LIAISE | Cooperation, development and cross-border transfer of industrial symbiosis



# D3.3. Industrial Symbiosis Key Performance Indicators dashboard compilation to support decision-making actions of industrial actors.

Author: LIAISE WGs
Created 16/10/2026 Rev 0

cost EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

Funded by the European Union

**Publisher**
Technological Centre of Furniture and Wood of the Region of Murcia (CETEM), Yecla Spain

**For the publisher**
Almudena Muñoz Puche

**Editors**
Almudena Muñoz Puche,
Llesh Lleshaj

**Main Contributors**
Almudena Muñoz Puche, Action Chair
Merim Kasumovic, WG3 leader
Llesh Lleshaj, D3.3 Leader
Anđelka Stojanović, WG3 co-leader
Gamze Nur Mujdeci, WG3 co-leader
Besa Shahini, Member
Blisard Zani, Member
Katerina Shapkova Kocevsk, Member

**Other Contributors**
Aleksandar Erceg, Pawel Krzeminski, Vicky Skloulou, Aleksandar Anastasovski, Apostolos Michopoulos, Marta Munoz Marti, Turgay Dindaroglu, Angela Neves, Hugo Ferreira, Vladan Pavlović, Biljana Činčurak Erceg, Jovanka Damoska Sekuloska, Pablo J. Arauzo, Mine Güngörmüşler, Vaida Jonaitienė, Aida Szilagyi, Ezgi Güney, Hasan Volkan Oral, Istemi Berk, Azemina Mashovic, Jiri Strouhal, Paul Refalo, Massimo Borg, Radu Godina, Macej Kluz, Aida Szilagyi, Estelle Giacommi, Vaida Jonaitienė

This report is part of LIAISE COST Action. Concretely, it is the D3.3. Industrial Symbiosis Key Performance Indicators dashboard compilation to support decision-making actions of industrial actors. LIAISE COST Action (CA22110) is a project funded by the COST Action Programme in 2023, whose objective is to ensure an inclusive and holistic Industrial Symbiosis approach by generating relevant synergies among different actors from the q-helix stakeholder model and by setting the groundwork for increased and robust development of knowledge, apart from promoting future results-oriented R&D.

No portion of this publication may be reproduced, copied, or transmitted without written permission. Any person who does any unauthorized act to this publication may be liable for criminal prosecution and civil claims for damages.

# TABLE OF CONTENT

Project Action Context ..... 5
1. Introduction ..... 8
2. Scope and methodology ..... 11
2.1. Scope of the report ..... 11
2.2. Methodology ..... 12
2.2.1. Methodological approach and workflow ..... 12
2.2.2. Identification and preparation of the indicator dataset ..... 13
2.2.3. Classification into performance dimensions and thematic clusters ..... 13
2.2.4. Expert review and selection of dashboard KPIs ..... 14
2.2.5. KPI documentation and interpretation framework ..... 15
2.2.6. Dashboard implementation and feedback logic ..... 16
2.2.7. Methodological limitations and conditions of use ..... 17
3. KPI compilation and selection results ..... 20
3.1. Overview of the indicator compilation and selection results ..... 20
3.2. Environmental KPIs ..... 21
3.2.1. Thematic coverage and selected indicators ..... 21
3.2.2. Selected environmental KPI specifications ..... 22
3.2.3. Interpretation and contribution to industrial decision-making ..... 28
3.3. Technical KPIs ..... 29
3.3.1. Thematic coverage and selected indicators ..... 29
3.3.2. Selected technical KPI specifications ..... 30
3.3.3. Interpretation and contribution to industrial decision-making ..... 37
3.4. Economic and Business KPIs ..... 37
3.4.1. Thematic coverage and selected indicators ..... 38
3.4.2. Selected economic and business KPI specifications ..... 38
3.4.3. Interpretation and contribution to industrial decision-making ..... 42
3.5. Cultural and Social KPIs ..... 42
3.5.1. Thematic coverage and selected indicators ..... 43
3.5.2. Selected cultural and social KPI specifications ..... 43
3.5.3. Interpretation and contribution to industrial decision-making ..... 47
3.6. Consolidated set of dashboard KPIs ..... 47
4. Dashboard functionality and practical application ..... 51
4.1. Dashboard overview and access ..... 51
4.2. KPI selection and data preparation ..... 52
4.3. Using the KPI cards ..... 53

4.4. Illustrative examples of results and feedback ..... 54
4.5. From dashboard results to industrial actions ..... 56
5. Conclusions and recommendations ..... 59
6. References ..... 61
Annex I. Consolidated inventory of 329 indicators ..... 66
Annex II. Shortlisted KPIs following quantitative expert evaluation ..... 98

## Project Action Context



In the context of addressing climate change, industrial sectors play a significant role as major contributors to carbon dioxide emissions, energy consumption, and waste generation. To combat these challenges, adopting a Circular Economy strategy is imperative. The Circular Economy model diverges from the traditional linear approach by promoting sustainable production and consumption practices while considering societal, environmental, and economic factors in a balanced manner.

Industrial Symbiosis (IS) emerges as a practical solution within this framework. In IS, waste or by-products generated by one industry are repurposed as resources for another, presenting opportunities for environmental sustainability and economic efficiency. Despite its potential, many companies and industrial actors lack awareness of IS, and its development is hindered by various barriers, including environmental, economic, technical, regulatory, organizational, social, and cultural challenges.

To address these issues, the LIAISE COST Action seeks to foster an inclusive and holistic IS approach. By fostering synergies among stakeholders from diverse sectors and laying the groundwork for knowledge enhancement, LIAISE COST Action aims to bridge the gap between theory and practice. This initiative will involve developing a participatory approach to support cross-sector collaborations and establishing Key Performance Indicators (KPIs) for assessing the effectiveness of IS business models in industry.

The LIAISE COST Action represents a collective effort to make the Industrial Symbiosis a reality across Europe, fostering collaboration among researchers, practitioners, and policymakers. To achieve these objectives, LIAISE COST Action will leverage the expertise of four interdisciplinary Working Groups (WGs) and integrate their findings through a reference framework. This holistic approach aims to drive meaningful progress towards sustainable industrial practices and contribute to a more Circular Economy.

## List of Abbreviations

| | |
|---|---|
| BP | By-product |
| CAPEX | Capital expenditure |
| CB | Share of IS exchanges benefiting the community |
| CCA | Change in community attitude towards industry |
| CE | Circular Economy |
| CF | Characterisation Factor |
| CI | Circularity Index |
| CSR | Corporate Social Responsibility |
| DMI | Domestic material input |
| EA | Enabling assets |
| EC | Energy Consumption |
| ECI | Energy Cascading Index |
| EDP | Environmentally adjusted net domestic product |
| eq | Equivalent |
| EQS | Ecosystem quality score |
| EU-28 | European Union comprising 28 member countries |
| FTE | Full-time equivalent |
| GDP | Gross domestic product |
| GHG | Greenhouse gas |
| GRI | Global Reporting Initiative |
| GWP | Global warming potential |
| I-US | Industrial-urban symbiosis |
| IBC | Increase in business competitiveness |
| IRR | Internal rate of return |
| IS | Industrial Symbiosis |
| ISO | International Organisation for Standarization |
| KPI | Key Performance Indicator |
| LCA | Life Cycle Assessment |
| LCC | Life cycle cost |
| LESTS | Legal-Economic-Spatial-Technical-Social assessment |
| NC | Networking Complexity Score |
| NPS | Net Promoter Score |
| NPV | Net present value |
| OPEX | Operating expenditure |
| PDF | Potentially disappeared fraction of species |
| PM | Particulate Matter |
| R&D | Research and Development |
| Ra-226 | Radium-226 |
| RE | Resource Efficiency |
| RM | Raw Materials |
| ROI | Return on Investment |
| ROIC | Return on invested capital |
| RR | Recovery Rate |

| | |
|---|---|
| RS | Resources supply |
| SLD | Symbiotic Link Density |
| Th-232 | Thorium-232 |
| TRL | Technology Readiness Level |
| WCI | Water Circularity Index |
| WG/ WGs | Working Group/ Working Groups |
| WT | Workforce trained in IS-relevant skills |

# 1. Introduction

Industrial Symbiosis (IS) supports the transition towards a circular economy through cooperation between industrial actors and the exchange and valorisation of materials, energy, water, by-products and other underutilised resources. Its successful implementation requires industrial actors to understand both the benefits achieved and the conditions that enable resource exchanges to operate effectively over time. Performance measurement therefore has a practical role in identifying areas for improvement, informing corrective actions and supporting decisions throughout the implementation of IS initiatives.

Deliverable D3.3, *Industrial Symbiosis Key Performance Indicators dashboard compilation to support decision-making actions of industrial actors*, documents the indicator compilation and selection process underpinning the KPI dashboard developed within the LIAISE COST Action, together with its structure, functionality and intended use. The dashboard is available at https://www.liaise-action.eu/dashboard/ and translates the selected indicators into an accessible tool for assessing changes in IS performance over time. It supports the task of developing a KPI dashboard to assist industrial actors in making decisions during IS implementation.

The work started from an initial collection of 329 indicators, drawing on scientific literature, existing assessment frameworks, policy and institutional sources, and expert contributions. The compilation and selection process addressed differences in terminology, overlapping concepts and measurement approaches, considering indicators' relevance to IS, measurability, data availability and usefulness for decision-making. This process resulted in a final set of 29 KPIs incorporated into the dashboard. The deliverable explains the progression from the broader indicator compilation to this operational set and provides the information needed to understand and apply the selected KPIs.

The dashboard covers four complementary dimensions: Environmental KPIs, Technical KPIs, Economic and Business KPIs, and Cultural and Social KPIs. Together, they address both the outcomes of IS activities and the conditions that support their implementation and continuity. The eight Environmental KPIs cover climate change, networking complexity, ecosystem quality, land occupation, gas emissions, radiation emissions, waste sent to landfill and water discharged. The eleven Technical KPIs address energy cascading, system circularity, enabling assets, energy consumption, resource efficiency, technical cooperation, resource supply, productivity, recovery, symbiotic link density and technical feasibility. The five Economic and Business KPIs consider investment returns, raw material cost savings, revenue from by-product sales, business competitiveness and private sector investment in the circular economy. Finally, the five Cultural and Social KPIs address community benefits, attitudes towards industry, workforce training, job creation and cooperation.

These dimensions provide complementary perspectives on IS performance. Environmental indicators help users examine changes in environmental pressures and resource-related impacts; technical indicators address operational performance and implementation conditions; Economic and Business indicators connect IS activities with financial and business considerations; and cultural and social indicators capture aspects of collaboration, skills, employment and community relationships. Some indicators concern closely related aspects of IS and should therefore be interpreted together, with attention to their definitions and assessment boundaries. The dashboard presents individual KPI results to support this interpretation rather than combining them into a single overall performance score.

The dashboard is implemented as a single web page containing 29 KPI cards, with dynamic filtering by KPI category. Each card displays the KPI name, a brief description, its measurement unit, two input fields labelled “Baseline” and “Current value”, a calculation button and a “+Info” button. The latter opens a pop-up window on the same page containing more detailed information about the indicator. This structure combines a concise interface for routine use with access to the supporting information needed to interpret each KPI.

Users enter the two values for the selected KPI, and the dashboard calculates the percentage change between them. The result is accompanied by feedback that reflects both the magnitude of the change and the direction considered favourable for that indicator. This distinction is essential: an increase may represent an improvement for indicators such as resource efficiency or revenue from by-product sales, whereas a decrease may be favourable for indicators such as energy consumption or waste sent to landfill. The interpretation adopted for each KPI is informed by the relevant literature and explained through its supporting documentation.

The dashboard uses defined percentage-change intervals to communicate the extent of the observed variation and provide corresponding feedback. These intervals are interpretation bands for changes over time; they do not represent universal sustainability thresholds, minimum compliance requirements or absolute performance targets. No single reference value is prescribed for all users, since appropriate performance levels depend on factors such as the industrial sector, company size, resource characteristics, technological conditions and assessment boundaries. A favourable change consequently indicates progress relative to the value used for comparison, but does not, by itself, demonstrate that an optimal or sufficient level of performance has been reached.

The feedback associated with each result helps users recognise favourable developments, identify limited progress and draw attention to changes that may warrant further investigation or corrective action. It provides a starting point for reviewing performance in its operational context. For example, an unfavourable change may prompt an industrial actor to examine resource use, operational conditions or cooperation arrangements, while a favourable result may support the continuation or further development of existing practices. Decisions should also consider the other relevant KPIs, since improvements in one dimension may coexist with pressures or constraints in another.

Calculations can be repeated as new data become available, allowing users to examine the evolution of individual KPIs against a selected baseline. The “Baseline” field represents the reference value chosen for comparison, while “Current value” represents the value being assessed. Users can retain a fixed baseline to monitor cumulative progress or update it to compare successive assessment periods. Meaningful interpretation requires consistent units, calculation methods, organisational or network boundaries, and comparable reporting periods. Users should document their chosen baseline and retain their input data and results to support consistent comparisons over time.

The deliverable provides the methodological and interpretative information supporting this application, including KPI definitions, measurement units, calculation approaches, data requirements and limitations. Particular attention is needed where data are incomplete, commercially sensitive or collected using different methods. Changes in production volumes, network composition or assessment boundaries may also affect results and should be considered when comparing values over time. Clear documentation of these conditions is necessary to avoid misleading interpretations.

By bringing together the indicator compilation, the selected set of 29 KPIs and an implemented web-based dashboard, D3.3 connects IS performance assessment with practical monitoring and decision support. Its principal contribution is to help industrial actors understand how selected aspects of their performance are changing, interpret whether those changes are favourable and identify priorities for further action. Used alongside contextual knowledge and more detailed assessments where required, the dashboard supports the continuous improvement of IS initiatives across their environmental, technical, economic, business, cultural and social dimensions.

# 2. Scope and methodology

## 2.1. Scope of the report

This report covers the compilation, selection, documentation and practical application of KPIs to support industrial actors in monitoring and improving IS implementation. Its scope encompasses both the indicator framework and its implementation through the LIAISE web-based KPI dashboard.

The report presents the progression from an initial compilation of 329 indicators to the final set of 29 KPIs incorporated into the dashboard. It describes the methodological approach underpinning this selection and documents the selected indicators to support their consistent use and interpretation. The KPI framework covers four complementary dimensions:

- Environmental KPIs: eight indicators addressing environmental pressures and impacts associated with IS activities.
- Technical KPIs: eleven indicators covering operational performance, resource exchanges and the technical conditions supporting IS implementation.
- Economic and Business KPIs: five indicators addressing financial performance, economic benefits, competitiveness and investment.
- Cultural and Social KPIs: five indicators covering cooperation, skills, employment and relationships with communities.

The dashboard is primarily intended for industrial actors implementing or participating in IS initiatives. Depending on the indicator, the assessment may concern an individual company, a resource exchange or an industrial network. The relevant assessment level and boundaries must therefore be established for each KPI and applied consistently when comparing values.

The report also explains how the dashboard supports performance assessment by comparing a user-defined baseline with a current value. For each KPI, the dashboard calculates the percentage change and provides feedback according to the magnitude of that change and the direction considered favourable on the basis of the relevant literature. This functionality supports the identification of progress, performance gaps and areas that may require further investigation or corrective action.

The scope of this assessment is relative change over time. The percentage-change intervals used to organise feedback are not universal performance benchmarks, regulatory limits or absolute sustainability targets. Likewise, the baseline is a reference value selected by the user, rather than a prescribed standard. Results must be interpreted in light of the industrial context, data quality, assessment boundaries and relationships between indicators.

The dashboard provides decision support through individual KPI calculations and associated feedback. It does not aggregate the indicators into a single score, rank companies or networks, or provide an automated assessment of the overall viability or sustainability of an IS initiative. Where relevant, its results should inform further technical, environmental, financial or organisational analysis.

Accordingly, the report establishes the basis for using the dashboard as a practical monitoring and improvement tool, while explaining the conditions and limitations that industrial actors should consider when applying its results.

## 2.2. Methodology

### 2.2.1. Methodological approach and workflow

The methodology combined indicator compilation, quantitative expert evaluation, qualitative selection and dashboard implementation. Its purpose was to translate a broad collection of potential Industrial Symbiosis (IS) indicators into a manageable set of KPIs supporting industrial actors in monitoring performance and identifying priorities for improvement.

The process comprised six interconnected stages:

1. Indicator identification: compilation of 369 candidate indicator entries from literature and other relevant sources.
2. Duplicate removal and harmonisation: removal of duplicate entries to obtain a dataset of 329 indicators, followed by harmonisation of terminology and definitions.
3. Classification, thematic clustering and scope refinement: organisation of the indicators into thematic clusters within four retained performance dimensions: Environmental, Technical, Economic and Business, and Cultural and Social. The nine Legal KPIs were excluded from further dashboard selection because their interpretation requires case-specific assessment of the applicable jurisdiction, permits and exchange conditions. This reduced the dataset for subsequent evaluation from 329 to 320 indicators.
4. Quantitative expert evaluation: scoring against four criteria (relevance, measurability, data availability, and importance for IS and policy evaluation) to reduce the dataset from 320 to 78 shortlisted KPIs.
5. Qualitative review and consortium agreement: review of the shortlisted indicators by the report contributors and agreement within the consortium on the final set of 29 dashboard KPIs.
6. KPI documentation and dashboard implementation: preparation of indicator descriptions, measurement information and literature-informed interpretation guidance, followed by implementation in a web-based application comparing baseline and current values and providing indicator-specific feedback.

The approach combined structured quantitative screening with qualitative judgement to balance thematic coverage, practical relevance and simplicity of use. The final set provides an initial, multidisciplinary framework for monitoring IS implementation, while allowing for additional indicators where specific industrial contexts require more detailed assessment.

Figure 1 summarises the progression from indicator identification to dashboard implementation. The methodological limitations and conditions of use described in Section 2.2.7 apply throughout this workflow.

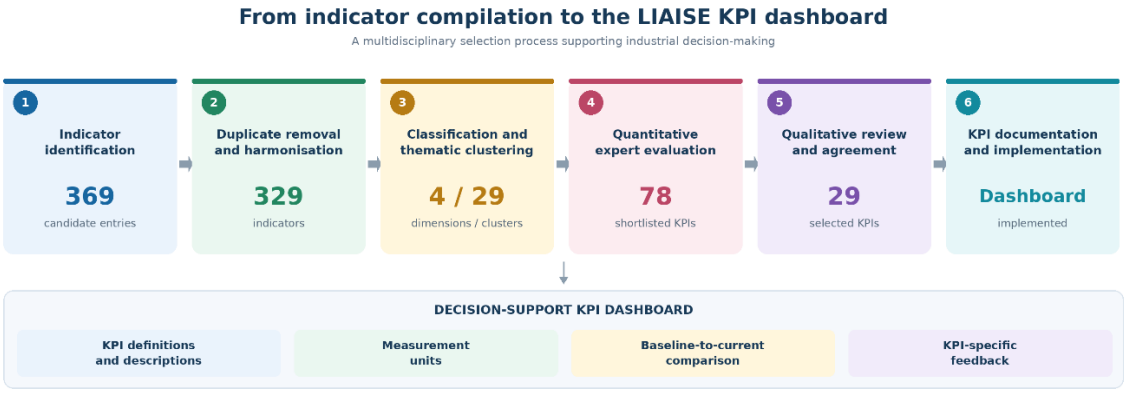



Figure 1. Workflow from indicator compilation to the implemented LIAISE KPI dashboard. Source: LIAISE WGs (2026).

### 2.2.2. Identification and preparation of the indicator dataset

The initial collection comprised 369 candidate indicator entries identified by contributors with complementary areas of expertise. Sources included academic literature, existing indicator frameworks, policy and regulatory documents, sustainability reports and institutional guidelines relevant to IS and related circular economy practices.

The initial compilation also included nine indicators classified as Legal KPIs, addressing regulatory non-compliance, licence-limit exceedances, certification, legal and ethical non-conformities, cooperation and legal feasibility. These entries were retained in the consolidated inventory to document the scope of the identification process, although legal indicators were not retained as a separate dimension of the final dashboard.

The review considered indicators addressing both the outcomes of industrial cooperation and the conditions supporting its implementation. This broad scope allowed environmental, technical, economic, business, cultural, social and legal considerations to be included in the initial collection.

Duplicate entries were identified and removed, resulting in a dataset of 329 indicators. The dataset was subsequently reviewed to identify conceptual overlaps, differences in terminology and variations in measurement scope. Indicator names and descriptions were harmonised where appropriate to facilitate comparison and thematic organisation.

Harmonisation did not imply that indicators with similar names were necessarily interchangeable. Differences in assessment level, system boundaries and calculation methods remained relevant to their interpretation and subsequent selection.

### 2.2.3. Classification into performance dimensions and thematic clusters

The classification process established four performance dimensions for the dashboard framework: Environmental, Technical, Economic and business, and Cultural and Social. The initial inventory additionally contained a Legal KPI category, which is documented in Annex I but was not carried forward as a separate dashboard dimension.

Within each dimension, indicators were grouped into thematic clusters according to the concept, process or outcome being assessed. This organisation supported the identification of common themes across the dataset and provided a structure for selecting representative indicators without allowing numerous closely related measures to dominate the dashboard.

The resulting framework comprised several thematic clusters, described in Table 1.

Table 1. Performance dimensions and thematic clusters used to organise the indicator dataset

| PERFORMANCE DIMENSION | THEMATIC CLUSTER |
|---|---|
| Environmental | Climate; network structure and resource exchange performance; ecosystem; land; air; radiation; waste; water. |
| Technical | Energy cascading; circularity; enabling assets; consumption; efficiency; technical cooperation; supply; productivity; recovery; network connectivity; technical feasibility. |
| Economic and Business | Financial feasibility and investment performance; cost reduction and economic savings; resource valorisation and operational efficiency; business development, cooperation and competitiveness; circular economy investment, innovation and employment enablers. |
| Cultural and Social | Social capital; cultural capital; employment impact; community inclusion and governance; education and capacity building. |

Source: LIAISE WGs (2026).

The classification provided an organisational framework rather than a claim that all dimensions were independent. For example, cooperation can have technical, business and social implications, while resource recovery can generate both environmental and economic benefits. Related indicators were therefore distinguished by their principal assessment purpose and measurement scope.

### 2.2.4. Expert review and selection of dashboard KPIs

The selection of dashboard KPIs followed a two-stage approach. A quantitative expert evaluation reduced the dataset from 329 to 78 indicators. A subsequent qualitative review identified the final set of 29 KPIs incorporated into the dashboard.

#### Quantitative evaluation and shortlisting

Candidate indicators were assessed against four criteria:

- Relevance for IS performance assessment.
- Measurability or potential for operationalisation.
- Availability of the data required for calculation.
- Importance for IS and policy evaluation.

Each criterion was evaluated on a scale from 1 to 5, with higher scores indicating greater suitability. Expert ratings were averaged for each criterion, and the resulting criterion scores were averaged to obtain an overall score for each indicator. Equal weight was assigned to the four criteria.

For an indicator (k), the overall score was calculated as:

$$S(k) = \frac{1}{m}\sum_{c=1}^{m}\left(\frac{1}{n}\sum_{e=1}^{n} s_{k,c,e}\right)$$

where (m) is the number of criteria, (n) is the number of experts rating the indicator, and (s_{k,c,e}) is the score assigned by expert (e) to indicator (k) under criterion (c).

During the reduction from 329 indicators to the intermediate shortlist of 78 KPIs, the nine indicators classified as Legal KPIs were excluded on scope grounds. Their interpretation requires reference to the jurisdiction, sector, material classification, permits and specific conditions applicable to each exchange. A generic baseline-to-current comparison would not, by itself, establish legal feasibility or compliance. Legal assessment was therefore retained as a separate, case-specific requirement outside the dashboard.

The remaining candidates were shortlisted through the quantitative expert evaluation, resulting in 78 KPIs across the four retained performance dimensions. This shortlist formed the basis for the subsequent qualitative review and selection of the final 29 dashboard KPIs.

#### Qualitative review and final selection

The report contributors reviewed the 78 shortlisted KPIs to identify a concise set representing the principal thematic areas of the broader compilation. The review considered conceptual representativeness, relevance to industrial decisions, practical applicability, measurement requirements and overlap between indicators.

The objective was to balance thematic coverage with simplicity of use. Contributors selected indicators they considered capable of representing the main concepts captured by the preceding compilation while keeping the dashboard manageable for an initial application.

The resulting set of 29 KPIs was agreed by the consortium and incorporated into the dashboard. It comprises eight Environmental KPIs, eleven Technical KPIs, five Economic and Business KPIs, and five Cultural and Social KPIs.

The final selection was therefore informed by quantitative screening but was not determined solely by numerical ranking. Qualitative judgement supported the choice of a complementary and representative set, taking account of the dashboard's intended use. The selected indicators constitute a practical starting point rather than an exhaustive or universally applicable assessment framework.

### 2.2.5. KPI documentation and interpretation framework

For each of the 29 selected KPIs, supporting information was compiled to explain the concept measured, its relevance to Industrial Symbiosis (IS), its measurement unit and the interpretation of changes in its value. This documentation connects the indicator compilation and selection process with practical application in the dashboard.

The documentation addresses the indicator definition, measurement approach and contextual considerations needed to obtain and interpret comparable values. Particular attention is given to clarifying the scope of measurement and distinguishing indicators that address related concepts but differ in their calculation or assessment boundaries.

A central element of the interpretation framework is the identification of the favourable direction of change for each KPI, informed by the relevant bibliography. Depending on the indicator, an increase or a decrease is considered favourable. This direction provides guidance for interpreting changes over time rather than an instruction to maximise or minimise values without regard to operational conditions, practical limits or other dimensions of performance. It does not establish an absolute target or a universally satisfactory performance level.

The documentation also distinguishes the calculation of an indicator from the calculation of its variation. Users first obtain baseline and current values using the measurement approach specified for the KPI. The dashboard subsequently calculates the relative percentage change between these values and provides feedback according to its direction and magnitude, as described in Section 2.2.6.

To support accessibility, the dashboard presents the information at two levels. Each KPI card displays the indicator name, a concise description and its measurement unit, while the "+Info" function provides access to a more detailed explanation within the same page.

The resulting set of 29 KPIs, including their measurement scope, units and favourable direction of change, is presented in the subsequent section on selected KPIs. Detailed definitions, calculation methods and supporting references are provided in the corresponding indicator descriptions.

### 2.2.6. Dashboard implementation and feedback logic

The selected KPIs were implemented in a single-page web application, available at https://www.liaise-action.eu/dashboard/. The interface contains 29 KPI cards and allows users to filter them dynamically by performance dimension.

Each card includes the KPI name, a brief description, its measurement unit, two input fields labelled "Baseline" and "Current value", a calculation button and a "+Info" button. Detailed information is displayed in a pop-up window within the same page.

#### Baseline and current-value comparison

The baseline is the reference value selected by the user, while the current value is the value being assessed. For a positive baseline, relative percentage change is calculated as:

$$\text{Percentage change} = \frac{\text{Current value} - \text{Baseline}}{\text{Baseline}} \times 100$$

A positive result indicates an increase, a negative result indicates a decrease, and zero indicates no change. Whether the result represents a favourable development depends on the direction defined for the selected KPI.

For indicators already expressed as percentages, the result represents relative percentage change rather than percentage-point difference. For example, an increase from 40% to 50% represents a relative increase of 25%, equivalent to an increase of 10 percentage points. Users must therefore distinguish the unit of the underlying indicator from the percentage variation calculated by the dashboard.

#### Percentage-change bands

The feedback framework combines the direction and magnitude of change. Changes in the favourable direction are organised into five bands. A change in the opposite direction receives an unfavourable-change message, while an unchanged value receives a separate message.

Table 2. KPI percentage-change bands and associated feedback categories

| RESULT CATEGORY | MAGNITUDE OF CHANGE IN THE FAVOURABLE DIRECTION |
|---|---|
| Improvement band 1 | Greater than 0% and up to 5% |
| Improvement band 2 | Greater than 5% and up to 15% |
| Improvement band 3 | Greater than 15% and up to 25% |
| Improvement band 4 | Greater than 25% and up to 50% |

| | |
|---|---|
| Improvement band 5 | Greater than 50% |
| Unfavourable change | Any change opposite to the favourable direction |
| No change | Current value equal to the baseline |

Source: LIAISE WGs (2026).

For KPIs where an increase is favourable, the improvement bands apply to positive percentage changes. For KPIs where a decrease is favourable, they apply to the magnitude of the percentage reduction. Unfavourable changes are grouped into one feedback category rather than subdivided by magnitude.

These bands structure the interpretation of relative change. They do not establish universal sustainability thresholds, regulatory limits, minimum acceptable performance levels or externally validated benchmarks. The literature-informed favourable direction and the feedback bands serve different purposes: the former supports interpretation of the direction of change, while the latter determines the message associated with its magnitude.

#### Indicator-specific feedback

A feedback matrix was prepared for the 29 KPIs, with seven possible messages for each indicator: five for favourable-change bands, one for an unfavourable change and one for no change.

The feedback describes the result and highlights considerations relevant to the selected KPI. For example, increased revenue from by-product sales can prompt users to examine the contribution of sales volumes, prices and market relationships, whereas increased waste sent to landfill can prompt a review of recovery opportunities and operational conditions.

Messages are specific to the indicator and calculated result, but they are not a diagnosis of the causes of change. Possible explanations and suggested areas of attention should be understood as matters for investigation rather than conclusions established by the two input values. Likewise, descriptions of a large relative improvement do not establish statistical significance or a large absolute benefit.

#### Repeated application

Users can repeat calculations as new data become available. Retaining a fixed baseline supports assessment of cumulative change, while updating the baseline supports comparison between successive assessment periods. Users should document which approach they adopt and retain the relevant values and results for longer-term analysis.

The dashboard provides individual KPI calculations and associated feedback. It does not combine the indicators into an overall score or automatically determine the most appropriate management response. Its results support the identification of issues for further assessment and informed action by industrial actors.

### 2.2.7. Methodological limitations and conditions of use

The methodology provides a structured basis for practical IS monitoring, subject to limitations associated with indicator selection, measurement and interpretation.

#### Representativeness and applicability

The initial compilation reflects the sources reviewed and the expertise of the report contributors. Selection combined quantitative expert evaluation, which reduced the dataset from 329 to 78 KPIs, with qualitative review and consortium agreement on the final 29 indicators. Although this approach

provides a structured basis for selection, it does not establish exhaustive coverage or independent validation across all industrial sectors and IS configurations.

Not every KPI will be equally relevant to every user. Additional sector-specific or exchange-specific indicators may be required, and users should establish whether each selected indicator is applicable to their activities and decision-making needs.

### Legal assessment outside the dashboard scope

Legal indicators identified during compilation were not retained in the final dashboard. Dashboard results therefore do not establish legal feasibility, regulatory compliance or authorisation to undertake an exchange. These matters require a separate, case-specific assessment, irrespective of whether the selected KPIs show favourable changes.

### Data consistency and assessment boundaries

Meaningful comparisons require consistent definitions, units, measurement methods and organisational or network boundaries. Reporting periods should be comparable. Changes in production volumes, workforce size, network membership, accounting practices or survey methods can affect results independently of changes in IS performance.

Absolute indicators, such as total energy consumption or water discharge, are particularly sensitive to changes in activity levels. Where relevant, users should examine them alongside production data or complementary intensity indicators. Financial comparisons should also consider changes in prices, currency values and the expenditure categories included.

### Baseline selection and calculation constraints

The baseline affects both the magnitude and interpretation of change. Users should select and document a reference that is relevant to the assessment purpose and avoid changing it without explaining the implications for comparability.

A zero baseline prevents calculation using the standard relative percentage-change formula. Small positive baselines can generate large percentage variations despite limited absolute change. Negative baselines can reverse the usual interpretation of the percentage-change sign and require separate treatment, particularly for financial indicators. The standard feedback bands should therefore not be applied automatically to such cases without an explicit calculation and interpretation rule.

For indicators whose values already express a change against another reference, such as cost-saving percentages, users must also document that underlying reference. Changing it between assessments can make the dashboard comparison misleading.

### Interpretation of direction and magnitude

A favourable direction is a contextual guide rather than evidence that unlimited increases or decreases are desirable. Increased investment, networking complexity or cooperation scores, for example, should be considered alongside effectiveness, costs and actual outcomes. Lower water discharge alone does not demonstrate improved water quality, and reduced land occupation does not capture every land-related impact.

Relative improvement does not demonstrate that an adequate absolute performance level has been achieved. Conversely, no change does not necessarily indicate poor performance. An unchanged recovery rate of 100%, for example, has a different meaning from an unchanged rate

at a low level. Indicators with bounded scales also have different improvement potential depending on their starting value.

Percentage changes in ordinal assessment scores require additional caution. Where a score represents ordered categories rather than equal measurement intervals, its relative variation should not be interpreted as a proportional increase in the underlying capability or condition.

### Attribution, feedback and trade-offs

The comparison of two values does not establish that an observed change was caused by IS activities. Operational developments, market conditions and other external factors may influence results. The feedback provides interpretative guidance and cannot replace investigation of these factors.

Finally, indicators should be read together where their outcomes are related. Progress in one dimension may coexist with adverse developments in another, and individual results should not be added or treated as interchangeable. The dashboard supports monitoring and decision-making alongside contextual knowledge and further technical, environmental, financial or organisational assessment where required.

# 3. KPI compilation and selection results

This section presents the results of the indicator compilation and selection process described in Section 2.2. It traces the progression from the initial collection to the final set of 29 KPIs implemented in the LIAISE dashboard.

The results are organised into four performance dimensions: Environmental, Technical, Economic and business, and Cultural and Social. For each dimension, the following subsections present the thematic coverage, shortlisted indicators and final dashboard selection, together with the information needed to understand and apply the selected KPIs. A consolidated overview brings together the final set and its principal measurement characteristics.

## 3.1. Overview of the indicator compilation and selection results

The process produced three main outputs: a consolidated dataset of 329 indicators, an intermediate shortlist of 78 KPIs and a final set of 29 dashboard KPIs. These outputs serve different purposes. The consolidated dataset captures the breadth of the reviewed indicators; the shortlist identifies candidates prioritised through quantitative evaluation; and the final set provides a manageable selection for practical dashboard use. Table 3 summarises the progression through the compilation and selection stages.

Table 3. Summary of indicator compilation and selection results

| STAGE | OUTPUT | NUMBER OF INDICATORS |
|---|---|---|
| Initial compilation | Candidate indicator entries collected from the reviewed sources. | 369 |
| Dataset consolidation | Indicators remaining after duplicate removal, forming the dataset for classification and evaluation. | 329 |
| Quantitative screening and scope refinement | Exclusion of nine Legal KPIs on scope grounds, leaving 320 candidates, followed by expert evaluation and review to establish the intermediate shortlist. | 78 |
| Qualitative selection | Final representative set agreed by the consortium and incorporated into the dashboard. | 29 |

Source: LIAISE WGs (2026).

The removal of duplicate entries reduced the initial collection by 40, establishing the 329-indicator dataset. Its organisation into four dimensions and several thematic clusters provided a structure for examining related measures and identifying complementary aspects of IS performance.

Quantitative expert evaluation subsequently reduced the dataset to 78 KPIs. The qualitative review of this shortlist resulted in the final 29 indicators, balancing representation of the thematic areas with practical relevance and simplicity of use.

The final dashboard set comprises eight Environmental KPIs, eleven Technical KPIs, five Economic and business KPIs, and five Cultural and Social KPIs. The distribution reflects the thematic structure adopted for the compilation and does not imply a weighting or ranking of the importance of the four dimensions.

Together, the selected indicators address resource use and environmental pressures, technical conditions and operational performance, financial and business outcomes, and the social

relationships and capabilities supporting IS implementation. They include both performance outcomes and enabling conditions, allowing users to examine complementary aspects of their activities.

The final set provides a common starting point for monitoring rather than a requirement for every industrial actor to apply all 29 indicators. The appropriate selection depends on the activities assessed, the level of analysis and the availability of suitable data. The following subsections explain the contribution of each dimension and detail the indicators selected for dashboard application.

## 3.2. Environmental KPIs

Environmental KPIs support the assessment of changes in resource-related pressures and environmental impacts associated with IS. They help industrial actors examine whether resource exchanges, shared infrastructure and recovery activities are accompanied by improvements in environmental performance.

The reviewed literature addresses outcomes such as reduced greenhouse gas emissions, waste disposal, primary resource consumption and water use, while highlighting the importance of consistent assessment boundaries and reliable data (Ehrenfeld, 2004; Jacobsen, 2006; Jensen et al., 2011). Environmental assessment is particularly relevant where a symbiotic exchange reduces one pressure but introduces another, for example through additional transport, treatment or energy requirements.

The environmental dimension comprises eight thematic clusters and eight selected dashboard KPIs. Seven selected indicators address environmental pressures or impacts, while Networking complexity characterises an enabling condition: the structure and diversity of the resource-exchange network. Its inclusion within this dimension does not imply that greater complexity automatically produces environmental benefits.

### 3.2.1. Thematic coverage and selected indicators

The environmental indicators were organised into clusters covering climate, network structure and resource exchange performance, ecosystems, land, air, radiation, waste and water. These clusters capture the broader thematic coverage of the compilation; the selected dashboard KPIs provide a more focused representation of each area.

Table 4. Environmental thematic clusters and selected dashboard KPIs

| CLUSTER | THEMATIC COVERAGE | SELECTED DASHBOARD KPI |
|---|---|---|
| CL1 – Climate | Greenhouse gas emissions and climate-related effects associated with industrial activities and resource exchanges. | Climate change |
| CL2 – Network Structure and Resource Exchange Performance | Interconnections, exchange diversity and structural development of IS networks. | Networking complexity |
| CL3 – Ecosystem | Ecosystem-related pressures and damage, including effects associated with emissions and resource use. | Ecosystem quality |
| CL4 – Land | Land requirements associated with industrial operations, storage and infrastructure. | Land occupation |

| | | |
|---|---|---|
| CL5 – Air | Atmospheric emissions associated with industrial processes and symbiotic exchanges. | Gas emission |
| CL6 – Radiation | Radiological characteristics and potential concerns associated with relevant materials or resource streams. | Radiation emission |
| CL7 – Waste | Waste generation, recovery and reliance on final disposal. | Total waste sent to landfill |
| CL8 – Water | Water use, reuse and discharge within industrial systems. | Water discharged |

Source: LIAISE WGs (2026).

The selected indicators do not measure every aspect covered by their respective clusters. For example, Water discharged measures discharge volume rather than the full range of water withdrawal, reuse and quality considerations. Similarly, Land occupation measures occupied surface area rather than the complete ecological consequences of land use. These distinctions define the scope within which dashboard results should be interpreted.

### 3.2.2. Selected environmental KPI specifications

CLIMATE CHANGE (G)

**Definition and measurement.** This KPI measures greenhouse gas emissions within a defined assessment boundary, expressed in kilograms of carbon dioxide equivalents (kg $CO_2$eq). Emissions of individual greenhouse gases are converted using their global warming potential factors and aggregated:

$$G = \sum_i E_i \times GWP_i$$

where (G) is the total climate-change impact expressed in kg $CO_2$eq, ($E_i$) is the mass of greenhouse gas (i), and ($GWP_i$) is its characterisation factor. The assessment must specify the characterisation method and time horizon used.

**Data requirements.** Relevant inputs include fuel and electricity consumption, process emissions, measured emission data and applicable emission or characterisation factors. Baseline and current assessments must use consistent boundaries and methods.

**Decision-making relevance.** The indicator supports the assessment of emission-related developments associated with resource substitution, energy exchanges and changes in industrial processes. It can inform investigation of emission hotspots and opportunities for improvement.

**Favourable direction and limitations.** A decrease is considered favourable. However, lower emissions within one facility do not necessarily demonstrate lower emissions across the full symbiotic system. Additional transport, processing and displaced activities may need to be considered. The indicator measures an emission footprint; avoided emissions require a separate, explicitly defined comparison with a reference scenario. Ozone depletion is a distinct environmental impact category and is not included simply by expressing emissions in $CO_2$ equivalents.

**Source identified in the compilation:** Erhart and Erhart (2023).

NETWORKING COMPLEXITY (C)

**Definition and measurement.** Networking complexity characterises the diversity of resource exchanges and richness of interactions within an IS network. The dashboard expresses it as an index from 0 to 100, combining connectance and flow diversity.

Connectance measures active directed links relative to the total number of potential directed links:

$$C = \frac{L}{N(N-1)}$$

where (L) is the number of active directed links and (N) is the number of participating organisations. Self-links are excluded, and each ordered pair of organisations is counted once, regardless of the number of resource types exchanged between them.

Flow diversity measures the number of observed resource categories relative to the total number of categories defined in the assessment framework:

$$D = \frac{k_{\text{obs}}}{k_{\text{max}}}$$

where $k_{obs}$ is the number of resource categories exchanged and $k_{max}$ is the total number of possible categories under the adopted classification.

The Networking Complexity Score is calculated as:

$$NC = (\omega_1 C + \omega_2 D) \times 100$$

Where $\omega_1$ and $\omega_2$ are the weights assigned to connectance and flow diversity. Both weights must be non-negative and sum to one to maintain the index within the 0–100 range.

The calculation requires at least two participating organisations and a positive value of $k_{max}$. The assessment must document the network boundaries, link-counting rules, resource classification and chosen weights. These must be applied consistently to baseline and current values.

**Data requirements.** Inputs include participating organisations, active directed links and the categories of resources exchanged. These may be obtained from exchange registries, company inventories and IS platforms. Missing or confidential exchange data may lead to an incomplete representation of the network.

**Decision-making relevance.** The indicator supports examination of network development, diversification and opportunities for additional cooperation. Reviewing its two components separately can help distinguish changes driven by increased connectivity from those driven by a broader range of exchanged resources.

**Favourable direction and limitations.** An increase is treated as favourable in the dashboard as a signal of greater interconnectedness or resource-flow diversity. Nevertheless, complexity is not a direct measure of environmental benefit or resilience. Additional interdependencies can create vulnerabilities, and a new link may provide limited benefit or introduce additional burdens. The

result should therefore be interpreted alongside environmental outcomes and operational conditions.

Results depend on the selected weights and resource classification. Changes in network membership also alter the number of potential links and can affect the score even when existing exchanges remain unchanged. Consistent calculation and documentation are therefore essential for meaningful comparisons.

Sources identified in the compilation: Barrau and Glaus (2023); Chopra and Khanna (2014); Li and Shi (2015); Wang et al. (2018).

ECOSYSTEM QUALITY (EQS)

Definition and measurement. For dashboard purposes, this KPI represents ecosystem damage expressed in PDF·m²·year, where PDF denotes the potentially disappeared fraction of species. Despite the indicator's title, the entered value represents damage rather than a positive ecosystem-quality score.

Ecosystem damage is calculated by combining environmental inventory quantities with the corresponding ecosystem characterisation factors:

$$D = \sum_{x} (M_x \times CF_{\text{eco},x})$$

where:

- (D) is the ecosystem damage, expressed in PDF·m²·year.
- ($M_x$) is the quantity of inventory flow (x) included in the assessment.
- ($CF_{eco,x}$) is the ecosystem characterisation factor corresponding to that flow.

Inventory quantities and characterisation factors must use compatible units so that each contribution is expressed in PDF·m²·year. The assessment must identify the method used, its characterisation factors and the system boundaries. Results expressed through other ecosystem indices or endpoint units are not directly interchangeable.

As a complementary assessment, avoided ecosystem damage can be calculated by comparing a reference scenario with an IS scenario:

$$\Delta D_{\text{eco}} = D_{\text{base}} - D_{\text{IS}}$$

where ($D_{base}$) is the damage associated with the reference scenario and ($D_{IS}$) is the damage associated with the IS scenario. A positive result indicates lower modelled damage in the IS scenario, provided both scenarios are assessed on an equivalent basis.

The dashboard inputs should contain the damage values (D), rather than the avoided-damage result. Its "Baseline" and "Current value" fields are used to calculate relative change as described in Section 2.2.6.

Data requirements. Inputs include environmental inventory quantities, such as emissions and relevant resource or land-use flows, together with compatible characterisation factors from the

selected assessment method. Baseline and current assessments require consistent boundaries, methods and functional or reporting bases.

Decision-making relevance. The indicator broadens assessment beyond resource savings and climate change, supporting consideration of whether an exchange reduces ecosystem-related burdens or shifts them between activities or locations. Where equivalent reference and IS scenarios are available, the complementary avoided-damage calculation can support assessment of the potential benefit of a proposed exchange.

Favourable direction and limitations. A decrease in the damage value is considered favourable. Results represent modelled potential damage and depend on the assessment method, inventory quality and geographical and temporal assumptions. They should not be interpreted as direct observations of local biodiversity loss.

A weighted ecosystem-condition score, such as:

$$EQS = \sum_i w_i s_i$$

represents a different measurement approach and should not be substituted for the damage indicator without changing its definition, unit and interpretation.

Sources identified in the compilation: Marcinkowski (2019); Sturbois (2023)

LAND OCCUPATION ($A_{occupied}$)

Definition and measurement. The dashboard KPI measures the surface area occupied by the industrial operations, storage or infrastructure included in the assessment boundary, expressed in square metres (m²). It is calculated by summing the relevant non-overlapping occupied areas:

$$A_{occupied} = \sum_i A_i$$

where ($A_i$) is each distinct area included in the assessment.

This area-based measure differs from time-integrated land occupation, expressed in m²·year, and from characterised ecological damage associated with land use.

Data requirements. Sources include site plans, geographic information systems, land-use inventories and company infrastructure records. Shared facilities require a consistent approach to allocation and avoidance of double counting.

Decision-making relevance. The indicator supports assessment of space requirements, shared infrastructure and opportunities to use existing industrial sites more efficiently.

Favourable direction and limitations. A decrease is considered favourable within a comparable operational boundary. However, occupied area alone does not indicate land quality, biodiversity effects or restoration potential. Changes in activity levels and relocation of activities outside the boundary must also be considered.

**Sources identified in the compilation:** Chen et al. (2022); Goedkoop & Spriensma (2000); Jolliet et al. (2003); Kantor et al. (2019); Pakarinen et al. (2010); Shi et al. (2025); Van Berkel et al. (2009); Zou et al. (2026).

GAS EMISSION ($I_p$)

**Definition and measurement.** This KPI measures emissions of a specified gaseous pollutant per tonne of production output, expressed in kg/t output:

$$I_p = \frac{M_p}{Q}$$

where ($M_p$) is the mass of pollutant (p) emitted and (Q) is the production output in tonnes over the same reporting period.

The pollutant must be identified explicitly. Separate assessments may be needed for different pollutants; their masses should not be added into an undifferentiated result.

**Data requirements.** Inputs include emission-monitoring records or documented emission estimates and corresponding production data.

**Decision-making relevance.** The indicator supports evaluation of changes in emission intensity following resource substitution, process modifications or emission-control measures.

**Favourable direction and limitations.** A decrease is considered favourable. Reduced emission intensity can coexist with increased total emissions if production rises, so both may need consideration. Results do not establish compliance with concentration limits or other permit conditions. Climate-related assessment should remain distinguishable from the Climate change KPI.

**Source identified in the compilation:** Boubel et al. (2013).

RADIATION EMISSION ($Ra_{eq}$)

**Definition and measurement.** For this KPI, the measurement adopted is radium equivalent activity ($Ra_{eq}$), expressed in Bq/kg. It combines the activity concentrations of Ra-226, Th-232 and K-40 into a single radiological screening indicator for the assessed material or resource stream:

$$Ra_{eq} = C_{Ra} + 1.43C_{Th} + 0.077C_{K}$$

where ($C_{Ra}$), ($C_{Th}$) and ($C_K$) are the activity concentrations of Ra-226, Th-232 and K-40, respectively, expressed in Bq/kg.

Despite the dashboard title "Radiation emission", this calculation characterises the material's radium equivalent activity rather than a rate of radiation release or a directly measured exposure dose. Baseline and current inputs must both represent $Ra_{eq}$, calculated using the same method.

**Complementary radiological indicators.** The source material also provides external and internal hazard indices:

$$H_{ex} = \frac{C_{Ra}}{370} + \frac{C_{Th}}{259} + \frac{C_K}{4810}$$

$$H_{in} = \frac{C_{Ra}}{185} + \frac{C_{Th}}{259} + \frac{C_K}{4810}$$

The denominators are expressed in Bq/kg, yielding dimensionless indices. These measures provide complementary screening information and must not be entered in the dashboard field intended for $Ra_{eq}$. Their applicability and interpretation depend on the material, intended use and assessment framework; they do not independently establish safety or regulatory compliance.

Data requirements. Inputs include representative material samples and measurements of Ra-226, Th-232 and K-40 activity concentrations, obtained through suitable radiological analysis. Sampling procedures, material characteristics and measurement methods must be documented and kept comparable between assessments.

Decision-making relevance. The indicator supports screening of relevant secondary materials before their exchange or incorporation into another process. It can help identify changes in radiological characteristics that warrant further assessment, including consideration of intended applications and potential exposure pathways.

Favourable direction and limitations. A decrease is treated as favourable when comparing equivalent materials and measurement conditions. However, a lower value does not independently establish that a material is suitable for a particular application.

The calculation covers the three specified radionuclides and does not characterise every possible radiological concern. Exposure also depends on material quantities, geometry, use conditions and exposure pathways. Absorbed dose rates, annual effective doses and hazard indices are complementary measures with different meanings and units and cannot be substituted for the dashboard input.

Sources identified in the compilation: Habib et al. (2019); Mas et al. (2021); Namq and Wais (2026) Sahoo and Joseph (2021).

TOTAL WASTE SENT TO LANDFILL ($W_L$)

Definition and measurement. This KPI measures the mass of waste directed to landfill within the defined assessment boundary and reporting period, expressed in tonnes per year:

$$W_L = \sum_j W_{L,j}$$

where ($W_L$) is the mass of each waste stream sent to landfill during the year.

Data requirements. Sources include waste-transfer documentation, disposal records, contractor reports and company or industrial-park waste inventories. Network-level reporting must avoid counting the same waste more than once.

Decision-making relevance. The indicator helps users identify disposal hotspots, monitor reliance on landfill and investigate opportunities for prevention, reuse and recovery through IS.

**Favourable direction and limitations.** A decrease is considered favourable. However, reduced landfill disposal does not independently demonstrate that waste was prevented or beneficially exchanged. Users should identify its destination and distinguish IS-related recovery from other changes in waste management. Production levels, waste classification and residual waste generated by recovery processes also affect interpretation.

**Sources identified in the compilation:** Albino et al. (2026); Sellitri et al. (2026); Silva et al. (2020); Van Berkel et al. (2009).

WATER DISCHARGED ($V_{discharged}$)

**Definition and measurement.** For dashboard purposes, this KPI measures the volume of effluent discharged into natural receiving environments within the defined boundary, expressed in cubic metres per year:

$$V_{\text{discharged}} = \sum_{r} V_r$$

where ($V_r$) is the volume discharged to each receiving environment during the reporting year.

Water transferred to another industrial actor for reuse should be distinguished from discharge to the environment. Transfers to third-party treatment should also be recorded separately to preserve consistency with this measurement scope.

**Data requirements.** Sources include flow-meter readings, discharge records, water balances and documented estimates. Each stream must be accounted for consistently.

**Decision-making relevance.** The indicator supports identification of water-reuse opportunities and monitoring of changes in discharge volumes associated with IS activities.

**Favourable direction and limitations.** A decrease is considered favourable, subject to operational context. Lower discharge volume does not necessarily mean lower pollutant loads or improved receiving-water conditions. Effluent quality, freshwater withdrawal, production levels and treatment requirements should also be considered. A reduction achieved through transfer outside the assessment boundary should not automatically be interpreted as an environmental improvement.

**Sources identified in the compilation:** Chertow (2000); Global Reporting Initiative (2018); Hu et al. (2020); Kumar and Yaashikaa (2019); Onita (2006).

### 3.2.3. Interpretation and contribution to industrial decision-making

The eight environmental KPIs provide complementary information. Climate change and Ecosystem quality address characterised environmental impacts; Land occupation, Gas emission, Radiation emission, Total waste sent to landfill and Water discharged address specific pressures or material characteristics; and Networking complexity describes network structure.

Their combined use can help industrial actors identify issues requiring investigation, monitor changes following interventions and consider potential trade-offs. For example, reduced landfill disposal may coexist with increased transport emissions or additional wastewater treatment requirements. Individual improvements should therefore be considered within the wider system.

The dashboard facilitates comparison between baseline and current values but does not perform the underlying environmental assessment or establish causality. Users must obtain each input using the appropriate measurement method and interpret the feedback alongside absolute values, activity levels and other relevant indicators.

Application of the environmental set should reflect the industrial context. Radiation-related assessment, for example, is relevant where material characteristics warrant it, while network-level indicators require information beyond an individual facility. Selecting applicable indicators and documenting their boundaries are essential to using the dashboard as a credible basis for monitoring and improvement.

## 3.3. Technical KPIs

Technical KPIs address the operational conditions, resource flows and technological capabilities supporting IS. They help industrial actors examine whether exchanges can be implemented, whether the necessary infrastructure and cooperation arrangements are available, and how resource use and operational performance evolve over time.

The reviewed material covers both achieved performance and enabling conditions. Indicators such as energy consumption, resource efficiency and recovery rate describe operational results, while enabling assets, technical cooperation and technical feasibility address conditions necessary to establish and maintain exchanges. Network connectivity provides an additional perspective on the structure of relationships between participating organisations.

The technical dimension comprises eleven thematic clusters and eleven selected dashboard KPIs. Together, they support assessment at company, exchange and network levels, depending on the indicator and the boundaries adopted.

### 3.3.1. Thematic coverage and selected indicators

The technical clusters cover energy cascading, circularity, enabling assets, consumption, efficiency, technical cooperation, supply, productivity, recovery, network connectivity and feasibility. Table 5 summarises their scope and corresponding dashboard indicators.

Table 5. Technical thematic clusters and selected dashboard KPIs

| CLUSTER | THEMATIC COVERAGE | SELECTED DASHBOARD KPI |
|---|---|---|
| CL1 – Energy Cascading | Recovery and sequential use of thermal energy across compatible temperature demands. | Energy Cascading Index |
| CL2 – Circularity | Circulation of resources and substitution of primary inputs within the assessed system. | Circularity Index (System Level) |
| CL3 – Asset | Availability and operational readiness of infrastructure and other assets enabling exchanges. | Enabling Assets |
| CL4 – Consumption | Energy demand associated with the activities included in the assessment. | Energy Consumption |
| CL5 – Efficiency | Useful output obtained relative to resource inputs consumed. | Resource Efficiency |
| CL6 – Technical Cooperation | Coordination, knowledge exchange and joint technical arrangements between partners. | Level of Technical Cooperation |

| | | |
|---|---|---|
| CL7 – Supply | Secondary resource inputs supplied and integrated into productive activities. | Resources Supply |
| CL8 – Productivity | Production output relative to workforce input | Productivity |
| CL9 – Recovery | Recovery of generated residual streams for productive use. | Recovery Rate |
| CL10 – Network Connectivity | Active symbiotic links relative to potential connections. | Symbiotic Link Density |
| CL11 – Feasibility | Practical compatibility and operational requirements of proposed exchanges. | Technical Feasibility |

Source: LIAISE WGs (2026).

The selected indicators provide focused measures within these broader clusters. Their definitions and units must remain consistent between assessments. Alternative measures discussed in the underlying compilation can provide complementary information but should not be substituted for dashboard inputs without adjusting the measurement definition and interpretation.

### 3.3.2. Selected technical KPI specifications

ENERGY CASCADING INDEX (ECI)

Definition and measurement. The Energy Cascading Index measures the proportion of technically recoverable waste heat that is usefully reused within the defined system. For the dashboard's simplified energy-based measure:

$$ECI = \frac{Q_{\text{reused, useful}}}{Q_{\text{recoverable}}}$$

where ($Q_{reused,useful}$) is the useful, recovered heat delivered to receiving processes and ($Q_{recoverable}$) is the technically recoverable heat available within the same boundary and period. Both quantities must use the same energy unit. The resulting index ranges from 0 to 1 when the accounting boundaries are consistent.

The denominator represents technically recoverable heat rather than all heat generated. Internal transfers must be accounted for consistently to avoid counting the same energy repeatedly. Heat quantities should also be reported by temperature class, since the ratio alone does not capture thermal quality or demonstrate effective sequential cascading.

Data requirements. Inputs include heat-flow measurements, energy balances, source and receiving-process temperatures, operating schedules and heat-exchanger records. Recovered quantities may additionally be reported in MWh/year.

Decision-making relevance. The indicator supports identification of unused recovery opportunities and monitoring of heat utilisation. Temperature information helps assess compatibility between sources and receiving processes and the need for additional heat integration.

Favourable direction and limitations. An increase is considered favourable. However, higher heat reuse does not independently demonstrate optimal thermodynamic performance. Intermittency, temperature mismatch, transport losses and additional energy requirements affect the practical value of an exchange. More detailed assessments may use exergy-based measures, which must remain distinguishable from this energy-based dashboard input.

**Sources identified in the compilation:** Dincer and Rosen (2013); Forman et al. (2016); Kemp (2007); Linnhoff and Hindmarsh (1983); Sokka et al. (2011).

CIRCULARITY INDEX (CI)

**Definition and measurement.** For dashboard purposes, this KPI measures secondary material inputs as a percentage of total material inputs within the defined system at system level:

$$CI = \frac{M_{\text{secondary, input}}}{M_{\text{total, input}}} \times 100$$

where ($M_{\text{secondary, input}}$) is the mass of secondary materials entering the assessed production system and ($M_{\text{total, input}}$) is the total mass of primary and secondary material inputs over the same period.

At network level, internal exchanges must be distinguished from external inputs and recorded using a consistent accounting rule. Repeated transfers of the same material must not unintentionally inflate the result.

The compilation also discusses broader circularity measures based on the Material Circularity Indicator, including output recovery and utility factors. Those measures are distinct from the secondary-input share used by the dashboard and are not interchangeable with it.

**Data requirements.** Inputs include procurement records, material balances, secondary-material classifications and records of exchanges between participating organisations.

**Decision-making relevance.** The indicator supports monitoring of secondary material uptake and identification of opportunities to substitute primary inputs.

**Favourable direction and limitations.** An increase is considered favourable. The indicator does not independently capture product lifetime, output recovery, material quality, environmental impact or water and energy circularity. A higher secondary-input share should therefore be considered alongside resource efficiency, recovery and environmental results.

**Sources identified in the compilation:** Ellen MacArthur Foundation (2015); Fraccascia et al. (2017, 2021); ISO 59020 (2024); Lyons (2007); Mayer et al. (2019); Tiejun (2010).

ENABLING ASSETS (EA)

**Definition and measurement.** This KPI measures the proportion of required enabling assets that are available and operational for the assessed IS exchanges:

$$EA = \frac{A_{\text{available, operational}}}{A_{\text{required}}} \times 100$$

where ($A_{\text{available, operational}}$) is the number of required assets meeting the defined availability and operational criteria, and ($A_{\text{required}}$) is the total number of assets identified as necessary.

Assets may include pipelines, storage, treatment facilities, transport connections, monitoring systems and digital platforms. The assessment must define asset categories and acceptance criteria before calculating the percentage.

**Data requirements.** Inputs include asset inventories, engineering assessments, infrastructure maps, maintenance records and exchange-specific requirements.

**Decision-making relevance.** The indicator supports identification of infrastructure gaps, investment priorities and readiness for new or expanded exchanges. Operational use can highlight assets whose unavailability affects ongoing cooperation.

**Favourable direction and limitations.** An increase is considered favourable. A simple count assigns equal importance to each asset and may conceal critical bottlenecks. Availability does not necessarily demonstrate adequate capacity or reliability. Changes to the required-asset list must be documented, and the ratio is undefined where no required assets have been identified.

**Sources identified in the compilation:** Felício et al. (2016); Fraccascia et al. (2017, 2021); Kantor et al. (2019); Scafà et al. (2020); Yeo et al. (2019).

ENERGY CONSUMPTION (EC)

**Definition and measurement.** This KPI measures total energy consumed within the defined operational boundary during the reporting year, expressed in MWh/year:

$$EC = \sum_{i} E_i$$

where ($E_i$) represents each non-overlapping energy consumption category included in the assessment.

Energy carriers must be converted into consistent units. The accounting approach must avoid counting both an energy input and its internally converted output as separate consumption of the same energy. Network assessments must also distinguish internal transfers from additional energy entering the system.

**Data requirements.** Sources include electricity and fuel meters, utility bills, energy balances, process-monitoring systems and records of purchased or recovered heat.

**Decision-making relevance.** The indicator supports identification of energy-demand hotspots and monitoring of changes following process optimisation, heat recovery or shared-utility arrangements.

**Favourable direction and limitations.** A decrease is considered favourable within a comparable activity boundary. Total consumption is influenced by production volumes, product mix and operating conditions. It should therefore be examined alongside activity data or energy-intensity measures. Lower consumption does not independently establish lower greenhouse gas emissions, which also depend on the energy sources used.

**Sources identified in the compilation:** Branca et al. (2021); Dincer and Rosen (2013).

RESOURCE EFFICIENCY (RE)

**Definition and measurement.** For the dashboard, Resource Efficiency measures saleable product output per unit of material resource input:

$$RE = \frac{M_{\text{saleable output}}}{M_{\text{resource input}}}$$

The unit is tonnes of saleable output per tonne of input. Numerator and denominator must refer to the same reporting period and production boundary.

The assessment must specify which products and inputs are included. Measures of resource savings, energy intensity or virgin-material substitution are complementary indicators and should not be entered interchangeably in this card.

Data requirements. Inputs include material balances, production records, input quantities and saleable-output data. Network-level calculations require consistent treatment of intermediate products and internal transfers.

Decision-making relevance. The indicator supports identification of material losses and monitoring of changes in useful output obtained from resource inputs.

Favourable direction and limitations. An increase is considered favourable. Results can change because of product mix, moisture content or the inclusion of previously unrecorded inputs. The ratio does not capture material scarcity, product value or environmental impact and does not independently attribute an improvement to IS.

Sources identified in the compilation: Ellen MacArthur Foundation and Granta Design (2015); Fraccascia et al. (2017, 2021); ISO 14044 (2006); Sokka et al. (2011).

LEVEL OF TECHNICAL COOPERATION (LTC)

Definition and measurement. This KPI assesses the extent to which participating organisations coordinate the technical arrangements supporting their exchanges. Relevant aspects include specification alignment, technical information sharing, joint monitoring and maintenance, and collaborative problem-solving.

The dashboard uses a LESTS score from 0 to 5. LESTS refers to Legal–Economic–Spatial–Technical–Social assessment. The compilation links technical cooperation to its technical dimension.

The value must be assigned using a documented scoring rubric and supporting evidence. Where sub-criteria are aggregated, their definitions, weights and aggregation rule must be stated. A 1–5 scale or a normalised 0–1 score cannot be entered as an equivalent value without an explicit conversion.

Data requirements. Sources include structured questionnaires, stakeholder interviews, cooperation agreements, coordination records and evidence of joint technical activities.

Decision-making relevance. The indicator helps identify gaps in partner coordination that may prevent otherwise promising exchanges from operating effectively.

Favourable direction and limitations. An increase is considered favourable. Scores depend on the rubric, assessor judgement and evidence quality. As an ordinal measure, a percentage increase in the score should not be interpreted as an equivalent proportional increase in cooperation. It must also be distinguished from Technical Feasibility: cooperation concerns joint working arrangements, whereas feasibility concerns whether an exchange can function under the specified conditions.

Sources identified in the compilation: Cervo et al. (2019); Chertow (2007); Lombardi and Laybourn (2012); Maqbool et al. (2017).

RESOURCES SUPPLY (RS)

**Definition and measurement.** For dashboard purposes, this KPI measures the annual quantity of secondary material resources supplied and integrated into productive use within the assessed system, expressed in tonnes/year:

$$RS = \sum_{i} M_{\text{secondary},\,i}$$

where ($M_{secondary,i}$) is each secondary material quantity included during the reporting year.

This definition is narrower than total resource supply, which can include primary materials, water and energy. Flows measured in cubic metres or MWh cannot be added directly to the dashboard's mass-based value.

**Data requirements.** Sources include delivery and acceptance records, procurement systems, material balances, warehouse inventories and exchange-platform records. The accounting rule must prevent unintended double counting of successive transfers.

**Decision-making relevance.** The indicator supports monitoring of secondary resource integration and assessment of supply developments relevant to production planning.

**Favourable direction and limitations.** An increase is considered favourable where the supplied materials are suitable and productively used. Higher tonnage alone does not demonstrate reduced primary-resource consumption, reliable supply or lower environmental impacts. Quality, substitution rates, demand and additional processing requirements must also be considered.

**Sources identified in the compilation:** Jacobsen (2006); Chertow (2007); Lombardi and Laybourn (2012); Sokka et al. (2011); Yeo et al. (2019).

PRODUCTIVITY (P)

**Definition and measurement.** The dashboard uses labour productivity, expressed as production output per worker:

$$P = \frac{Q_{\text{output}}}{N_{\text{workers}}}$$

where ($Q_{output}$) is production output in tonnes over the defined reporting period and ($N_{workers}$) is the corresponding workforce measure. The unit is t/worker for that period.

The workforce basis must be specified, for example average headcount or full-time equivalents, and retained consistently. This measure differs from a material output-to-input ratio.

**Data requirements.** Inputs include production records, reporting-period information and workforce data.

**Decision-making relevance.** The indicator supports examination of changes in labour productivity following process or organisational developments associated with IS.

**Favourable direction and limitations.** An increase is considered favourable within the scope of this measure. Results are influenced by automation, outsourcing, product mix and workforce changes. Higher productivity does not automatically indicate reduced waste, improved employment conditions or an IS-related benefit.

**Sources identified in the compilation:** Peters et al. (2003).

RECOVERY RATE

**Definition and measurement.** For the dashboard, Recovery Rate measures the share of a defined waste or by-product stream recovered through IS for useful material application:

$$RR = \frac{M_{\text{recovered, useful}}}{M_{\text{generated}}} \times 100$$

where ($M_{recovered, useful}$) is the mass recovered and meeting the receiving application's requirements, and ($M_{generated}$) is the total mass of the corresponding stream generated within the same boundary and period.

The denominator must be stated explicitly. The recovered quantity may additionally be reported in tonnes/year.

**Data requirements.** Sources include mass balances, waste records, transfer documentation, receiving-company acceptance records and quality analyses.

**Decision-making relevance.** The indicator supports identification of unused recovery potential and monitoring of the effectiveness of waste-to-input exchanges.

**Favourable direction and limitations.** An increase is considered favourable. Recovery should reflect useful application rather than transfer or storage alone. Material, nutrient and energy recovery ratios have different denominators and must not be combined without a defined method. A high rate does not independently establish environmental benefit or reduced waste generation.

**Sources identified in the compilation:** Arauzo et al. (2019, 2022); Ellen MacArthur Foundation and Granta Design (2015); ISO 59020 (2024).

SYMBIOTIC LINK DENSITY (SLD)

**Definition and measurement.** This KPI measures active symbiotic links relative to the potential links within the network. For directed links between distinct organisations:

$$SLD = \frac{L}{N(N-1)}$$

where (L) is the number of active directed links and (N) is the number of participating organisations.

The result is a dimensionless ratio from 0 to 1. Self-links are excluded, and each ordered pair is counted once. Multiple resource exchanges between the same ordered pair do not create additional links under this convention.

**Data requirements.** Sources include verified exchange records, cooperation agreements and network databases. The assessment must define which relationships qualify as active symbiotic links.

**Decision-making relevance.** The indicator supports monitoring of connectivity and identification of gaps or opportunities for additional exchanges.

**Favourable direction and limitations.** An increase is treated as favourable as a signal of greater connectivity. Density does not measure exchange volume, reliability or environmental benefit, and greater connectivity does not automatically imply resilience. Network membership changes affect the denominator.

This indicator corresponds to the connectance component of Networking complexity. Their relationship should be recognised when interpreting results, rather than treating them as independent evidence of improvement.

**Sources identified in the compilation:** Albino et al. (2015); European Commission (2014).

TECHNICAL FEASIBILITY

**Definition and measurement.** Technical Feasibility assesses whether a proposed IS exchange can operate under the specified industrial conditions. Relevant considerations include feedstock quality and variability, process compatibility, infrastructure, logistics, operational reliability, safety and receiving-product requirements.

The dashboard expresses this assessment as a dimensionless score on a 0–5 scale. The supporting compilation also refers to a 1–5 expert-assessment scale, with three reference points: 1 indicates that the exchange is not technically feasible; 3 indicates feasibility with relevant adaptation; and 5 indicates technical feasibility with existing infrastructure and stable operation.

These reference points provide partial guidance but do not constitute a complete rubric for the dashboard's 0–5 scale. The assessment protocol must define all score categories, including zero, the evidence required and how individual technical criteria are combined, including any weights applied. Missing information must be distinguished from demonstrated technical infeasibility.

A normalised score on a 0–1 scale may also be reported where an explicit conversion rule is defined. However, baseline and current values entered into the dashboard must both use its adopted 0–5 scale and the same assessment protocol. The available documentation does not establish that this KPI follows a specific LESTS scoring protocol.

**Data requirements.** Sources include feasibility studies, laboratory and pilot data, company process data, material and energy balances, feedstock analyses, quality specifications, infrastructure assessments, logistics data and production records. Technology Readiness Level assessments, permits, safety documentation and life cycle assessment inventories may provide additional supporting evidence where relevant.

The evidence supporting each score, the assessment date and the assumptions applied should be documented. Permits inform the conditions under which an exchange may operate but do not replace the separate assessment of legal feasibility and compliance.

**Decision-making relevance.** The indicator supports screening before investment, trials or long-term exchange agreements. It helps industrial actors identify technical constraints, compare

implementation options and determine whether adaptations, additional infrastructure or further testing are required.

Favourable direction and limitations. An increase is considered favourable when baseline and current values use the same scoring protocol and comparable assessment conditions. Scores depend on the quality of available evidence, assessor judgement and the application assessed. Changes in feedstock, receiving-process requirements or infrastructure may affect feasibility independently of improvements in the proposed exchange.

An overall score must not conceal a critical incompatibility or unresolved safety requirement. The score is not equivalent to a Technology Readiness Level and does not replace detailed engineering assessment. As an ordinal assessment, its percentage change should not be interpreted as a proportional increase in technical feasibility.

Sources identified in the compilation: Arauzo et al. (2019, 2022); European Commission (2014); Olszewski et al. (2019); Sommer (2020).

### 3.3.3. Interpretation and contribution to industrial decision-making

The technical KPIs support complementary stages of IS implementation. Technical Feasibility and Enabling Assets help identify whether an exchange can be implemented and what adaptations are required. Level of Technical Cooperation addresses the coordination needed to operate it. The remaining indicators help monitor resource flows, operational results and network development.

Several indicators are related but measure different concepts. Circularity Index describes the secondary share of material inputs, Resources Supply measures their quantity, and Recovery Rate concerns the recovered share of a generated residual stream. Resource Efficiency measures useful output relative to input, while Productivity relates output to workforce input. These distinctions prevent different aspects of performance from being interpreted as equivalent.

Technical improvements should also be considered alongside environmental, economic and social results. Increased secondary-material supply may require additional energy, while higher connectivity may introduce dependencies or coordination requirements.

The dashboard supports repeated comparison of consistently measured values. It does not calculate the underlying engineering or scoring assessments from raw data, establish the causes of change or determine whether a proposed exchange should proceed. Its contribution is to make selected developments visible and support identification of priorities for further investigation and action.

## 3.4. Economic and Business KPIs

Economic and business KPIs connect Industrial Symbiosis (IS) activities with investment decisions, operating costs, revenue generation and business development. They help industrial actors examine whether resource exchanges offer a financially credible proposition and how their economic performance changes during implementation.

The compiled material addresses both the financial outcomes of individual initiatives and the investment supporting circular economy development. Five thematic clusters structure this dimension: financial feasibility and investment performance; cost reduction and economic savings; resource valorisation and operational efficiency; business development, cooperation and competitiveness; and circular economy investment, innovation and employment enablers.

The final dashboard includes five KPIs representing these areas. Their combined use provides complementary information about investment attractiveness, material purchasing savings, by-product revenue, operating cost advantages and financial commitment to circular activities. They do not constitute a complete business case or capture every organisational and economic effect of IS.

### 3.4.1. Thematic coverage and selected indicators

Table 6 summarises the five clusters and their corresponding dashboard KPIs. The selected indicators provide focused measures within broader thematic areas; they do not measure every aspect covered by each cluster.

Table 6. Economic and business thematic clusters and selected dashboard KPIs

| CLUSTER | THEMATIC COVERAGE | SELECTED DASHBOARD KPI |
|---|---|---|
| CL1 – Financial Feasibility and Investment Performance | Investment requirements, financial returns and the attractiveness of IS initiatives. | Internal Rate of Return (IRR) |
| CL2 – Cost Reduction and Economic Savings | Purchasing and operating cost reductions associated with resource substitution and efficiency. | Cost Savings from Raw Material Purchase |
| CL3 – Resource Valorisation and Operational Efficiency | Economic value generated from by-products and secondary resource flows. | Revenue from By-product Sales |
| CL4 – Business Development, Cooperation, and Competitiveness | Business performance and advantages associated with participation in IS. | Increase in Business Competitiveness |
| CL5 – Circular Economy Investment, Innovation, and Employment Enablers | Financial commitment and enabling conditions supporting circular economy development. | Private sector investment in CE |

Source: LIAISE WGs (2026).

Consistent definitions are particularly important for this dimension. Revenue differs from profit, expenditure differs from financial return, and cost savings represent only one aspect of competitiveness. These distinctions guide the measurement specifications below.

### 3.4.2. Selected economic and business KPI specifications

INTERNAL RATE OF RETURN (IRR)

**Definition and measurement.** IRR is the discount rate at which the net present value of an investment's cash flows equals zero. It is obtained by solving:

$$0 = -I_0 + \sum_{t=1}^{T} \frac{CF_t}{(1+r)^t}$$

where:

($I_0$) is the initial investment outlay.

($CF_t$) is the net cash flow in period (t).

(T) is the assessment horizon.

(r) is the internal rate of return, expressed as a decimal in the equation.

The dashboard value is expressed as a percentage. Where periods are annual, the result represents an annual rate. Other investment outlays, operating costs, revenues and residual values must be included in the appropriate periods.

**Data requirements.** Inputs include the initial investment, expected or updated cash flows, their timing and the assessment horizon. Relevant sources include investment plans, financial models, supply agreements, cost estimates and revenue forecasts.

**Decision-making relevance.** IRR supports strategic assessment of investment attractiveness. Comparisons between baseline and current estimates can reveal how the investment outlook changes as costs, revenues or operational assumptions are updated.

**Favourable direction and limitations.** An increase is generally considered favourable for comparable assessments of the same investment. However, IRR does not measure the absolute value created or independently determine whether an investment should proceed.

Results depend on cash-flow assumptions and timing. Some cash-flow patterns may produce multiple IRRs or no meaningful IRR. Comparisons should therefore be supported by net present value, investment scale and risk assessment. Negative or zero baseline IRRs also require separate treatment when interpreting percentage changes through the dashboard.

**Source identified in the compilation:** Li et al. (2015).

COST SAVINGS FROM RAW MATERIAL PURCHASE ($CS_{RM}$)

**Definition and measurement.** This KPI measures the reduction in material purchasing costs associated with substituting virgin raw materials with secondary materials obtained through IS:

$$CS_{RM} = C_{reference} - C_{actual}$$

where ($C_{reference}$) is the estimated purchasing cost under conventional sourcing conditions and ($C_{actual}$) is the purchasing cost under the assessed sourcing arrangement. Both must relate to equivalent production requirements and the same reporting period.

The dashboard expresses the result in euros saved. The calculation boundary must specify whether purchasing costs include delivery and other acquisition charges. Additional treatment, storage or processing costs should be reported separately or included consistently if the indicator is explicitly defined as net material-sourcing savings.

The reference cost used to calculate savings is distinct from the dashboard baseline: the latter is the previously established savings value against which the current savings value is compared.

**Data requirements.** Sources include procurement records, supplier invoices, material quantities, production requirements and documented reference prices.

**Decision-making relevance.** The indicator supports assessment of the purchasing advantage associated with secondary material substitution and identification of sourcing opportunities.

**Favourable direction and limitations.** An increase is considered favourable. However, savings can change because of market prices, production volumes, material quality or sourcing conditions. A

decrease in savings does not necessarily indicate lower use of secondary materials. Equivalent quantities and specifications are essential for a meaningful reference comparison.

Source identified in the compilation: Mirata et al. (2024).

REVENUE FROM BY-PRODUCT SALES ($R_{BP}$)

**Definition and measurement.** This KPI measures gross revenue generated from by-product sales during the reporting year, expressed in euros/year:

$$R_{BP} = \sum_{i=1}^{n} Q_i P_i$$

where ($Q_i$) is the quantity of by-product (i) sold and ($P_i$) is its corresponding unit selling price. Where prices vary, transaction-level records or appropriately weighted prices should be used.

Processing, upgrading, transport and other costs are not deducted from this revenue indicator. A calculation deducting those costs represents a net contribution or margin and must be reported separately.

**Data requirements.** Sources include sales invoices, accounting records, contractual prices and by-product delivery records.

**Decision-making relevance.** The indicator makes the income generated through by-product valorisation visible and supports monitoring of market development and sales arrangements.

**Favourable direction and limitations.** An increase is considered favourable within the scope of revenue generation. However, increased revenue does not establish increased profitability: costs may rise at the same time. Revenue may also change because of prices rather than quantities sold.

Higher revenue should not become an incentive to generate more residual material where prevention is feasible. Results should therefore be considered alongside waste generation, resource efficiency and the costs of making by-products suitable for sale.

Sources identified in the compilation: Fraccascia et al. (2022); Kantor et al. (2019).

INCREASE IN BUSINESS COMPETITIVENESS (IBC)

**Definition and measurement.** For dashboard purposes, this KPI uses operating cost savings associated with IS as a proxy for cost-related competitiveness. It is expressed as a percentage of the defined reference operating cost:

$$IBC = \frac{C_{op,\,reference} - C_{op,\,IS}}{C_{op,\,reference}} \times 100$$

where ($C_{op,\,reference}$) is the operating cost of the reference arrangement and ($C_{op,\,IS}$) is the comparable operating cost under the assessed IS arrangement.

The calculation requires equivalent production or service requirements and consistent cost categories. Its reference cost must be positive. The resulting percentage is entered into the dashboard, which then calculates its relative change against the baseline percentage.

The indicator does not combine market share, profit margins and cost savings into a composite score. Those measures can provide complementary business information but require separate definitions and assessment methods.

Data requirements. Inputs include operating cost records and a documented reference scenario. Relevant categories may include material procurement, energy, waste management, logistics and additional costs associated with operating the exchange.

Decision-making relevance. The indicator supports assessment of whether IS contributes to a stronger operating cost position and helps identify areas where expected savings are being achieved or eroded.

Favourable direction and limitations. An increase is considered favourable. Nevertheless, cost advantage is only one component of competitiveness. Product quality, innovation, customer relationships, market position and supply reliability are not fully represented.

Attribution requires care because prices, production changes and unrelated efficiency measures can affect operating costs. Savings already reported through other KPIs must not be added again as independent benefits. Changes in the underlying reference scenario must also be documented.

Source identified in the compilation: Jacobsen (2006).

PRIVATE SECTOR INVESTMENT IN CE ($I_{CE}$)

Definition and measurement. This KPI measures private expenditure allocated to circular economy capital investment and research and development within the defined reporting period, expressed in euros:

$$I_{CE} = CAPEX_{CE} + RD_{CE,\ \text{not included in CAPEX}}$$

where ($CAPEX_{CE}$) is qualifying circular economy capital expenditure and the second term represents qualifying R&D expenditure not already included in that capital expenditure.

The calculation requires a documented definition of eligible circular economy activities. For mixed-purpose expenditure, only the justified circular economy share should be included. Actual expenditure must be distinguished from announced budgets or commitments.

The dashboard measures an expenditure amount rather than a percentage of total investment. An investment ratio may be calculated separately but is not interchangeable with the euro value.

Data requirements. Sources include capital expenditure records, project accounts, R&D expenditure records and documented allocation rules. Network assessments must avoid counting the same jointly financed expenditure more than once.

Decision-making relevance. The indicator supports monitoring of private financial commitment to circular infrastructure, technology development and related activities. It can inform discussions about implementation capacity and the development of IS initiatives.

Favourable direction and limitations. An increase is treated as favourable as an indication of greater financial commitment. It does not independently demonstrate effective implementation, financial returns or environmental improvement.

Investment is often uneven over time. Lower expenditure after completion of a major infrastructure project may reflect its investment cycle rather than weaker commitment. Results also depend on eligibility definitions, allocation methods and access to confidential financial information.

Source identified in the compilation: Hubs4Circularity, Deliverable 3.1 (2022).

### 3.4.3. Interpretation and contribution to industrial decision-making

The five KPIs provide complementary views of the economic and business aspects of IS. IRR addresses investment returns over an assessment horizon. Raw material purchasing savings and by-product revenue describe specific financial effects. The competitiveness indicator examines operating cost advantage, while private sector investment records expenditure supporting circular economy activities.

These values should not be added into a single economic benefit. Purchasing savings may already be included in operating cost savings and project cash flows, while by-product revenue may contribute to the same IRR calculation. Investment expenditure is an input to implementation rather than a financial benefit in itself.

Meaningful interpretation requires consistent reporting periods, currencies, price bases and assessment boundaries. Users should distinguish changes caused by quantities and operational performance from those caused by market prices or revised financial assumptions. Forecast values must also be distinguished from realised results.

The dashboard supports comparison of baseline and current KPI values and provides corresponding feedback. It does not construct the underlying business case, verify financial assumptions or establish that observed changes are caused exclusively by IS. Its results help identify developments requiring further analysis and support decisions on sourcing arrangements, exchange conditions, investment and operational improvement.

## 3.5. Cultural and Social KPIs

Cultural and Social KPIs address the relationships, perceptions and capabilities supporting IS, together with selected benefits for workers and communities. They complement technical, environmental and economic assessment by examining the human dimension of industrial cooperation.

The compiled material identifies trust, community acceptance, knowledge sharing, workforce skills and inclusive governance as relevant conditions for implementation (Domenech et al., 2021; Neves et al., 2020). These conditions can influence whether organisations establish partnerships, exchange information and sustain cooperation over time.

This dimension comprises five thematic clusters and five selected dashboard KPIs. The indicators cover community benefits, attitudes towards industry, workforce training, employment and cooperation. They provide focused measures of these areas rather than a complete assessment of social sustainability.

### 3.5.1. Thematic coverage and selected indicators

Table 7. Cultural and Social thematic clusters and selected dashboard KPIs

| CLUSTER | THEMATIC COVERAGE | SELECTED DASHBOARD KPI |
|---|---|---|
| CL1 – Social Capital | Cooperation, mutual support and relationships between participating organisations. | Social level of cooperation |
| CL2 – Cultural Capital | Community perceptions, acceptance and attitudes towards industrial activity. | Change in Community Attitude Toward Industry |
| CL3 – Employment Impact | Employment generated through participation in IS activities. | Jobs created via IS-network participation |
| CL4 – Community Inclusion and Governance | Connections between IS activities and benefits for surrounding communities. | % of IS Exchanges Benefiting Community |
| CL5 – Education and Capacity Building | Workforce participation in training relevant to IS implementation. | Workforce Trained in IS-Relevant Skills |

Source: LIAISE WGs (2026).

Several complementary measures appear in the underlying compilation, including counts of engagement activities, training sessions and stakeholder diversity. These provide additional information but are not equivalent to the selected dashboard KPIs. An engagement activity does not itself demonstrate a community benefit, a training session does not establish workforce coverage, and stakeholder diversity does not directly measure cooperation.

### 3.5.2. Selected cultural and social KPI specifications

<u>% OF IS EXCHANGES BENEFITING COMMUNITY (CB)</u>

Definition and measurement. This KPI measures the share of active IS exchanges explicitly identified as providing a community benefit within the assessment boundary and reporting period:

$$CB = \frac{N_{\text{exchanges, community benefit}}}{N_{\text{exchanges, total}}} \times 100$$

where ($N_{exchanges,community\ benefit}$) is the number of qualifying exchanges with a documented community benefit and ($N_{exchanges,total}$) is the total number of active IS exchanges assessed.

The assessment must define what constitutes a community benefit and the evidence required to substantiate it. Each exchange is counted once in the numerator, even where it provides several qualifying benefits. General claims of environmental improvement should not automatically be treated as evidence of a specific community benefit.

Data requirements. Inputs include an exchange register, documented benefit criteria and evidence linking qualifying exchanges with the identified benefits. Community feedback, monitoring records and agreements can support this assessment.

Decision-making relevance. The indicator helps users examine how extensively community benefits are represented across network activities and identify exchanges where those benefits could be strengthened or better documented.

**Favourable direction and limitations.** An increase is considered favourable. However, the indicator measures the proportion of qualifying exchanges, not the scale, distribution or duration of benefits. A small exchange and a large exchange receive equal weight. The percentage can also change because the total number of exchanges changes.

Counts of consultations, workshops or outreach events are complementary engagement measures and cannot replace the numerator. Where no active exchanges exist, the ratio is undefined.

**Reference context.** Lindfors et al. (2020)

CHANGE IN COMMUNITY ATTITUDE TOWARD INDUSTRY (CCA)

**Definition and measurement.** The dashboard compares the percentage of positive community responses recorded at baseline and in the current assessment. For each assessment period:

$$P_t = \frac{N_{\text{positive},\,t}}{N_{\text{valid},\,t}} \times 100$$

where ($N_{positive,\,t}$) is the number of responses classified as positive and ($N_{valid,\,t}$) is the total number of valid responses to the defined attitude question.

Although the KPI title refers to change, users enter the two positive-response percentages rather than a previously calculated change. The dashboard then calculates their relative variation:

$$CCA = \frac{P_{\text{current}} - P_{\text{baseline}}}{P_{\text{baseline}}} \times 100$$

The survey must define the question, response scale and classification of positive responses consistently.

**Data requirements.** Sources include community perception surveys, questionnaires and comparable public-opinion assessments. Sampling methods, respondent characteristics and survey timing should be documented.

**Decision-making relevance.** The indicator supports monitoring of community perceptions and identification of issues requiring dialogue, investigation or changes to engagement practices.

**Favourable direction and limitations.** An increase in positive responses is considered favourable. However, attitudes can be influenced by events unrelated to IS, including employment developments, environmental incidents and media coverage. Changes do not independently establish an IS-related effect.

Results depend on sampling quality, response rates and question wording. Relative percentage change must be distinguished from percentage-point difference. A zero baseline prevents the standard relative-change calculation; the percentage-point difference can be reported separately.

**Sources identified in the compilation:** Dragan et al. (2024); Fizaine et al. (2026).

WORKFORCE TRAINED IN IS-RELEVANT SKILLS (WT)

**Definition and measurement.** This KPI measures the percentage of a defined workforce or eligible participant group that has completed qualifying IS-relevant training:

$$WT = \frac{N_{\text{trained}}}{N_{\text{eligible}}} \times 100$$

where ($N_{trained}$) is the number of unique individuals meeting the training-completion criteria and ($N_{eligible}$) is the total number of individuals in the defined group.

The assessment must specify eligible training topics, completion requirements and whether the measure concerns training completed during the reporting period or the current workforce holding qualifying training. The same approach must be retained across assessments.

Data requirements. Sources include workforce records, attendance registers, learning management systems and training-completion documentation. Individuals completing several modules must not be counted repeatedly in the numerator.

Decision-making relevance. The indicator supports identification of training-coverage gaps and planning of capacity-building activities relevant to resource exchanges, monitoring and collaboration.

Favourable direction and limitations. An increase is considered favourable. Training completion does not independently demonstrate competence, retention or application of learning. Results should therefore be considered alongside assessment outcomes and evidence of workplace application where available.

Changes in workforce composition can affect the percentage independently of training delivery. Counts of sessions or participant attendances provide complementary information but do not measure the share of unique individuals trained.

Source identified in the compilation: Akyazi et al. (2023

JOBS CREATED VIA IS-NETWORK PARTICIPATION ($J_{IS}$)

Definition and measurement. This KPI measures employment created through IS activities and sustained within the defined assessment period, expressed in full-time equivalents (FTEs).

For each qualifying role or group of roles:

$$FTE_i = \frac{H_i}{H_{\text{full-time}}}$$

$$J_{\text{IS}} = \sum_i FTE_{i,\,\text{IS}}$$

where ($H_i$) represents qualifying working hours during the reporting period and ($H_{time}$) is the corresponding full-time working-hours basis. Only the documented IS-related share is included for roles partly allocated to IS activities.

The assessment must distinguish newly created employment from pre-existing positions reassigned to IS and specify whether it reports employment sustained during the period or new positions created within it. These reporting approaches must not be mixed.

**Data requirements.** Sources include employment and payroll records, working-time allocations, job descriptions and project-monitoring records linking the employment to IS activities.

**Decision-making relevance.** The indicator supports assessment of direct employment associated with resource recovery, shared infrastructure, logistics and other IS activities. It can inform workforce planning and discussion of local socio-economic benefits.

**Favourable direction and limitations.** An increase is considered favourable within the indicator's scope. Attribution requires evidence: participation in an IS network does not make every new job IS-related.

The measure does not independently capture job quality, remuneration, inclusion or employment displaced elsewhere. Shared posts must not be counted more than once across participating organisations. Annual and cumulative figures must also remain distinct.

**Source identified in the compilation:** De Gobbi (2026).

SOCIAL LEVEL OF COOPERATION (SLC)

**Definition and measurement.** This KPI assesses collaboration and mutual support among organisations participating in IS. Its scope concerns the social relationships supporting cooperation, including trust, willingness to share relevant information and constructive engagement with partners.

The dashboard expresses the result as a LESTS score. A documented social-axis scoring rubric must specify the scale, assessment criteria, evidence requirements and interpretation of each score. Where several sub-criteria or respondent assessments are combined, the aggregation method and any weights must also be stated.

A stakeholder-diversity index, including the Shannon index discussed in the compilation, measures a different concept and cannot be substituted for this cooperation score.

**Data requirements.** Sources may include structured partner questionnaires, interviews, facilitator assessments and documented examples of joint activities or mutual support. Consistent questions and assessment procedures are necessary for comparison.

**Decision-making relevance.** The indicator supports identification of relational barriers that can hinder information exchange, partnership development and continuity of cooperation. It complements the technical-cooperation indicator by focusing on social relationships rather than engineering interfaces or operational coordination.

**Favourable direction and limitations.** An increase is considered favourable. Scores are sensitive to respondent selection, assessor judgement and willingness to disclose difficulties. Network averages may conceal weak relationships affecting particular exchanges.

Where the scale is ordinal, a percentage increase in the score does not represent an equivalent proportional improvement in cooperation. The score should be interpreted alongside the supporting evidence and documented changes in relationships.

**Reference context.** Neves et al., 2019

### 3.5.3. Interpretation and contribution to industrial decision-making

The five KPIs provide complementary perspectives on the social dimension of IS. Social cooperation and workforce training describe enabling conditions, community attitudes capture perceptions, and the community-benefit and employment indicators address selected outcomes.

These measures should be interpreted together without assuming a direct causal relationship. Increased training coverage may strengthen implementation capacity but does not establish that cooperation has improved. Similarly, more exchanges with documented community benefits may coexist with concerns about particular industrial activities.

Quantitative results require contextual explanation. The distribution of benefits, quality of employment, relevance of training and influence of community feedback remain important even where they are not fully captured by the selected indicators. Qualitative evidence can help explain changes and identify appropriate responses.

The dashboard supports repeated comparison of consistently measured values and highlights developments requiring attention. It does not verify the quality of participation, establish causality or provide a complete assessment of community wellbeing. Its contribution is to make selected social conditions and outcomes visible within the wider IS decision-support framework.

## 3.6. Consolidated set of dashboard KPIs

The compilation and selection process resulted in a final set of 29 KPIs incorporated into the LIAISE Industrial Symbiosis dashboard. The set comprises eight Environmental KPIs, eleven Technical KPIs, five Economic and business KPIs, and five Cultural and Social KPIs.

Table 8 consolidates the measurement scope, input unit and favourable direction of change of each indicator. It provides a concise reference for selecting applicable KPIs and preparing the values entered into the dashboard. Definitions, calculation methods, data requirements and limitations are detailed in Sections 3.2–3.5.

Table 8. Consolidated set of dashboard KPIs: measurement scope, input units and favourable direction of change

| CATEGORY | KPI NAME | MEASUREMENT SCOPE | DASHBOARD INPUT UNIT | FAVOURABLE DIRECTION |
|---|---|---|---|---|
| Environmental | Climate change | Greenhouse gas emissions within the defined boundary, characterised using consistent global warming potential factors. | kg $CO_2$eq | Decrease |
| | Networking complexity | Weighted combination of network connectance and resource-flow diversity. | Index (0–100) | Increase |
| | Ecosystem quality | Modelled ecosystem damage expressed through the potentially disappeared fraction of species. | PDF·m²·year | Decrease |
| | Land occupation | Surface area occupied by the operations, storage and | m² | Decrease |

| | | | | |
|---|---|---|---|---|
| | | infrastructure included in the assessment. | | |
| | Gas emission | Emissions of a specified gaseous pollutant per tonne of production output. | kg/t output | Decrease |
| | Radiation emission | Radium equivalent activity calculated from Ra-226, Th-232 and K-40 activity concentrations in the assessed material. | Bq/kg | Decrease |
| | Total waste sent to landfill | Mass of waste directed to landfill within the defined boundary and reporting year. | t/year | Decrease |
| | Water discharged | Effluent volume discharged into natural receiving environments within the reporting year. | m³/year | Decrease |
| Technical | Energy Cascading Index | Useful, recovered waste heat reused relative to technically recoverable heat. | Index (0–1) | Increase |
| | Circularity Index (System Level) | Secondary material inputs as a share of total material inputs within the defined system. | % | Increase |
| | Enabling Assets | Required enabling assets that are available and operational as a share of all required assets. | % | Increase |
| | Energy Consumption | Total energy consumed within the defined operational boundary and reporting year. | MWh/year | Decrease |
| | Resource Efficiency | Saleable product output per unit of material resource input consumed. | t/t input | Increase |
| | Level of Technical Cooperation | Technical coordination and joint working arrangements supporting symbiotic exchanges. | LESTS score (0–5) | Increase |
| | Resources Supply | Secondary material resources supplied and integrated into productive use during the reporting year. | t/year | Increase |
| | Productivity | Production output per worker over a defined reporting period. | t/worker | Increase |
| | Recovery Rate | Share of a defined generated waste or by-product stream recovered through IS for useful material application. | % | Increase |
| | Symbiotic Link Density | Active directed symbiotic links relative to potential directed | Ratio (0–1) | Increase |

| | | | | |
|---|---|---|---|---|
| | | links between participating organisations. | | |
| | Technical Feasibility | Assessment of whether an exchange can operate under the specified technical and industrial conditions. | Score (0–5) | Increase |
| Economic and business | Internal Rate of Return (IRR) | Discount rate at which the net present value of the investment's cash flows equals zero. | % | Increase |
| | Cost Savings from Raw Material Purchase | Difference between reference and actual material purchasing costs for equivalent production requirements. | € saved | Increase |
| | Revenue from By-product Sales | Gross revenue generated from by-product sales during the reporting year. | €/year | Increase |
| | Increase in Business Competitiveness | Operating cost savings relative to a defined reference operating cost, used as a proxy for cost-related competitiveness. | % cost saving | Increase |
| | Private sector investment in CE | Qualifying private circular economy capital and R&D expenditure, excluding double counting. | € invested | Increase |
| Cultural and Social | % of IS Exchanges Benefiting Community | Share of active IS exchanges meeting documented community-benefit criteria. | % | Increase |
| | Change in Community Attitude Toward Industry | Positive community responses to a consistently defined attitude question. The dashboard calculates change between assessment values. | % positive responses | Increase |
| | Workforce Trained in IS-Relevant Skills | Unique individuals completing qualifying training as a share of the defined workforce or eligible group. | % trained | Increase |
| | Jobs created via IS-network participation | Direct IS-related employment measured using a consistent reporting basis. | FTEs | Increase |
| | Social level of cooperation | Social cooperation and mutual support among participating organisations, assessed using a documented rubric. | LESTS score | Increase |

Source: LIAISE WGs (2026).

The input units describe the underlying KPI values, rather than the percentage variation calculated by the dashboard. Users enter a baseline and a current value in the same unit, using consistent definitions, calculation methods and assessment boundaries. For percentage-based KPIs, the application calculates relative percentage change rather than percentage-point difference.

The favourable direction indicates how the dashboard interprets change within each indicator's defined scope. It does not establish an absolute performance target or imply that continued increases or decreases are always desirable. Network complexity, investment and employment, for example, require interpretation alongside their effectiveness, context and associated outcomes.

The consolidated set combines performance outcomes with enabling conditions. It allows users to select indicators relevant to their activities while retaining a view of the relationships between environmental, technical, economic and social developments. Related indicators should be interpreted together without adding overlapping results or treating them as independent evidence of the same benefit.

The following section presents the dashboard interface and practical application of these indicators, including data entry, calculation and interpretation of feedback.

# 4. Dashboard functionality and practical application

The LIAISE KPI dashboard translates the indicator framework presented in Section 3 into a web-based tool for monitoring changes in Industrial Symbiosis (IS) performance. It enables users to compare baseline and current values for selected KPIs and receive feedback reflecting the direction and magnitude of change.

This section explains how to access and navigate the dashboard, select relevant indicators, prepare input values and interpret the results. Illustrative examples demonstrate its use, while practical guidance explains how the information generated can support investigation, improvement actions and subsequent monitoring.

The dashboard calculates changes between KPI values supplied by users. The underlying measurements and assessments must therefore be completed using the definitions and methods described in Section 3.

## 4.1. Dashboard overview and access

The dashboard is available through the LIAISE COST Action website: https://www.liaise-action.eu/dashboard/

It is primarily intended for industrial actors implementing or participating in IS initiatives. Depending on the KPI selected, users may assess an individual company, a resource exchange or an industrial network.

The application is organised as a single web page containing 29 KPI cards across four categories: Environmental, Technical, Economic and business, and Cultural and Social. Dynamic category filters allow users to focus on a particular dimension and locate relevant indicators.

Each card provides the elements needed to undertake a comparison:

- KPI name, brief description and measurement unit, identifying what the indicator measures.
- "Baseline" and "Current value" fields, for entering the reference value and the value being assessed.
- "+Info" button, opening detailed indicator information in a pop-up window on the same page.
- Calculation button, generating the percentage change and its associated feedback.

The interface combines concise information for routine use with access to more detailed explanations. Users can consult the indicator information before entering data and repeat calculations as updated values become available.

[Screenshot of the dashboard overview, showing the category filters and representative KPI cards.]

Figure 2. Overview of the LIAISE KPI dashboard interface and category filters. Source: LIAISE KPI dashboard.

Users do not need to apply all 29 KPIs in every assessment. The appropriate selection depends on the activities examined, the decisions to be informed and the availability of suitable data. Category filters facilitate navigation; they do not establish a weighting or priority among dimensions.

The dashboard presents results for individual indicators rather than an aggregated performance score. Its practical value lies in helping users recognise developments, identify questions requiring

further analysis and monitor changes following action. The next subsection explains how to select applicable KPIs and prepare comparable input values.

## 4.2. KPI selection and data preparation

The first step in using the dashboard is to select indicators relevant to the activities and decisions being assessed. Users should consider the resource exchanges involved, the stage of implementation and the availability of suitable data. Applying a focused selection consistently can provide more useful information than completing indicators for which reliable values are unavailable.

### Selecting applicable indicators

Users can browse the four categories and consult the "+Info" content to understand each KPI's scope, measurement unit and interpretation. Section 3 provides the corresponding measurement specifications and limitations.

Selection should reflect the assessment level. Company-level indicators require data for the defined facility or organisation, while network indicators require coordinated information from participating actors. For example, Symbiotic Link Density cannot be assessed from one company's records alone unless those records cover the entire network being examined.

Where relevant, users should select complementary indicators across dimensions. Assessing material exchange through recovery, energy consumption and financial results can help reveal developments that would remain unclear from a single measure. Indicators that are not applicable or lack adequate data should be identified as such rather than assigned an assumed value.

### Preparing baseline and current values

Before entering data, users should calculate or obtain the underlying KPI values using the methods described in Section 3. The dashboard compares these values; it does not derive them from raw operational records.

The baseline is the documented reference value against which the current assessment is compared. It may represent a pre-implementation condition or an earlier reporting period. A fixed baseline supports monitoring of cumulative change, while a periodically updated baseline supports comparisons between successive periods. Users should retain a clear record of the approach adopted.

For each selected KPI, the following information should be established:

Table 9. Data preparation requirements for comparable KPI assessments

| PREPARATION ELEMENT | INFORMATION TO STABLISH |
|---|---|
| Assessment boundary | Facility, organisation, exchange or network covered, including relevant exclusions. |
| Measurement method | Formula, assessment model or scoring rubric used to obtain the KPI value. |
| Unit | The unit specified for the dashboard card, applied consistently to both inputs. |
| Reference periods | Dates or periods represented by the baseline and current values. |
| Data sources | Records, measurements or assessments supporting each value. |

| | |
|---|---|
| Comparability | Changes in production, network membership, methods or other conditions affecting interpretation. |
| Data quality | Estimates, missing information and uncertainties relevant to the result. |

Source: LIAISE WGs (2026).

#### Ensuring comparability

Baseline and current values must represent the same concept and use consistent calculation methods and boundaries. Annual quantities should cover comparable periods. Financial values should use a consistent currency and price basis, and survey or scoring indicators should use the same questions, criteria and assessment procedures.

For percentage-based KPIs, users enter the percentage values themselves. For example, if the share of trained workers rises from 40% to 50%, the inputs are 40 and 50. The dashboard then calculates the relative increase of 25%; users should not enter the 10-percentage-point difference as the current value.

Changes in activity levels should also be documented. An increase in total energy consumption may accompany increased production, while a change in network membership may alter link density without any existing exchange being discontinued. Such information is necessary to interpret the feedback appropriately.

#### Handling missing or unsuitable values

Missing information must not be entered as zero. A zero is a measured or calculated value and has a different meaning from unavailable data. Likewise, qualitative scores should only be entered where the relevant scoring procedure has been applied.

The standard percentage-change calculation requires a non-zero baseline. Zero or negative baselines require specific treatment, as discussed in Section 2.2.7, and should not be interpreted automatically through the standard feedback bands. Very small positive baselines also warrant attention because they can produce large relative changes from small absolute differences.

Once comparable values have been prepared, users can enter them into the selected KPI card and generate the result. Retaining the supporting data and assessment assumptions allows subsequent calculations to form a consistent monitoring record.

## 4.3. Using the KPI cards

Once the relevant indicators and comparable input values have been prepared, users can perform an assessment through the corresponding KPI cards. The same interaction sequence applies across the four dashboard categories.

#### Step 1 – Locate the KPI

Use the category filters to locate the selected indicator. Check its name, brief description and measurement unit to confirm that it corresponds to the values prepared.

#### Step 2 – Consult the detailed information

Select “+Info” to open the indicator’s detailed explanation in a pop-up window on the same page. Review the measurement scope and interpretation before proceeding, particularly where the input requires a prior calculation or a structured assessment score.

[Screenshot of a KPI information pop-up.]

Figure 3. Detailed KPI information accessed through the "+Info" function. Source: LIAISE KPI dashboard.

### Step 3 – Enter the baseline and current values

Enter the reference value in the "Baseline" field and the value being assessed in the "Current value" field. Both must use the unit displayed on the card and follow the same measurement approach.

For example, when assessing Total waste sent to landfill, a baseline of 100 tonnes/year and a current value of 80 tonnes/year are entered as 100 and 80, respectively. The user enters the underlying quantities, rather than their difference or a previously calculated percentage change.

### Step 4 – Run the calculation

Select the calculation button to obtain the relative percentage change and the associated feedback. In the example above, the change is −20%. Since a decrease in waste sent to landfill is considered favourable, this result corresponds to improvement band 3.

### Step 5 – Read the result and feedback together

Interpret the percentage change according to the selected KPI's favourable direction. A negative result can represent improvement for an indicator intended to decrease, while a positive result can represent deterioration.

The feedback provides an indicator-specific explanation of the calculated change. It should be considered alongside the underlying values and operating conditions. It does not establish why the change occurred or whether an absolute performance target has been achieved.

[Screenshot of a completed KPI card showing the input values, calculated change and feedback.]

Figure 4. Example of a completed KPI assessment and associated feedback. Source: LIAISE KPI dashboard; illustrative input values.

### Step 6 – Record and repeat the assessment

Retain the input values, result, assessment date and relevant contextual notes in the organisation's monitoring records. This supports traceability and comparison with subsequent assessments.

Calculations can be repeated for other applicable KPIs or when new values become available. If the baseline is updated, document the change so that successive results remain interpretable.

The following subsection presents illustrative examples of favourable change, unfavourable change and unchanged performance.

## 4.4. Illustrative examples of results and feedback

The following examples illustrate how the dashboard interprets changes according to each KPI's favourable direction. All input values are hypothetical and do not represent observations from participating companies or validation results.

Table 10. Illustrative KPI comparisons and corresponding result categories

| KPI | UNIT | BASELINE | CURRENT VALUE | PERCENTAGE CHANGE | INTERPRETATION |
|---|---|---|---|---|---|
| Revenue from By-product Sales | €/year | 10,000 | 12,000 | +20% | Favourable increase: improvement band 3. |
| Total waste sent to landfill | t/year | 100 | 80 | −20% | Favourable decrease: improvement band 3. |
| Energy Consumption | MWh/year | 500 | 550 | +10% | Unfavourable change. |
| Workforce Trained in IS-Relevant Skills | % trained | 60 | 60 | 0% | No change. |

Source: LIAISE WGs (2026), illustrative calculations.

### Example 1 – Favourable increase in by-product revenue

Annual revenue from by-product sales increases from €10,000 to €12,000. The relative change is +20%, placing the result in improvement band 3, which covers favourable changes greater than 15% and up to 25%.

The associated feedback highlights increased economic valorisation of by-products. Further analysis should distinguish whether this development reflects larger quantities sold, higher prices or both. Processing and delivery costs should also be examined before concluding that profitability has improved.

### Example 2 – Favourable decrease in waste sent to landfill

Annual waste sent to landfill decreases from 100 to 80 tonnes. The calculated change is −20%. Since a decrease is favourable for this KPI, the result also falls within improvement band 3.

The feedback recognises reduced reliance on landfill disposal. Users should investigate the destination of the diverted material and whether the reduction reflects prevention, useful recovery through IS or another change in waste management. Production levels should also be considered.

### Example 3 – Unfavourable increase in energy consumption

Annual energy consumption increases from 500 to 550 MWh, producing a relative change of +10%. Since the favourable direction is a decrease, the result receives the unfavourable-change feedback.

This result prompts investigation rather than establishing that operational efficiency has deteriorated. Users should examine production volumes, product mix, operating hours and any additional treatment or recovery activities. Comparison with energy consumption per unit of output can help explain the development.

### Example 4 – No change in workforce training coverage

The share of the workforce completing qualifying IS-relevant training remains at 60%. The calculated change is zero, and the dashboard returns the no-change feedback.

This indicates unchanged coverage, but not necessarily an absence of training activity. New employees may have joined, trained employees may have left, or further training may have been provided to individuals already counted. Reviewing workforce composition and outstanding skills needs helps determine whether additional action is appropriate.

### Reading the examples together

The examples demonstrate that the sign of the percentage change does not determine whether a result is favourable. A +20% change in revenue and a −20% change in landfill disposal both represent favourable developments within their respective measurement scopes.

The feedback bands describe relative change rather than absolute performance. The examples therefore support interpretation of individual results without establishing that targets have been achieved or that the overall IS initiative has improved. Decisions require consideration of the underlying values, contextual information and related KPIs, as discussed in Section 4.5.

## 4.5. From dashboard results to industrial actions

Dashboard results provide a starting point for investigating performance and identifying appropriate actions. Their practical value depends on connecting the calculated changes with operational evidence, business priorities and the perspectives of the actors involved.

The following steps outline how industrial actors can incorporate the results into a monitoring and improvement process.

### Review the result and its context

First, check that the input values are correct and comparable. Examine both the relative change and the underlying absolute values, considering changes in production, prices, network membership or other relevant conditions.

An unfavourable result warrants investigation but does not automatically establish a need to reverse an activity. Similarly, a favourable result should be examined before attributing it to a particular intervention. Unchanged performance may indicate stability, limited progress or maintenance of an already high level.

### Investigate the factors influencing change

Use supporting records and discussions with relevant staff or partners to explore possible explanations. These may include process settings, equipment availability, material quality, exchange schedules, market conditions or cooperation arrangements.

For example, reduced raw material savings may reflect higher secondary-material prices, additional preparation costs or lower substitution volumes. Each explanation suggests a different response. The dashboard identifies the development; further analysis establishes which factors can be addressed.

### Consider related indicators and trade-offs

Review complementary KPIs before selecting an action. Increased recovery may require additional energy, while a new exchange may generate revenue but introduce infrastructure costs or supply dependencies. Improvements should therefore be considered across the relevant environmental, technical, economic and social dimensions.

The magnitude of percentage change alone should not determine priority. Decisions should also consider absolute impacts, operational importance, risks, feasibility and the resources available for action.

### Define and implement proportionate actions

Where investigation identifies an opportunity or problem, translate it into a specific action with an assigned responsibility, timetable and expected outcome. Actions may concern individual processes or require agreement between exchange partners.

Table 11 provides illustrative connections between dashboard findings and possible responses. These are options for consideration rather than automatic recommendations.

Table 11. Illustrative links between KPI findings, further investigation and potential industrial actions

| KPI findings | Questions for further investigation | Potential action |
|---|---|---|
| Reduced Energy Cascading Index | Have heat availability, temperature compatibility or operating schedules changed? | Review heat-exchanger performance and coordinate supply and demand schedules. |
| Increased waste sent to landfill | Which streams account for the increase, and have receiving requirements or recovery arrangements changed? | Investigate quality issues and suitable prevention or recovery routes with partners. |
| Reduced raw material purchasing savings | Have prices, quantities, substitution rates or acquisition costs changed? | Review sourcing conditions and the technical and financial suitability of substitution options. |
| Reduced technical cooperation score | Which coordination arrangements or technical interfaces are causing difficulties? | Agree responsibilities, information-sharing procedures and joint monitoring arrangements. |
| Reduced positive community attitudes | Which concerns are reported, and are survey results comparable? | Discuss concerns with community representatives and agree appropriate follow-up measures. |
| Unchanged workforce training coverage | Are priority roles still untrained, or has workforce turnover offset training delivery? | Target identified skills gaps and review completion and workplace application. |

Source: LIAISE WGs (2026), illustrative guidance.

### Monitor subsequent developments

After implementation, repeat the relevant KPI assessments at an appropriate interval using consistent methods. Retain the results alongside records of actions taken and contextual changes.

Where a fixed baseline is used, subsequent calculations show cumulative development against that reference. Comparisons between successive periods can additionally help assess recent changes. Neither approach independently establishes causality, but both can support a better-informed review of whether actions are associated with the expected outcomes.

Embedding this process in routine management reviews allows the dashboard to support ongoing improvement. Responsibilities for data collection, interpretation and follow-up should be clear, particularly where indicators depend on information shared across organisations.

# 5. Conclusions and recommendations

Deliverable D3.3 brings together a multidisciplinary KPI framework and an implemented web-based dashboard to support industrial actors in monitoring IS performance and identifying priorities for action. Developed through contributions from the four LIAISE Working Groups, it connects indicator compilation and assessment knowledge with a practical tool for comparing values and interpreting changes.

The collaborative process required harmonisation of terminology, indicator definitions and assessment approaches across disciplines and industrial contexts. The initial collection of 369 candidate entries was reduced to 329 indicators following duplicate removal. Quantitative expert evaluation produced a shortlist of 78 KPIs, followed by qualitative review and consortium agreement on the final 29. The resulting set comprises eight Environmental, eleven Technical, five Economic and Business, and five Cultural and Social KPIs.

The framework recognises that IS performance depends on both outcomes and enabling conditions. Resource recovery, environmental pressures and financial results need to be considered alongside infrastructure availability, technical feasibility, cooperation and workforce capabilities. The selected indicators provide complementary perspectives on these relationships rather than interchangeable measures of overall success.

The dashboard makes the framework accessible through 29 KPI cards, category filters, detailed indicator information and baseline-to-current comparisons. Its feedback combines the literature-informed favourable direction of each KPI with bands describing the magnitude of relative change. This supports recognition of progress and identification of developments requiring investigation or corrective action. The bands do not establish universal performance targets, and favourable change does not independently demonstrate sufficient absolute performance or overall sustainability.

Application should reflect the contribution and limitations of each dimension:

- Environmental KPIs should support examination of greenhouse gas emissions, waste disposal, water discharge and other relevant pressures or impacts. Consistent assessment boundaries and complementary information are essential to identify potential burden shifting and distinguish reduced quantities from improved environmental outcomes.
- Technical KPIs should inform assessment of feasibility, infrastructure readiness, resource efficiency, recovery, energy use and cooperation arrangements. Their use can help identify implementation constraints and operational improvement opportunities, while recognising that greater connectivity or resource circulation does not automatically establish better overall performance.
- Economic and business KPIs should support investment appraisal and monitoring of purchasing savings, by-product revenue and operating cost advantages. Users should distinguish revenue from profit, expenditure from returns, and forecast results from realised outcomes, avoiding double counting of related financial effects.
- Cultural and Social KPIs should make community benefits, perceptions, training coverage, employment and cooperation visible within IS monitoring. Quantitative results should be complemented by evidence concerning the quality of relationships, learning outcomes, employment conditions and the distribution of benefits.

Effective use depends on reliable data and consistent measurement. Users must establish appropriate boundaries, apply documented calculation methods and retain comparable reporting periods and units. Small, zero or negative baselines, bounded indicators and ordinal scores require particular attention. Contextual information remains necessary to distinguish operational developments from changes in production, prices, network composition or assessment practices.

The selection also has methodological limitations. Expert evaluation and qualitative review provide a structured basis for prioritisation, but do not establish universal applicability or exhaustive coverage. Differences in data availability, scoring practices and industrial conditions may affect comparability. The 29 KPIs should therefore be treated as a common starting point, with additional indicators used where specific activities require more detailed assessment.

To strengthen practical application and further development, the following recommendations are proposed:

- Establish traceable monitoring practices. Assign responsibilities for data collection and review, document baseline choices and retain source records, calculation methods and contextual explanations.
- Interpret complementary indicators together. Examine relevant results across the four dimensions before acting, recognising trade-offs and overlaps between measures.
- Connect findings with follow-up actions. Investigate the factors behind changes, assign proportionate responses and repeat assessments to monitor subsequent developments.
- Undertake documented application and validation in industrial settings. Assess data requirements, calculation and feedback consistency, usability and decision-making relevance through company, exchange and network cases. This would provide evidence beyond the illustrative examples presented in the report.
- Refine the framework through practical feedback. Review definitions, scoring procedures, calculation conventions and feedback messages as experience becomes available, maintaining consistency between the report, supporting documentation and dashboard.

D3.3 establishes a basis for more structured performance monitoring within IS implementation. Its continued value will depend on consistent application, transparent interpretation and the use of results to inform collaboration and improvement.

## 6. References

Akyazi, T., Goti, A., Bayón, F., Kohlgrüber, M., & Schröder, A. (2023). Identifying the skills requirements related to industrial symbiosis and energy efficiency for the European process industry. Environmental Sciences Europe, 35, 54. https://doi.org/10.1186/s12302-023-00762-z

Albino, V., Fraccascia, L., & Giannoccaro, I. (2015). Measuring complexity of industrial symbiosis networks. In Proceedings of the 10th IFKAD Conference.

Albino, V., Fraccascia, L., & Yazan, D. M. (2026). Performance measures of industrial symbiosis with inventory. International Journal of Production Economics, 294, Article 109766. https://doi.org/10.1016/j.ijpe.2025.109766

Arauzo, P. J., Du, L., Olszewski, M. P., Meza Zavala, M. F., Alhnidi, M. J., & Kruse, A. (2019). Effect of Protein during Hydrothermal Carbonization of Brewer's Spent Grain. Bioresour. Technol., 293, 122117. https://doi.org/10.1016/j.biortech.2019.122117

Arauzo, P. J., Maziarka, P. A., Schoder, K. A., Pfersich, J., Ronsse, F., & Kruse, A. (2022). Influence of Sequential HTC Pre-Treatment and Pyrolysis on Wet Food-Industry Wastes: Optimisation toward Nitrogen-Rich Hierarchical Carbonaceous Materials Intended for Use in Energy Storage Solutions. Sci. Total Environ., 816, 151648. https://doi.org/10.1016/j.scitotenv.2021.151648

Barrau, E., & Glaus, M. (2023). Structural and environmental performance of evolving industrial symbiosis: A multidimensional analysis. Sustainability, 15(1), 693. https://doi.org/10.3390/su15010693

Branca, T. A., Fornai, B., Colla, V., Pistelli, M. I., Faraci, E. L., Cirilli, F., & Schröder, A. J. (2021). Industrial Symbiosis and Energy Efficiency in European Process Industries: A Review. Sustainability, 13(16), 9159. https://doi.org/10.3390/su13169159

Boubel, R. W., Vallero, D. A., Fox, D. L., Turner, D. B., & Stern, A. C. (2013). Fundamentals of Air Pollution (5th ed.). Elsevier.

Cervo, H., Ogé, S., Maqbool, A.S., Mendez Alva, F., Lessard, L., Bredimas, A., Ferrasse, J.-H., & Van Eetvelde, G. (2019). A Case Study of Industrial Symbiosis in the Humber Region Using the EPOS Methodology. Sustainability, 11(24), 6940. https://doi.org/10.3390/su11246940

Chen, X., Dong, M., Zhang, L., Luan, X., Cui, X., & Cui, Z. (2022). Comprehensive evaluation of environmental and economic benefits of industrial symbiosis in industrial parks. Journal of Cleaner Production, 354, 131635. https://doi.org/10.1016/j.jclepro.2022.131635

Chertow, M. R. (2000). Industrial symbiosis: Literature and taxonomy. Annual Review of Energy and the Environment, 25, 313–337. https://doi.org/10.1146/annurev.energy.25.1.313

Chertow, M. R. (2007). "Uncovering" industrial symbiosis. Journal of Industrial Ecology, 11(1), 11–30.

Chopra, S. S., & Khanna, V. (2014). Understanding resilience in industrial symbiosis networks: Insights from network analysis. Journal of Environmental Management, 141, 86–94. https://doi.org/10.1016/j.jenvman.2013.12.038

De Gobbi, M. S. (2026). Employment creation through industrial symbiosis: Quantity and quality of jobs in selected developing countries. Circular Economy and Sustainability, 6, Article 22. https://doi.org/10.1007/s43615-026-00780-y

Dincer, I., & Rosen, M. A. (2013). Exergy: Energy, environment and sustainable development (2nd ed.). Elsevier.

Domenech, T., Bleischwitz, R., Doranova, A., Panayotopoulos, D., & Roman, L. (2021). Mapping industrial symbiosis development in Europe: Typologies of networks, characteristics, performance and contribution to the circular economy. Resources, Conservation and Recycling, 141, 76–98. https://doi.org/10.3390/su13137123

Dragan, G. B., Ben Arfi, W., Tiberius, V., Ammari, A., & Ferasso, M. (2024). Acceptance of circular entrepreneurship: Employees' perceptions on organizations' transition to the circular economy. Journal of Business Research, 172, 114461. https://doi.org/10.1016/j.jbusres.2023.114461

Ellen MacArthur Foundation & Granta Design (2015). Circularity Indicators: An Approach to Measuring Circularity—Methodology. Ellen MacArthur Foundation. https://www.ellenmacarthurfoundation.org/material-circularity-indicator

Ehrenfeld, J. (2004). Industrial ecology: A new field or only a metaphor? Journal of Cleaner Production, 12(8–10), 825–831.

Erhart, S., & Erhart, K. (2023). Environmental ranking of European industrial facilities by toxicity and global warming potentials. Scientific Reports, 13(1), 1772.

European Commission (2014). Horizon 2020 Work Programme 2014–2015. General Annex G: Technology Readiness Levels. European Commission: Brussels. https://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf

Felicio, M., Amaral, D., Esposto, K., & Gabarrell Durany, X. (2016). Industrial symbiosis indicators to manage eco-industrial parks as dynamic systems. Journal of Cleaner Production, 118, 54–64. https://doi.org/10.1016/j.jclepro.2016.01.031

Fizaine, F., Le Borgne, G., & Chatel, G. (2026). Between refuse and recycle: Asymmetric polarization in circular economy representations. Journal of Cleaner Production, 571, 148801. https://doi.org/10.1016/j.jclepro.2026.148801

Forman, C., Muritala, I. K., Pardemann, R., & Meyer, B. (2016). Estimating the Global Waste Heat Potential. Renewable and Sustainable Energy Reviews, 57, 1568-1579. https://doi.org/10.1016/j.rser.2015.12.192.

Fraccascia, L., Albino, V., & Garavelli, C. A. (2017). Technical efficiency measures of industrial symbiosis networks using enterprise input–output analysis. International Journal of Production Economics, 183(A), 273–286. https://doi.org/10.1016/j.ijpe.2016.11.003

Fraccascia, L., Giannoccaro, I., & Albino, V. (2021). Ecosystem indicators for measuring industrial symbiosis. Ecological Economics, 183, 106944. https://doi.org/10.1016/j.ecolecon.2021.106944

Fraccascia, L., Giannoccaro, I., & Albino, V. (2022). Business models for industrial symbiosis: A taxonomy based on the reuse of waste and by-products. Journal of Cleaner Production, 345, 131100

Global Reporting Initiative. (2018). GRI 303: Water and effluents 2018. https://globalreporting.org/pdf.ashx?id=12488

Goedkoop, M., & Spriensma, R. (2000). The Eco-indicator 99: A damage oriented method for life cycle impact assessment: Methodology annex. PRé Consultants B.V.

Habib, M. A., Basuki, T., Miyashita, S., Bekelesi, W., Nakashima, S., Techato, K., & Phoungthong, K. (2019). Assessment of natural radioactivity in coals and coal combustion residues from a coal-based thermoelectric plant in Bangladesh. Environmental Monitoring and Assessment, 191(1), 27.

Hu, W., Tian, J., Li, X., & Chen, L. (2020). Wastewater treatment system optimization with an industrial symbiosis model: A case study of a Chinese eco-industrial park. Journal of Industrial Ecology, 24(6), 1338–1351. https://doi.org/10.1111/jiec.13032

Hubs4Circularity. (2022). Deliverable 3.1. Key Performance Indicators for H4C Available at: https://cordis.europa.eu/project/id/101058416/results. Access date: 14.05.2026

ISO (2006). ISO 14044:2006 Environmental Management—Life Cycle Assessment—Requirements and Guidelines; International Organization for Standardization: Geneva

ISO (2024). ISO 59020:2024 Circular Economy—Measuring and Assessing Circularity Performance; International Organization for Standardization: Geneva.

Jacobsen, N. B. (2006). Industrial symbiosis in Kalundborg, Denmark: A quantitative assessment of economic and environmental aspects. Journal of Industrial Ecology, 10(1–2), 239–255.

Janz, N., Lööf, H. & Peters, B. (2003). Firm Level Innovation and Productivity - is There a Common Story Across Countries? ZEW Discussion Paper No. 03-26. http://dx.doi.org/10.2139/ssrn.416444

Jensen, P. D., Basson, L., Hellawell, E. E., & Leach, M. (2011). Quantifying geographic proximity: Experiences from the United Kingdom's National Industrial Symbiosis Programme. Resources, Conservation and Recycling, 55(7), 703–712.

Jolliet, O., Margni, M., Charles, R., Humbert, S., Payet, J., Rebitzer, G., & Rosenbaum, R. (2003). IMPACT 2002+: A new life cycle impact assessment methodology. International Journal of Life Cycle Assessment, 8, 324–330. https://doi.org/10.1007/BF02978505

Kantor, I., Bütün, H., Robineau, J.-L., Maqbool, S., Zwaenepoel, B., Norbert, R., Arias, S., Cervo, H., Wolf, F., & Santecchia, A. (2019). Long- and short-lists of key performance indicators in industry and for industrial symbiosis. Authorea. https://doi.org/10.22541/au.155326167.77536381

Kemp, I. C. (2007). Pinch analysis and process integration: A user guide on process integration for the efficient use of energy (2nd ed.). Butterworth-Heinemann.

Kumar, P. S., & Yaashikaa, P. R. (2019). Introduction—Water. In S. S. Muthu (Ed.), Water in textiles and fashion (pp. 1–20). Woodhead Publishing. https://doi.org/10.1016/B978-0-08-102633-5.00001-4

Li, W., Cui, Z., & Han, F. (2015). Methods for assessing the energy-saving efficiency of industrial symbiosis in industrial parks. Environmental Science and Pollution Research, 22(1), 275-285.

Li, Y., & Shi, L. (2015). The resilience of interdependent industrial symbiosis networks: A case of Yixing Economic and Technological Development Zone. Journal of Industrial Ecology, 19, 264–273. https://doi.org/10.1111/jiec.12267

Lindfors, A., Gustafsson, M., Anderberg, S., Eklund, M., & Mirata, M. (2020). Developing biogas systems in Norrköping, Sweden: An industrial symbiosis intervention. Journal of Cleaner Production, 277, 122822. https://doi.org/10.1016/j.jclepro.2020.122822

Linnhoff, B., & Hindmarsh, E. (1983). The pinch design method for heat exchanger networks. Chemical Engineering Science, 38(5), 745–763. https://doi.org/10.1016/0009-2509(83)80185-7

Lombardi, D. R., & Laybourn, P. (2012). Redefining industrial symbiosis: Crossing academic–practitioner boundaries. Journal of Industrial Ecology, 16(1), 28–37.

Lyons, D. I. (2007). A spatial analysis of loop closing among recycling, remanufacturing, and waste treatment firms in Texas. Journal of Industrial Ecology, 11(1), 43–54. https://doi.org/10.1162/jiec.2007.1029

Maqbool, A.S., Piccolo, G.E., Zwaenepoel, B., & Van Eetvelde, G. (2017). A Heuristic Approach to Cultivate Symbiosis in Industrial Clusters Led by Process Industry. In Campana, G., Howlett, R., Setchi, R., & Cimatti, B. (eds) Sustainable Design and Manufacturing. Smart Innovation, Systems and Technologies, vol 68. Springer, Cham. https://doi.org/10.1007/978-3-319-57078-5_55

Marcinkowski (2019). The Spatial Limits of Environmental Benefit of Industrial Symbiosis – Life Cycle Assessment Study. Journal of Sustainable Development of Energy, Water and Environment Systems, 7(3), 521-538. https://doi.org/10.13044/j.sdewes.d7.0270

Mas, J. L., Ramírez, J. C., Bermúdez, S. H., & Fernández, C. L. (2021). Assessment of natural radioactivity levels and radiation exposure in new building materials in Spain. Radiation Protection Dosimetry, 194(2–3), 178–185.

Mayer, A., Haas, W., Wiedenhofer, D., Krausmann, F., Nuss, P., & Blengini, G. A. (2019). Measuring progress towards a circular economy: A monitoring framework for economy-wide material loop closing in the EU28. Journal of Industrial Ecology, 23(1), 62–76. https://doi.org/10.1111/jiec.12809

Mirata, M., Lindfors, A., & Kambanou, M. L. (2024). A business value framework for industrial symbiosis. Journal of Industrial Ecology. https://doi.org/10.1111/jiec.13545

Namq, B. F., & Wais, T. Y. (2026). Radiological hazard assessment of soil at North Oil Company using spatial distribution and Monte Carlo simulation in Kirkuk Governorate, Iraq. Scientific Reports. Advance online publication.

Neves, A., Godina, R., Azevedo, S. G., & Matias, J. C. O. (2019). Environmental, economic, and social impact of industrial symbiosis: Methods and indicators review. In N. Melão, J. Reis, & S. Pinelas (Eds.), Industrial Engineering and Operations Management II – XXIV IJCIEOM 2018 (pp. 157–165). Springer Proceedings in Mathematics and Statistics, Vol. 281. Springer.

Neves, A., Godina, R., Azevedo, S. G., & Matias, J. C. O. (2020). A comprehensive review of industrial symbiosis. Journal of Cleaner Production, 247, 119113. https://doi.org/10.1016/j.jclepro.2019.119113

Olszewski, M. P., Arauzo, P. J., Maziarka, P. A., Ronsse, F., & Kruse, A. (2019). Pyrolysis Kinetics of Hydrochars Produced from Brewer's Spent Grains. Catalysts, 9 (7), 625. https://doi.org/10.3390/catal9070625

Onita, J. A. (2006). How does industrial symbiosis influence environmental performance? (Master's thesis, Linköping University). DiVA Portal. https://www.diva-portal.org/smash/get/diva2:22727/FULLTEXT01.pdf

Pakarinen, S., Mattila, T., Melanen, M., Nissinen, A., & Sokka, L. (2010). Sustainability and industrial symbiosis—The evolution of a Finnish forest industry complex. Resources, Conservation and Recycling, 54, 1393–1404. https://doi.org/10.1016/j.resconrec.2010.05.015

Sahoo, P., & Joseph, J. (2021). Radioactive hazards in utilization of industrial by-products: Comprehensive review. Journal of Hazardous, Toxic, and Radioactive Waste, 25(3), 03121001.

Scafà, M., Marconi, M., & Germani, M. (2020). A critical review of symbiosis approaches in the context of Industry 4.0. Journal of Computational Design and Engineering, 7(3), 269-278. https://doi.org/10.1093/jcde/qwaa022

Sellitri, A., Pizzol, L., Bonfà, A., Meneghin, G., Menegaldo, M., Scanferla, P., Zabeo, A., Schileo, G., Devecchi, S., Breda, S., Bardos, P., & Semenzin, E. (2026). Circularity indicators for remediation activities: Assessing circularity at the ex-ante and ex-post phases in compliance with the latest standards. Cleaner Environmental Systems, 21, 100431. https://doi.org/10.1016/j.cesys.2026.100431

Shi, R., Fei, F., Wang, X., Liu, D., Wu, S., Bai, J., Zhang, Y., Su, W., Lei, R., Wang, H., & Ma, H. (2025). Urban-industrial synergies in sustainability: Evaluating the co-processing of MSWI fly ash in industrial kilns from environmental and economic perspectives. Journal of Cleaner Production, 523, 146457. https://doi.org/10.1016/j.jclepro.2025.146457

Silva, F. A. D., Simioni, F. J., & Hoff, D. N. (2020). Diagnosis of circular economy in the forest sector in southern Brazil. Science of the Total Environment, 706, 135973. https://doi.org/10.1016/j.scitotenv.2019.135973

Sokka, L., Pakarinen, S., & Melanen, M. (2011). Industrial symbiosis contributing to more sustainable energy use: An example from the forest industry in Kymenlaakso, Finland. Journal of Cleaner Production, 19(4), 285–293. https://doi.org/10.1016/j.jclepro.2009.08.014

Sommer, K. H. (2020). Study and Portfolio Review of the Projects on Industrial Symbiosis in DG Research and Innovation: Findings and Recommendations. Publications Office of the European Union: Luxembourg. https://doi.org/10.2777/381211

Sturbois, A., De Cáceres, M., Bifolchi, A., Bioret, F., Boyé, A., Gauthier, O., Grall, J., Grémare, A., Labrune, C., Robert, A., Schaal, G., & Desroy, N. (2023). Ecological Quality Assessment: A framework to report ecosystems quality and their dynamics from reference conditions. Ecosphere, 14(12). https://doi.org/10.1002/ecs2.4726

Tiejun, D. (2010). Two quantitative indices for the planning and evaluation of eco-industrial parks. Resources, Conservation and Recycling, 54(7), 442–448. https://doi.org/10.1016/j.resconrec.2009.09.010

Van Berkel, R., Fujita, T., Hashimoto, S., & Geng, Y. (2009). Industrial and urban symbiosis in Japan: Analysis of the Eco-Town program 1997–2006. Journal of Environmental Management, 90, 1544–1556. https://doi.org/10.1016/j.jenvman.2008.11.010

Wang, Q., Tang, H., Qiu, S., Yuan, X., & Zuo, J. (2018). Robustness of eco-industrial symbiosis network: A case study of China. Environmental Science and Pollution Research, 25(27), 27203–27213. https://doi.org/10.1007/s11356-018-2764-x

Yeo, Z., Masi, D., Low, J. S. C., Ng, Y. T., Tan, P. S., & Barnes, S. (2019). Tools for promoting industrial symbiosis: A systematic review. Journal of Industrial Ecology, 23(5), 1087–1108. https://doi.org/10.1111/jiec.12846

Zou, Q., Li, S., Ding, Y., Yang, Z., Wang, X., Hou, H., Shi, X., Duan, H., & Yang, J. (2026). Towards a state-of-art co-utilization for multiple solid wastes by integrating deep reinforcement learning. Journal of Cleaner Production, 566, 148617. https://doi.org/10.1016/j.jclepro.2026.148617

## Annex I. Consolidated inventory of 329 indicators

| Dimension | KPI Name | Description | Unit of Measure |
|---|---|---|---|
| Legal KPIs | Environmental regulatory noncompliances resulting in fines or prosecutions | This KPI tracks instances where participating firms face legal actions due to environmental violations. A lower frequency indicates better adherence to environmental regulations and reflects positively on the symbiosis network's governance and responsibility. | number |
| Legal KPIs | Environmental licence limit exceedances & other noncompliances | This measures instances where industrial activities exceed licence limits or violate other compliance requirements. It is essential for identifying areas needing improvement to ensure sustainable operations within the industrial symbiosis. | number |
| Legal KPIs | Number of certifications gained by cooperation | This KPI tracks the number of new certifications obtained through collaborative efforts in the symbiosis network. It reflects the success of joint initiatives in achieving recognized standards and practices | number |
| Legal KPIs | Number of certifications maintained by cooperation | This measures how many existing certifications are consistently upheld through cooperative efforts. It indicates continuous compliance and effective collaboration in maintaining high standards | number |
| Legal KPIs | Number of certifications lost by cooperation | This KPI assesses the number of certifications that could not be retained, which could signal lapses in cooperation or compliance mechanisms within the network | number |
| Legal KPIs | Level of cooperation | This measures the degree of collaborative engagement among firms in the symbiosis. A higher level indicates robust partnerships and effective resource-sharing mechanisms, essential for achieving sustainability goals | LESTS score |
| Legal KPIs | certifications | These are formal recognitions of a firm's compliance with certain standards, often required for participating in industrial symbiosis. They serve as benchmarks for quality and sustainability, reflecting the commitment of the network to best practices | List of certifications |

| | | | |
|---|---|---|---|
| economic KPI | Generate local business opportunities | Measures whether industrial symbiosis initiatives create new local business opportunities or strengthen existing local enterprises through resource exchanges and inter-firm collaboration. Indicates if local businesses benefit from industrial symbiosis activities | Yes / No |
| economic KPI | Sales | Measures the total revenue generated from products and services within the industrial symbiosis network at the site level. Increased sales indicate successful collaboration, market expansion, and effective commercialization of symbiotic activities | Currency (EUR) |
| economic KPI | Profit | Measures the net profit earned by participating firms from industrial symbiosis activities after deducting all operational and capital-related costs. Improved profit levels indicate efficient resource utilization, cost savings, and strong financial performance of symbiotic operations at the site level. | Currency (EUR) |
| economic KPI | Wages paid | Measures the total gross wages paid to employees within the industrial symbiosis network, including amounts withheld for taxes or insurance. This KPI reflects employment generation, income distribution, and local economic growth resulting from symbiotic activities. | Currency (EUR) |
| economic KPI | Tangible environmental costs | Measures the total measurable costs associated with environmental management within the industrial symbiosis network, including waste disposal, pollution control, environmental taxes, fines, and eco-investments. Lower or decreasing costs indicate improved environmental performance and more efficient, sustainable practices. | Currency (EUR) |
| economic KPI | Transport costs | Measures the total costs associated with the transportation and logistics of materials and products within the industrial symbiosis network. Lower transport costs indicate optimized logistics, shorter supply chains, improved circularity, and more efficient inter-firm exchanges enabled by symbiotic cooperation. | Currency (EUR) |
| economic KPI | Return on Investment | Measures the profitability of industrial symbiosis projects by comparing the net economic benefit (or net profit generated from IS activities) to the total initial capital expenditure (CAPEX) required to implement symbiotic infrastructure or | Percentage (%) |

| | | | |
|---|---|---|---|
| | | technologies. A higher ROI indicates stronger economic performance and successful value creation through industrial symbiosis | |
| economic KPI | Internal Rate of Return (IRR) | Measures the expected annualized rate of return of industrial symbiosis projects. It is defined as the discount rate at which the net present value (NPV) of project cash flows equals zero. A higher IRR indicates stronger financial viability, faster value creation, and more attractive investment performance of symbiotic initiatives | Percentage (%) |
| economic KPI | Payback period | Measures the time required to recover the initial capital investment of industrial symbiosis activities from generated savings and revenues, without discounting cash flows. A shorter payback period indicates quicker cost recovery, lower financial risk, and higher attractiveness of the symbiotic investment. | years |
| economic KPI | Discounted payback period | Measures the time required to recover the initial investment of industrial symbiosis projects while accounting for the time value of money by discounting future cash flows. This KPI provides a more accurate assessment of investment recovery and financial risk compared to the simple payback period. | years |
| economic KPI | Net Present Value (NPV) | Measures the profitability of industrial symbiosis projects by calculating the difference between the present value of future cash inflows and cash outflows, discounted at an appropriate rate. A positive NPV indicates that the symbiotic activity generates net economic value and is financially viable. | Currency (EUR) |
| economic KPI | Return on Invested Capital (ROIC) | Measures how efficiently capital invested in industrial symbiosis activities is used to generate operating profit. ROIC evaluates the return earned on invested capital and indicates the effectiveness of capital allocation and value creation within symbiotic operations. | Percentage (%) |
| economic KPI | Capital expenditure (CapEx) | Measures the total investments made in physical assets, infrastructure, and equipment required to implement and support industrial symbiosis activities. This KPI reflects the scale, commitment, and long-term investment intensity of symbiotic initiatives. | Currency (EUR) |
| economic KPI | Operating expenditure (OpEx) | Measures the total day-to-day operational costs required to run and maintain industrial symbiosis activities, including labor, energy, maintenance, logistics, | Currency (EUR) |

| | | | |
|---|---|---|---|
| | | and administrative expenses. Lower OpEx indicates higher operational efficiency and effective management of symbiotic operations. | |
| economic KPI | Level of economic cooperation | Measures the extent, quality, and intensity of economic collaboration among firms participating in the industrial symbiosis network. It captures financial cooperation, resource sharing, number and depth of partnerships, reciprocal economic benefits, and the level of trust and integration among participants. Higher values indicate stronger, more effective economic partnerships and successful collective action toward shared economic and sustainability goals. | LESTS score |
| Spatial KPI | Efficient use of land | This KPI assesses how effectively land is utilized within an industrial symbiosis setup. It considers the density of industrial activities and the extent to which the land is optimized for resource sharing and waste reduction. Efficient land use indicates minimal environmental impact and maximized output per unit of land area | number of activities / km2 |
| Spatial KPI | Distance between the partner industries | This measures the geographical proximity of participating industries within the symbiosis. Shorter distances generally facilitate easier and more cost-effective resource exchanges, contributing to reduced transport costs and emissions. This KPI impacts the logistic efficiency of the symbiosis network | km |
| Spatial KPI | Availability of major connections (routes / channels) between partner industries | This KPI evaluates the infrastructure and logistical connections that enable the movement of materials and resources between industries. Efficient and well-established routes reduce transit time and costs, enhance collaboration, and support continuous operations | List of modalities |
| Spatial KPI | Economic intensity | Economic intensity refers to the level of economic activity within the symbiosis network, measured by indicators like the volume of transactions, the value of exchanges, and the economic output generated per unit of resource used. It reflects the economic dynamism and viability of the symbiosis network | eur/km2 |
| Technical KPI | Domestic Material Input DMI | Measures the total amount of raw materials used in the production process, calculated as domestic extraction plus imports. This KPI reflects the reliance on primary material resources and supports the assessment of resource efficiency and the potential for reducing environmental impacts through industrial symbiosis and material substitution | tonne |

| | | | |
|---|---|---|---|
| Technical KPI | Total Material Requirement | Direct material input + indirect flows + unused DE - TMR encompasses all the materials required throughout the production process, including both domestic and imported raw materials. This KPI is essential for understanding the overall material intensity and potential waste reduction through industrial symbiosis | t |
| Technical KPI | DMIw (t/worker) | DMI/number of workers - This indicator measures the domestic material input per worker, providing insights into labor productivity relative to material use. It helps evaluate the efficiency of workforce utilization in resource-intensive processes | t/worker |
| Technical KPI | TWGw (t/worker) | TWG/number of workers - Total Waste Generated per worker (TWGw) indicates the amount of waste produced relative to the workforce size, highlighting areas for process efficiency improvements and waste reduction | t/worker |
| Technical KPI | Worker Productivity WP | Total production/number of workers - This KPI measures the output per worker in the context of industrial symbiosis, gauging efficiency and value added by the workforce in collaborative exchanges and processes | t/worker |
| Technical KPI | Total Water Input TWI | Measures the total volume of water consumed during industrial operations, including process water and cooling water. This KPI reflects water resource efficiency and helps identify opportunities for water conservation, reuse, and exchange through industrial symbiosis partnerships. | tonne |
| Technical KPI | Total WasteWater Generated | Measures the total volume of wastewater produced as a result of industrial processes. This KPI serves as an indicator of process efficiency and environmental impact, and helps identify opportunities for wastewater reduction, treatment, reuse, and exchange through industrial symbiosis. | tonne |
| Technical KPI | Total Water Input /worker | TWI/number of workers - This metric indicates the amount of water used per worker, providing insights into the resource efficiency of labor-intensive processes | t/worker |
| Technical KPI | Total Energy Input | Total energy consumption - This represents the total energy consumed in production processes. It aids in assessing energy efficiency and identifying potential for energy savings through symbiotic exchanges | GJ |

| | | | |
|---|---|---|---|
| Technical KPI | Total Energy Input per worker | TEI/number of workers - Measures the energy consumption relative to the workforce, highlighting energy efficiency and guiding improvements in energy use per unit of labor | GJ/worker |
| Technical KPI | Energy Intensity E-In | Measures the amount of energy consumed per unit of product output, calculated as total energy input divided by total production. This KPI indicates process and energy demand efficiency and helps identify opportunities to reduce energy consumption through industrial symbiosis initiatives, energy optimization, and cascading. | GJ/t (or kWh/unit, MJ/unit) |
| Technical KPI | Energy efficiency | Measures the ratio of useful energy contained in products or services to the total energy input used in industrial processes. This KPI evaluates how effectively energy is converted into productive output and highlights the sustainability benefits achieved through energy optimization and industrial symbiosis. | % |
| Technical KPI | Exergy efficiency | Measures the ratio of useful product exergy to input exergy, reflecting the quality and effectiveness of energy transformations in industrial processes. Higher exergy efficiency indicates more effective use of energy resources, reduced losses, and improved thermodynamic performance within the industrial symbiosis network. | % |
| Technical KPI | Material efficiency | Measures the effectiveness of material use by calculating the ratio of product output mass to raw material input mass. This KPI indicates how much of the input material ends up in the final product versus losses or waste, providing insights into resource conservation, waste minimization, and the benefits of industrial symbiosis. | % |
| Technical KPI | Level of technical cooperation | 0 - No technical feasible cooperation to 5, principles of circular economy met - This indicator measures the degree and success of technical collaboration among industries engaged in symbiosis, reflecting on the exchange of processes, technologies, and knowledge aimed at enhancing efficiency and sustainability | LESTS score |

| | | | |
|---|---|---|---|
| Social KPI | Fatalities (employees only) | Tracks the number of fatal incidents involving employees, serving as a critical safety KPI for mitigating workplace hazards and ensuring a safe working environment | |
| Social KPI | Lost Time Injury (employees only) | Measures workplace incidents leading to significant injury resulting in absence from work, which is essential for assessing and improving occupational safety practices | |
| Social KPI | Near misses | Counts incidents that almost resulted in injury or required minimal first aid, providing insights into potential hazards and areas for improving safety protocols | |
| Social KPI | First aid injuries | Counts incidents that almost resulted in injury or required minimal first aid, providing insights into potential hazards and areas for improving safety protocols | |
| Social KPI | Medical treatment injuries | Focuses on injuries that necessitate medical intervention, helping organizations to evaluate the severity and frequency of workplace incidents | |
| Social KPI | Restricted work injuries | Measures incidents limiting an employee's ability to perform regular duties, highlighting areas for ergonomic improvements and job safety enhancements | |
| Social KPI | Occupational illness | Tracks diseases arising from workplace exposures, critical for assessing long-term health impacts and implementing preventive measures | |
| Social KPI | A sketch of all the supply chain actors | Provides a comprehensive overview of participants in the supply chain, identifying potential areas for collaboration and optimization in industrial symbiosis | y/n |
| Social KPI | Ratio of supply chain actors showing their commitment to CSR (Corporate Social Responsibility) criteria | Measures the proportion of supply chain members adhering to Corporate Social Responsibility protocols, which reflects the commitment to ethical and sustainable practices | % |
| Social KPI | Taxation revenue | Evaluates the overall fiscal contributions from industries involved in symbiosis, highlighting economic benefits at the local and national levels | EUR |
| Social KPI | Membership in an initiative that promotes social responsibility | Counts enterprises participating in CSR-focused initiatives, indicating a collective effort towards social and environmental responsibility | |

| | | | |
|---|---|---|---|
| | along the supply chain (number of enterprises) | | |
| Social KPI | Skill level | The level of skills of employees | number |
| Social KPI | Leadership positions held by women | Assesses gender representation in leadership roles, supporting diversity and inclusion initiatives within industrial symbiosis networks | % |
| Social KPI | Ratio of salary of female employee wages to male employee wages | Monitors gender wage equality within organizations participating in symbiosis, highlighting areas for improvement in pay equity | % |
| Social KPI | Ratio of female employees | Gauges the proportion of women in the workforce, supporting gender diversity and balanced representation | % |
| Social KPI | Ratio of employees with a foreign origin | Tracks workforce diversity by measuring the proportion of employees from various nationalities, reflecting the inclusion of different cultural perspectives | % |
| Social KPI | Job security - Percentage of workers with a long-term contract | Measures the stability of employment contracts, indicating job security and workforce contentment | % |
| Social KPI | Evidence of violations of laws and employment regulation | Monitors compliance with legal and regulatory frameworks to ensure ethical practices and worker rights protections | |
| Social KPI | Mechanism for registering grievances of community | Evaluates processes for addressing community concerns and complaints, fostering transparency and accountability | y/n |
| Social KPI | Aesthetic and visual acceptability | Assesses the visual impact of industrial activities on the community, ensuring integration with surrounding environments | number of complaints |
| Social KPI | Noise | Measures sound levels generated by symbiotic industrial activities, aiding in minimizing noise pollution impacts on local communities | decibels + number of complaints |
| Social KPI | Dust | Tracks particulate emissions from industrial processes, ensuring air quality standards are met | number of complaints |
| Social KPI | Odour | Monitors the presence of odorous emissions, aiming to minimize olfactory nuisances for surrounding areas | number of complaints |

| | | | |
|---|---|---|---|
| Social KPI | Workforce employed locally | Measures the extent of local employment, promoting economic growth and community integration | % |
| Social KPI | Social level of cooperation | Evaluates the degree of collaboration and mutual support among firms engaged in symbiosis, essential for collective social welfare and sustainability | LESTS score |
| Environmental KPI | Total production volume | Measures the overall output of goods produced by industries within the symbiotic network, indicating the scale of production and resource efficiency | M t |
| Environmental KPI | Raw materials used | Assesses the quantity and type of raw materials consumed in production processes. Optimized use and substitution with secondary materials can reduce environmental impact | M t |
| Environmental KPI | Materials for packaging purposes | Evaluates the amount and sustainability of materials used specifically for packaging, aimed at reducing environmental footprint through eco-friendly alternatives | M t |
| Environmental KPI | Total on-site energy consumption from renewable sources | Tracks the proportion of energy consumed on-site that is derived from renewable sources, reflecting a commitment to sustainable energy use | % |
| Environmental KPI | CO2e emissions from power generation | Measures carbon dioxide equivalent emissions associated with energy production, particularly those reduced through symbiotic energy exchanges and renewable sources | k t |
| Environmental KPI | NOx emissions | Focuses on emissions of nitrogen oxides, which are pollutants resulting from combustion processes, with initiatives aimed at reducing these emissions through optimized industrial practices | k t |
| Environmental KPI | SOx emissions | Measures sulfur oxides emissions, typically from burning fossil fuels, and evaluates reductions achieved through cleaner energy and process innovations | k t |
| Environmental KPI | Total particulate emission | Monitors airborne particulate matter released during production, with emphasis on control measures that industrial symbiosis can provide | k t |
| Environmental KPI | Water withdrawal from marine water sources | Assesses quantities of water sourced from marine environments, promoting sustainable usage and minimizing ecological disruption | M m3 |

| | | | |
|---|---|---|---|
| Environmental KPI | Water withdrawal from freshwater sources | Quantifies freshwater sourced for industrial processes, aiming to encourage reductions through effective resource sharing | M m3 |
| Environmental KPI | Water withdrawal from municipal water sources | Evaluates dependence on municipal water supplies, which can be lessened by reusing water within the symbiotic network | M m3 |
| Environmental KPI | Water discharged- cooling water to marine water sources | Tracks volumes of water used for cooling processes discharged back into marine sources, focusing on minimizing temperature and pollutant impacts | M m3 |
| Environmental KPI | Water discharged- treated wastewater to marine water sources | Monitors treated wastewater released into marine environments, stressing the importance of treatment to mitigate ecological effects | M m3 |
| Environmental KPI | Water discharged- treated wastewater to freshwater sources | Assesses impacts of discharged treated wastewater into freshwater systems, with improvements in treatment processes showing symbiotic benefits | M m3 |
| Environmental KPI | Water discharged- waste water to sewerage | Measures waste liquids sent to sewage treatment, highlighting how recycling initiatives within the symbiotic setup can reduce volumes | M m3 |
| Environmental KPI | Water discharged- waste water to other destinations | Evaluates effluents directed elsewhere, ensuring compliance and minimizing harmful impacts on diverse ecosystems | M m3 |
| Environmental KPI | hazardous waste produced | Quantifies hazardous waste generated, with efforts towards minimizing production through innovative processes and resource exchanges | t (solid) or m3 (liquids) |
| Environmental KPI | hazardous waste recycled | Tracks recycling rates of hazardous materials, focusing on creative reuse within the symbiotic network | t (solid) or m3 (liquids) |
| Environmental KPI | Non-hazardous waste produced | Measures the generation of non-hazardous waste with goals of reduction and prevention through efficiency and collaboration | t (solid) or m3 (liquids) |
| Environmental KPI | Non-hazardous waste recycled | Shows recycling efforts of non-hazardous waste, achieving significant volume reductions | t (solid) or m3 (liquids) |
| Environmental KPI | Direct GHG emissions | Measures greenhouse gas emissions released directly from industrial production activities and on-site operations. This KPI supports the assessment | t $CO_2$eq or kg $CO_2$eq / t product |

| | | | |
|---|---|---|---|
| | | of climate impact and highlights opportunities for emission reductions through cleaner technologies, process optimization, fuel switching, and industrial symbiosis initiatives | |
| Environmental KPI | Total waste sent to landfill | Monitors the volume of waste directed to landfills, stressing landfill diversion through industrial symbiosis | k t |
| Environmental KPI | Carcinogens | Measures emissions of carcinogenic substances released from industrial activities, expressed as vinyl chloride equivalents (kg $C_2H_3Cl$ eq). This KPI assesses potential human health impacts and supports the identification of opportunities to control, reduce, and mitigate carcinogenic emissions through cleaner processes and industrial symbiosis practices. | kg $C_2H_3Cl$ eq |
| Environmental KPI | Non-carcinogens | Measures emissions of substances that contribute to non-carcinogenic human health effects from industrial activities, expressed as vinyl chloride equivalents (kg $C_2H_3Cl$ eq). This KPI supports the assessment and reduction of toxic exposures through improved process control, substitution, and industrial symbiosis initiatives | kg $C_2H_3Cl$ eq |
| Environmental KPI | Respiratory inorganics | Measures emissions of inorganic substances, particularly particulate matter, that affect air quality and respiratory health, expressed as $PM_{2.5}$ equivalents. This KPI helps assess health-related air pollution impacts and supports emission reduction through cleaner technologies, process optimization, and industrial symbiosis collaborations. | kg $PM_{2.5}$ eq |
| Environmental KPI | Ionising radiation | Measures emissions related to ionising radiation from industrial activities, expressed in becquerels (Bq). This KPI ensures adherence to radiation safety standards and supports monitoring and mitigation of radiological impacts within industrial symbiosis networks | Bq |
| Environmental KPI | Ozone layer depletion | Measures emissions of substances that contribute to ozone layer depletion, expressed as CFC-11 equivalents. This KPI supports the identification and elimination of ozone-depleting substances through cleaner technologies and industrial symbiosis practices. | kg CFC-11 eq |
| Environmental KPI | Respiratory organics | Measures emissions of organic compounds that affect air quality and respiratory health, expressed as ethylene equivalents (kg $C_2H_4$ eq). This KPI | kg $C_2H_4$ eq |

| | | | |
|---|---|---|---|
| | | helps assess and reduce health-related air pollution through industrial innovation and symbiotic process improvements. | |
| Environmental KPI | Aquatic ecotoxicity | Assesses the toxic impact of industrial emissions on aquatic ecosystems, expressed as toxic equivalents for water (kg TEG water). This KPI promotes strategies to prevent, reduce, and manage toxic discharges through industrial symbiosis and improved wastewater management. | kg TEG water |
| Environmental KPI | Terrestrial ecotoxicity | Measures the toxic impacts of emissions on terrestrial ecosystems, expressed as toxic equivalents for soil (kg TEG soil). This KPI supports the control and reduction of land-based contamination through cleaner production and symbiotic exchanges. | kg TEG soil |
| Environmental KPI | Terrestrial acidification/nutrification | Quantifies acidifying and eutrophying emissions affecting soils, expressed as sulfur dioxide equivalents. This KPI highlights the need for emission reductions and nutrient management through improved processes and industrial symbiosis. | kg $SO_2$ eq |
| Environmental KPI | Land occupation | Measures the extent of land use associated with industrial activities, expressed in square meters of arable land occupation. This KPI supports land-use minimization, efficient spatial planning, and ecosystem restoration within industrial symbiosis systems. | $m^2$org arable |
| Environmental KPI | Aquatic acidification | Measures emissions contributing to the acidification of aquatic environments, expressed as sulfur dioxide equivalents. This KPI supports the monitoring and reduction of acidifying pollutants through cleaner production and symbiotic process integration. | kg $SO_2$ eq |
| Environmental KPI | Global warming | Measures the contribution of industrial activities to global warming, expressed as global warming potential (GWP) in carbon dioxide equivalents. This KPI reflects the average temperature increase impact of greenhouse gas emissions, typically excluding biogenic $CO_2$ to focus on industrial contributions and climate-related ecosystem effects. | kg $CO_2$ eq |
| Environmental KPI | Non-renewable energy | Measures the amount of energy consumed from non-renewable sources such as coal, oil, and natural gas in industrial processes. This KPI reflects dependence | MJ primary |

| | | | |
|---|---|---|---|
| | | on finite energy resources and supports the evaluation of energy transition and efficiency improvements enabled by industrial symbiosis. | |
| Environmental KPI | Mineral extraction | Measures the energy surplus associated with the extraction of mineral resources required for industrial activities, reflecting the intensity and environmental burden of mineral extraction. This KPI supports the assessment of resource depletion and the potential for reducing primary mineral demand through industrial symbiosis and material circularity. | MJ surplus |
| Environmental KPI | Land occupation, biodiversity | This indicator evaluates the extent of land used by industrial activities and its impact on biodiversity and ecosystems within that area. | ha.yr arable |
| Environmental KPI | Fossil energy use | This KPI specifically measures the total consumption of fossil energy for production and operational activities within an industry. | MJ deprived |
| Environmental KPI | Mineral resources use | This indicator assesses the total volume and management of mineral resources consumed across the entire production lifecycle. | kg deprived |
| Environmental KPI | Water use | This KPI measures the total volume of water utilized in various industrial processes, including both withdrawal from natural and municipal sources and discharge back into the environment. | m3 deprived |
| Environmental KPI | Aquatic eutrophication | Measures nutrient enrichment of aquatic environments, particularly from phosphorus and nitrogen emissions, which can lead to excessive algal blooms, oxygen depletion, and harm to aquatic ecosystems. This KPI supports the assessment and reduction of nutrient-related water pollution through improved process control and industrial symbiosis practices. | kg $PO_4^{3-}$ (P-limiting) |
| Environmental KPI | marine eutrophication | This indicator specifically addresses nutrient over-enrichment in marine environments, examining its causes, such as agricultural run-off and wastewater discharge, leading to detrimental ecological effects like hypoxic zones. | kg N eq |
| Environmental KPI | Aquatic ecotoxicity, short-term | Measures the immediate toxic effects of various substances in water on aquatic organisms, typically evaluated over short exposure periods to assess acute poisoning risks. | CTUe |

| | | | |
|---|---|---|---|
| Environmental KPI | Aquatic ecotoxicity, long-term | Assesses the prolonged toxic effects of pollutants on aquatic life, focusing on cumulative and chronic risks over extended periods. | CTUe |
| Cultural and Social KPIs | Stakeholder Engagement Quality | Measures the effectiveness of interactions/communications with key stakeholders regarding CSR/sustainability issues | Number of stakeholders/Engagement Score |
| Cultural and Social KPIs | Average Response Time to Stakeholder Inquiries | Time taken (e.g., hours/days) to respond to stakeholder questions, comments or feedback. | Response rate |
| Cultural and Social KPIs | Stakeholder Suggestions Implemented | Tracks how many stakeholder inputs/ideas are acted upon or implemented in decisions/projects. | Number of implementations |
| Cultural and Social KPIs | Stakeholder Net Promoter Score (NPS) | Measures stakeholder loyalty/advocacy: how likely stakeholders are to recommend the organisation | Satisfaction score |
| Cultural and Social KPIs | Diversity of Stakeholder Engagement (demographics) | Variety of stakeholder types engaged (age, gender, geography, income class, cultural/linguistic background) | Satisfaction score |
| Cultural and Social KPIs | Jobs created via IS-network participation | Measures the number of new and sustained jobs generated directly by industrial symbiosis (IS) initiatives, including employment from by-product reuse activities, shared infrastructure or services, and community spin-off enterprises. This KPI reflects the social benefits and local employment impacts of IS participation. | Number of jobs (FTEs or headcount) |
| Cultural and Social KPIs | Training & Skills Development | Measures the scale of capacity building related to industrial symbiosis by capturing workforce and community engagement in training, education, and learning activities. This KPI reflects both the total training effort and participation levels supporting the implementation of IS practices and skills for circular and symbiotic operations. | Number of training hours and/or number of people trained per year |
| Cultural and Social KPIs | Number of Stakeholder Engagement Sessions | Number of consultative meetings, workshops, information sessions held with stakeholders (community, firms) about IS | Count of sessions |
| Cultural and Social KPIs | Perceived Social Value Index | Survey-based index measuring how much value stakeholders believe the IS initiative brings to society (community perception) | Survey score (e.g., scale 1-5) or % rating high value |

| | | | |
|---|---|---|---|
| Cultural and Social KPIs | % of IS Exchanges Benefiting Community | Proportion of material/energy/resource exchanges in the IS network that explicitly include community benefit (e.g., heat to local homes, waste reuse by local SMEs) | % of exchanges |
| Cultural and Social KPIs | Cultural/Local Business Inclusion Rate | % of local cultural or small enterprises integrated into the IS network (to reflect cultural/social dimension) | % of local cultural/business entities participating |
| Cultural and Social KPIs | Change in Community Attitude Toward Industry | Measures shift in local community's attitude toward industrial activity because of IS engagement / social programmes | % change in positive attitude responses over time |
| Cultural and Social KPIs | Number of Community Benefit Projects Associated with IS | Counts of social/cultural/community projects (e.g., education, local amenity, cultural events) initiated as part of the IS programme | Number of projects |
| Cultural and Social KPIs | Engagement Channel Diversity | Number of different engagement channels used to reach stakeholders (workshops, online platforms, newsletters, site visits) — higher diversity may reflect better cultural inclusivity | Count of channels |
| Cultural and Social KPIs | % Women Participating in IS Network Roles | roportion of women in key roles (e.g., project leads, management of IS exchanges, stakeholder liaison) within the IS network. | Persentage |
| Cultural and Social KPIs | Gender Pay Gap for Jobs Created by IS Initiatives | Difference in average pay between men and women in new jobs generated by the IS network. | (Average pay of men – Average pay of women) ÷ Average pay of men × 100% |
| Cultural and Social KPIs | % Target Customers Aware of IS Offering | The proportion of your target customer base (e.g., firms in your region or network) who are aware of the IS programme, value-proposition or services (i.e., know that IS exchanges, by-product reuse or resource sharing are available). | (Number of customers aware ÷ Total target customers) × 100 % |

| | | | |
|---|---|---|---|
| Cultural and Social KPIs | Customer Awareness Growth Rate | The percent change over time in the number or proportion of customers aware of the IS offering — indicates how well outreach/education efforts are improving awareness. | ((Awareness this period − Awareness previous period) ÷ Awareness previous period) × 100 % |
| Cultural and Social KPIs | Number of Public Outreach Events for IS Awareness | Measures how many events (workshops, open-days, site visits, seminars) are held to raise awareness of the IS initiative among the public/community/local stakeholders. Reflects the scale of efforts to engage the public. | Count of events per period (e.g., per year) |
| Cultural and Social KPIs | Local Community Aware of IS Initiative | Proportion of surveyed community members or local stakeholders who indicate they are aware of the IS initiative (its purpose, benefits or existence). Indicates how well awareness reaches the public. | (Number of respondents aware ÷ Number of respondents surveyed) × 100 % |
| Cultural and Social KPIs | Number of Educational Partnerships for IS Training | Measures how many formal partnerships (e.g., between the IS network/project and educational institutions—universities, technical colleges, training centres) are established to deliver training or curricula related to industrial symbiosis, circular economy or resource-sharing. | Count of partnerships (e.g., "# of memoranda of understanding signed with educational institutions") |
| Cultural and Social KPIs | Workforce Trained in IS-Relevant Skills | Reflects the share of participant group (e.g., employees in the companies, students in partner institutions) that have completed training modules or courses on industrial symbiosis, circular economy, resource-sharing. Shows how much educational-sector engagement translates into skills development | (Number trained ÷ Total target group) × 100 % |
| Cultural and Social KPIs | Number of Knowledge-Sharing Workshops / Trainings Conducted | Counts how many formal sessions (workshops, seminars, training events) are held to share IS knowledge among participating firms, educational institutions, and stakeholders. Reflects the scale of knowledge-transfer efforts. | Count (e.g., number of workshops per period) |
| Cultural and Social KPIs | Rate of Participants in IS Knowledge Events who Report Increased Understanding | Proportion of participants in knowledge-transfer events who, via post-event survey, indicate they have increased their understanding of IS concepts, processes or opportunities. Shows the effectiveness of knowledge transfer. | (Number of participants reporting increased |

| | | | |
|---|---|---|---|
| | | | understanding ÷ Total participants) × 100% |
| Cultural and Social KPIs | Rate of New Firms Adopting IS Practices Based on Knowledge Transfer | Proportion of new participating firms that adopt IS practices/initiatives as a result of the knowledge-transfer efforts (e.g., via attending trainings or accessing resources). Indicates that knowledge transfer leads to uptake. | (Number of new firms adopting ÷ Number of firms exposed to knowledge-transfer activities) × 100% |
| Cultural and Social KPIs | Time from Knowledge Transfer Intervention to First IS Exchange Implementation | Measures the average time elapsed between a knowledge-transfer event/intervention (training, workshop, resource sharing) and the firm's first actual IS exchange or participation. Reflects how effective and timely the knowledge transfer is in enabling action. | Time unit (e.g., months) |
| Cultural and Social KPIs | Number of Cross-Border IS Exchanges | The count of resource exchanges (materials, energy, water, by-products) that occur between firms located in different national borders participating in the IS network. | Count (e.g., cout of exchange transactions per period) |
| Cultural and Social KPIs | Time to First Cross-Border Exchange Post-Agreement | Measures how quickly (e.g., in months) after a cross-border agreement an actual resource exchange is implemented—reflecting implementation efficiency of cross-border collaboration. | Time unit (months) |
| Cultural and Social KPIs | Improvement Rat in Resource Efficiency from Cross-Border Collaboration | Percentage gain (or reduction) in resource input or waste output attributable to cross-border IS collaborations compared to a baseline before such collaborations. | percentage |
| Cultural and Social KPIs | Rate of Local Firms Participating that Reflect Traditional Industry Sector | Measures the percentage of participating firms in the IS network that belong to the region's historic/traditional industry sectors (thus preserving local industrial heritage/identity) | (Number of participating firms from traditional sectors ÷ Total participating firms) × 100 % |

| | | | |
|---|---|---|---|
| Cultural and Social KPIs | Stakeholder Perception of IS Respecting Local Cultural/Industrial Heritage | Assesses via survey how stakeholders (local community, firms, workers) believe that the IS initiative supports/reflects the region's industrial culture and identity (e.g., "It values our local manufacturing heritage") | Rate (scale 1 - 5) |
| Cultural and Social KPIs | Number of IS Initiatives Embedded with Local Cultural/Industrial Heritage Elements | Count of IS projects/exchanges that explicitly incorporate local cultural or heritage features — for example reuse of historic facilities, incorporating local craft/manufacture practices, or retaining regional identity in the exchange design | Count per period (e.g., projects/year) |
| Cultural and Social KPIs | Change in Local Community Sense of Industrial Identity Pre/Post IS Implementation | Measures change over time in how strong the local community feels its industrial identity is preserved or enhanced because of the IS network (via surveys) | % change in survey score or % of respondents reporting |
| Industrial, Cultural and Social KPIs | Industrial symbiosis readiness scales for high energy industrial processes | Includes technology and integration readiness level, business readiness level, organisational readiness level, legal and ethical readiness level, societal readiness level and environmental readiness level | TRL level from 1-10 |
| Circular Economy | Material Reuse Rate | Share of materials reused internally or exchanged with other companies instead of being discarded | % |
| Circular Economy | Secondary Material Input | Proportion of recycled or recovered materials used as inputs in production | % |
| Circular Economy | By-Product Valorisation Rate | Percentage of by-products converted into usable materials, sold, or exchanged via symbiosis | % |
| Circular Economy | Waste-to-Resource Conversion Rate | Amount of waste transformed into resources for other companies | tons/year or % |
| Circular Economy | Loop Closure Index | Degree to which outputs (materials/energy) are reintegrated as inputs in the industrial network | Index (0–1) |
| Waste Reduction & Diversion | Total Waste Reduction Rate | Reduction in waste generated compared to baseline year | % |
| Circular Economy | Hazardous Waste Recovery Rate | Portion of hazardous waste safely recovered, treated, or reused | % |

| | | | |
|---|---|---|---|
| Circular Economy | Avoided Waste due to Symbiosis | Waste avoided because it is exchanged as an input for another company | tons/Year |
| Energy | Energy Intensity E-In | Energy consumption per unit of output | kWh/unit or MJ/unit |
| Energy | Renewable Energy Share | Share of total energy consumption from renewable sources | % |
| Energy | Waste Heat Recovery Rate | Amount of waste heat captured and reused internally or externally | GJ/year or % |
| Energy | Total waste heat generation | Waste heat generation is the process of producing excess heat as a byproduct of a primary process, such as energy conversion in a power plant, internal combustion engine, or industrial manufacturing. | kWh/unit or MJ/unit |
| Energy | Waste heat generation intensity | Waste heat generation is the production of excess heat as a byproduct of a process or machine that is not the primary purpose of the activity | kWh/unit or MJ/unit |
| Energy | Waste heat valorisation | the process of capturing and reusing "waste" heat, which is typically discarded from industrial processes, and converting it into a usable form of energy or applying it to other processes | kWh/unit or MJ/unit |
| Energy | Energy Cascading Index | Number and quality of cascading energy loops among park firms | Index (0–1) |
| Water | Total Ground Water Consumption | The total volume of groundwater extracted from wells, boreholes, or aquifers for industrial use during a defined period. | $m^3$/year |
| Water | Ground Water efficiency | Ratio of useful output (products or value added) to the volume of groundwater consumed. | % or €/$m^3$ |
| Water | Total water consumption | The total volume of all water used by the facility or industrial park, including groundwater, surface water, municipal water, and reused internal water. | $m^3$/year |
| Water | Water intensity (Specific water consumption) | Share of total water demand that is met using alternative, non-freshwater sources (e.g., treated wastewater, process water, symbiosis) | $m^3$/unit product |
| Water | Water substitution | Share of total water demand that is met using alternative, non-freshwater sources (e.g., treated wastewater, process water, symbiosis water exchanges) | % |
| Water | Water Efficiency | The ratio of water used effectively in the process to the total water input, or the reduction in water consumption against a baseline. | % |
| Water | Water Reuse / Recycling Rate | Percentage of total water intake reused or exchanged via symbiosis | % |

| | | | |
|---|---|---|---|
| Water | Freshwater Reduction Rate | Decrease in freshwater withdrawals compared to baseline | % |
| Water | Industrial Water Exchanges | Volume of water exchanged or reused between companies | m³/year |
| Water | Wastewater Recovery Rate | Share of wastewater treated and reused instead of being discharged | % |
| Environmental | Water Circularity Index (WCI) | The WCI is a single-focused indicator. A single-focused indicator is a single indicator designed to measure circularity with a single score ranging from 0 to 1 | % |
| Environmental | Water Recirculation Rate / Reuse Rate | A critical KPI that measures the percentage of water recycled and reused within operations. | % |
| Environmental | Water Intensity / Water Productivity | The volume of water consumed (or withdrawn) per unit of product, revenue, or service. | $\text{Volume of Water Consumed} / \text{Unit of Production (e.g., } m^3/\text{ton or gal/widget)}$ |
| Environmental | Water Footprint (Total & Blue) | The total volume of water used to produce a product, categorized by source (Blue: surface/groundwater; Green: rainwater; Grey: volume needed to dilute pollutants). | $\text{Volume (e.g., } m^3 \text{ or gallons)}$ |
| Economic and business | Resource Use Efficiency (or Intensity) | he physical quantity of output (product) produced per unit of a specific resource consumed (material, energy, water). Improved efficiency is a key benefit of IS. | (Tons of Product / Unit of Resource) |
| Economic and business | Raw Material Dependency Reduction | The reduction in the proportion of virgin raw materials needed for production, achieved by substituting them with symbiotic by-products. | % |
| Economic and business | Economic and business Cost Savings from Waste Disposal | The reduction in costs associated with the disposal of waste or by-products due to their transfer to another company for use as an input. | Currency |
| Economic and business | Cost Savings from Raw Material Purchase | The reduction in costs for purchasing virgin raw materials achieved by replacing them with by-products or waste streams from the IS partner. | Currency |
| Economic and business | Revenue from By-product Sales | Measures the income generated from selling formerly disposed waste streams or by-products to industrial symbiosis partners or other firms. This KPI reflects | Currency (per year) |

| | | | |
|---|---|---|---|
| | | value creation from waste valorisation and the economic benefits of circular resource exchanges enabled by industrial symbiosis. | |
| Economic and business | Symbiotic Exchange Volume | The total mass, energy, or volume of by-products, water, or energy exchanged between companies in the IS network over a period | Mass/Energy/Volume |
| Economic and business | GDP | The total monetary value of all the finished goods and services produced within a country's borders in a specific time period. | Currency |
| Economic and business | Inflation Rate (CPI) | The rate at which the general level of prices for goods and services is rising, and consequently, purchasing power is falling. | Currency |
| Economic and business | Unemployment Rate | The percentage of the total labor force that is unemployed but actively seeking employment and willing to work. | % |
| | | | |
| Economic and business | Cost Avoidance | Monetary value of costs that would have been incurred without symbiosis (landfilling, incineration, virgin material purchase). | Currency/year |
| Economic and business | Value Added from Upcycled Materials | Incremental economic value created when low-value waste streams are upgraded into higher-value products | Currency/year or % increase in product value |
| Economic and business | Increase in Business Competitiveness | Improvement in firm performance attributable to symbiosis, typically measured through productivity, cost efficiency, or profitability indicators. | % change per year (productivity, profit margin, etc.) |
| Environmental / Structural / Network | Symbiotic Link Density (Network Connectivity) | Number (or density) of actual symbiotic exchanges (material, energy, by-product) per number of potential links between firms which indicates how interconnected the network is. | # of links / # of potential links, or # exchanges per firm |
| Environmental KPI | Circularity Index (System Level) | A metric capturing the degree to which material/energy flows cycle within the IS network rather than being lost: a higher value indicates more circular system. | Index or % (context-defined) Represented as Cs |
| Environmental / Structural / Network | Eco-connectance (Network Complexity) | A measure of how complex and diversified the symbiotic network is (i.e. exchange diversity and interaction richness). | Index (context-defined) |

| | | | |
|---|---|---|---|
| Environmental | Resource efficiency | Resource efficiency - how much tonnes per hour are wasted? Not clear | t/h |
| Social | Child Labor: Children in Employment | Statistical measure of children (ages 5-17) engaged in economic activity. | Percentage (%) |
| Social | Child Labor: Sector Risk | Assessment of whether a specific sector is known to use child labor (based on qualitative lists). | Qualitative (Presence on Lists) |
| Social | Forced Labor: Goods Produced by Forced Labor | Identifies if the specific commodity appears on the US Dept. of Labor's blacklist. | Qualitative (Presence on List) |
| Social | Forced Labor: Trafficking in Persons | Evaluation of a country's government efforts to combat human trafficking. | Tier Score (1 to 3) |
| Social | Wages: Sector Wage vs. Minimum | Comparison of the average hourly wage in the sector against the legal minimum wage. | Ratio |
| Social | Wages: Poverty Rate (<$2/day) | Percentage of the population living on less than $2 (or $3.20) per day (working poor). | Percentage (%) |
| Social | Working Time: Excessive Working Hours | Share of the employed population working more than 48 hours per week. | Percentage (%) |
| Social | Freedom of Association: Right to Strike/Bargain | Practical enforcement of union rights (e.g., arrest of leaders, violent strikes). | Index Score (1-5+) |
| Social | Freedom of Association: ILO Ratification | Legal status check: Has the country signed ILO Core Conventions 87 & 98? | Binary (Yes/No) |
| Social | Discrimination: Gender Wage Gap | The difference between median earnings of men and women relative to men's earnings. | Percentage (%) |
| Social | Discrimination: Migrant Worker Rights | Assessment of laws and practices regarding the treatment of migrant workers. | Index Score |
| Social | Occ. Injuries: Fatal Injury Rate | Frequency of work-related deaths in the sector. | Deaths per 100,000 workers |
| Social | Occ. Injuries: Non-Fatal Injury Rate | Frequency of work-related accidents/injuries in the sector. | Cases per 100,000 workers |

| | | | |
|---|---|---|---|
| Social | Occ. Health: Toxin-related DALYs | Disability-Adjusted Life Years lost due to exposure to toxins/carcinogens. | DALYs per 100,000 people |
| Social | Occ. Health: Indoor Air Pollution | Share of population relying on solid fuels (wood, coal) for cooking. | Percentage (%) |
| Social | Indigenous Rights: ILO 169 / UNDRIP Status | Legal status check: Has the country ratified key indigenous rights conventions? | Qualitative (Status) |
| Social | Indigenous Rights: Land Rights Violations | Recorded incidents of land grabbing or violation of indigenous land rights. | Qualitative (Count/Severity) |
| Social | Conflict: Global Peace Index | Composite measure of the peacefulness of a country (ongoing conflict, militarization). | Index Score (1-5) |
| Social | Conflict: Political Terror Scale | Measure of state-sponsored political violence (torture, disappearance, imprisonment). | Index Score (1-5) |
| Social | Gender Equity: Global Gender Gap | Measure of gender-based gaps in resources, opportunities, and political participation. | Index Score (0-1) |
| Social | Labor Laws: Employment Protection | Strictness of regulations concerning hiring and firing (OECD indicators). | Index Score (0-6) |
| Social | Corruption: Corruption Perceptions (CPI) | Perceived levels of public sector corruption according to experts/businesspeople. | Score (0-100) |
| Social | Corruption: Control of Corruption (WGI) | Extent to which public power is exercised for private gain (petty and grand forms). | Normalized Score (-2.5 to 2.5) |
| Social | Rule of Law: Rule of Law Index | Confidence in the rules of society, contract enforcement, and property rights. | Normalized Score (-2.5 to 2.5) |
| Social | Stability: Political Stability | Likelihood that the government will be destabilized by unconstitutional or violent means. | Normalized Score (-2.5 to 2.5) |
| Social | Legal System: Legal Rights Strength | Degree to which collateral and bankruptcy laws protect the rights of borrowers/lenders. | Score (0-12) |
| Social | Water: Improved Water Access | Percentage of population with reasonable access to an adequate amount of safe water. | Percentage (%) |

| | | | |
|---|---|---|---|
| Social | Sanitation: Improved Sanitation Access | Percentage of population using improved sanitation facilities (sewer, septic). | Percentage (%) |
| Social | Health Access: Hospital Beds Density | Availability of inpatient services, serving as a proxy for general health infrastructure. | Beds per 1,000 people |
| Social | Education: Children Out of School | Percentage of primary and secondary school-age children who are not enrolled. | Percentage (%) |
| Social | Poverty: National Poverty Headcount | Percentage of the population living below the national poverty line. | Percentage (%) |
| Social | Unemployment: Total Unemployment Rate | Share of the labor force that is without work but available for and seeking employment. | Percentage (%) |
| Economic and business | Revenue share from circular products | Percentage of the company's total revenue generated from products/components where circular (R-principles) approaches are applied. Higher percentage indicates stronger implementation of circular economy business models. | Percentage (%) |
| Economic and business | Inventory ratio | Reflects how much capital is tied up in unused or unsold goods. A lower value indicates more efficient resource use and improved circularity. | Ratio |
| Economic and business | Storage costs | Measures total warehousing and location expenses. Lower storage costs suggest efficient inventory management and higher circularity. | Currency/year |
| Economic and business | Waste-disposal costs | Includes costs of waste collection, handling and pre-treatment. Lower values reflect higher circularity and efficient recycling. | Currency/year |
| Economic and business | Environmental damage fines | Costs resulting from environmental violations or pollution incidents. Fewer or lower fines indicate better environmental management. | Currency/year |
| Economic and business | Value generated by CE sector | Total economic value created by companies operating within the circular economy sector. | Currency |
| Economic and business | Gross value added | Difference between output and intermediate consumption in CE activities; measures economic contribution. | Currency |

| | | | |
|---|---|---|---|
| Economic and business | Household spending on product repair and maintenance | Expenditure by households on repairing or maintaining products, reflecting circular practices. | Currency |
| Economic and business | Environmentally adjusted net domestic product (EDP) | GDP adjusted for environmental costs; shows sustainable economic performance. | Currency |
| Economic and business | £ generated per land use area | Economic output per unit of land used for CE activities. | £ / ha |
| Economic and business | Patents delivered in CE products and services | Count of patents granted related to circular economy innovations. | Number |
| Economic and business | Private sector investment in CE | Funds invested by private companies in circular economy initiatives. | Currency |
| Economic and business | Public R&D spending to support CE innovation | Government-funded research and development for circular economy projects. | Currency |
| Economic and business | Average households income | Mean annual income of households impacted by circular economy activities. | Currency/Year |
| Economic and business | Change in GDP through circular activities | GDP growth or reduction attributable to circular economy practices. | Percentage (%) |
| Economic and business | Population below poverty line | Percentage of people living under poverty thresholds in CE-affected areas. | Percentage (%) |
| Economic and business | % circular jobs | Share of jobs directly related to circular economy activities. | Percentage (%) |
| Economic and business | % circular businesses | Share of businesses adopting circular economy models. | Percentage (%) |
| Economic and business | Employment | Total number of people employed in circular economy activities. | Number |
| Economic and business | Average households' consumption | Mean annual spending of households on products/services influenced by circular economy practices. | Currency/Year |

| | | | |
|---|---|---|---|
| Economic and business | Annual Cost Savings | Measures the total annual reduction in operating costs achieved through industrial symbiosis activities, including savings from avoided waste disposal, reduced transport and gate fees, lower raw material procurement costs, and improved energy and resource efficiency. This KPI represents the combined financial benefits of cost avoidance and operational optimization enabled by symbiotic exchanges. | Currency (per year) |
| Economic and business | Capital investment for IS / RECP | Upfront capital required to implement symbiosis or resource-efficiency projects | Currency (total capex) |
| Economic and business | Capital already invested / committed | Amount of capital already spent or formally committed toward IS measures | Currency (USD) |
| Economic and business | Avoided waste disposal cost | Reduction in costs that would have been paid for landfill/treatment due to reuse/diversion | Currency / year |
| Economic and business | Avoided procurement cost (substitution) | Savings from substituting purchased virgin inputs with exchanged by-products | Currency / year = quantity substituted × unit procurement price |
| Economic and business | Energy cost savings (electricity / fuel / heat) | Lower energy bills owing to shared heat, recovered energy or reduced consumption | Currency / year or MWh saved × energy price |
| Economic and business | Water cost savings | Reduced water procurement/treatment costs from reuse or shared supply | Currency / year or m3 × water tariff |
| Economic and business | Chemical cost savings | Reduction in chemical purchases due to reuse or process change | Currency / year or mass × unit price |
| Economic and business | Carbon cost avoided | Monetary value of avoided GHG emissions (e.g., via carbon price or tax) | Currency / year = tCO2eq avoided × carbon price (e.g., €/tCO2) |
| Economic and business | Life-cycle cost (LCC) of waste management | Total life-cycle cost associated with waste handling under current vs symbiosis scenario | Currency (total LCC) |

| | | | |
|---|---|---|---|
| Economic and business | Annual net savings from optimization | Net annual monetary benefit after accounting for additional costs of IS implementation | Currency / year = (savings + revenues) - additional O&M costs |
| Economic and business | Value added per resource input (VRE) | Economic value created per unit of resource consumed (captures value-retention) | Currency of value added / resource unit |
| Economic and business | Material Input per Service unit (MIPS) | Mass of material input required per unit of service or product | kg input / service unit |
| Economic and business | Number of companies engaged / surveyed | Count of firms participating in or surveyed for IS activities | Count (number) |
| Economic and business | Number of IS opportunities identified / implemented | Count of potential synergies identified and those progressed to implementation | Count (identified / feasible / implemented) |
| Economic and business | Exchange transaction count / value | Number of resource/by-product exchanges and their aggregated monetary value | Count; Currency total of exchanges |
| Economic and business | By-product utilization rate | Share of generated by-products that are reused within the system vs disposed | % = reused mass / total by-product mass generated |
| Economic and business | Life Cycle Cost (LCC) of IS Application | Total discounted cost of an IS application over its entire life-cycle for comparison of different options. | Currency (total LCC) |
| Economic and business | Utilization rate of shared IS infrastructure | Particularly relevant for ecoindustrial parks and other ecosystems: assessment of to what degree shared infrastructure (waste-treatment plants, steam networks/pipes) in place are utilized | capacity utilization rate (%) of shared IS assets |
| Economic and business | IS Investments financed by Green Instruments | Ratio of IS investments financed trough green instruments (green bonds; sustainability-linked loans etc.) to total IS investment | % of total IS/CE investment |
| Technical | Technical feasibility | Assessment of the practicality and reliability of implementing a technology, measured by LESTS score | LESTS score |

| | | | |
|---|---|---|---|
| Environmental | Human health | Impact on human health | DALY |
| Environmental | Ecosystem quality | Potentially disappeared fraction of species | PDF·m²·yr |
| Environmental | Climate change | Contribution to climate change | kg $CO_2$ eq |
| Environmental | Resources | Use of primary resources | MJ primary |
| Environmental | GHG emission leaving the system | Direct GHG emissions | tonne CO2eq/year |
| Environmental | GHG emission ratio (GHGR1) | Emissions of GHG per selected product | kg CO2eq/tonne |
| Environmental | SO2 emmission to air | Sulfur dioxide emissions leaving the system | kg/year |
| Environmental | NOx emmission to air | Nitrogen oxides emissions leaving the system | kg/year |
| Environmental | NH3 emmission to air | Ammonia emissions leaving the system | kg/year |
| Environmental | NMVOC emmission to air | Non-methane volatile organic compounds leaving the system | kg/year |
| Environmental | PM2.5 emmission to air | Fine particulate matter (≤2.5 µm) emissions leaving the system | kg/year |
| Environmental | PM10 emmission to air | Particulate matter (≤10 µm) emissions leaving the system | kg/year |
| Environmental | Wastewater generation | Total wastewater leaving the system | m3/year |
| Environmental | Waste generation | Generation of specified waste type leaving the system for external treatment | tonne/year |
| Environmental | Metal content in waste for external treatment | Share of specified metal x in waste y | % |
| Technical | Raw material consumption | Consumption of raw material coming in to the system | tonne/year |
| Technical | Water consumption | Consumption of water coming in to the system | m3/year |
| Technical | Electricity consumption | Consumption of electricity coming in to the system | MWh/year |
| Other | IS organisational capacity | Full-time equivalent capacity dedicated to industrial symbiosis | FTE/year |
| Social | Regional employments | Number of full-time equivalent jobs in the region | FTE/year |

| | | | |
|---|---|---|---|
| Social | IS skills improvements | Participants in education & training in IS area | Number of participants/year |
| Legal | Legal/ethical nonconformities | Findings from compliance audit | Number/year |
| Economic and business | OPEX: cost of electricity | Annual cost for electricity | M€/year |
| Economic and business | OPEX: cost of water | Annual cost for water | M€/year |
| Economic and business | OPEX: cost of raw materials | Annual cost of raw materials | M€/year |
| Economic and business | OPEX: cost of GHG emissions (Fe4) | Annual cost of GHG emissions | M€/year |
| Environmental | Resources raised through the waste hierarchy | Tonnage of material involved in industrial–urban symbiosis (I-US) where the end point is at a higher waste hierarchy level than without the I-US activity. | tonne |
| Environmental | GHG saving ($CO_2$ equivalent) | Net $CO_2$ emission reductions resulting from I-US activity (including reductions from process changes, diversion from landfill, raising resources through the waste hierarchy, or transport changes; include Scope 3 where applicable). | tonne $CO_2$ equivalent |
| Environmental | Energy saving | Energy savings through reduced or substituted energy use as a result of I-US activity. | kWh |
| Environmental | Reduced water usage | Embodied and direct water-use savings arising from I-US activity. | $m^3$ |
| Economic and business | Additional sales | New business and revenue generated by the sale of products/services attributable to I-US activity. | € |
| Economic and business | Private investment | Investment in new or existing processes, equipment and infrastructure as a result of I-US activity. | € |
| Social | Social acceptance | | LESTS score |
| Spatial | Spatial Feasibility | | LESTS score |
| Legal | Legal Feasibiltiy | | LESTS score |

| | | | |
|---|---|---|---|
| Technical | Enabling assets | How the hub uses and identifies shared assets for exchange/input/output of mass and energy; includes shared frameworks, risk mitigation and digitalisation. | depends on the specific asset |
| Technical | Primary raw materials, energy and water | What resource flows exist and how they are processed (materials, water incl. urban/industrial/treated/cooling, energy incl. waste energy); considers exchange, suppliers, logistics, pre-treatments, quality, demand and energy efficiency. | depends on material type (tonne, m3, etc.) |
| Environmental | Environmental | Extent to which the hub measures/controls/abates/integrates environmental impacts: $CO_2$, GHG, other air emissions, wastewater discharge quality and compliance. | depends on the emission type (tonne, kg, m3, etc.) |
| Environmental | Solid waste management | Flows and processing of secondary raw materials, MSW and industrial solid waste; monitoring generation, valorisation, recycling rates, markets for SRM, pre-treatment, sorting, hierarchy, eco-design, disposal without energy recovery, permits. | depends on material type (tonne, m3, etc.) |
| Other | Managerial | Degree to which the hub integrates members and communication, handles legal/ethical issues, provides facilitation (start-ups, training, benefits monitoring, support to innovation) and defines governance. | |
| Economic and business | Competitiveness | Extent to which the hub strengthens initiatives and creates opportunities to increase local/EU/global competitiveness (finance & cost sharing, strategy, job & knowledge creation, technology transfer, new skills, promotion of CE). | |
| Economic and business | Circular investments | amount invested in circular technologies/assets | EUR |
| Economic and business | Circular R+D spent | % of R+D budget spent on circular design | % |
| Economic and business | Cost Savings from circularity | EUR saved via waste reduction or reuse | EUR |
| Economic and business | Circular economy jobs | No of FTEs working specifically on circular principles | employees |

| | | | |
|---|---|---|---|
| Economic and business | Employee training on circularity | % of staff trained on circular principles | % |
| Economic and business | Supplier engagement score | % of suppliers with circular targets | % |
| Economic and business | Green bond allocation | % of bond proceeds allocated to circular projects | % |
| Economic and business | Circular value at risk | revenue at risk from resource scarcity | EUR |
| Economic and business | Total recycling rate | % of waste sent to recycling | % |
| Economic and business | Collection rate | product collected / products sold 10 years ago | % |
| Economic and business | Material recovery rate | % of material mass recovered from collected products | % |
| Economic and business | Composting rate | % of organic waste to composting | % |
| Economic and business | Waste to Energy (incineration) | tonnes sent to incineration with energy recovery | t |
| Economic and business | Incineration (no recovery) | tonnes sent to incineration without energy recovery | t |
| Economic and business | Landfill rate | % of total waste sent to landfill | % |
| Economic and business | E-waste recovered | tonnes of WEEE collected | t |
| Economic and business | Downcycling rate | % of material recycled into lower-value applications | % |
| Economic and business | Export of waste | tonnes of waste exported to non-OECD countries | t |

| | | | |
|---|---|---|---|
| Economic and business | Total waste generated | absolute tonnes of waste generated | t |
| Economic and business | Waste intensity | tonnes of waste per 1,000,000 EUR revenue | t/mil. EUR |
| Economic and business | Zero waste to landfill status | % of sites generating zero waste | % |
| Economic and business | Internal scrap recycling rate | % of production scrap bed back into manufacturing | % |
| Economic and business | Hazardous waste ratio | hazardous waste to total waste | % |

## Annex II. Shortlisted KPIs following quantitative expert evaluation

| PERFORMANCE DIMENSION | KPI NAME |
|---|---|
| Environmental | Climate change |
| | Networking complexity |
| | Ecosystem quality |
| | Ecotoxicty |
| | Eutrophication |
| | Footprint |
| | Gas emission |
| | Hazardous waste produced |
| | Hazardous waste recycled |
| | Land occupation |
| | Non-hazardous waste produced |
| | PM emission |
| | Radiation emission |
| | Total waste sent to landfill |
| | Waste generation |
| | Waste heat generation |
| | Water discharged |
| | Water withdrawal |
| Technical | Energy Cascading Index |
| | Loop Closure Index |
| | Circularity Index (System Level) |
| | Enabling assets |
| | Energy consumption |
| | Energy efficiency |
| | Energy intensity |
| | Exergy efficiency |
| | Level of technical cooperation |
| | Material consumption |
| | Material efficiency |
| | Non-renewables (Tech/Env) |
| | Productivity |
| | Recovery rate |
| | Renewables (Tech/Env) |
| | Resource efficiency |
| | Resources supply |
| | Material consumption (or water consumption) |
| | Symbiotic Link Density (Network Connectivity) |
| | Technical feasibility |
| Economic and Business | Internal Rate of Return (IRR) |
| | Capital expenditure (CapEx) |
| | Operating expenditure (OpEx) |
| | Return on Investment |
| | Tangible environmental costs |
| | Cost Savings from Waste Disposal |

| | |
|---|---|
| | Cost Savings from Raw Material Purchase |
| | Energy cost savings (electricity / fuel / heat) |
| | Carbon cost avoided |
| | Resource Use Efficiency (or Intensity) |
| | By-product utilization rate |
| | Revenue from By-product Sales |
| | Revenue share from circular products |
| | Level of economic cooperation |
| | Generate local business opportunities |
| | Increase in Business Competitiveness |
| | Value generated by CE sector |
| | Private sector investment in CE |
| | Public R&D spending to support CE innovation |
| | % Circular jobs |
| Cultural and Social | % of IS Exchanges Benefiting Community |
| | Number of Public Outreach Events for IS Awareness |
| | Ratio of supply chain actors showing their commitment to CSR (Corporate Social Responsibility) criteria |
| | Change in Community Attitude Toward Industry |
| | Social acceptance |
| | Industrial symbiosis readiness scales for high energy industrial processes |
| | Number of Knowledge-Sharing Workshops / Trainings Conducted |
| | Skill level |
| | Time from Knowledge Transfer Intervention to First IS Exchange Implementation |
| | Workforce Trained in IS-Relevant Skills |
| | Fatalities (employees only) |
| | Jobs created via IS-network participation |
| | Occupational illness |
| | Workforce employed locally |
| | Diversity of Stakeholder Engagement (demographics) |
| | Improvement Rat in Resource Efficiency from Cross-Border Collaboration |
| | Number of Community Benefit Projects Associated with IS |
| | Social level of cooperation |
| | Stakeholder Engagement Quality |
| | Stakeholder Net Promoter Score (NPS) |