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Toward a Generalized Scale-Up Framework in Prospective Life Cycle Assessment

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Prospective Life Cycle Assessment (pLCA) plays a crucial role in evaluating emerging technologies from the early stages of development. A major challenge is the absence of generalized approaches for translating laboratory-scale information into industrial-scale inventories. Existing scaling methods, engineering approximations, simulations, and empirical relations, have been applied in isolated studies but lack a unified, generally applicable structure. Laboratory data typically shows inflated electricity demand, excess solvent use, limited separation performance, and batch-related losses, producing non-linear deviations when extrapolated to industrial conditions.

This study develops a systematic framework for scaling production steps within pLCA. We combine a structured review of upscaling approaches with an assessment of the physical and operational mechanisms driving scale-dependent changes. A critical-point analysis identifies the flows most affected by scale, including energy use, solvent and reagent consumption, waste generation, and infrastructure effects, clarifying which parameters require adjustment.

A general upscaling strategy is introduced based on dominant unit operations such as heating, cooling, drying, and solvent recovery, supported by a calculation tool that derives energy and fuel demand from low-TRL data and enables scenario building. Minimum data requirements (stoichiometry, yields, solvent and reagent flows, thermal loads, waste streams) provide a consistent basis for extrapolation.

Sector-specific mechanisms in petrochemical, biochemical and pharmaceutical systems are incorporated, accounting for thermodynamic integration, mass-transfer limitations, bioreactor behavior, high-purity separation and utility-intensive operations.

The resulting framework offers a transparent and reproducible pathway to construct industrial-scale inventories when only early-stage information is available, improving robustness, comparability and interpretability in pLCA.

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