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Research Article

Refining the Greenhouse Gas Emission Accounting Boundary in Typical Papermaking Enterprises: A Techno-Economic Assessment of Mitigation Pathways

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Abstract: The intricate interplay of biomass-derived carbon, purchased energy, and process-specific fugitive emissions renders the determination of an appropriate accounting boundary in the pulp and paper industry a nontrivial exercise, one that fundamentally conditions the perceived efficacy of subsequent decarbonization strategies. This study undertakes a systematic refinement of the emission accounting boundary for a representative integrated papermaking facility, moving beyond the conventional corporate-level or Scope 1/2 frameworks to incorporate a tiered, process-based delineation that distinguishes between energy conversion, chemical recovery, and end-of-pipe treatment stages. A hybrid life cycle inventory, combining on-site operational data with sector-specific emission factors, was constructed to quantify baseline emissions under the default boundary, revealing a possible underestimation of biogenic methane contributions from wastewater anaerobic treatment by approximately 12-18%, a gap that carries non-negligible implications for mitigation prioritization. Subsequently, three mitigation levers—black liquor gasification efficiency enhancement, anaerobic digestion with biogas upgrading, and integration of waste-heat-driven organic Rankine cycles—were evaluated individually and in combination, employing a discounted cash flow model coupled with sensitivity analyses on carbon pricing and energy tariff fluctuations.

Keywords: Papermaking industry; Greenhouse gas accounting boundary; Mitigation pathways; Techno-economic optimization; Biomass-derived emissions;

1. Introduction

The contemporary discourse surrounding industrial decarbonization has, with considerable justification, gravitated toward sectors characterized by both high energy intensity and significant process-related emissions—a category within which the pulp and paper industry occupies a somewhat paradoxical position. On one hand, the sector is frequently cited for its substantial reliance on biomass-derived fuels, a feature that ostensibly confers a degree of carbon neutrality when viewed through a narrowly biogenic lens; on the other, the sheer scale of thermal energy consumption, the chemical complexity of the kraft recovery cycle, and the fugitive release of methane from effluent treatment systems collectively render the industry a non-negligible contributor to the national greenhouse gas inventories of many manufacturing economies. Early investigations into papermaking emissions, such as those conducted by Laurijssen et al. (2010) and later by Manda et al. (2015), tended to adopt a somewhat aggregated approach, treating the integrated mill as a black box whose total fuel consumption could be straightforwardly converted to a carbon dioxide equivalent figure. While methodologically convenient, this black-box perspective conceals a more troublesome reality: the point at which one draws the system boundary—whether to include the carbon stored in finished paper products, whether to account for the off-site generation of purchased electricity, whether to incorporate the decomposition dynamics of sludge-derived organics—exercises a profoundly non-linear influence on the resulting emission estimates, a sensitivity that has been acknowledged in principle but rarely subjected to systematic quantitative scrutiny within the specific context of a modern, integrated Chinese papermaking facility.

The existing literature, for all its contributions, exhibits a curious asymmetry in its treatment of boundary definition. Several studies, notably those emerging from the European Integrated Pollution Prevention and Control reference documents, have proposed detailed process-level allocation rules, yet these protocols were developed largely with regulatory compliance in mind, rather than with an explicit orientation toward identifying cost-effective reduction opportunities. Conversely, the techno-economic optimization literature, exemplified by the modeling efforts of Fleiter et al. (2012) and subsequent refinements by Schulze et al. (2019), has demonstrated a sophisticated capacity for evaluating marginal abatement costs across a portfolio of mitigation technologies—but these analyses typically accept the emission baseline as a given, derived from whatever reporting framework the facility happens to employ. This implicit assumption, namely that the baseline is stable and unambiguous, is precisely what this study seeks to problematize. The research gap, as we perceive it, does not lie in the absence of either boundary guidance or optimization algorithms; rather, it resides in the under-explored terrain where these two domains intersect—that is, the extent to which the choice of accounting perimeter systematically biases the ranking and selection of mitigation measures, and whether this bias operates consistently across different technology classes or exhibits a more capricious pattern.

From a broader policy perspective, the issue acquires additional urgency when one considers the evolving architecture of carbon pricing mechanisms in China and other major pulp-producing regions. The transition from voluntary reporting to mandatory compliance, which many jurisdictions are currently navigating, will inevitably foreground the question of what counts and what does not a question that, as we have come to appreciate through preliminary conversations with plant operators, is far from settled even among experienced environmental managers. Some argue for a maximalist boundary that captures all carbon flows entering the facility gate, while others advocate for a more restricted perimeter that excludes biogenic emissions on grounds of carbon neutrality; neither position, upon closer examination, proves entirely defensible without careful qualification regarding the time horizon of analysis and the specific fate of the carbon atoms in question. This study, accordingly, does not purport to settle the boundary debate once and for all—such an ambition would be both hubristic and ultimately counterproductive—but rather seeks to illuminate, through a combination of empirical accounting and scenario-based optimization, the practical consequences that flow from different boundary conventions, with the hope that such illumination might inform more context-sensitive reporting protocols in the future.

2. Methodology and System Boundary Definition

The methodological architecture of this study was conceived through a iterative process of refinement, one that initially aspired to a degree of comprehensiveness that, in retrospect, proved impractical given the constraints of data availability and the inherent opacity of certain production sub-processes. The facility selected for analysis is a typical integrated pulp and paper mill located in the Shandong province, with an annual production capacity of approximately 450,000 tonnes of containerboard and a corresponding chemical recovery loop based on the conventional kraft pulping technology. Our initial approach, which we now recognize as somewhat naïve, attempted to construct a fully mass-balanced model encompassing every material stream from woodchip receipt to finished product dispatch, inclusive of the internal recycling of process water and the intermittent operation of the regenerative thermal oxidizer used for odorous gas control. This ambition foundered, to some degree, on the practical challenge of reconciling the disparate data sources the continuous emissions monitoring system (CEMS) provided hourly flue gas measurements, whereas the utility metering records were aggregated on a shift basis, and the laboratory analyses of black liquor

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solids content arrived with a frequency that was neither synchronized nor easily interpolated. The methodological adjustment that emerged from this confrontation with data reality was a hybrid approach, one that combines direct measurement for the major combustion sources with emission factor-based estimates for the diffuse and intermittently monitored streams, an eclectic strategy that, while perhaps lacking the elegance of a unified first-principles model, possesses the compensatory virtue of being operationally feasible and, we would argue, sufficiently robust for the comparative analysis that constitutes the core of this study.

A critical methodological foundation for the emission accounting framework adopted in this study draws upon the recent modeling work by Chen et al. [1], who developed a comprehensive carbon emission accounting model specifically tailored for the paper and paper products industry. Their contribution is noteworthy for its systematic treatment of the full production chain—from raw material procurement through pulping, papermaking, and finishing operations, with particular attention paid to the allocation of emissions between the chemical recovery process and the energy generation functions of the recovery boiler. The model proposed by Chen et al. [1] offers an operational procedure for quantifying emissions at each discrete process node, and it provides a methodological anchor that guided our own boundary delineation decisions, particularly in the treatment of the notoriously ambiguous allocation between the recovery boiler's chemical regeneration and steam generation roles. The model's strength lies in its reliance on facility-specific process parameters rather than generic industry averages, yet we observed that its application to facilities with non-standard black liquor compositions requires careful calibration, a limitation that the authors themselves appear to acknowledge through their emphasis on context-specific data collection. In adapting their framework to the Shandong facility, we found it necessary to supplement their proposed default emission factors with measured values from the facility's own chemical recovery laboratory, an adjustment that introduced additional complexity but, in our view, enhanced the accuracy of the resulting baseline estimates.

The optimization component of our methodology was informed, in part, by recent advances in data-driven modeling approaches that have found increasing application in industrial environmental management. Wang et al. [2] developed an adaptive supervised learning framework for streaming data that addresses the challenge of concept drift in dynamic process environments, a consideration that resonates with our own experience of acquiring emissions data from the continuously operating recovery boiler and the downstream treatment units. Their approach, which incorporates a sparsity constraint to improve computational efficiency while maintaining predictive accuracy, suggests that online monitoring of process parameters could be integrated with real-time emission estimation, an avenue that, though not directly implemented in the present study, points toward a possible enhancement for future iterations of the boundary optimization framework. Similarly, the methodological innovations of Zhang et al. [3] in evaluating language models' adherence to instruction hierarchies, while developed in a distinctly different domain (natural language processing), offer an intriguing parallel to our own concern with hierarchical boundary definitions: just as their work examines how models follow (or fail to follow) nested instructions, our three-tier boundary framework examines how accounting conventions at different levels of inclusiveness generate systematically different emission portraits. The cross-disciplinary resonance, though not immediate, is suggestive of broader patterns in how complex systems respond to hierarchical structuring, a consideration that may warrant further theoretical exploration.

The system boundary, as finally operationalized, comprises three nested tiers of increasing inclusiveness, each corresponding to a distinct analytical purpose. Tier 1, which we designate the "core process boundary," encompasses all stationary combustion sources directly associated with the production process—namely, the recovery boiler, the biomass-fired power boiler, and the auxiliary fossil-fuel boilers used for peak-shaving and startup operations. This tier, importantly, adopts the convention of reporting all carbon emissions, including those from biogenic sources, without applying a neutrality adjustment, a decision that deliberately departs from the prevailing practice in the sector and one that we defend on the grounds that it permits a more transparent comparison with non-biomass-based industries. Tier 2, the "extended energy boundary," incorporates the emissions associated with purchased electricity and steam, calculated using regional grid emission factors and, for the steam component, a marginal

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heat-rate approach that considers the specific efficiency of the local combined heat and power plant. The inclusion of this tier was motivated by a recognition that the trend toward cogeneration and on-site renewable electricity production is rendering the traditional Scope 1/Scope 2 distinction increasingly porous, a development that has been observed but not systematically accommodated in previous boundary studies. Tier 3, the "full life-cycle boundary," extends the accounting perimeter to include the upstream emissions from chemical production (notably lime and sodium sulfate), the transportation of raw materials, and, perhaps most contentiously, the downstream emissions from the decomposition of paper products in landfills—a category that remains largely excluded from current corporate reporting protocols but whose inclusion could, under certain decomposition assumptions, substantially alter the perceived carbon footprint of the sector.

What proved more challenging than the definition of these tiers themselves was the allocation of emissions among them, particularly in the case of the recovery boiler, which simultaneously serves the functions of chemical regeneration, heat recovery, and energy generation. The conventional approach, which apportions emissions based on the exergy content of the various outputs, was considered but ultimately rejected on the grounds that it introduces a normative judgment about the relative value of chemical recovery versus energy production—a judgment that itself depends on market conditions and is thus not inherently stable. Instead, we adopted a functional allocation scheme that attributes emissions to the primary function of the recovery boiler—namely, the regeneration of pulping chemicals—and treats the heat and power outputs as by-products, an allocation rule that, we acknowledge, tends to depress the apparent emissions intensity of the power generation component, thereby creating a possible upward bias in the attractiveness of on-site cogeneration relative to grid-purchased electricity. This bias, however, is not necessarily a limitation but rather a reflection of the real-world economics of integrated mills, where the recovery boiler's primary duty cycle is indeed dictated by the chemical recovery need, with energy production being a subordinate albeit increasingly important objective. The iterative process of refining this allocation scheme, which involved several rounds of consultation with plant engineers and a careful re-examination of the control philosophy for the boiler's air-to-fuel ratio, revealed an underlying tension between the accounting conventions inherited from the industrial ecology literature and the operational realities of continuous production, a tension that we suspect is not unique to this facility and merits broader discussion within the methodological community.

3. Baseline Emission Accounting and Boundary Sensitivity Analysis

The baseline emission accounting, conducted according to the three-tier boundary framework described in the preceding chapter, yielded a set of results that were, in several respects, unexpected and, in one particular instance, prompted a complete re-examination of the underlying data validation procedures. For the core process boundary (Tier 1), the annual total greenhouse gas emissions, expressed in carbon dioxide equivalents using the 100-year global warming potentials from the IPCC Fifth Assessment Report, were calculated at approximately 1.28 million tonnes, with the recovery boiler contributing roughly 62% of this total, the biomass power boiler accounting for 27%, and the auxiliary fossil-fuel units and process heaters comprising the remaining 11%. The dominance of the recovery boiler, while anticipated, was more pronounced than the facility's internal engineering estimates had suggested, a discrepancy that we traced to the rather conservative assumed value for the carbon content of the black liquor solids—the default value recommended by the national guidelines was 52%, whereas the limited available lab analyses indicated values closer to 48%, a 7.7% difference that translates into a non-negligible shift in the baseline figure. This observation underscores a point that, though elementary in retrospect, bears repeating: the uncertainty in emission factors for non-standardized fuels like black liquor substantially exceeds that for fossil-derived fuels, and the reliance on default values, while often unavoidable, introduces a level of imprecision that is rarely accounted for in policy discussions.

When the accounting boundary was extended to include purchased electricity and steam (Tier 2), the total emissions rose to 1.56 million tonnes, an increase of approximately 22% relative to Tier 1. This increment, however, is not solely attributable to the

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imported energy per se; rather, a more nuanced interpretation suggests that the Tier 1 figure already incorporates the combustion emissions from the on-site generation of steam, and the addition of Tier 2 effectively adjusts for the "implicit" emissions associated with the thermal energy not generated internally, a category that includes the steam used for paper drying and, to a lesser extent, for space heating within the facility's administrative buildings. One possible explanation for this substantial increment is the relatively high carbon intensity of the regional power grid, which, at the time of data collection, remained significantly coal-dependent; a second, more speculative explanation is that the facility's on-site power generation, despite its biogenic fuel source, is operated at lower efficiency than modern utility-scale plants, and the Tier 2 addition effectively compensates for this inefficiency by loading the emissions from make-up power onto the facility's account. This interpretation, however, is complicated by the methodological challenge of disentangling the emissions attributable to the facility's own power consumption versus those that would occur regardless of the facility's operation—a distinction that is conceptually clear but empirically difficult to operationalize.

The transition to Tier 3, which incorporated upstream chemical production, transportation, and downstream waste decomposition, introduced a further increment of 0.19 million tonnes, raising the total to 1.75 million tonnes. What proved more illuminating than the aggregate increase, however, was the sensitivity of the downstream component to assumptions regarding the methane generation potential of landfilled paper products—a parameter for which the literature offers estimates ranging from negligible to substantial, depending on the assumed moisture content, landfill gas capture efficiency, and the specific degradation kinetics. Adopting the default IPCC methane generation factor for mixed paper waste yielded a downstream contribution of approximately 0.11 million tonnes, whereas using a more optimistic literature value for landfills with active gas collection systems reduced this figure to roughly 0.04 million tonnes, a variation of nearly threefold that introduces a considerable degree of uncertainty into the Tier 3 total. This observation does not, in our view, invalidate the utility of the extended boundary; rather, it suggests that the results obtained under the full life-cycle accounting should be interpreted with appropriate caution, and that comparative analyses between facilities should, wherever possible, be conducted using a consistent assumption set for such highly variable parameters.

The water-related environmental dimensions of the papermaking process, while not the primary focus of this study, merit brief consideration given their interconnection with the energy and chemical cycles that dominate the carbon accounting picture. The research of Lu et al. [4] on industrial water conservation potential, though focused on a different sector, provides a methodological template for analyzing the resource efficiency of integrated industrial processes through the lens of conservation supply curves—an approach that has conceptual parallels to the marginal abatement cost curves we construct for carbon mitigation in Chapter 4. Their analytical framework, which combines engineering-economic assessment with scenario analysis, offers a useful reminder that the boundary question extends beyond carbon to encompass other environmental dimensions, and that a facility's overall environmental performance may be optimized more effectively through cross-media consideration than through single-pollutant accounting. Similarly, the work of Liu et al. [5] on grey correlation modeling for urban river water quality assessment demonstrates an analytical approach—that of identifying dominant factors through systematic correlation analysis that could potentially be adapted to identify the primary drivers of emission variability within the papermaking process, a direction that we consider worth exploring in subsequent research. The urban river quality assessment methodologies developed by Lu et al. [6] and the sediment pollution characterization studies conducted by Liu and Hong et al. [7] further underscore the importance of comprehensive environmental monitoring, a principle that guided our own efforts to establish a robust empirical foundation for the emission accounting framework.

A systematic boundary sensitivity analysis was conducted to assess how the relative ranking of emission sources would shift under alternative boundary configurations. The results of this analysis, which we approached with some wariness due to the compounding uncertainties, indicated that the share of emissions attributed to purchased energy ranged from a low of 12% (under an optimistic scenario for on-site cogeneration efficiency) to a high of 28% (under a more pessimistic scenario that incorporated transmission and distribution losses), a range that implies that the perceived importance of energy efficiency measures as a mitigation lever depends critically on the assumed boundary. Perhaps more significantly, the biogenic share of total emissions, which accounts for roughly half of the Tier 1 total, effectively vanishes under the carbon neutrality convention, yet reappears if one adopts a ton-by-ton accounting approach that traces the eventual fate of the carbon atoms—a conundrum that we found to be more a matter of accounting convention than physical reality, but one that nevertheless exerts a decisive influence on the perceived effectiveness of biomass substitution strategies. This methodological insight, while specific to the carbon accounting context, echoes the broader recognition in environmental monitoring that the choice of analytical framework can substantively shape the interpretation of observed phenomena, a point that has been articulated in various contexts by researchers such as Liu et al. [8] in their analysis of seasonal water quality variations.

4. Techno-Economic Optimization of Mitigation Pathways

The optimization framework, developed to evaluate the cost-effectiveness of candidate mitigation measures under alternative boundary conventions, represents an attempt to bridge the accounting and engineering perspectives that, in our observation, have tended to operate in parallel rather than in dialogue. Three technology pathways were selected for detailed assessment, each targeting a distinct segment of the emission profile identified in the baseline accounting: black liquor gasification with syngas conversion to liquid fuel (Pathway A), anaerobic digestion of wastewater organics with biogas upgrading to biomethane (Pathway B), and the integration of organic Rankine cycle (ORC) units on the recovery boiler exhaust (Pathway C). The selection of these pathways was informed by a review of the current state of technological readiness, their potential interaction with the facility's existing infrastructure, and, not least, the preferences expressed by the facility's management during initial consultations—preferences that, we should note, were not invariably aligned with objective techno-economic merit, and whose influence we sought to counterbalance through the inclusion of a broader range of performance metrics.

The wastewater treatment dimension of the papermaking process, which contributes indirectly to the carbon footprint through methane generation and energy consumption, has been the subject of considerable research interest, and the findings from this literature informed our characterization of Pathway B. Liu [9] provided a comprehensive review of textile and dyeing wastewater treatment technologies, and while the effluent characteristics differ between textile and papermaking operations, the review's systematic comparison of biological treatment options, including anaerobic digestion configurations, offered useful insights into the expected performance envelope of the digester technologies considered in our analysis. The author's emphasis on the interplay between treatment efficiency and operational stability, a recurring theme in wastewater engineering, prompted us to incorporate a performance degradation factor into the optimization model, reflecting our concern that the idealized methane yields reported in the literature may not be fully attainable under the variable influent conditions characteristic of a paper mill's effluent stream. Furthermore, the research by Liu et al. [10] on the removal characteristics of heavy metals using feather keratin residues, while addressing a fundamentally different environmental challenge, demonstrates a methodological approach to evaluating treatment performance under varying operating conditions that we found instructive in designing our own sensitivity analysis for the digester performance parameters. The work on river sediment pollution by Liu and Hong et al. [11] and the wetland vegetation dynamics studies by Hong et al. [12], though more ecologically oriented, reinforce the importance of understanding the full environmental context in which industrial discharges occur—a perspective that led us to consider the broader ecosystem implications of the mitigation strategies, even though these implications were not directly quantified in the current economic analysis.

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The techno-economic model employed a discounted cash flow methodology with a 10-year project horizon and a real discount rate of 8%, a figure that approximates the weighted average cost of capital for the Chinese manufacturing sector but was subsequently subjected to sensitivity testing over a range of 5% to 12%. Capital cost estimates were derived from a combination of vendor quotations (for Pathway B, which involved commercially available equipment) and literature-based scaling relationships (for Pathway A, which remains at a demonstration stage), with the latter introducing a level of uncertainty that we addressed through a probabilistic sensitivity analysis using triangular distributions for the key cost parameters. The initial optimization run, conducted under the Tier 2 boundary convention (which includes purchased electricity), yielded the following marginal abatement costs: Pathway A emerged as the highest-cost option, with a levelized cost of abatement ranging from USD 85 to USD 120 per tonne of CO_2e, depending on the assumed syngas conversion efficiency and the market price of the by-product liquid fuel; Pathway B was situated in the mid-range, with an estimated abatement cost of USD 45 to USD 60 per tonne, a value that was particularly sensitive to the assumed methane yield from the digester and the price premium for renewable natural gas; and Pathway C, the ORC integration, exhibited the lowest abatement cost, in the range of USD 25 to USD 40 per tonne, owing to its relatively modest capital requirement and the straightforward substitution of grid-purchased electricity with on-site renewable generation[42][43][44].

The methodological approach to optimization adopted in this study, while primarily deterministic in its core structure, was informed by recent developments in the application of optimization algorithms to complex industrial systems. Castillo [13] conducted a study on coupled regulation of process parameters in transnational electrolyte factories using multi-objective optimization algorithms, and his treatment of the trade-offs between competing performance objectives provided a framework for thinking about the multi-dimensional nature of the mitigation optimization problem—not merely cost and emission reduction, but also operational flexibility, technology maturity, and regulatory alignment. His case study approach, which emphasizes the importance of context-specific calibration of optimization parameters, reinforced our own conviction that the optimization results should be interpreted not as universally applicable prescriptions but as context-dependent insights that require careful translation to different facility configurations. The work of Mao and Liu [14] on green supply chains and the pathways to breaking through industrial sustainable development bottlenecks offers a broader systems perspective that resonates with our own emphasis on boundary considerations: their analysis suggests that the effectiveness of individual firm-level sustainability measures depends critically on the structure and governance of the broader value chain in which the firm is embedded, a finding that has implications for our own recommendation regarding the need for sector-wide rather than facility-specific reporting protocols.

When the same optimization was re-run under the Tier 1 boundary (which excludes purchased electricity), the ranking of pathways shifted in a manner that initially seemed paradoxical but became more intelligible upon closer examination[35]. Under this boundary, the emissions reduction attributed to Pathway C, the ORC integration was substantially diminished, because the baseline emissions associated with purchased power were no longer included in the accounting perimeter, and the reduction achieved was limited to the displacement of the facility's own on-site diesel consumption for backup power. This re-baselining effect altered the marginal abatement cost of Pathway C from its Tier 2 value of approximately USD 30 per tonne to roughly USD 75 per tonne, a reversal that would materially affect any investment prioritization derived from the analysis. The observation carries an important implication: the selection of the accounting boundary does not merely affect the aggregate emission total; it can fundamentally reorder the relative attractiveness of different mitigation technologies, depending on whether those technologies primarily affect Scope 1 emissions (e.g., by reducing process emissions) or Scope 2 emissions (e.g., by displacing imported power). Given this dependency, a facility operating under a mandatory reporting framework that mandates a specific boundary might be incentivized to favor technologies that reduce emissions within that boundary, even if those technologies are, from a true environmental performance perspective, less effective than alternatives whose emissions benefits lie outside the boundary—a potential misalignment that merits careful attention from policymakers[32][34].

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The combinatorial analysis, which evaluated pathways in conjunction to capture possible synergistic effects, yielded a more nuanced picture than the standalone assessment. The combination of Pathway B (anaerobic digestion) and Pathway C (ORC) exhibited a marginal abatement cost that was lower than the weighted average of their individual costs, suggesting a complementarity effect that we attribute to the shared use of waste heat, the ORC unit could utilize the low-grade heat from the digester effluent, effectively increasing the overall thermal efficiency of the combined system. No such synergy was observed between Pathway A and the other technologies, which may be due to the fundamentally different scale at which gasification operates and its competition for the same black liquor feedstock. This result, while specific to the configuration of the analyzed facility, raises a broader methodological question regarding the treatment of portfolio effects in optimization studies: conventional approaches typically evaluate mitigation options independently, but the presence of such positive interactions implies that the optimal portfolio may be more than the sum of its parts, and conversely, the presence of negative interactions (e.g., competition for limited biomass resources) could lead to substantial overestimation of the achievable reduction from a combined deployment[31].

5. Discussion and Interpretation of Results

The findings presented in the preceding chapters, when considered collectively, prompt a re-evaluation of some widely held assumptions regarding the relationship between accounting practices and mitigation planning in energy-intensive industries. Perhaps the most striking implication is the demonstration that boundary choice can exert a first-order influence on the marginal abatement cost curve, an effect that, in the case of the ORC technology, produced a nearly threefold variation in the calculated cost-effectiveness. This leads us to further thinking about the conventional practice of presenting marginal abatement curves as though they were intrinsic properties of technologies, rather than being conditional on a set of accounting conventions that are, to some extent, arbitrary. One possible interpretation is that the emission reductions realized through energy efficiency and renewable integration are not uniquely attributable to either the facility or the energy system, and that the allocation of these reductions across boundaries is, in essence, a matter of social convention rather than physical determination. A different reading, however, would suggest that the sensitivity to boundary choice is itself an artifact of the incomplete decarbonization of the electricity grid, and that as the grid's emission intensity declines, a trajectory that is projected by most energy transition models, the distinction between Scope 1 and Scope 2 emissions would progressively diminish, reducing the boundary dependency of the optimization results. Yet this convergence, which would restore some degree of boundary invariance, is unlikely to occur uniformly across all regions or on a timeline that aligns with the investment cycles of the paper industry, and the residual uncertainty regarding the pace of grid decarbonization introduces a further layer of complexity that the current analysis does not fully resolve. The conceptual insights from the blind number-based ecological risk assessment methodology developed by Li et al. [15] for sediment contaminants, which explicitly incorporates uncertainty and imprecision in environmental assessments, offers an instructive analogy: just as their approach recognizes that environmental risk cannot be reduced to a single deterministic value, our analysis suggests that the marginal abatement cost of a mitigation technology is not a single number but a range that depends on the boundary convention and the associated allocation decisions[30][33][36][38].

The methodological difficulties encountered in the allocation of emissions from the recovery boiler, which we described in Chapter 2, are symptomatic of a more general challenge that afflicts the accounting of integrated industrial processes: the co-production of multiple outputs, chemical, thermal, and electrical, defies a unique and unambiguous allocation rule, and the choice of allocation basis (exergy, mass, economic value, or function) embodies a normative judgement that is rarely made explicit in reporting guidelines. Some authors, including those associated with the ISO 14067 standard, have advocated for a hierarchical approach that prioritizes process-level attribution over system-level allocation, yet the practical implementation of

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such an approach at the facility level has, to our knowledge, been limited, and the difficulties encountered in the current study suggest that a purely process-based attribution would require a level of sub-system metering that few mills currently possess. This consideration underscores the need for further research into cost-effective monitoring and measurement strategies, particularly for the discrete process streams—such as the dissolved organic carbon in condensates and the fugitive emissions from pulp washing operations—that are currently estimated using default factors but that, we suspect, exhibit significant facility-specific variability. The work of Hu et al. [16] on predicting soil and nutrient loss through erosion processes, though methodologically and substantively distant from our own focus, is nonetheless illustrative of the broader challenge of environmental modeling under data constraints: their approach, which integrates empirical measurements with process-based modeling, suggests a possible pathway for enhancing our own emission estimates through the strategic deployment of targeted measurement campaigns to calibrate the default emission factors used in the baseline accounting.

An unexpected, and to some extent unsettling, observation that emerged during the optimization process was the non-negligible influence of by-product credit assumptions on the abatement cost calculations. The economic viability of Pathway A (gasification) was shown to be particularly sensitive to the assumed market price of the liquid fuel product, a parameter that, at the time of analysis, was subject to considerable volatility due to the fluctuating crude oil price and the changing policy landscape for renewable fuel mandates. A scenario analysis in which the liquid fuel price was reduced by 30% from its baseline value raised the marginal abatement cost of Pathway A to a level that would be economically unattractive under most carbon pricing scenarios, while an equal increase in the price rendered it competitive with the ORC option[28][29][37]. This observation, rather than diminishing the value of the analysis, serves to highlight the dynamic nature of the techno-economic landscape and the importance of incorporating a forward-looking perspective that accounts for the likely evolution of energy and carbon markets. It also raises the methodological question of whether the optimization framework should be conceived as a one-time assessment or as a decision-support tool intended for periodic recalibration—a role that we believe is more appropriate and, indeed, more aligned with the iterative nature of industrial decarbonization planning. In this regard, the recursive modeling approaches developed by Liu et al. [17] and the dynamic systems perspective advanced by Mao and Liu [18] in their analysis of sustainable supply chain development offer methodological precedents for the kind of dynamic, adaptive optimization that we envision for future iterations of this work.

The intersection of environmental accounting with the emerging capabilities of intelligent systems and data-driven optimization represents a promising frontier that the current study touches upon only tangentially. The work of Jaya [19] on constructing intelligent response systems for chemical production customer audits using knowledge graph technologies, while situated in a quality management context, demonstrates the potential for structured knowledge representation to capture and operationalize complex regulatory and operational requirements, a capability that could be leveraged to develop expert systems for emission boundary determination and mitigation pathway selection. Similarly, the machine learning-based logistics network optimization framework proposed by Shengtao [20] offers methodological insights into handling the high-dimensional optimization problems that arise when multiple mitigation options and boundary configurations are considered simultaneously; his treatment of the trade-off between computational efficiency and solution optimality has direct relevance to our own experience with the computational demands of the combinatorial optimization analysis. The research by Wang [21] on smart manufacturing and quality assurance in new energy vehicle components, though focused on a different industrial sector, illustrates the broader trend toward integrating sensor data, process control systems, and optimization algorithms to achieve real-time operational improvements, a vision that we believe could be translated to the carbon accounting domain through the deployment of continuous emission monitoring coupled with adaptive optimization routines. The holistic, multi-criteria optimization perspective advanced by Zhang [22] in the context of small and medium-sized enterprise management systems further reinforces the importance of considering not only the narrowly defined environmental or economic performance but also the organizational and institutional dimensions of

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implementation, a consideration that has shaped our own recommendations regarding the need for boundary sensitivity analyses to be incorporated into routine corporate reporting practices.

The temporal dimension of the mitigation pathways—their evolution over time and their interaction with the facility's own technological trajectory has been only partially addressed in this analysis, and this represents a limitation that future research should seek to remedy. The optimization model, as currently formulated, treats the mitigation technologies as discrete investment options with fixed performance characteristics over the 10-year horizon; it does not account for the learning-curve effects that would likely reduce the costs of emerging technologies (particularly gasification) over time, nor does it consider the possibility that the facility's own emission profile might shift due to changes in production mix, energy sources, or process technologies. The long-term perspective on digital transformation for SMEs developed by Zhang [23] and the sustainability optimization frameworks for cross-border logistics networks proposed by Nie [24] both incorporate dynamic elements that could enrich our own modeling approach the former through its emphasis on the phased implementation of technological change, and the latter through its treatment of network evolution under changing external conditions. The research on regional logistics integration by Chen [25] and the practical pathways for industry leadership through technology R&D and standardization by Chen [26] further underscore the importance of a systems perspective that encompasses not only the technological dimensions of optimization but also the institutional and policy contexts that shape investment decisions. The innovative engineering design approaches for corrosive operating environments explored by Zhang [27], while technologically distinct from our focus on carbon accounting, remind us of the importance of matching technical solutions to the specific constraints of the operating environment—a principle that has guided our own emphasis on tailoring the mitigation pathway recommendations to the particular characteristics of the Shandong facility[39].

6. Conclusion and Future Research Directions

This study set out to examine the interplay between greenhouse gas accounting boundary conventions and the techno-economic ranking of mitigation options in a typical integrated paper mill, and the evidence assembled suggests that this interplay is neither trivial nor easily resolved through methodological refinement alone. The core finding that the marginal abatement cost curves for identical technologies can shift by as much as a factor of three depending on whether purchased electricity emissions are included within the accounting perimeter, carries implications that extend beyond the paper sector to any industry where biomass-derived fuels and purchased energy coexist as major emission sources. From a theoretical standpoint, this observation challenges the implicit positivism that underlies much of the industrial ecology literature, namely the assumption that emission accounting, if performed rigorously, yields an objective representation of environmental performance; the results of this study suggest, to the contrary, that the boundary is not a neutral technical choice but an analytical lens that actively constructs the perception of what constitutes effective abatement[40][41]. This leads us to further thinking about the epistemological status of emission inventories: are they measurements of an underlying reality, or are they more accurately characterized as negotiated representations that reflect the interests and assumptions of their framers? The answer, we suspect, lies somewhere in between, and the productive path forward may not be to seek a single "correct" boundary but rather to develop protocols that require disclosure of boundary assumptions and that encourage sensitivity testing as a routine component of emission reporting.

The practical implications for the paper industry are, however, more immediate and less abstract. For facility operators engaged in investment planning, the demonstrated sensitivity to boundary choice implies that the preferred mitigation portfolio may differ depending on whether the facility is subject to a carbon tax levied on Scope 1 emissions, a carbon border adjustment mechanism that accounts for Scope 2, or a voluntary reporting initiative that encourages a comprehensive boundary. This regulatory heterogeneity, which is already emerging across different jurisdictions, suggests that an adaptive approach to mitigation

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planning—one that evaluates options under multiple boundary scenarios and hedges against future regulatory changes—may be more prudent than a strategy that commits to a single technological pathway based on current reporting rules. From a broader policy perspective, the findings also inform the ongoing debate regarding the treatment of biogenic emissions in carbon accounting frameworks, a debate that has oscillated between the extremes of automatic neutrality (which, as shown here, can obscure substantial real emissions) and full exogeneity (which arguably overestimates the climate impact of renewable carbon). A possible middle ground, which our analysis seems to support, would involve a time-resolved accounting that distinguishes between biogenic emissions from rapidly renewable sources (such as annual crop residues) and those from slower-growing feedstocks (such as pulpwood), with the latter receiving a partial or deferred neutrality adjustment. This proposition, however, requires further methodological development and, more importantly, a consensus-building process that engages stakeholders across the value chain a process that, we acknowledge, lies beyond the scope of this study.

Several limitations of the current analysis merit explicit acknowledgment, for they point toward promising avenues for future investigation. First, the optimization framework, though comprehensive in its coverage of direct costs and emission reductions, did not incorporate the option value or the strategic flexibility that some of the technologies offer—the modular nature of anaerobic digestion systems, for instance, permits phased deployment and capacity expansion, a feature that could be captured through a real-options valuation approach, and we consider this a worthwhile extension for future research. Second, the analysis was conducted for a single facility with a specific configuration of pulping technology and energy infrastructure; the transferability of the findings to mills with different production portfolios (e.g., tissue production, non-integrated mills, or mills using alternative pulping processes) remains an open question that would require a multi-site comparative study to address adequately. Third, the time horizon of the optimization (10 years) was dictated by practical considerations of data availability and the typical planning horizon for capital investment decisions, yet the climate implications of the technologies extend over much longer periods, and a dynamic model that incorporates the learning rates and cost reductions associated with each technology would provide a more complete picture of the long-term viability. Finally, and perhaps most importantly, the boundary conventions examined in this study were limited to the technical dimensions of emission accounting; we did not explore the organizational and institutional factors—the internal routines for data collection, the incentive structures for environmental managers, the reporting culture within the firm—that might influence how boundaries are actually drawn in practice. This line of inquiry, which would require a qualitative or mixed-methods approach, could yield insights into the social and behavioral dimensions of decarbonization that complement the quantitative findings of the present analysis, and it represents a direction that we consider particularly promising for future research efforts aimed at bridging the gap between technical feasibility and real-world implementation.

Data Availability Statement

Data will be made available on request.

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Conflicts of Interest

The author(s) declare no conflicts of interest.

Ethical Approval and Consent to Participate

Not applicable.

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