

Achieving Net-Zero Emissions in Industrial Parks Through Optimized Symbiotic Exchanges and Carbon Capture Utilization

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ABSTRACT

The integration of industrial symbiosis (IS) and carbon capture utilization (CCU) is recognized as a key strategy for achieving net-zero emissions in industrial parks (IPs). However, the optimization of these processes in combination remains an undeveloped research area. This work presents a multi-objective optimization framework implemented in Pyomo and linked with OpenLCA to simultaneously maximize material exchanges and minimize operational costs while evaluating CCU deployment. Applied to Portugal's largest industrial park, the model identified 26 feasible symbiotic exchange routes involving 14 enterprises and 7 potential CCU technologies. Maximum material exchange optimization yields 3,042,107 ton/year across 26 symbiotic routes and 7 CCU units, achieving 89.8 % reduction in climate change impact (from 13.5 to 1.76 million CO₂eq/year); Cost minimization achieves 2,223,298 ton/year with 27 % fewer exchanges, delivering 87.0 % environmental reduction and net revenue of €65.5M/year via carbon tax avoidance. The proposed trade-off configuration deploys 2 CCU units (both for methanol production), establishes 12 symbiotic routes, exchanges 2,925,556 ton/year, and generates €65.5M/year net benefit. Decision variables encompassed inter-enterprise flows, binary decisions to select exchanges, and CCU unit selection informed by technology readiness level (TRL). The epsilon-constraint method generated a Pareto front revealing the cost-benefit trade-offs of the symbiotic network. IS with CCU integration can reduce IP climate impact by 87-90 % while generating substantial economic returns. Methanol emerges as the critical CCU pathway for replacing fossil-imported feedstocks. This framework provides decision-makers with actionable optimization strategies for achieving near net-zero industrial parks by 2050, not only through CCU but also through IS.

Keywords: carbon capture, Pyomo, life cycle assessment, optimization

INTRODUCTION

Industrial Parks (IPs) face a fundamental sustainability challenge, optimizing economic benefits often contradicts minimizing environmental impacts. While Industrial Symbiosis (IS) aims to perform well on those two dimensions through resource sharing, achieving genuine economic and environmental impact, optimization remains an unsolved challenge. To complicate things, there is always a social dimension to be considered. Through IS, it is possible to reduce industrial waste, promoting the Circular Economy (CE) and extending the life cycle of

several materials ^{1,2}.

The evidence is compelling: industrial parks generate waste volumes nearly 18 times those of municipal waste, creating pollution hotspots and ecosystem degradation ³. Yet established symbiosis networks demonstrate that material, energy, and water exchanges can simultaneously reduce environmental footprints, cut operating costs, and generate economic growth ^{4,5}. The question is not whether industrial symbiosis can deliver sustainability benefits—empirical evidence from Kalundborg confirms it does—but rather how to systematically design industrial park networks that reconcile

economic performance, environmental, and social well-being without subordinating local firm viability to global system efficiency or compromising one sustainability dimension to advance another ⁵.

The optimization of IP has been the focus of numerous studies, encompassing the identification of potential symbiotic pathways ⁶ and the identification of redundancy and resilience in these potential exchanges ⁷. The integration and optimization of energy and water resources for IPs have also been a subject of extensive research. However, optimizing symbiotic pathways while accounting for the introduction of new facilities and their dynamics remains an active research field. A solid decision-making process is essential for proposing the introduction of process-specific alternations ⁸ and even more so for sounder still modifications at the IP level.

In this work, we propose a novel approach to IS in IPs. This approach is based on a model that aims to maximize material exchanges while minimizing the costs of implementation of such strategies. Furthermore, the model evaluates the implementation of a carbon capture and utilization (CCU) unit into the IP, based on some proven CCU technologies.

METHODOLOGY

The methodology presented in this section focuses on an optimization model that maximizes material exchanges between enterprises while minimizing the costs for the IP. A sustainability assessment is also carried to quantify the environmental gains of the symbiotic routes (OpenLCA is used to this end), enabling a tri-way assessment of the proposed IP configuration, total mass exchanges ($Total_{EM}$), total costs ($Total_{Cost}$), and environmental accountability ⁹.

$$\text{maximize } Z = Total_{EM} \quad (1)$$

$$\text{minimize } Z = Total_{Cost} = Operational_{cost} + CAPEX \quad (2)$$

Subject to:

The presented objective functions are subject to a set of constraints here presented:

The $Total_{EM}$ is determined by summing the flow of all material exchanges between enterprises (EM), between enterprises and proposed CCU units (EM_{CCU}), and the flow from CCU units to enterprises (EM_{CCUR}). Each exchanged material variable is subject to specific sets, namely, the donor enterprise (n) or CCU unit (n''), the material category (j) whether it is a residue, raw material, coproduct, or product. Furthermore, the material code (i), and the receiving enterprise or CCU unit. For clarity, all EM variables are indexed according to these sets.

$$Total_{EM} = \sum_n \sum_j \sum_i \sum_{n'} EM_{n,j,i,n'} + \sum_n \sum_j \sum_i \sum_{n''} EM_{CCU_{n,j,i,n''}} + \sum_{n''} \sum_j \sum_i \sum_n EM_{CCUR_{n'',j,i,n}} \quad (3)$$

Capital Expenditure

The CAPEX is estimated by a combination of the costs of introducing a new CCU unit into the IP C_{CCU} and the costs of establishing a new exchange route, C_{newEM} .

$$CAPEX = C_{CCU} \cdot Y_{CCU} + C_{newEM} \quad (4)$$

Gross operational costs from the exchanges

The operation costs, $Operational_{cost}$, are obtained as a sum of the current market cost of each material, $C_{i,j}$, multiplied by the total respective material exchanged. This cost varies by material category; for example, a material that is residue will have a different cost compared to its product value.

$$Operational_{cost} = \sum_n \sum_j \sum_i \sum_{n'} EM_{n,j,i,n'} \cdot C_{i,j} + \sum_n \sum_j \sum_i \sum_{n''} EM_{CCU_{n,j,i,n''}} \cdot C_{i,j} + \sum_{n''} \sum_j \sum_i \sum_n EM_{CCUR_{n'',j,i,n}} \cdot C_{i,j} \quad (5)$$

ε - Constraint

This constraint ensures that multiple points between the maximum and minimum $Total_{EM}$ obtained are covered in the solving of the multiobjective problem.

$$Total_{EM} \geq \varepsilon, \varepsilon \in \{Total_{EM}^{min}, Total_{EM}^{max}\} \quad (6)$$

Upper bound limited by availability

The following set of constraints ensures that the decision variables are within the available resources in each of the considered enterprises or CCU units. This data comes from parameters, real data, $RD_{n,j,i}$, and CCU data $RD_{CCU_{n'',j,i}}$.

$$\sum_n EM_{n,j,i,n'} \leq RD_{n,j,i} \cdot Y_{symb_{n,j,i,n'}}, \forall n \in \{1, \dots, N\}, j \in \{0, \dots, J\}, i \in \{1, \dots, I\} \quad (7)$$

Upper bound limited by reception capacity

$$\sum_{n'} EM_{n',j,i,n} \leq RD_{n,0,i} \cdot Y_{symb_{n,j,i,n}}, \forall n \in \{1, \dots, N\}, j \in \{0, \dots, J\}, i \in \{1, \dots, I\} \quad (8)$$

Lower bound of the flow

$$EM_{n,j,i,n'} \geq MinEM_{n,j,i} \cdot Y_{symb_{n,j,i,n}}, \forall n \in \{1, \dots, N\}, i \in \{1, \dots, I\} \quad (9)$$

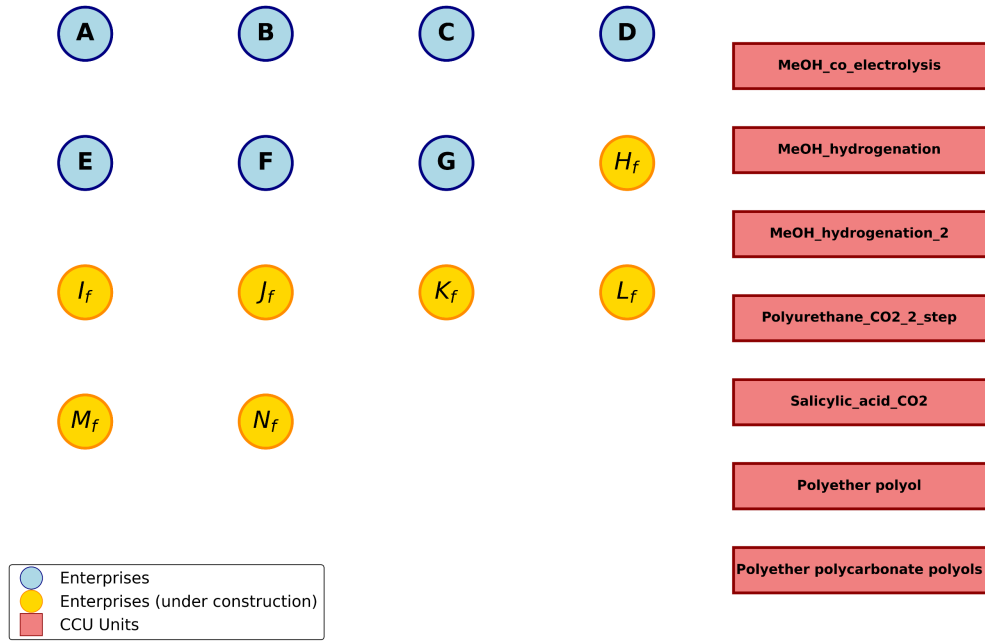


Figure 1. Enterprises considered in the IP and the possible CCU units to be activated.

$$\begin{aligned} & \text{Min} EM_{n,j,i} \\ & = \min \{ RD_{n,j,i} \sum Y_{\text{symp}_{n,j,i,n'}}, RD_{n,0,i} \sum Y_{\text{symp}_{n,j,i,n'}} \}, \\ & \forall n \in \{1, \dots, N\}, j \in \{0, \dots, J\}, i \in \{1, \dots, I\}, \wedge n \neq n' \end{aligned} \quad (10)$$

Constraints for integrating CCU technologies into the IP

$$\begin{aligned} \sum_{n''} EM_{CCU_{n,j,i,n''}} & \leq RD_{n,j,i} \cdot Y_{CCU_{n''}}, \forall n \\ & \in \{1, \dots, N\}, \\ & j \in \{0, \dots, J\}, i \in \{1, \dots, I\} \end{aligned} \quad (11)$$

$$\begin{aligned} \sum_n EM_{CCU_{n,0,i,n''}} & \leq RD_{CCU_{n'',0,i}} \cdot Y_{CCU_{n''}}, \forall n'' \\ & \in \{1, \dots, N\}, i \in \{1, \dots, I\} \end{aligned} \quad (12)$$

$$\sum_{n''} Y_{CCU_{n''}} \leq 7 \quad (13)$$

$$\begin{aligned} \sum_n EM_{CCUR_{n'',j,i,n}} & \leq RD_{CCU_{n'',j,i}} \cdot Y_{CCU_{n''}}, \forall n'' \\ & \in \{1, \dots, N\}, j \in \{0, \dots, J\}, i \\ & \in \{1, \dots, I\} \end{aligned} \quad (14)$$

$$\begin{aligned} \sum_{n''} EM_{CCUR_{n'',0,i,n}} & \leq RD_{n,0,i} \cdot Y_{CCU_{n''}}, \forall n \\ & \in \{1, \dots, N\}, i \in \{1, \dots, I\} \end{aligned} \quad (15)$$

CCU mass balance

$$\begin{aligned} \sum_n \sum_j EM_{n,j,i,n'} + \sum_c \sum_j EM_{CCUR_{n,j,i,c}} & \leq RD_{n',0,i}, \\ & \forall \{n \neq n', j \neq 0\} \end{aligned} \quad (16)$$

$$Y_{n,j,i,n'} \begin{cases} 1 & \vee 0 \text{ if } RD_{n',0,i} \wedge RD_{n',0,i} > 0 \\ 0 & \text{otherwise} \end{cases} \quad (17)$$

Sustainability assessment

OpenLCA is used to obtain climate change characterization factors ¹⁰. They are then used to quantify the environmental gains that can be obtained with the symbiotic exchanges calculated. The characterization factors are considered in eq. 18 in parameter CC_i , in $\text{CO}_{2\text{eq}}$.

$$\begin{aligned} & \sum_n \sum_j \sum_i \sum_{n'} EM_{n,j,i,n'} \cdot CC_i \\ & + \sum_n \sum_j \sum_i \sum_{n''} EM_{CCU_{n,j,i,n''}} \\ & \cdot CC_i \\ & + \sum_{n''} \sum_j \sum_i \sum_n EM_{CCUR_{n'',j,i,n}} \\ & \cdot CC_i \leq 0 \end{aligned} \quad (18)$$

Key assumptions

To implement the presented model, some key assumptions were made and are here listed:

- The costs of each material were determined from current market prices for Europe.
- The current EU ETS (European Union European Trading System) price for CO_2 was used to monetize the CO_2 emissions. As according to EU

ETS the free allowances are intended to be phased out until 2034. Therefore, a worst-case scenario, in which enterprises must pay 100 % of its emissions was considered.

- A cooperative approach to symbiotic routes was considered, as if economically viable the partners are expected to establish such exchanges.
- The presented results in this work are case-study specific, even though the Framework is generic and can be applied to any IP.

CASE STUDY

The methodology previously presented has been implemented in a case study, the largest industrial park in Portugal. Only publicly available data was assessed by the model. The IP features a large oil refinery, a petrochemical plant, and several other smaller enterprises. The list of the considered enterprises is presented in **Table 1**. It must be noted that enterprises from H_f to N_f are not yet built or operating in the IP, these have already received the necessary licensing approvals required for commissioning. Therefore, these might start operations in the near future, J_f and K_f , for example, are already under construction and are L_f is still to begin construction.

As stated in the Introduction, the incorporation of CCU technologies into the IP was considered. The data on CCU technologies were derived from existing literature and are presented in **Table 2**. A range of products is under consideration, and all technologies under review have currently a TRL of 9. This indicates that these technologies have already been proven and deployed at an industrial scale. Methanol, a chemical compound classified as a building block, facilitates the direct substitution for its fossil-based counterpart in various chemical industries ¹¹. In addition, methanol has been studied as a hydrogen carrier due to its superior transport properties compared with pure hydrogen ¹². In this case study, methanol assumes particular significance to the IP. Currently, there are currently imports of methanol to the IP, with local production of e-methanol some or indeed all of the imported methanol could be displaced. While salicylic acid is predominantly recognized for its pharmaceutical applications, it is noteworthy that this chemical compound utilizes CO₂ in its production process, thereby contributing to potential carbon conversion. The polyurethane and polyether polyols under consideration are exemplars of products of added value that can enable the utilization of CO₂ in their synthesis ¹³. The primary applications of these materials are in construction, where they are predominantly left untouched for long periods, thereby promoting carbon storage in the products themselves.

Table 1: Industries considered in the IP and the respective code considered.

Enterprise	Working field
A	Oil refining
B	Petrochemicals
C	Fibrous resins
D	Light gases production
E	Biodiesel
F	Diesel from slops
G	Terephthalic acid production
H_f	Batteries
I_f	Hydrogen
J_f	Biodiesel and SAF
K_f	Polypropylene and Polyethylene
L_f	Methanol
M_f	Hydrogen
N_f	Ammonia

Table 2: CCU technologies considered and their respective CAPEX and CO₂ capture capacity.

Product	CO ₂ captured (ton/year)	CAPEX (M€)	Ref.
<i>MeOH, co-electrol.</i>	7056	100	11
<i>MeOH, hydrogen</i>	352000	72.92	12
<i>MeOH, hydrogen</i>	644000	200	17
<i>Salicylic acid</i>	468	100	18
<i>Polyurethane</i>	20000	100	13
<i>Polyether polyol</i>	23000	383	19
<i>Polyether polycarbonate polyols</i>	1000	15	20

The considered CCU technologies were gathered considering state of the art peer-reviewed papers which concluded that these are the current CO₂ utilization pathways with TRL 9 ¹⁴⁻¹⁶.

RESULTS

The results obtained of the optimization model, applied to the case study data, are presented here. First, the results for maximizing the material exchanged and minimizing the total cost are presented, second the multiobjective optimization results and a Pareto front are presented and discussed.

The model identified a total of 26 possible exchange routes to be established between existing IP enterprises. This derives from the $Y_{symb_{n,j,i,n'}}$ variable, which enables the establishment of a symbiotic route, which can then be optimized by the model. Furthermore, the introduction of CCU units into the IP will open several possible symbiotic routes, from residues to products, that might displace the current import of raw materials by locally produced ones. Figure 1 presents a graph of all possible

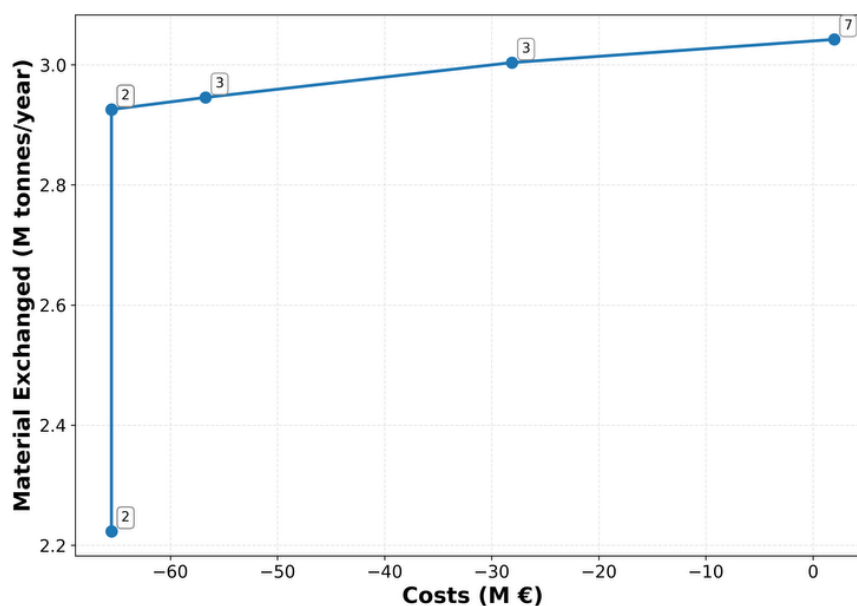


Figure 2: Pareto front between costs and material exchange. The number of CCU units is presented alongside each point.

symbiotic routes that can be established, with the introduction of a CCU unit highlighted to better illustrate the opportunities it can offer to the IP in this case study.

Material exchange maximization

First, the model was run to optimize the IP configuration and symbiotic routes to maximize material exchange between enterprises. This results in a total of 3,042,107 ton of material to be exchanged per year. This means that several residues, products, and co-products can be exchanged within the IP, leading to reduced environmental impacts. Mainly when residues can be directly or partially used in other processes, or when fossil-derived raw materials can be displaced by green products produced locally from captured CO₂. This is the case for methanol, which can be produced from CO₂ captured locally and is currently being imported to the IP. Seven CCU units were determined to be viable pathways for utilizing the CO₂ produced in the IP.

Total cost minimization

Secondly, the model was used to optimize total cost, resulting in a total material exchange of 2,223,298 ton/year. This value is 27 % lower than the obtained total material exchanged when optimized for material exchanges. The model identified the possibility of introducing only two CCU units, as these are expensive to build (significant CAPEX) and might not lead to further IS beyond CO₂, without proper incentive, might be hard to justify.

Multiobjective problem solving

As stated in the methodology section, to solve the multiobjective problem, an epsilon-constraint approach was used. The model was run to minimize total costs considering that the total material exchange should be greater than 2,223,298 plus an epsilon value, which lead to 20 values between the 2,223,298 and 3,042,107. The Pareto front of the non-dominated solutions can be found in **Figure 2**, where the obtained Pareto front is presented between the two objective functions. It is possible to identify that maximizing total material exchange also increases costs, requiring construction of 7 CCU units. However, this will also increase revenue as new products will be produced under the IP. It must be noted that the L_f unit, to which will be built in the upcoming years, be produce enough methanol to fulfil the current methanol requirements of the IP., This way, the introduction of a CCU unit to produce methanol from CO₂ will bring redundancy to the IP, in terms of methanol production. Yet, with the right incentives ⁴, and the increasing prices on CO₂ emissions ²¹, this might go from a redundant methanol production unit to a key player in the CO₂ valorization market. Furthermore, methanol is a building block chemical that can be used to produce several other products. It was also found that the costs show minimal variation among the first few points of the Pareto front. This is because only 2 CCU units are deployed in these first few points.

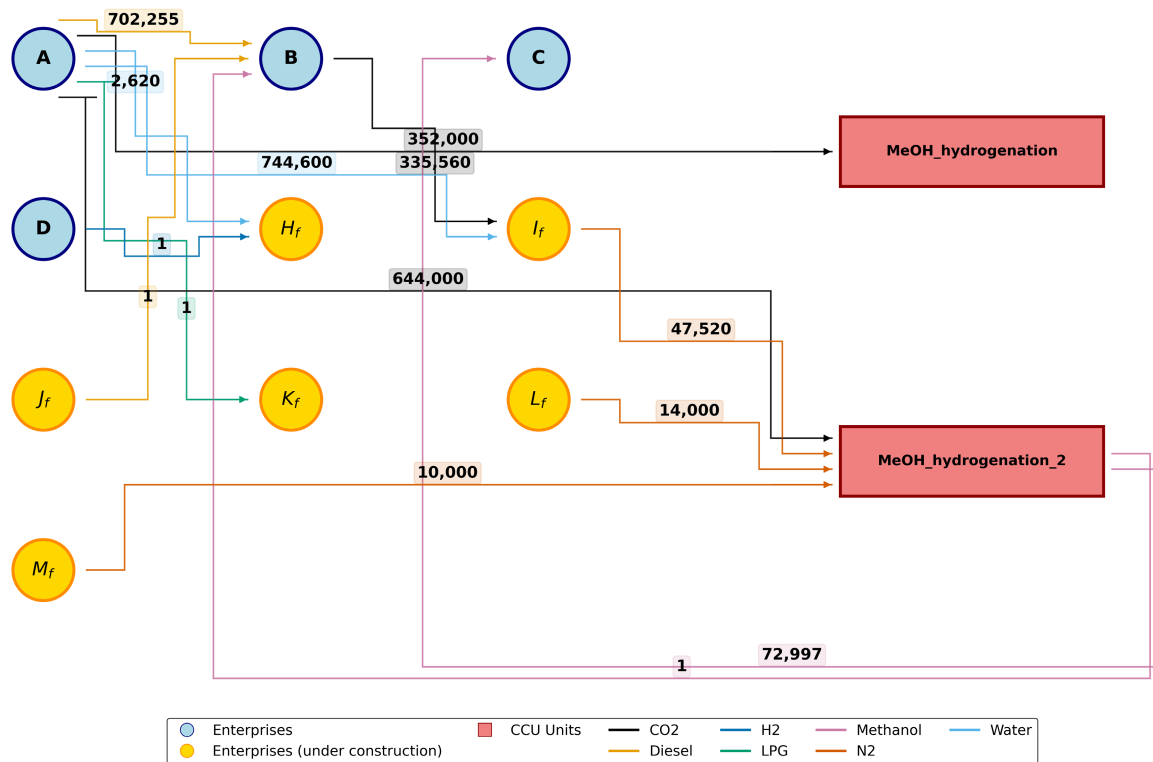


Figure 3. Proposed IP configuration, a trade-off between material exchanges and costs.

Table 3: Main results for the extreme pareto points, business as usual and proposed configuration of the IP with the introduction of IS and CCU units.

Iteration	T. EM (Mt/year)	T. Costs (M€/year)	Nr. con- nec- tions	CCU units
BAU	-	-	-	-
Min Costs	2,223	-65,503	10	2
Max EM	3,042	1,974	26	7
Proposed config	2,925	-65,503	14	2

The IP configuration with the introduction of 2 CCU units is determined to be the most effective approach and is presented in **Figure 3**, as it enables the reduction of the IP's climate change impacts through carbon capture and valorization. Furthermore, the introduction of symbiotic routes, where methanol from fossil fuels is replaced with locally produced methanol from CO₂. Even when minimizing the implementation costs, by missing out on several exchanges, the environmental gains are significant, with 87.4 % reduction in climate change.

Table 4: Climate change variation with the introduction of IS.

Iteration	Climate change (t CO _{2eq})	Change (%)
BAU	13,505,894	-
Min Costs	1,759,455	-87.0
Max EM	1,383,357	-89.8
Proposed config	1,707,930	-87.4

Environmental gains

The total climate change impact was also calculated to quantify the environmental gains of establishing new symbiotic routes. These routes are particularly beneficial in that they redirect residues away from waste treatment plants (such as landfills or specialized treatment) toward symbiotic valorization. As presented in **Table 4**, the BAU (business-as-usual) configuration—defined as the conventional park setup without symbiotic exchanges yields 13,505,894 ton CO_{2eq}. Conversely, all symbiosis-enabled configurations resulting in a reduction of this impact to between 1.38 and 1.76 million ton CO_{2eq}. Specifically, the Minimum Costs and Proposed Configuration scenarios achieved comparable climate change values (1,759,455 and 1,707,930 t CO_{2eq}, respectively), corresponding to reductions of 87.0 % and 87.4 % relative to BAU. In

contrast, the Maximum EM scenario yielded the lowest impact (1,383,357 t CO_{2eq}), representing an 89.8 % reduction.

SENSITIVITY ANALYSIS

To assess the robustness of the multi-objective optimization, a two-part sensitivity analysis was carried out. First, a deterministic scenario analysis was applied to CCU processing efficiency and material market prices using factors (κ) of 70 %, 85 %, 115 %, and 130 % to the baseline values. These parameters act uniformly on all exchanges and are well suited to assess the effects of CCU efficiency and market price in the overall results. To assess the enterprise-level feedstock availability, a deterministic approach that would consider a constant factor applied to all flows would not have been realistic, so a Monte Carlo (MC) analysis was performed, with 100 samples. In this case, each donor enterprise received an independent random perturbation drawn from a uniform distribution $U [1-\delta, 1+\delta]$, with $\delta \in \{10 \%, 20 \%\}$, to reflect heterogeneous supply conditions across enterprises. For each deterministic or MC scenario, the full ϵ -constraint routine was run (as presented in the Methodology section), and the resulting Pareto front was evaluated through the calculation of a hypervolume indicator (HV), which provides a single scalar measure of front quality. Robustness of individual Pareto solutions was quantified as the fraction of MC runs in which each baseline Pareto point remained non-dominated.

The main results for the sensitivity analysis are presented in **Table 5**. The deterministic analysis was assessed using a one at a time approximated first-order sensitivity index ²², which shows that the Pareto front is considerably more sensitive to market price than to CCU efficiency (approximate first-order indices $S_1 \approx 1.64$ and $S_1 \approx 0.35$, respectively). In the MC analysis (with 100 samples), the $\pm 10 \%$ feedstock perturbation led to a mean HV reduction of 0.29 % relative to the baseline, concurrently a coefficient of variation of 0.85 %, indicating that supply fluctuations of up to 10 % have a negligible impact on the trade-off structure. The $\pm 20 \%$ perturbations resulted in a mean HV loss of 1.61 % (and a coefficient of variation of 3.01 %), with larger spread (as it would be expected) but with still a modest degradation of the mean HV of around 1.3 % difference between the 10 and 20 % MC runs.

A Mann–Whitney U test (a non-parametric statistical test used to compare two independent distributions without assuming normality ²³) was applied to compare the HV distributions between the $\pm 10 \%$ and $\pm 20 \%$ bands. This test confirmed that the two HV distributions are statistically different ($p = 0.0069$), yet the magnitude of this difference remains small from an engineering perspective. Importantly, the minimum-cost exchange level

(total exchanged material lower bound) was unchanged across all MC runs, meaning that every solution on the baseline Pareto front remained non-dominated in all simulated supply scenarios.

Table 5: Sensitivity analysis results for key model parameters using deterministic and Monte Carlo (MC) methods. The perturbation κ is applied as a factor in the deterministic method. For MC analysis, parameters were sampled uniformly within the bands.

Parameter	Method	κ Range	HV (%)	CV (%)	S_1
CCU efficiency	Deterministic	0.70–1.30	—	—	0.35
Market price	Deterministic	0.70–1.30	—	—	1.64
MC bands					
Feedstock availability	MC	$\pm 10 \%$	0.29	0.85	—
Feedstock availability	MC	$\pm 20 \%$	1.61	3.01	—

MC – Monte Carlo, HV – hypervolume, CV – coefficient of variance, S_1 – first order index.

CONCLUSIONS

The concept of industrial symbiosis has the potential to simultaneously promote economic growth and environmental gain. In this study, a multi-objective optimization model is presented and solved to assess an industrial park. The analysis revealed that the optimization of IP for material exchanges resulted in enhanced environmental benefits. Conversely, cost minimization led to a decrease in the volume of exchanges.

The findings indicate that the maximum annual exchange capacity is 3,042,107 ton/year, thereby reducing overall IP climate change by 89.4 %. This objective is realized through the implementation of 26 symbiotic routes and the introduction of 7 CCU units into the IP. Optimizing for costs has been shown to result in 87.0 % reduction in the climate change impact of the overall IP, while concurrently achieving a net return (65.5 M €/year), primarily through the avoidance of carbon tax payments on avoided CO₂ emissions. The proposed IP configuration enables the introduction of 2 CCU units, a total of 12 symbiotic routes, 1,707,930 ton/year of total material exchanged, and a net gain of 65.5 M €/year. Additionally, it can be concluded that, while promoting IP integration, it is feasible to reduce both the economic costs of residues

and associated with environmental impacts. The findings of this study lay the foundation for further exploration into specific symbiotic pathways. These pathways have the potential to not only reduce current disposal costs but also to enhance circularity.

The sensitivity analysis demonstrated that the model is robust to parameter uncertainty: the Pareto front showed limited sensitivity to CCU efficiency ($S_1 = 0.35$) but higher sensitivity to market prices ($S_1 = 1.64$), while stochastic perturbations of up to $\pm 20\%$ in feed-stock availability led to a modest mean HV reduction of only 1.61 %, with all baseline Pareto solutions remaining non-dominated across all MC scenarios.

Subsequent research endeavors should concentrate on time discretization and deployment assessment, to facilitate a deeper understanding of IP dynamics and how IP actors interact.

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NOMENCLATURE

Sets and indices

n, n' - Index for enterprises in the industrial park

n'' - Index for CCU units

i - Index for material code

j - Index for material category (residue, raw material, coproduct, product)

Parameters

$RD_{n,j,i}$ - Available quantity of material i in category j at enterprise n

$RD_{n,0,i}$ - Reception capacity for material i at enterprise n

$RD_{CCU_{n'',j,i}}$ - Capacity of CCU unit n'' for material i and

category j

$C_{i,j}$ - Unit cost associated with material i in category j

C_{CCU} - Investment cost of a CCU unit

C_{newEM} - Investment cost associated with establishing new exchange routes

$MinEM_{n,j,i}$ - Minimum flow allowed for an exchange of material i and category j from enterprise n

CC_i - Climate change characterization factor of material i (CO₂-eq per unit of material)

$Total_{EM}^{min}, Total_{EM}^{max}$ - Minimum and maximum values of total exchanged material used in the epsilon-constraint

ε - Epsilon value enforcing the lower bound on $Total_{EM}$ in the multiobjective formulation

κ - Deterministic multiplication factor

δ - Monte Carlo band

Continuous Variables

$EM_{n,j,i,n'}$ - Material flow exchanged from enterprise n to enterprise n' for material i and category j

$EM_{CCU_{n,j,i,n''}}$ - Material flow from enterprise n to CCU unit n'' for material i and category j

$EM_{CCUR_{n'',j,i,n}}$ - Material flow from CCU unit n'' back to enterprise n for material i and category j

$Total_{EM}$ - Total material exchanged in the industrial park

$Total_{Cost}$ - Total annual cost of the industrial park configuration

Binary Variables

$Y_{Symb_{n,j,i,n'}}$ - Binary variable for symbiotic exchange between enterprises n and n' is established for material i and category j

$Y_{CCU_{n''}}$ - Binary variable for the activation of CCU units n''

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