, conserving materials, stabilizing operations and protecting water supply across decades.

Engineering integrity becomes climate action

when it is embedded directly into infrastructure.

APPENDIX

Supporting analysis

A — Service life assumptions

Service-life comparisons use conservative, industry-aligned assumptions drawn from long-term water infrastructure planning.

Engineered FRP pressure vessels. Designed and validated for service lives exceeding 30 years under rated operating pressure, temperature and chemical exposure.

Conventional FRP pressure vessels. Typically designed around a nominal ten-year service life, with replacement planned or conditionally extended through inspection.

Price-optimized FRP alternatives. Deployed primarily in price-sensitive applications, often exhibiting reduced reinforcement, variable manufacturing quality and limited tolerance to stress concentration, resulting in functional service lives of approximately three to five years.

All scenarios assume equivalent operating duty and system function over a 30-year plant horizon.

B — Replacement cycle methodology

Replacement counts were derived using deterministic lifecycle arithmetic rather than probabilistic failure modeling, consistent with high-level decarbonization assessment. This approach avoids optimistic assumptions and reflects the operational reality faced by utilities managing constrained budgets and procurement cycles.

C — Embodied carbon and operational burden scope

Lifecycle burden includes cumulative impacts from manufacturing and material processing; transportation and logistics; installation and commissioning; decommissioning, disposal or recycling; and emergency maintenance and unplanned downtime.

Absolute emissions vary by geography and supply chain, but **replacement frequency is a primary driver of cumulative environmental burden.** This analysis therefore addresses relative impact rather than site-specific carbon accounting.

D — Climate stress and system risk

Climate stressors increasingly affecting water infrastructure include elevated ambient and process temperatures, increased pressure cycling driven by demand variability, extreme weather events impacting access and maintenance, and supply-chain disruption during emergency replacement.

Failure-driven replacement amplifies these risks by forcing reactive intervention. Long-life engineered assets enable planned maintenance, predictable performance and improved system resilience under climate volatility.

E — Structural integrity at high-stress zones

Structural integrity at the port region is critical because of load transfer, pressure concentration and sensitivity to fiber termination. Engineered designs employ controlled fiber architecture and sealed terminations to maintain even stress distribution. Price-optimized designs often exhibit cut fibers and resin-starved zones, which accelerate degradation and shorten service life.

The construction detail is examined in Vol. 01 <https://impactfiltration.com/insights/ensuring-quality-ro-pressure-vessels/>.

Summary — why Lifecycle Integrity matters

Problem. Short-life infrastructure assets drive repeated replacement cycles, increasing embodied carbon, operational disruption and climate vulnerability.

Insight. Replacement frequency — not initial material choice — is a primary driver of lifecycle emissions in pressurized water systems.

Evidence. Over a 30-year horizon: engineered assets require 1 vessel, conventional assets 3, price-optimized assets 6 to 10. Each avoided replacement eliminates emissions from manufacturing, transport, installation and disposal.

Climate relevance. Failure-driven replacement amplifies risk under climate stress. Long-life assets enable planned maintenance, predictable performance and resilient operation.

Conclusion. Lifecycle Integrity is a scalable, system-level decarbonization lever aligned with climate resilience objectives.

Full citations are available in the Technical Appendix <https://impactfiltration.com/insights/technical-appendix/>.

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