From Linear to Circular Economy: A Physical and Monetary Inputâ€“Output Assessment of Industrial Symbiosis in a Regional Hydrogen-Based Hub for Circularity

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The transition from linear production systems toward circular configurations requires robust quantitative tools capable of assessing environmental gains, economic trade-offs, and systemic structural changes. While industrial symbiosis (IS) and Hubs for Circularity (H4C) are increasingly promoted as operational mechanisms for circular economy implementation, their integrated environmentalâ€“economic performance at hub scale remains underexplored within an enterprise inputâ€“output (EIO) modelling framework. This study addresses this gap by applying a combined physical and monetary inputâ€“output approach to evaluate the transformation from a linear industrial configuration to a circular hub configuration in a real-world case.
The central research question is: How does the implementation of industrial symbiosis within a Hub for Circularity reshape the environmental, economic, and systemic performance of a regional industrial ecosystem compared to a linear reference configuration? Sub-questions examine (i) how internal resource loops modify the structural interdependencies of the system, (ii) whether environmental improvements translate into economic gains at process and system levels, and (iii) under which conditions circular hubs can become economically viable.
Methodologically, the study develops an integrated modelling framework combining Physical Inputâ€“Output Tables (PIOTs) and Monetary Inputâ€“Output Tables (MIOTs). First, a physical representation of the system is constructed to capture material and energy flows among processes, including renewable electricity generation, electrolysis-based hydrogen production, wastewater treatment, residential heating, and crematorium operations. Two configurations are modelled: a linear system relying primarily on fossil-based inputs and limited inter-process exchanges, and a circular configuration incorporating renewable electricity integration, hydrogen substitution of natural gas, oxygen valorisation in wastewater treatment, treated water reuse, and waste heat recovery.
The PIOT framework enables explicit modelling of primary resource inputs, intermediate exchanges, final demand outputs, and emissions to the environment. Structural differences between linear and circular systems are analysed through changes in internal loop formation and reductions in primary inputs and waste outputs. Subsequently, the physical flows are monetized through price integration and cost allocation procedures to construct MIOTs. System-level profitability and process-level costâ€“revenue balances are derived through comparison of total system revenues and costs under both configurations.
Empirically, the analysis is based on the Dutch Hub developed within the European IS2H4C (Industrial Symbiosis to Hubs for Circularity) project. Data sources include engineering design specifications, project documentation, reported process capacities, energy conversion efficiencies, emission factors, and cost parameters derived from project partners and publicly available market data. The modelling boundary is defined at hub level, enabling a meso-scale assessment between firm-level case studies and macroeconomic IO models.
The results show that the circular configuration substantially reduces fossil electricity consumption, natural gas use, and CO_2 emissions through renewable energy integration and hydrogen substitution. Internal reuse of oxygen, treated water, and waste heat significantly improves resource efficiency and decreases waste disposal requirements. However, these gains are partially offset by high capital investments in electrolysis, storage, pipelines, and renewable energy infrastructure. Consequently, short-term profitability is lower in the circular configuration, highlighting the importance of investment structures, policy incentives, and carbon pricing mechanisms for long-term viability.

The novelty of this research lies in three main contributions. First, it develops a structured hub-scale PIOTâ€“MIOT integration framework capable of capturing both physical loop establishment and economic feedback effects in circular industrial ecosystems. Second, it applies EIO modelling at the meso-industrial hub level rather than at macroeconomic sectoral aggregation, enabling a customisable representation of technological scale-up impacts of industrial symbiosis. Third, it provides a comparative analysis of linear versus circular configurations, demonstrating how circularity reshapes inter-process dependencies and financial feasibility.

By bridging industrial symbiosis research and inputâ€“output modelling, this study contributes to the advancement of IO-based tools for circular economy assessment and provides insights for policymakers and investors on the systemic conditions required for scaling Hubs for Circularity.

Keywords: industrial symbiosis, enterprise input-output modelling, hubs for circularity, economic and environmental sustainability, regional sustainable development