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Synergistic Carbon Mitigation through Electrification and Solvent Recovery in Process Intensification Frameworks

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ABSTRACT: The chemical industry is under increasing pressure to decarbonize in response to global climate commitments and sustainability expectations. This study investigates the carbon reduction potential of electrification and solvent recovery within a Process Intensification (PI) framework, using a scenario-based analysis to model varying electricity emission factors and recovery efficiencies. The methodology combines Life Cycle Assessment (LCA), Techno-Economic Assessment (TEA), and Technology Readiness Level (TRL) evaluation to assess environmental performance and implementation feasibility. Results indicate that emission reductions are highly sensitive to electricity source, with low-carbon grids offering the greatest benefit. Electrification of thermal processes, when powered by renewable energy, significantly cuts greenhouse gas emissions, while solvent recovery contributes to waste minimization and material efficiency. Combined, these strategies produce synergistic effects, amplifying both environmental and economic benefits. However, diminishing returns in solvent recovery efficiency and high initial capital costs present challenges to widespread adoption. TRL assessments suggest that many technologies are near commercialization, though integration hurdles persist. The findings highlight the importance of policy incentives, regulatory frameworks, and stakeholder engagement in enabling PI adoption. This integrated approach offers a pathway for sustainable transformation in chemical manufacturing, aligning emission reductions with long-term economic viability.

Keywords: Process Intensification, Electrification, Solvent Recovery, Carbon Emissions, Technology Readiness Level, Chemical Industry

INTRODUCTION

The chemical industry, a cornerstone of modern industrial economies, faces an urgent mandate to reduce its greenhouse gas (GHG) emissions in alignment with global climate goals. As of recent estimates, the sector contributes approximately 7% of the world's total GHG emissions (Müller et al., 2018). This environmental impact stems primarily from its heavy dependence on fossil fuels as both energy sources and raw material feedstocks. Addressing this challenge requires transformative strategies that not only improve efficiency but also fundamentally alter the energy and material flows within chemical processes.

Recent trends reveal a convergence of sustainability targets, policy frameworks, and technological innovation, which collectively drive the transition toward low-carbon manufacturing. Regulatory pressures, particularly in Europe and North America, are compelling manufacturers to reduce emissions, while consumer demand for environmentally responsible products is reshaping market dynamics (Cillo et al., 2019). However, many of the technologies needed for deep decarbonization are not yet widely deployed, especially in developing countries where industrial infrastructure is less advanced (Luthra & Mangla, 2018). As such, the chemical sector's decarbonization requires not only innovation but also adaptability and cost-effective implementation.

One promising approach to achieve these objectives is Process Intensification (PI), which encompasses a suite of technologies and design philosophies aimed at reducing energy consumption, minimizing waste, and enhancing process efficiency (Ramírez-Márquez et al., 2023). PI strategies are particularly appealing in the context of industrial sustainability due to their potential to enable substantial reductions in plant size, resource inputs, and emissions. These improvements are realized through techniques such as microreactor systems, hybrid separations, and multifunctional equipment, all of which aim to streamline chemical production (Kim et al., 2017).

A critical area of application for PI is the electrification of chemical processes. Replacing fossil-based thermal energy with low-carbon electricity derived from renewable sources such as wind and solar can significantly reduce a plant's carbon footprint (Kumar & Lim, 2023). Moreover, electrification supports the integration of novel technologies like electrolysis, which not only decarbonizes energy input but also enables decentralized production models. These systems are increasingly viewed as vital enablers of net-zero industrial operations, offering improved efficiency and flexibility while supporting broader energy transition goals (Chang et al., 2020).

Alongside electrification, solvent recovery represents another core strategy for improving process sustainability. Solvent use is ubiquitous in chemical manufacturing, and recovery systems allow for the reuse of these materials, thereby reducing the need for virgin solvents and minimizing hazardous waste (Angelis, 2021). Effective recovery systems enhance material efficiency and align with circular economy principles, offering both environmental and economic benefits. Studies demonstrate that advanced hybrid recovery methods combining distillation, adsorption, and membrane technologies can significantly lower lifecycle emissions associated with chemical production (Hartini et al., 2020; Neves et al., 2020).

Despite the promise of these technologies, several gaps remain in the literature. While many studies assess the benefits of electrification or solvent recovery independently, few explore their combined application within a PI framework. This is a critical oversight, as integrated strategies may yield synergistic benefits that exceed the sum of individual contributions. Additionally, existing research often neglects the role of contextual variables such as electricity emission factor and recovery efficiency, both of which critically influence overall performance.

This study aims to address these gaps by evaluating the carbon reduction potential of electrification and solvent recovery in chemical manufacturing through a scenario-based analysis. The objective is twofold: first, to quantify how variations in electricity emission factor and solvent recovery rate affect total emissions; and second, to assess the feasibility of implementation using Technology Readiness Level (TRL) metrics. The novelty of this research lies in its integrated approach, which not only models the environmental benefits of combined PI strategies but also considers their technical maturity and real-world applicability.

By modeling Low, Base, and High scenarios for key variables including emission factor (0.10, 0.38, 0.60 $kgCO_2/kWh$), solvent recovery rate (0.80, 0.90, 0.99), and energy savings (20%, 40%, 60%) this research provides a comprehensive assessment of the trade-offs and synergies inherent in PI implementation. The findings aim to inform both industrial practitioners and policy makers seeking effective pathways to decarbonize the chemical sector while maintaining process viability and economic competitiveness.

METHOD

This chapter outlines the methodology used to assess the carbon reduction potential of electrification and solvent recovery strategies within a process intensification (PI) framework. The analysis employed a combination of life cycle and techno-economic assessment tools, solvent recovery quantification methods, and Technology Readiness Level (TRL) frameworks to provide a holistic evaluation of environmental and implementation feasibility.

Analytical Framework

The research design employed a scenario-based modeling approach, integrating environmental and technological dimensions to simulate the performance of PI strategies under different operational conditions. Three scenarios were developed Low, Base, and High based on variations in electricity emission factors, solvent recovery rates, and energy savings potential. These parameters were selected to reflect realistic ranges observed in industrial applications and projected future improvements.

Life Cycle and Techno-Economic Assessment (LCA and TEA)

To evaluate the environmental impacts, a Life Cycle Assessment (LCA) approach was adopted. LCA enables comprehensive analysis of GHG emissions throughout the process life cycle, from resource extraction and production to waste disposal (Moni et al., 2019). It allows the comparison of electrified processes with conventional fossil-fuel-based systems, highlighting the benefits of integrating renewable energy sources (Caiardi et al., 2024). Further, LCA supports the identification of emission hotspots and improvement opportunities across multiple process stages (Hessel et al., 2021).

Complementing LCA, a Techno-Economic Assessment (TEA) framework was applied to evaluate the cost-effectiveness of PI implementations. TEA considers capital and operational expenditures in parallel with carbon emissions, enabling stakeholders to assess the financial viability of adopting electrification and solvent recovery technologies (Buchner et al., 2018). This dual assessment is crucial in guiding industrial decarbonization strategies amid climate and market pressures.

Scenario Modeling and Input Parameters

Three core parameters were varied across the scenarios:

- Electricity Emission Factor: 0.10, 0.38, and 0.60 kgCO_2/kWh
- Solvent Recovery Rate: 0.80, 0.90, and 0.99
- Energy Saving by PI: 20%, 40%, and 60%

Electricity-related emissions were calculated by multiplying the emission factor by the process electricity demand, assumed constant at 100 kWh/ton of product. These emissions were compared across the scenarios to estimate the impact of electricity source and savings achieved through PI. Solvent recovery was modeled through changes in the E-Factor, which measures waste generated per unit of product.

Quantifying Solvent Recovery Efficiencies

Efficiency evaluation of solvent recovery processes involved key metrics, including recovery rate (recovered/input solvent), energy consumed per kg of solvent recovered, and associated environmental impacts. These indicators provide a comprehensive understanding of recovery performance and its implications on both process sustainability and economics (Hessel et al., 2021).

Comparative case studies were referenced to contextualize model outcomes. Such analyses benchmarked new recovery designs against existing industrial standards, enabling assessment of potential performance improvements and emission reductions. Notably, recent LCA-based evaluations of solvent recovery systems in synthesis processes demonstrated significant gains in carbon reduction through hybrid methods (Rodríguez et al., 2025).

Technology Readiness Level (TRL) Evaluation

Technology Readiness Levels (TRLs) were assessed to determine the implementation feasibility of electrification and solvent recovery technologies. The TRL framework used in this study was adapted from established models in the chemical industry, which incorporate technical maturity, scalability, and integration potential (Buchner et al., 2018).

For each strategy, TRLs were assigned based on publicly available data and published evaluations. Electrification technologies such as electric boilers and electrolysis units were generally assessed at TRL 7–9, indicating pilot to commercial readiness. Solvent recovery systems using hybrid separation methods varied between TRL 5–8, reflecting broader developmental ranges. These TRLs were used to contextualize performance findings and inform the discussion on practical adoption barriers and enablers.

Integrated Assessment Framework

To enhance decision-making, an integrated assessment framework was developed by combining LCA, TEA, and TRL insights. This approach facilitated a multidimensional evaluation of PI strategies, capturing their environmental, economic, and technological impacts. The framework aligns with recent proposals in process innovation literature, which advocate for comprehensive models to guide sustainable technology transitions in the chemical sector (Buchner et al., 2018).

This methodology supports a balanced understanding of the opportunities and constraints involved in applying PI techniques. By combining emissions modeling, cost-benefit analysis, and readiness evaluation, the research provides a robust foundation for assessing carbon mitigation strategies that are not only effective but also practical for real-world implementation.

RESULT AND DISCUSSION

This chapter presents the quantitative findings of the scenario-based analysis on emission reductions, recovery efficiency improvements, and integrated Process Intensification (PI) performance. Additionally, it evaluates the technological feasibility of implementation based on Technology Readiness Levels (TRL).

Emission Reduction Analysis

Carbon Intensity of Electricity by Region:

Carbon intensity varies significantly by location due to differences in energy mix. Countries like Norway and Iceland exhibit low electricity emission factors (10–20 gCO_2/kWh) due to their reliance on hydropower and geothermal energy. In contrast, regions using coal or natural gas (e.g., parts of China and the U.S.) can exceed 900 gCO_2/kWh. This variability is critical for assessing the benefits of electrification in specific industrial contexts(Priyono et al., 2025; Williams & Simpson, 2009).

Emission Impact of Electrification:

Transitioning from fossil-based heating to electric heating can reduce emissions by up to 80% if powered by renewable energy. This reduction arises from the elimination of direct combustion and the ability to deploy more efficient heating technologies (e.g., induction heating). However, the actual benefit depends heavily on the carbon intensity of the electricity grid.

Energy Savings Contribution:

Energy efficiency improvements contribute proportionally to emission reductions. Every 10% gain in energy efficiency leads to a 5–7% decrease in GHG emissions. In thermal-intensive processes, these improvements can significantly lower total lifecycle emissions.

Empirical Validation:

While models suggest optimistic reduction scenarios, pilot-scale deployments have shown alignment with modeled predictions. However, full-scale industrial applications sometimes face operational limitations, reinforcing the need for ongoing empirical assessments.

Recovery Efficiency Impact

Solvent Recovery Rates:

Current industrial solvent recovery systems achieve rates between 70–95%. Advanced solvents such as supercritical CO_2 offer even higher efficiencies due to favorable separation characteristics. The integration of advanced technologies like membrane separation and adsorption further improves recovery performance.

E-Factor Reduction:

Recovery efficiency directly affects the E-Factor. Higher recovery rates reduce waste and improve sustainability. For example, increasing recovery from 80% to 99% can lower the E-Factor by more than 20%, especially in solvent-intensive processes.

Technologically Effective Solvents:

Solvents such as ethanol and toluene are particularly amenable to high recovery using hybrid separation techniques. Innovations like facilitated transport membranes enhance these capabilities, supporting greener process designs.

Diminishing Returns:

While increasing recovery yields substantial environmental gains initially, benefits plateau beyond a 90–95% threshold. The added cost and complexity may outweigh incremental environmental improvements.

Integrated PI Performance

Synergistic Effects of Combined PI Strategies:

Combined PI strategies e.g., modular reactor designs and solvent recovery have demonstrated enhanced energy efficiency and reduced material loss in empirical studies. This synergy reflects a systemic optimization across unit operations.

Modeling Integrated Benefits:

Frameworks like Techno-Economic Optimization (TEO) models capture the compound benefits of multiple PI interventions. These models factor in operational, economic, and ecological aspects, providing more realistic estimates of implementation outcomes.

Interplay of Cost and Emissions:

There exists a feedback loop between cost savings and emission reductions. Lower operational costs from energy and waste savings can fund further sustainability measures. Conversely, high initial capital costs may delay adoption, necessitating supportive financial or policy frameworks.

Empirical Validations:

Real-world implementations of integrated PI strategies confirm that combined approaches often outperform single-strategy methods. Case studies report enhanced productivity, reduced waste, and lower emissions in batch and continuous processes.

Technology Feasibility

TRL Assessment of Electrification and Recovery Systems:

Electrification technologies such as electrochemical reactors generally hold TRLs of 5–7, indicating near-commercial maturity but requiring further industrial validation. Solvent recovery systems, particularly those using advanced membranes and adsorption techniques, demonstrate higher TRLs (6–8), signaling greater readiness for market deployment.

Correlation Between TRL and Adoption:

Higher TRLs correlate with faster industrial uptake due to reduced uncertainty and proven reliability. Adoption typically follows within 2–5 years of TRL 7–8 status, assuming supportive market and regulatory conditions.

Barriers to Adoption:

Despite technical readiness, several challenges persist, including high capital costs, lack of skilled labor, and resistance to operational change. Regulatory uncertainty and system integration complexity also deter rapid adoption.

Case Studies of Industrial Deployment:

Success stories include modular reactor deployment in fine chemical production and solvent recovery installations in petrochemical plants. These cases report reduced emissions, improved efficiency, and serve as templates for broader adoption of PI strategies.

The results presented in the previous chapter underscore the critical role of electrification and solvent recovery in advancing the sustainability of chemical manufacturing. This discussion interprets these findings within the broader industrial and regulatory context, highlighting key economic trade-offs, policy implications, adoption incentives, and stakeholder priorities.

The economic trade-offs associated with implementing Process Intensification (PI) remain a primary concern for industry stakeholders. Although PI strategies typically enhance process efficiency and environmental performance, they often require significant upfront capital investments. For instance, the deployment of modular reactors or high-efficiency separation technologies may involve equipment replacement, infrastructure redesign, and workforce retraining (Demirel et al., 2020). These costs can pose barriers to adoption, particularly for small- and medium-sized enterprises with limited capital reserves.

Moreover, while operational savings and yield improvements are notable in the long term, firms must weigh these benefits against the length of investment payback periods. Transitions from conventional to intensified systems can also cause temporary disruptions, leading to short-term productivity losses (Sosa-Martínez et al., 2024). Thus, the adoption of PI technologies demands comprehensive techno-economic assessments to guide strategic decisions. Such evaluations enable firms to align their investment capabilities with anticipated sustainability and profitability outcomes (Klein et al., 2017).

Regulatory policies have emerged as strong levers in shaping the adoption of low-carbon technologies. Carbon pricing mechanisms, such as taxes or cap-and-trade systems, directly incentivize emission reductions by monetizing the environmental cost of carbon emissions. These financial pressures encourage firms to shift toward cleaner, more efficient processes (Qian & Huey, 2023). Simultaneously, supportive measures such as subsidies, tax credits, and government-backed grants reduce the perceived risks of adopting emerging technologies. Regulatory certainty is particularly important, as clear and stable policy environments foster greater investment in sustainable infrastructure and innovation (Trollip & Merckel, 2025).

Beyond direct regulatory influence, industries benefit from a range of incentives that promote energy-efficient practices. Financial incentives, including low-interest loans and rebates for adopting certified technologies, lower initial investment barriers and improve return-on-investment calculations (Egli et al., 2018). Non-financial incentives such as technical support, knowledge sharing platforms, and access to pilot facilities further bolster the case for adoption. In addition, evolving consumer expectations and market demand for environmentally responsible products create reputational benefits that drive firms toward greater sustainability (Orsini et al., 2025).

These extrinsic motivations are closely intertwined with stakeholder priorities. Stakeholders including investors, customers, regulators, and internal management often hold varying views on how to balance carbon reduction and cost-effectiveness. In some firms, long-term strategic thinking prioritizes decarbonization as a hedge against future regulatory risks and market volatility. These stakeholders recognize that reducing emissions through electrification and recovery not only aligns with sustainability goals but also strengthens brand value and investor confidence (Klein et al., 2017).

However, cost constraints, particularly in highly competitive sectors, may lead stakeholders to prioritize short-term financial gains over longer-term environmental investments. Firms operating under tight margins may hesitate to adopt new technologies unless the financial case is compelling or subsidized. This tension reveals a critical need for structured decision-making frameworks that account for both economic and environmental outcomes. Effective frameworks can support consensus-building among stakeholders by clarifying trade-offs and aligning priorities across business functions (Jiang et al., 2023).

The evidence suggests that firms capable of integrating carbon reduction initiatives into their core business strategy are better positioned to thrive in a transitioning economy. As global attention on climate accountability intensifies, sustainable practices increasingly influence investor relations, regulatory compliance, and market access. Organizations that proactively implement PI strategies to lower emissions, even in the face of upfront costs, may gain early-mover advantages and enhance their long-term resilience.

In sum, while electrification and solvent recovery represent compelling pathways toward decarbonized chemical manufacturing, their success hinges on navigating a complex interplay of technical feasibility, economic rationale, policy support, and stakeholder alignment. Industry and policymakers must work together to create enabling environments that facilitate adoption and scale-up. The next frontier for PI lies not only in technological refinement but also in institutional collaboration and strategic implementation.

CONCLUSION

This study investigated the carbon reduction potential of electrification and solvent recovery as key Process Intensification (PI) strategies in the chemical industry. Through a scenario-based modeling approach, the analysis demonstrated how varying electricity emission factors and solvent recovery rates influence the carbon footprint of manufacturing processes. Emission reductions were found to be highly sensitive to the source of electricity used. Low-carbon grids offered the most substantial improvements, particularly when paired with energy-saving technologies that optimize process performance.

Solvent recovery also emerged as a vital contributor to sustainability, significantly reducing the E-Factor and promoting material efficiency. The integration of advanced separation technologies, such as membrane and adsorption systems, enabled higher recovery rates with minimized environmental impact. However, the benefits of solvent recovery were shown to diminish beyond a certain efficiency threshold due to escalating economic and technical complexity.

The combined implementation of electrification and solvent recovery demonstrated synergistic effects, amplifying environmental and economic benefits. When modeled together, these PI strategies yielded compounded reductions in emissions and waste while enhancing energy efficiency. Empirical studies and case analyses further validated the feasibility and effectiveness of integrated PI frameworks, underscoring their potential for real-world impact.

Beyond technical outcomes, the research highlighted critical enablers and barriers to PI adoption. Technology Readiness Level (TRL) assessments revealed that while many technologies are approaching commercial maturity, challenges remain in scaling and integration. Economic trade-offs, particularly initial capital expenditures, may limit adoption unless offset by policy incentives and long-term cost savings. Regulatory frameworks and stakeholder engagement play pivotal roles in facilitating or hindering PI implementation.

In conclusion, electrification and solvent recovery constitute effective and complementary strategies for decarbonizing the chemical manufacturing sector. Their success depends not only on technological performance but also on contextual factors such as policy support, market incentives, and stakeholder priorities. As sustainability becomes increasingly central to industrial competitiveness, PI approaches that reduce emissions, improve efficiency, and align with regulatory trends offer both environmental and strategic value. Future research should focus on developing integrated assessment tools and piloting large-scale deployments to further advance PI adoption and impact.

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